World Premier International Research Center Initiative (WPI) Executive Summary (For Extension Application Screening)

Host Institution	Tokyo Institute of Technology	Host Institution Head	Kazuya Masu
Research Center	Earth-Life Science Institute	Center Director	Kei Hirose

Instruction:
Based on the Center's Progress Report and Progress Plan, prepare this summary within 6 pages.

A. Progress Report of the WPI Center

I. Summary

The production of life from non-living matter has been solved at least once, not by humans but rather by naturally occurring processes on the early Earth, more than 3.8 billion years ago. ELSI is inspired by the idea of following this successful historical example as both a scientific and organizational strategy to solve the challenging puzzle of the origins of life. This novel idea motivates a new kind of adaptive organization that evolves with the science, and creates opportunities that would not otherwise exist. We diversify our intellectual lineages (internationalization), we catalyze novel evolutionary innovations by concentrating and cross-fertilizing ideas from multiple fields (fusion), and we establish a unique culture that is adapted to our needs (reform).

ELSI creates value, and multiplies both the scientific and financial investments made by its researchers and benefactors. This is evidenced by the scientific and organizational breakthroughs, the new opportunities, connections, visions, solutions, and discoveries that ELSI makes possible as an institute. The assembly of a leading team of scientists to ELSI guaranteed that we would produce great science, but we have gone much further by achieving results (scientifically and organizationally) that would not have been possible without ELSI serving as a primary catalyst. We strongly leveraged WPI support, raising additional funding well in excess of the WPI grant, including development of large private donations from both Japan and abroad that are unprecedented in the history of Tokyo Tech.

Prior to ELSI, the origins of life field was slowly progressing, as specialists from different fields talked past (instead of to) one another, as artificial walls were constructed between phenomena whose natural collaboration is crucial to the origin of life, and where origins researchers did not have a place to call their home. Today, ELSI is home.

II. Items

1. Overall Image of Your Center

ELSI is the only brick-and-mortar research institution in the world dedicated to integrated studies of the origins of planets and life, and attracts top researchers from around the globe in our fields of study. We have capitalized on strong public and scientific interest in origins of life studies, and the possibility of life elsewhere in the universe. Our outreach activities, TV appearances, press releases, and internet presence has allowed ELSI to build a respected public image in Japan and abroad. ELSI has been a transformational presence at Tokyo Tech, both as an international oasis as well as a leading presence for our collective ambition to transform Japan's top science and engineering school into a globally top-ranked international university. We proudly carry the WPI banner, whose 4 pillars inspire us and have helped us to recruit many visionary leaders (both junior and senior) from around the world to come work at our home in Japan.

2. Advancing Research of the Highest Global Level

ELSI set out to address an ambitious science goal: the origins of life within the context of the origin of the Earth and other planets, and has been extraordinarily successful (~900 publications) in making significant progress and yielding a wide-reaching impact in all of these areas.

A. Origin of the Earth – ELSI scientists reconstructed key stages in the formation of the Earth, where and how our planet formed, what determined its composition and the changes in its internal state over time, how crucial elements responsible for the atmosphere and oceans were delivered and why they were retained, and how surface conditions responsible for life depended on these earlier stages. We developed the first integrated models of accretion and transport in stellar disks across scales from gas and dust, through crucial intermediates known as "pebbles," to the migrating orbits of early planets, and effects of giant impacts. By combining computer models with cosmochemical evidence, we have explained the diversity seen in the solar system (as well as exoplanetary systems), while constraining the possible sources for light elements (C, O, Si, H, S, N) on early Earth.

Our researchers have also performed flagship work addressing questions about how to power planetary magnetic fields, connecting the deep interior of planets to the surface environment. We discovered that Earth's core incorporated much more hydrogen than previously thought. A key discovery at our world-leading high pressure experimental labs showed that early precipitation of silicon oxides from the core could have powered an early magnetic field protecting Earth's atmosphere from loss by solar wind, providing a new solution to a major paradox in geophysics.

Finally, we have learned that the cooling rate of early planetary surfaces is highly sensitive to solar irradiance and why, even with similar starting compositions, Venus dried and fell into a greenhouse from the beginning, while Earth retained an ocean and sequestered most of its CO_2 in the subsurface.

B. Birth of the Earth-Life System –We examined the origin of life as the emergence of a new geological system, accounting for the interactions between oceans, atmosphere, and solid Earth that are key ingredients for early chemical evolution. ELSI's researchers broke new ground to provide evidence for the formation and sustenance of a reducing environment on the early Earth, with important consequences for prebiotic organic chemistry. We discovered that a single late giant impact produces a secondary hydrogen atmosphere that lasts for 200 million years at the beginning of the Hadean eon. Consistent with these findings, the geochemistry team showed that complex stable isotope signatures of Sulfur in ancient rocks require a high ratio of CO to CO_2 well into the Archean, a breakthrough that has eluded geochemists for decades and a crucial condition for synthesis of complex organics.

Our work builds the case that diverse planetary surface conditions are essential to the emergence of life. We studied the roles of ocean bottoms and land as sources of nutrients, the roles of the sun, rock/water interface, and radioactive subsurface as sources of energy, the timing and extent of water delivery, and the composition of the earliest oceans and crust to predict the earliest conditions supporting prebiotic chemistry and the emergence of life. ELSI researchers developed a new field of study, geoelectrochemistry, where bulk-phase electrical potential interacts with geological redox chemistry to produce reactive C and N compounds, which drive downstream pathways that mimic the central metabolism of all extant life on Earth. In a seminal work of ELSI scientists, the requirements for life are identified and elaborated to further extend the example of early Earth geology into a framework for the search for other habitable planets.

The most important contribution that ELSI is presently making would not have been possible if theorists and experimentalists were not brought together under the same roof. Life did not emerge in a controlled laboratory setting, such as a beaker. ELSI scientists have established a new robust approach to move these studies into the realm of combinatorial complexity that characterizes real planetary geochemical environments, creating novel computational and analytic methodologies, and applying these to formation, structure, and properties of functional polymer families.

C. Coevolution of Life with the Earth – We worked to identify major transitions that shaped the evolving biosphere, its architecture, modes of evolution, and dependence on planetary conditions through time, and how bio-evolution has fed back to shape Earth's geological history.

ELSI researchers reconstructed genomes and bioenergetic systems of ancient bacteria, and shown how those changed in response to evolving planetary chemistry. We reconstructed isotopic and mineral signatures linking biological major transitions to the rock record, both for sulfur metabolism and for oxygenic photosynthesis, the biological innovation that has most impacted every surface environment on Earth. Genomes on Earth are carried by two kinds of lifecycles: one in free-living cells and the other in viruses. We have expanded worldwide knowledge of the diversity of viruses of thermophilic Archaea by nearly 100%, and are exploring the limiting conditions for single-stranded DNA and RNA viruses to understand constraints on an RNA world. ELSI now hosts one of the largest collections of Archaeal viruses of any institution in the world.

We integrated synthetic and evolutionary biology to understand elements of structure and function in early organisms. We demonstrated functional proteins translated using simpler genetic codes, and enzymes to synthesize key amino acids that do not require those acids in their sequences. We achieved increasingly complex functions in synthetic cell membranes, and coordination of molecular systems within and across them. To understand what processes drive biological innovation, we demonstrated new evolutionary paradigms for the use of external constraints as scaffolds to create novel complexity. We have also shown how catalytic imprecision can be the gateway to new functions – likely an essential mechanism in early eras of short genomes and unreliable replication.

D. Life in the Universe – Our studies of the history of Earth and its Life reveal a unifying paradigm, of alternating stages of diversification and selection, which serves as a springboard to understand the habitability of planets around other stars and the principles that make life on them different or similar to our own.

Principles of life are essential features that can be formalized independently of the way they are expressed in Earth's biology. One such feature is heredity, without which selection cannot lead to adaptation. ELSI derived measures of capacity for heritable variation that do not depend on genes or genomes, and apply across a range of widely studied compositional models and even more general dynamical systems. Computational combinatorial methods allow us to ask which aspects of Earth-Life reflect inherent limits of chemistry, and thus may be universal. We have shown that the biological amino acids as a set cover a much wider range of properties essential to protein function than random sets of possible amino acids of similar size. Selection has made the biological set more unique because they are closer to the limits of chemical possibility.

A universal biology must explain how simple patterns of dynamical complexity create more complex patterns in a self-maintaining hierarchy. We have studied this problem for the emergence of lineages at the forming of the genetic code, showing how an era of innovation-sharing in which all components are exchanged independently can produce the error-buffering properties of the biological code, which then permit reliable protein synthesis, faithful molecular replication, and the emergence of vertical descent in a Darwinian world.

3. Generating Fused Disciplines

Nature did not produce life >3.8 billion years ago by constructing artificial walls between astrophysical, geological, and biological phenomena...neither should we. The achievement of great advances in the evolution of life, such as photosynthesis or multi-cellularity, required bringing unique combinations of life together (proximity), facilitating cross-fertilization (communication), and enabling the development of concerted and robust systems level behaviors (culture) in response to the same kinds of external influences. At ELSI we enable fusion between disciplines in much the same way as life achieved its major revolutions.

ELSI's fusion science has blossomed under these conditions. Our highlighted science results (above) are all catalyzed by hosting experimentalists and theorists under the same roof, and bringing together researchers from many fields. Interdisciplinary teams at ELSI have tackled numerous additional challenges together, including models for the origin and circulation of water in the Earth and use of amoebas as virtual computers to solve problems that are otherwise impossible to solve using conventional computers. We brought together astrophysicists and cosmochemists to explain Mars' composition and orbital radius, modeled prebiotic chemistry in icy moons, formulated new approaches to studying origin of life, and proposed biology-inspired models for the Earth's formation, composition, long-term evolution. We brought new ideas to the discussion of biomarkers on exoplanets, modeled nitrogen cycles in planets without life to see what they would look like, unified important ideas around the geochemical and geoelectrical output of deep sea vents and how they power life in a deep marine environment, and explored how the geochemical availability of various metals in the early Earth environment facilitated a variety of chemical pathways for biological metabolism. All of this work requires an unprecedented degree of breadth, which is critical for tackling the greatest challenges and opening new opportunities.

ELSI actively engages in creating conditions for fusion. Traditional funding is targeted to specialized subjects rather than broadly integrative fusion, so ELSI took advantage of interdisciplinary research funding opportunities and achieved great success, including the ELSI Origins Network (EON, PI: Hut) supported by the US-based Templeton Foundation, and interdisciplinary JSPS grants like Hadean Bioscience (FY2014-2019, PI: Kurokawa), Co-evolution of the Core and Mantle (FY2015-2020, PI: Tsuchiya), and Aquaplanetology (FY2017-2022, PI: Sekine). ELSI also established internal funding mechanisms to support fusion science within the institute that could not be covered by other grants. ELSI maintains interdisciplinary study groups, bringing together researchers from multiple fields to learn the best strategies to communicate and collaborate across discipline boundaries. We also established hands-on tutorials (ELSI "youchien"), strategy meetings, interdisciplinary courses led by ELSI PIs in campus departments, and beyond.

4. Realizing an International Research Environment

Nothing distinguishes ELSI's achievements more than its strong international research environment and staff, which are catalysts for breakthrough science (above) and administrative reform (below). ELSI has grown a vast international network and recruited top scientists from around the world at both junior and senior levels. ELSI is now globally considered the place for the very highest level of research in our fields. Applications from graduate students are on the rise, and our staff positions are highly coveted.

ELSI's management has ardently worked to meet the requirements to be a WPI research center, including (1) establishing a research environment capable of attracting the world's best minds, (2) mandating English in all communications involving ELSI researchers and required for all events, workshops and institutional email lists, and (3) recruiting the majority of our junior and senior researchers from outside Tokyo Tech (including abroad). Today, 7 out of 17 PIs are world-class foreign researchers recruited from overseas, of which 4 are based in Tokyo full-time. Recruitment of talented bilingual secretarial staff and life support advisors was crucial to assist our international research staff, who provide relocation and daily life support, Japanese language classes, support for acquisition of competitive funds, safety management training, cultural diversity training, and a confidential method of reporting issues to the management.

ELSI pursues a targeted strategy for the recruitment of internationally competitive young researchers that is unique in Japanese universities. ELSI PIs employ their personal international networks to source top quality graduate students and postdocs as potential candidates. ELSI's activities to invite students of our symposium speakers, hosting winter and summer schools, and active sponsorship of young researcher conferences have paid great dividends. In our past junior recruitment, ELSI received 363 applications from more than 30 countries around the world, most of which (75%) were from abroad. ELSI also attracts competitive Japanese candidates applying from overseas.

ELSI maintains satellites at Ehime University, the Institute for Advanced Study, Harvard University, University of Tokyo, and Columbia University in New York. ELSI has formalized collaborations with 23 research institutes and universities around the world, a number that continues to expand. ELSI has hosted 7 international symposia, dozens of workshops, several short schools, has a vigorous visitor program to invite top scientists to spend time and collaborate at ELSI. The ELSI Origins Network (EON), launched by a large Templeton Foundation grant, provided a concrete measure of our global visibility. EON's funding for post-docs working half time in an institution abroad and the other half time at ELSI, and establishment a new global network in origins of life research allowed ELSI to significantly expand its profile, adding leverage to the funding provided by WPI.

5. Making Organizational Reforms

A key to ELSI's success is the implementation of new organizational strategies that are customized to our unique brand of science and position in the university. As a "special zone" within Tokyo Tech, where new administrative systems can be developed, tested, and exported to the broader university, ELSI is a key collaborator with our President in carrying out his vision to become a leading global university. Tokyo Tech administrative staff who regularly circulate into ELSI posts and then back to the broader university call it the "ELSI style," and we have seen many ELSI-inspired reforms advanced across the entire university via this conveyor system.

ELSI has worked with Tokyo Tech to achieve many important reforms, many of which have spread to the entire university:

●WPI style of top-down management under the leadership of a center Director, allowing flexibility we need to adapt to our special scientific, cultural, and logistical challenges.

●Performance-based salary system and competitive salaries in a global context.

●Cross-appointment system to acquire top researchers. After ELSI's first case, Tokyo Tech has utilized it to hire 22 researchers (as of January 2019).

●Amendment of regulations on private donations, enabling ELSI's first endowed professorship.

●Tokyo Tech adopted English-based support in university-wide email notifications, a consultation desk for personnel matters, safety training.

●Open and flat research organization that stimulates interdisciplinary research.

●Change in university regulations for travel insurance for work travel, and corporate credit card.

●Tokyo Tech USA non-profit organization enabling private donations from the US.

ELSI's signature achievement in administrative reform was to work with the Tokyo Tech President, our advisors, and MEXT to find a practical way to transition to a new Director following the initial WPI 10-year funding period. In 2018 we successfully recruited a prominent senior scientist and administrator from the US-National Aeronautics and Space Administration (NASA) to take on the new roles of Executive Director and Specially Appointed

Adviser to the President (of Tokyo Tech). Dr. Voytek is already active in improving ELSI's organizational and scientific strategy and efforts to develop new sources of funding (public and private).

6. Others

(1) ELSI has made a significant contribution towards nurturing the next generation of researchers by having our world-renowned scientists supervise graduate students. ELSI has also been contributing the development of postgraduate education programs by accepting excellent foreign students recruited through ELSI's overseas network.

(2) ELSI has received global funds in recognition of its unique research environment and its aspirational goals. In July 2015, ELSI was awarded funds totaling JPY670 million (USD1=JPY122) from the John Templeton Foundation in the United States. The purpose of the grant was to build an international network of origins of life research with ELSI as a hub. The fact that the John Templeton Foundation chose to award ELSI to be a key player in origins of life research is testament to ELSI's international reputation.

(3) ELSI is positioning itself as a leader in science communication. As an integral part of our internationalization efforts, ELSI is focused on transforming science communication in Japan that is conducted in English. We hosted the Japan Scicom Forum 2018 and 2019 as events to bring together communicators, writers, scientists, journalists and selected experts from abroad to share ideas and to inspire and boost the cohesion of science communication in Japan. In addition to building ELSI's communications, our new Communications Director (joined Nov. 2018), meets with Tokyo Tech PR to join efforts on increasing effective output.

World Premier International Research Center Initiative (WPI)
Progress Report of the WPI Center
(For Extension Application Screening)

Host Institution	Tokyo Institute of Technology	Host Institution Head	Kazuya Masu
Research Center	Earth-Life Science Institute	Center Director	Kei Hirose

Common Instructions:
* Unless otherwise specified, prepare this report based on the current (31 March 2019) situation of your WPI center.
* As a rule, keep the length of your report within the specified number of pages. (The attached forms are not included to this page count.)
* Use yen (¥) when writing monetary amounts in the report. If an exchange rate is used to calculate the yen amount, give the rate.

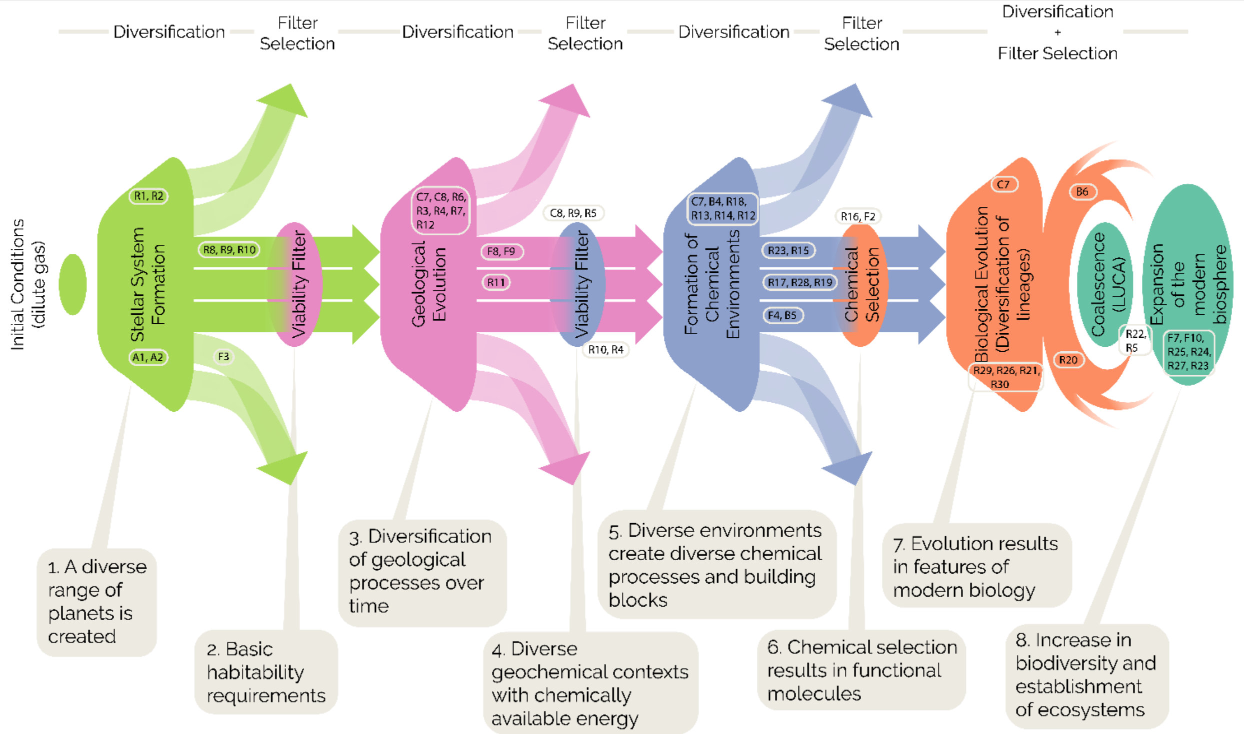
1. Overall Image of Your Center (write within 2 pages including this page)

Describe the Center's current identity and overall image.

・ List the Principal Investigators in Appendix 2, and enter the number of center personnel in Appendix 3-1, 3-2, diagram the center's management system in Appendix 3-3, draw a campus map in Appendix 3-4, and enter project funding in Appendix 3-5, 3-6.

Only at ELSI is a phrase that visiting colleagues use to describe their experience at our home in Tokyo. It beckons a conversation, a collaboration, an idea that could occur only at ELSI. It refers to the unique combination and enormous breadth of our researchers, the spontaneous discussions between astrophysicists, chemists, geophysicists, and biologists that occur daily in our Agora meeting space over tea and coffee, and the uniquely powerful new scientific concepts that are cultivated in an institute of unprecedented breadth and ambition. These impressions are amplified by the context of the institute, its position within Tokyo Tech, and the powerful synergy between Japan and the world that naturally emerges in a custom-designed environment that encourages and supports a new brand of science that simply does not exist elsewhere in our respective fields.

How did the Earth and its life form and evolve together? Is there life elsewhere in the universe and how could we find it? These are the fundamental questions that motivated us to launch a one-of-a-kind institute in December 2012, with generous support from the World Premiere International (WPI) research center initiative. ELSI specifically proposed to investigate (A) how the Earth formed, (B) the



The ELSI models is both a theoretical framework and a roadmap for origin of life research. It captures the idea that the events from the Big Bang to life was a series of diversification's followed by selections. Numbers R1-30 map the citations used in the results described below and F1-10 map the citations described in the Fusion section. A, B, C, and D map the science goals from our founding proposal.

emergence of life in the early environment, (C) co-evolution of the Earth-life system, and (D) the emergence/occurrence of life elsewhere in the universe. In each of these domains ELSI has successfully established itself as a global hub, assembled teams of world class scientists at both the junior and senior levels, and achieved important breakthroughs that drive the scientific direction and dialogue around the world (Section 2).

ELSI was the first, and presently remains the only, permanent brick-and-mortar research institute that is dedicated to research surrounding origins of life. ELSI's recognition as a global center is highlighted by a large ($5.6M USD) private investment by the US Templeton Foundation (unprecedented in the history of Tokyo Tech. Even inside Japan ELSI has attracted private donations (30M yen) to support a newly endowed professor position. Our reputation is apparent in the high quality and overwhelming number of world class applicants who apply to our recruitments, a talent pool from which we are only able to hire a small fraction. It manifests in the newly launched initiatives that have sprung up around the world since ELSI was born, which have been inspired by our example. ELSI is the place where hundreds of leading scientists from all over the world have made a pilgrimage to experience what a genuinely collaborative, inter-disciplinary, and open research environment can be like.

ELSI achieved these successes by formulating a newly inspiring and unique vision for our science, launching an ambitious in-house global headhunting/recruiting/PR operation, adapting our organization and management system to support non-traditional modes of enormously broad inter-disciplinary research, constructing an attractive and inviting work environment, and working closely with Tokyo Tech to achieve our mutual aims. Our young scientists have moved to faculty and research positions at top universities and research institutions around the world, carrying the ELSI virus to affect a generational change across our sciences. Excellent students from the world's top universities have sought out, and are presently pursuing, graduate opportunities at ELSI.

Our ideas are innovative and transformative. ELSI's philosophy is that life emerges as a collaboration among geological processes in an open-system context that is intimately connected by fluxes of energy and matter in the natural environment. Instead of separating geology and biology and emphasizing their difference, we instead seek understanding through their unification and placement within a common context. Following a century of compartmentalization, specialization, and limited progress on origins of life, ELSI is leading the re-integration and synthesis of knowledge across the natural sciences to address these fundamental questions with a fresh approach.

A key result of ELSI's effort thus far is to establish a new framework for the origin of life as a sequence of diversification and selection of processes that begin prior to planet formation, proceed through the emergence of diverse planetary environments, overcoming the key hurdle of cultivating self-replicating chemical systems with the capacity for open-ended evolution, the colonization of life forms in myriad niches with a variety of energy sources, and the emergence of a planet-life co-evolutionary relationship that span billions of years (illustrated in the above figure). This is an evolutionary conception that goes beyond biology, and weaves together a narrative extending all the way back to planet formation and

The WPI pillars of cutting edge science, inter-disciplinary fusion, globalization, and administrative reform are woven deeply into the fabric of ELSI, our unwavering and total commitment to all of these aims is our guiding light. We found that we could not achieve success in any one of the pillars without working in concert with the others. Ambitious and broadly inter-disciplinary science of this scope requires an international effort from world class scholars in a variety of fields, while attracting and supporting them can only be accommodated by reforming and internationalizing a work environment and allowing us to establish a unique institutional culture that has become famous around the world.

ELSI has been a transformational presence at Tokyo Tech, both as an international oasis as well as a leading presence for our collective ambition to transform Japan's top science and engineering school into a globally top-ranked international university. The QS university world ranking for Tokyo Tech (presently #58) cites ELSI in its assessment, stating that "findings from research institutes such as ELSI are fed back into curricula, and as laboratory members, students are in close contact with the world's top researchers." Our mandated English-language research environment preceded Tokyo Tech's migration to English-only graduate curriculum by 6 years. We led a wave of high profile international recruitments to Tokyo Tech, and established models that will be increasingly important as the university seeks to attract more global talent in other areas. ELSI's open research environment facilitating inter-disciplinary collaboration has been exported to the broader university, and incorporated into its organizational structure. ELSI's administrative staff have circulated in and out of our institute, transmitting their innovations for "ELSI-style" to other sectors of the university.

Continuing into the future, our collective vision is for ELSI to continue pushing the frontiers of science, and exporting our transformational fruits to all of Japan, Asia, and the world.

2. Advancing Research of the Highest Global Level (within 12 pages)

2-1. Research results to date

Describe issues of a global level that the Center has challenged, and give the results. Select 15 representative results achieved during the period from 2012 through March 2019. Number them [1] to [15] and provide a description of each. Place an asterisk (*) in front of those results that could only have been achieved by a WPI center and explain the reason in the description.

- In Appendix 1-1, list the papers underscoring each research achievement (up to 30 papers) and provide a description of each of their significance. And in Appendix 1-4 list the center's research papers published in 2018.

ELSI's goal

The Earth-Life Science Institute (ELSI) aims to answer the fundamental question "when and where did life originate and how did it evolve?" ELSI proposes to carry out research in order to understand the origin of life in the context of planetary environments by addressing the following four goals:

(A) Origin of the Earth. Identify the key stages in the formation of Earth, by answering questions such as: how are planets formed and how did the Earth emerge in the early solar system, what was the composition and internal state of the early planet, and how was water delivered to the Earth.

(B) Birth of Earth-Life system. Seek the origin of life as the emergence of a new geological system, accounting for the interactions between oceans, atmosphere, and solid Earth that are key ingredients for early chemical evolution.

(C) Evolution of Earth-Life system. Investigate the co-evolution of the Earth-life system. For example, how did life modify its environment, such as by producing an oxygen atmosphere? What are the influences and feedbacks between the solid Earth and surface environment? What is the importance of extra-terrestrial events in the Earth-life system?

(D) "Bioplanets" in the Universe. Use the foundation of Earth-life science as a springboard to identify habitable environments in the universe, and thereby establish a new dialogue for studies of the origin of universal life. Answer the questions: How unique is our planet? How should we search for extraterrestrial life?

2-1.A Origin of the Earth

The story of how life emerged on Earth begins when various types of stars are formed in molecular clouds in galaxies and then planets are formed in protoplanetary disks, byproducts of star formation, orbiting around these young stars. What features of our solar system, and what characteristics of Earth and its evolution over time, led to the only known planet to support life? How was our Earth born? What are the mechanisms that created the diversity of planetary systems we know today? These questions are fundamental and essential ones for us to understand the universality and uniqueness of Earth and its biosphere. ELSI researchers have reconstructed key stages in the formation of the Earth, answering the questions where and how our planet formed, what determined its composition and the changes in its internal state over time, how crucial elements responsible for the atmosphere and oceans were delivered and why they were retained, and how surface conditions responsible for life depended on these earlier stages.

<u>*Research results 1: How do terrestrial planets form?</u>

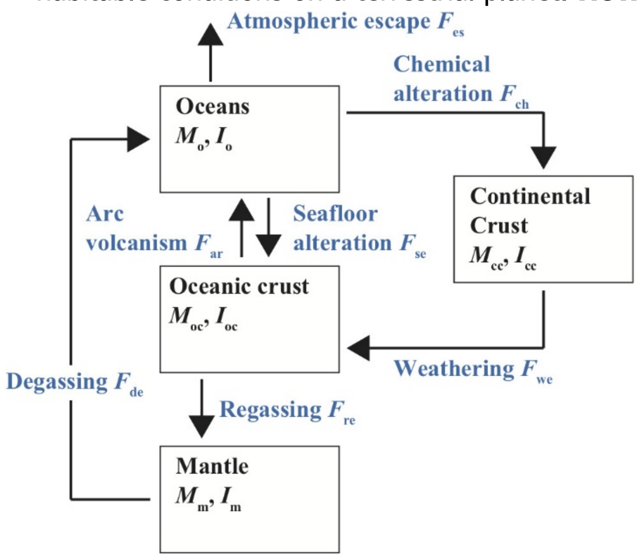
The leading models for planet formation hold that planets are born by the gradual accumulation of dust and gas inside a protoplanetary disk, beginning as the dust grains coalesce to form larger and larger rocks, and continuing as asteroids, planetesimals, and planets emerge. Previous-generation models have not adequately accounted for particle accretion from cm to km scales. In two seminal papers, Shigeru Ida, Ramon Brasser and their co-workers [1,2] have developed the first integrated models of accretion and transport in stellar disks across scales from gas and dust, through crucial intermediates known as "pebbles", to the migrating orbits of early planets, and effects of giant impacts. Going further to combine approaches from separate fields, particularly N-body computational simulations together with cosmochemical evidence, they can account for the diversity seen in planetary systems – which have become observable only within the last 5 years – while also constraining the possible sources for light elements (water, C, N) on early Earth. For example, it is understood that pebbles that formed in the outer solar system could supply volatile elements to the terrestrial planets. However, cosmochemical analysis [2] argues against this scenario, suggesting that Earth's volatiles originated in the relatively water-poor inner solar system, explaining Earth's low volatile budget compared to some extrasolar systems. The unification afforded by pebble accretion sets the standard that in order to correctly infer how planetary systems form, detailed prescriptions of disk evolution and pebble growth, sublimation, destruction and migration are required.

<u>*Research results 2: How did the composition of the Earth's core result in a magnetic field?</u>

The Earth's magnetic field deflects harmful radiation that otherwise could destroy the atmosphere essential for retaining life-sustaining water on the surface. ELSI has done flagship work addressing questions about how to power magnetic fields in general, and more specifically Earth's magnetic field history. ELSI researchers have discovered that as Earth's core separated from its rocky mantle, it could have incorporated much more Silicon and Oxygen than had been believed, along with significant Hydrogen which remains there to this day. Crucially, the early precipitation of Silicon oxides as the core cooled created a vigorous buoyant stirring force, increasing the likelihood to form an early magnetic field protecting Earth's atmosphere from loss by solar wind. Using high pressure and temperature experiments, Kei Hirose led a team of ELSI researchers [3.4] to characterize how complex multi-component liquids (namely the Fe-Si-O ternary) can provide a buoyancy source to drive dynamo activity where it would not be predicted from binary systems only. These experiments using laser-heated diamond-anvil cells characterize the liquidus phase in the iron-rich portion of the Fe-Si-O system and demonstrate that SiO2 would be the first phase to crystallize as the core cools, leaving dense iron-rich liquid behind. Addressing the same issue from a completely different field, geobiologist Joe Kirschvink and co-workers [5] provide evidence of the timing and evolution of the geodynamo. Their work shows that magnetotaxis evolved in bacteria during the Archean, before or near the divergence between the Nitrospirae and Proteobacteria phyla, suggesting that magnetotactic bacteria are among the earliest magnetic-sensing and biomineralizing organisms on Earth. In the absence of an active geodynamo and a magnetic field it is hard to explain why microorganisms would have evolved this adaptive capability. An early origin of magnetotaxis would have created evolutionary advantages in coping with environmental challenges faced by microorganisms on early Earth; its persistence in separate lineages implies the temporal continuity of a geomagnetic field, providing a biological constraint on the evolution of the geodynamo.

***Research results 3: Inventory of Earth's water.**

An essential element for the origins and sustenance of life, water is unequally distributed among the terrestrial planets of our solar system. **Why does liquid water exist at the surface of the Earth and not on other planets?** One part of this question concerns delivery (see Result 1 above), but several other planetary properties also play a role. Through ELSI's work we now understand why, from similar starting compositions, Venus dried and fell into a runaway greenhouse, while Earth retained an ocean and sequestered most of its CO_2 in the subsurface. By recognizing that the cooling rate of early planetary surfaces is highly sensitive to solar irradiance at certain thresholds, changing by more than a factor of ten over the small difference of orbital radius between Earth and Venus, Keiko Hamano, Hidenori Genda and Yutaka Abe [6] have provided a widely-accepted explanation for why Venus lost its water and Earth did not. Hamano et al. developed an evolutionary model for magma ocean crystallization, and showed that, assuming water delivery occurs early, the crystallization timescale of a primordial magma ocean plays a major role in controlling the bulk water amount. That timescale has a strong dependence on the planet's distance from the star through the energy balance between stellar radiation and radiation from a steam atmosphere. Beyond a critical orbital distance, magma ocean crystallization takes ~1 Myr and the volatile inventory can be retained, whereas planets closer than that radius crystallize on ~10 Myr timescales and hydrodynamic escape to space has time to desiccate the planet. The sensitivity regime for magma ocean cooling provides a first-order constraint on how to establish habitable conditions on a terrestrial planet. **How much water was on the early earth** is a question answered by Kurokawa et al. [7]. Using the deuterium/hydrogen (D/H) isotope ratio, which reflects the global cycling and evolution of water on Earth as it fractionates through planetary processes, this paper reconstructs the early Earth's ocean volume. It models the combined effects of seafloor hydrothermal alteration, chemical alteration of continental crust, slab subduction, and hydrogen escape from the early Earth, as well as degassing at mid-ocean ridges, hot spots, and arcs. In order to produce observed isotope ratios in these improved fractionation models, secular net regassing and/or early fast plate tectonics are needed, suggesting that the volume of Earth's initial oceans – while still small in absolute magnitude – could have been 2 to 3 times larger than those on Earth today.

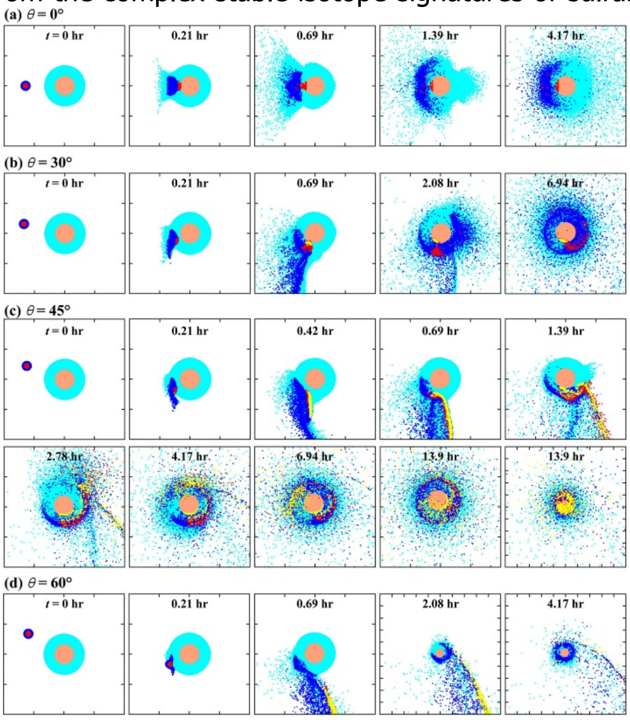


2-1.B. Birth of the Earth-Life System

We seek to understand the origin of life as the emergence of a new geological system, accounting for the interactions between oceans, atmosphere, and solid Earth that are key ingredients for early chemical evolution. In order to answer the question **where and how did life emerge on Earth**, ELSI researchers have reconstructed essential characteristics of the conditions on early Earth. They go on to examine three conceptual stages in chemical evolution, which may overlap spatially and temporally: 1) the formation of the basic inventory of chemical building blocks driven by geological environments; 2) the diversification of the abiotic chemical inventory through the formation of dynamic reaction networks with an emphasis on networks' propensity towards self-organization; 3) the formation of functional chemical assemblies within the dynamic reaction networks under geological, environmental or physicochemical selective pressures. Prebiotically plausible organic and inorganic chemical processes are numerous, and therefore the scientists explore combinatorially complex reaction spaces. Improved understanding of the breadth of chemical reactivity in planetary environments, and of selective geological and chemical processes that promoted the emergence of life-like ordered chemical reaction networks, are brought together in a *new ELSI model of the origin of life*.

***Research results 4: What were the initial conditions on early Earth that would support the emergence of life?**

The oxidation states of carbon and nitrogen in early Earth's atmosphere are fundamental to its capacity for organic synthesis. This aspect of the state of the early Earth's atmosphere has historically remained unresolved. A highly reduced atmosphere in which methane, ammonia, and water were all major constituents was first proposed as necessary for prebiotic chemistry by the famous Miller-Urey experiments of the 1950s. However, subsequent photochemical studies showed that any methane or ammonia in the atmosphere would quickly be destroyed, and other geologically based arguments supported an atmosphere of H_2O, CO_2 and N_2, which would be unfavorable for prebiotic chemistry. ELSI's researchers have pursued and reported on two lines of evidence to support a reducing environment on early Earth essential for prebiotic chemistry. First, we have discovered that mantle composition and early atmospheres can be linked through models of the frequency and size of late impactors. Hidenori Genda and co-workers [8,9,10], using a hybrid numerical simulation of giant impacts and fragment dynamics, showed that a single lunar-sized body, striking the Earth between the moon-forming event at 4.51 Ga and the last terrestrial differentiation that separated silicate reservoirs at 4.45 Ga, best accounts for the "late veneer", an excess of iron-loving elements observed in the current Earth's mantle. The differentiation implied within such a large impactor then predicts core fragmentation and ejection of metallic Fe, which would have re-accreted on Earth as an iron "rain", producing a secondary hydrogen atmosphere that lasted for 200 million years at the beginning of the Hadean eon. These results for Earth suggest that giant impacts would be key events determining the redox state of early atmospheres of any terrestrial planets. Second, we have found, from the complex stable isotope signatures of sulfur, that Earth should have maintained a higher ratio of CO to CO_2 than has been expected well into the Archean, with implications for synthesis of complex organics. The source of stable sulfur isotopic anomalies recorded in ancient sedimentary rocks from 4.0 to 2.4 billion years ago has eluded geochemist for decades. Using an experimental system to mimic the atmosphere of early Earth, Yuichiro Ueno and his PhD student [11] succeeded in reproducing the Archean sedimentary S-Mass-Independent-Fractionation record including the rarest isotope sulfur-36. The oxidation state required in the laboratory model suggests that the early Earth's atmosphere should not have been a simple CO2 atmosphere but must have contained more reducing gasses, most likely CO. A CO-rich atmosphere may have been critical for prebiotic synthesis, and extends the era of reducing conditions by another 1.5 billion years beyond the episode inferred by Genda et al.

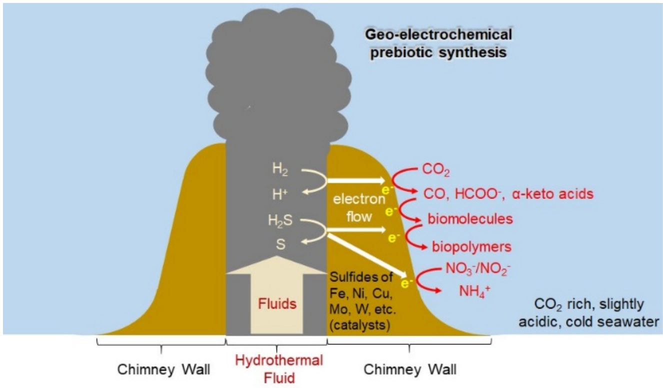


Research results 5: Where did life emerge?

Challenging oversimplified narratives often assumed for a single "birthplace of life", ELSI researchers have shown that diversity and complexity of planetary surface conditions are essential prerequisites to life's emergence. We have studied the roles of ocean bottoms and land as sources of nutrients, the sun, atmosphere, rock/water interface, and radioactive subsurface as sources of energy, the depth and timing of water delivery, and the chemistry and mineralogy of the earliest oceans and crust. Through these parameters we can say in how far Earth is special in its capacity to originate life. To address the question where life emerged on Earth, ELSI researchers consider geologically reasonable environments or networks of environments furnished with energy sources and chemical fluxes capable of initiating organic synthesis. The requirements for life are identified and elaborated in the seminal work of ELSI scientists, Maruyama, Genda, Hirose and their coworkers [12]. These researchers were the first to evaluate the contribution of the Hadean land mass as a source of essential nutrients for life. They also examined the size and the chemistry of the early ocean and the initial size of the planet, and concluded that Earth's advantages towards bearing life arise from our planet's diverse sources of inorganic nutrients. Moreover, early Earth's relatively shallow oceans and the presence of land masses allowed for nutrient concentration and recycling. Maruyama et al. have further extended the example of early Earth geology into a framework for the search for other habitable planets.

Research results 6: What fueled prebiotic synthesis from existing raw materials?

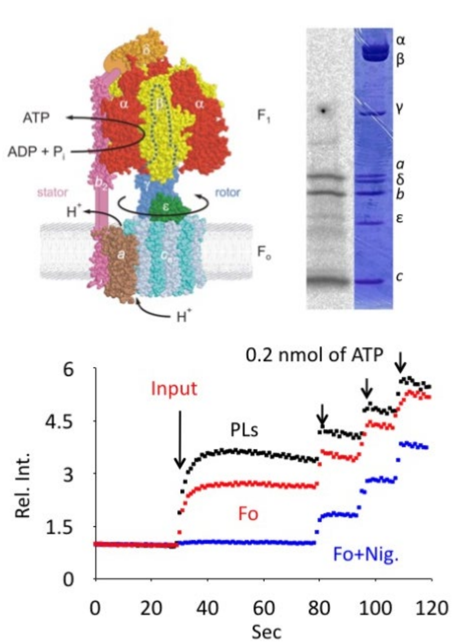
A signature of life is the harnessing of energy transduction to produce biomolecules. ELSI researchers have demonstrated the potential contribution of numerous energy sources to production of reactive C and N compounds, including the voltages produced at hydrothermal chimneys, secondary electrons liberated by ionizing γ-radiation, and atmospheric UV. We have derived the consequences for availability of species such as nitrate, ammonia, and CO in the early oceans, and shown how similar reaction pathways produce both precursors to key compounds such as nucleobases, and activators that can drive ligation of both amino acids and nucleotides. ELSI researchers have developed a new field of study within Origin of Life (OoL) research, "**geoelectrochemistry**", at the interface where bulk-phase electrical potential interacts with geological redox chemistry to drive biologically relevant processes. ELSI researchers Kitadai, Nakamura, Takai, Li, Gilbert, Ueno, Yoshida, and Oono along with their colleagues have demonstrated abiogenic electrochemical reduction of CO_2 to CO under geochemically plausible conditions [13]. The significance of this result is that abiogenic CO has long been proposed as a feedstock for complex organic synthesis (see Result 4 above); the efficient reduction of Kitadai et al. shows that the potentials obtained at hydrothermal vents are sufficient to drive carbon fixation. A second powerful energy source that triggers a multitude of chemical transformations is γ-radiation. This source would have been available on early Earth in the upper atmospheric layers and possibly near subterranean radioactive zones. ELSI researchers Fahrenbach, Yi, Cleaves, and Hongo took advantage of Tokyo Tech's irradiation facilities that are free for internal use to study the response of organic compounds to ionizing radiation [14]. In exploring how γ-radiation can help transform simple molecules such as HCN and HCONH2 into precursors of nucleic acids, they found that chloride induces the oxidation of HCN, at the same time as solvated electrons are generated. These products together open new chemical activation mechanisms for amino acids and nucleotides, furnishing potential abiotic routes to peptides and nucleic acids. A third source of energy important for prebiotic chemistry is UV radiation. Endo et al. [11] demonstrated that formaldehyde and other simple organic molecules, including glyoxylic acid, can be steadily supplied from a CO-atmosphere subject to solar UV radiation. The resulting steady supply of reactive organics can drive downstream pathways that mimic the central metabolism of all extant life on Earth.



***Research results 7: Escaping the lab to understand the evolution of the early chemosphere**

This result is by far the greatest contribution that ELSI has made to the origin of life community and would not have been possible if theorists and experimentalists were not brought together. All OoL researchers know that the Earth's chemosphere was and is a "messy" and dynamic environment.

However, most of the foundational research on prebiotic chemistry and the formation of the earliest biomolecules was conducted on laboratory benches in non-reactive containers, with pure substrates and under controlled conditions. ELSI researchers are moving the laboratory control of traditional Origins studies deeper into the domain of combinatorial complexity that now characterizes real planetary surface geochemistry, combining new computational and analytic methods, and applying these to formation, structure, and properties of functional polymer families. Organic chemical complexity is enormous in principle, yet living systems use only a small subset of the possible chemical space. In biology, this restriction partly results from selection in constructed settings, such as encapsulation and enzymatic catalysis. In contrast, prebiotic chemistry was much less controlled, and in its synthesis should have accessed a more extensive combinatorial diversity of products. ELSI scientists Chandru, Guttenberg, Giri, Hongo, Butch, Mamajanov and Cleaves [15] have demonstrated this premise by invoking oligomerization of likely prebiotically abundant compounds: the α-hydroxy acids (AHA). Mixtures of five distinct species of AHA under mild, plausibly common environmental conditions, give rise to extremely high diversity dynamic combinatorial polyester libraries. These libraries contain trillions of unique oligomer sequences and are the largest combinatorial libraries deliberately prepared to date. Having demonstrated the propensity of a prebiotic chemical system towards intractable diversity, ELSI researchers have begun to organize research in a field they call "messy chemistry" that takes a complex systems approach towards prebiotic chemistry. Many model prebiotic environments produce "messy chemical systems," or large assortments of compounds through a variety of mechanisms. In that respect they are strikingly different from the controlled, high yield worlds of synthetic chemistry or enzyme-controlled biochemistry. How did such complex chemical systems give rise to biology? The answer must lie in opportunities for self-organization and function within complex chemical systems. Identifying those requires capabilities to measure and quantify the chemical complexity of a system, to monitor its dynamics, and to discern its behavior. Analytical chemistry at this level is currently undeveloped. ELSI researchers Guttenberg, Virgo, Chandru, and Mamajanov, have made the pioneering case that it should be an area of research focus for the global OoL community [16]. The paper addresses the disconnect between Origin of Life research using restricted and controlled chemical models from the likelihood that chemical systems plausibly involved in the origins of terrestrial life produced a wide range of compounds via a wide range of mechanisms. This work is significant because it advocates a branch of OoL research concentrating systematically on the overall behavior, function, and properties of complex chemical systems. Understanding mechanisms of monomer coupling, and finding plausible prebiotic conditions for peptide and nucleic acid synthesis, do not on their own account for the formation of particularly sequenced and folded biopolymers in the absence of enzymatic machinery.



Research results 8: Formation of biomolecules.

Biopolymers, such as proteins and nucleic acids, play essential roles in modern biology. Proteins perform catalytic and structural functions, and nucleic acids store and transcribe genetic information. Abiotic formation of biopolymers is a mostly unsolved problem, despite extensive effort by scientists in the Origins of Life field. Several groups of ELSI researchers have approached the question of biopolymer synthesis from different angles and have made significant advances toward understanding the process. First, ELSI researchers Fahrenbach, Hongo, Aono, Szostak along with coworkers from other institutions explored the prebiotic synthesis of 2-aminoimidazole, a superior activating group for non-enzymatic RNA polymerization [17]. The researchers demonstrate a straightforward and prebiotically plausible synthesis of 2-aminoimidazole that shares a common mechanistic pathway with that of 2-aminooxazole, a key intermediate in synthesis of the nucleotides themselves. In one system they thus suggest a reaction network that could lead both to RNA monomers and to their subsequent chemical activation. Second, ELSI researchers Kitadai, Umemoto, Usui and their colleagues conducted a combined theoretical, computational and experimental study of abiotic glycine polymerization on metal oxide surfaces [18]. On the basis of calculations of affinities, and of the orientation of aggregations of glycine molecules on a collection of metal oxide surfaces, the researchers ranked these minerals from most to least favorable for catalysis. Such data help to survey and constrain prebiotic conditions conducive to the formation of peptides.

Research results 9: Theory in the origin of the Genetic Code.

We seek to understand why the genetic code is nearly universal across all organisms, and why the arrangement of the codons in the standard codon table is highly non-random. The rise of biological complexity is generally viewed as a transition from initial dependence on properties of particular chemicals, to emergent relations that are abstracted further from chemical detail and become more distinctively biological. The consolidation of a fixed amino acid inventory and a universal assignment of amino acids to trinucleotides in the genetic code was a major horizon in this transition, and the subject of our founding questions **"What were the genomes of the first community like?"** and **"What was the nature of the first genetic systems employed in the "progenote?"**. ELSI researchers address both aspects of the code. Jim Cleaves and colleagues [19] studied the diversity and specificity of amino acids adopted by Life as a question of chemical possibilities (see result 15 below). Virgo, Fujishima, and Kiga and collaborators [20] considered the emergence of the genetic code as a dynamical process, showing that optimization of the amino acid assignments can occur as a result of interactions between and within cells, prior to the emergence of vertical descent. They extend a theory of the robustness of the code due to Carl Woese, the first to emphasize the importance of horizontal gene transfer for establishment of the code, to a model that does not require the accurate preservation of information that it is invoked to explain.

2-1.C. Coevolution of Life with the Earth

ELSI researchers have identified major transitions that shaped the evolving biosphere: its architecture and modes of evolution, its dependence on planetary conditions through time, and how biological evolution has fed back to shape Earth's geological history. We integrate methods from synthetic and evolutionary biology to understand the problems of structure and function that were solved by early organisms.

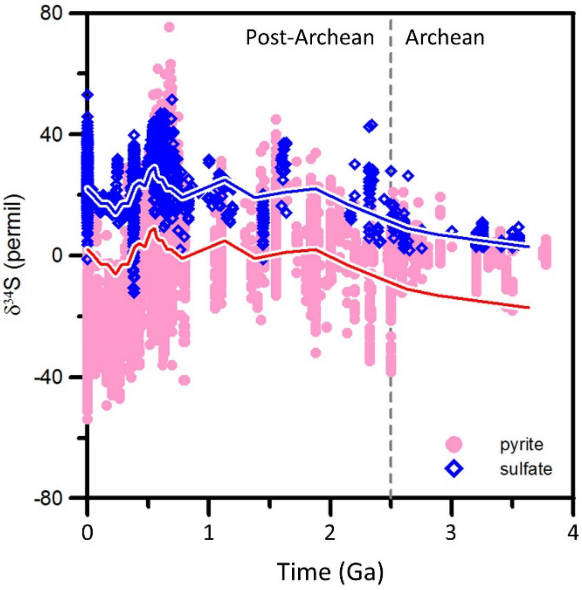
Research results 10: Understanding the nature of the first cell.

Using synthetic biology to understand the problems that living systems solved, ELSI researchers have implemented increasingly complex functions for synthetic cell membranes, and shown what is required for the intricate coordination of molecular systems within and across them. Yutetsu Kuruma's research aims to reproduce the emergence of cellular life in the laboratory. He has achieved several milestones in developing a new artificial system for synthesizing the protein and lipid components of an artificial cell in a system free of cell extracts containing only purified chemical species [21]. In this work, membrane protein complexes (ATP synthase and the Sec Translocon), which are essential for cell function, were synthetically expressed and translated, and their activities were confirmed. This new technique is likely to be adopted by researchers in synthetic biology and medicine, and will improve our understanding of the abiogenesis of components in cell membranes and the origins of complex membrane function.

Research results 11: Understanding the nature of the first genome.

ELSI researchers have reconstructed genomes and bioenergetic systems of ancient bacteria, and shown how those have changed in response to evolving planetary chemistry and Life's own capacity to maintain ever larger and more reliable molecular systems. By reconstructing some of the deepest-branching clades of chemolithoautotrophic bacteria (and perhaps modern representatives of the oldest genomes) we have begun to answer the question **"What were the major transitions in bioenergetic systems, what drove them, and how did they affect the spread of life?"**. Giovannelli et al. [22] published the genome and analyzed the metabolism of *Thermovibio ammonificans*, a chemolithoautotrophic bacterium at the base of the phylum Aquificae, finding evidence for enzymes from both of the most ancient carbon fixation pathways, the reductive TCA cycle and the Wood-Ljungdahl pathway. Their work is the first empirical indication of the coalescence of these two pathways, which had been proposed in 2016 by ELSI PI Smith. Giovannelli et al. also argue that an organism ancestral to the Aquificae catalyzed the reductive TCA cycle with multifunctional enzymes (a hypothesis suggested by results from the laboratory of former ELSI Research Scientist M. Kameya), addressing the question **"How were ancient enzymes and genomes different from modern ones, and can we reconstruct models of ancestral phenotypes?"**. The combination of enzyme multifunctionality with inherent redundancy in pathways such as the TCA cycle may have been critical to establishing the earliest metabolisms, by enabling complex metabolic functions to be achieved with limited numbers of genes

Research results 12: Evidence for major transitions.



ELSI researchers have reconstructed isotopic and mineral signatures linking biological major transitions to the rock record, both for sulfur metabolism and for oxygenic photosynthesis, the biological innovation that has most impacted every surface environment on Earth. Shawn McGlynn and co-authors [23] measured the sulfur kinetic isotope effect of the enzyme adenosine phosphosulfate reductase (APR), which is present in all known microbes that perform sulfate reduction (believed to be an ancient metabolism), catalyzing the first reductive step in the pathway. Based on these results, they reinterpret the sedimentary sulfur isotope record over geological time to understand the redox couples available to drive microbial metabolisms. Archean sediments lack fractionation exceeding the APR value of 20‰, indicating that sulfate reducers had access to ample electron donors to drive their metabolisms. Large fractionations in post-Archean sediments suggest a decline of favorable electron donors as aerobic and other high potential metabolic competitors evolved. These findings link cellular biochemistry and physiology with the rock record of life on Earth. The later evolution of oxygenic photosynthesis on planet Earth is probably the most dramatic example of biological alteration of the earth system. Remarkably, only one group of organisms is known today to produce oxygen from water: the oxygen-producing Cyanobacteria, which are unique in possessing dual photosystems, one containing the water oxidizing manganese cluster. Together with co-authors at Caltech, J. Kirschvink discovered ancient manganese oxide deposits which predate the great oxidation event on Earth [24]. They explain these features by proposing that a light-driven microbial manganese-oxidizing physiology preceded the water-oxidizing chemistry found in Cyanobacteria. Both the protein of the Mn-dependent oxygen-evolving complex, and large-scale pre-oxygenic deposition of manganese oxides, would then be due to light driven manganese oxidation chemistry.

Research results 13: Role of viruses in evolution

The evolutionary history and dynamics of genomes on Earth are carried by two major genetic lifecycles: one associated with free-living cells and the other with viruses. ELSI researcher Tomohiro Mochizuki and his co-workers have expanded the global scientific knowledge of the diversity of viruses of thermophilic Archaea by nearly 100%, and ELSI now hosts one of the largest collections of Archaeal viruses of any institution in the world. Their work explores the limiting growth conditions for single-stranded DNA viruses and for RNA viruses, characterizing the limits of the viral life form and also fundamental constraints on an RNA world. One surprising recent finding is that convergent evolution of structure appears to have resulted in multiple morphologically similar, yet evolutionarily unique viruses [25]. These advances were made by developing an in-house culturing capability for hyperthermophilic viruses, and relying on screening techniques capable of identifying viruses that do not elicit strong phenotypic responses on the host organism.

Research results 14: Emergent properties of evolution

What processes drive biological innovation? Two ELSI Origins Network (EON) postdocs have demonstrated new paradigms for the way evolution uses external constraints as scaffolds for the creation of novel complexity. In each case, loosely-controlled mechanisms with local feedbacks create the contexts for higher-level adaptation. By studying an arms race between bacteriophage and its host, Katherine Petrie et al. [26] demonstrated a new mechanism of molecular evolution that could function even in organisms with short or unstable genomes. In their experiment, mutations in a host recognition gene of phage λ led to protein bistability enabling the gene product to interact with two host receptor proteins. Flexible host recognition by pleiotropy may enable sequences to traverse fitness barriers in the absence of better-known processes such as gene duplication followed by functional divergence. As for the case of multifunctionality in core metabolism (see Result 11 above), adaptive mechanisms that require fewer or less specific enzymes were likely even more important in the deep past than they are today, because error catastrophes from unreliable replication or translation would have limited genome length in the earliest stages of life. Jennifer Hoyal Cuthill [27] found the same paradigm repeated in the evolution of development, as animals in the age before complex regulatory programs used fractal growth rules to transduce feedbacks from nutrient limits into variable, adaptive phenotypes. The evolution of multicellular organisms created the possibility for phenotypes and ecological roles that are unavailable to unicells. Remarkably, however, the study of animals from the Cambrian radiation suggests much more diversity of body plans among early animals than among those on Earth today. The two questions implied are how such regulatory complexity burst so suddenly into existence, and whether either regulatory systems or the phenotypes they produced were more variable in the Cambrian than they are today. To understand how complex forms could be produced with only limited regulation, Cuthill studied rangeomorphs, the dominant animals of the Ediacaran transition. She combined computerized tomography of fossils with numerical models of shape-limited diffusion to infer that they obeyed a local nutrient-controlled growth law. Her simulations reproduce the diverse phenotypes of rangeomorphs as reflections of different environmental nutrient densities and flows, and highlight physical mechanisms that large organisms can use to circumvent environmentally imposed nutrient limitation.

2-1.D. "Bioplanets" in the Universe.

Our studies of the history of Earth and its Life reveal a unifying paradigm, of alternating stages of diversification and selection, which serves as a springboard to understand the habitability of planets around other stars and what principles may make life on them different or similar to our own. Working on those questions has also allowed us to tackle the issue of how unique our planet is. While the papers presented above focus on specific observations within our solar system, they permit us to understand the place of the Earth in the universe. If our planet's orbital distance (c.f. Hamano), volatile delivery history (c.f. Genda, Brasser), mineralogy (c.f. Ballmer, Hirose; see Fusion section below) all contributed to generate the conditions that led to the origins of life, what is the probability of generating similar conditions on other terrestrial bodies elsewhere? To understand whether life is likely even given these conditions, we must address the difficulty that the emergence of Life anywhere will be an outcome of bootstrapping. A universal biology must explain how simple patterns of dynamical complexity can create more complex patterns in a self-maintaining hierarchy. A concrete instance of this problem is the emergence of lineages, studied in the work of Froese et al. [20] (see result 9 above). The researchers show how an era of innovation-sharing, in which all components are exchanged independently, can produce the error-buffering properties of the biological code, which then permit reliable protein synthesis, faithful molecular replication, and the emergence of vertical descent in a Darwinian world.

***Research results 15: Towards a universal biology.**

A core group of experimentalists and theorists study the principles underlying life in order to conceptualize its essential features independently of the way they are realized in Earth's biology. Cleaves and co-workers [19,28] have made use of computational combinatorial methods that allow us to ask which elements of Earth-Life may be universal because they reflect limits inherent in chemistry. They use exhaustive enumeration tools to compile libraries with thousands of possible amino acids, and then compare the coverage of biologically important chemical properties by our coded amino acids, to the coverage by randomly-sampled sets of 20 acids from the combinatorial libraries. They conclude that the biological amino acids as a set have been strongly optimized by selection for coverage. In moving the coded set away from random assemblies and closer to the limits of chemical possibility, evolution has made them more nearly predictable from first principles. Guttenberg et al. [29] have worked to formalize the concept of heredity, without which selection cannot lead to adaptation, in terms not limited to its instantiation in Earth-Life. They have derived tests for the presence of heredity that do not depend on the roles of genes or genomes, and which quantify the capacity for heritable variation across a range of widely studied compositional models and even more general dynamical systems. These results are early examples of ELSI's commitment to expanding the scope of a universal theory of biology. Furthermore, this concept of heredity allowed for the identification of the evolutionary capacity of prebiotic autocatalytic chemical systems [30], establishing a scaling law for the number of distinct chemical attractors and contributing to resolving the debate about whether compositional heredity (GARD) is evolvable. We plan to understand why all levels of biological organization arise, from organisms to communities to biospheres as a whole, and which part each level carries, of the information and functions that define living states. We will show which biosignatures may be derived from constraints on overall functions, without dependence on details that may vary between biospheres, supporting a new generation of experimental search for life in the universe.

2-2. Research environment including facilities and equipment

Describe the degree to which the Center has prepared a research environment appropriate for a world premier international research center, including facilities, equipment and support systems, and describe the functionality of that environment.

(1) ELSI Buildings 1 and 2

In addition to ELSI-2 (Ishikawadai building No.8: 2, 670 m^2) that was the existing building refurbished in 2012, ELSI-1 (Ishikawadai building No.7: 5,000 m^2) was newly built in 2015. The laboratories and researcher's office space have been expanded and an environment comfortable for researchers has been realized. Both buildings have a large communication space which helps bring research activities into the open, encouraging interactions, and removing potential "language barriers" and "cultural barriers" among researchers and staff, thereby promoting an attractive international environment and facilitating inter-disciplinary research.

(2) Research equipment owned by ELSI

* Earth history simulator system (Cray XC30): A 960-core supercomputer manufactured by Cray has been used to study the physical state of the Earth core material by first-principles computation, and to perform numerical simulations on the Earth's mantle and formation of the Moon, planets, and galaxies.

* High resolution isotope-ratio mass spectrometer (Thermo Scientific 253 Ultra): The origin of a molecule is coded in the stable isotopes of hydrogen to sulfur that constitute the molecule. This device, with only a few existing in the world, of which ELSI has one, can analyze molecules containing multiple heavy isotopes, and provides new indicators of life and conditions in early Earth and the Solar System.

* Scanning SQUID microscope: This device, installed in a magnetically shielded class-100 clean room (3-m cube), can measure the vertical component of the magnetic field on a room temperature or cooled sample with 20 μm spatial resolution and 10^{-16} A^2 magnetic moment sensitivity. This is a powerful device for paleomagnetic researches.

* Diamond anvil cell: A device for measuring physical properties of a sample under ultra-high pressure by sandwiching the sample with diamond pieces. Since diamond is transparent, by illuminating a laser and heating the sample, it is possible to reproduce an environment deep in the Earth with ultra-high pressure and temperature.

(3) Research facilities at satellite organization (Geodynamics Research Center (GRC), Ehime University)

* 3000-ton multi-anvil ultra-high pressure device: This is the world's largest DIA-type device, and is used for phase equilibrium studies, material synthesis, melting experiments, and ultrasonic wave velocity measurements under high-pressure and temperature.

* 6000-ton multi-anvil ultra-high pressure device: Samples of large volume (> 1 cm^3) can be pressurized with this world-largest multi-anvil device. This device is used for sample synthesis of large-volume aggregate and single crystal, and for the synthesis of nano-polycrystalline diamond and other novel materials.

2-3. Competitive and other funding

Describe the results of the Center's researchers to date in securing competitive and other research funding.

・ In Appendix 3-6, describe the transition in acquiring research project funding.

ELSI has been exceptionally successful in securing research funds including the Grant-in-Aid for Science Research (KAKENHI), sponsored research funds, collaborative research funds, and university grants/operating subsidies. The total amount of competitive research funds obtained by ELSI from 2013-2018 has often exceeded the WPI grant. The most notable external funds include (* indicates international grant/fund):

(1) Grant-in-Aid for Specially Promoted Research (Kei Hirose): JPY291,000,000 (2013-2016)

(2) Grant-in-Aid for Scientific Research on Innovative Areas "Hadean Bioscience" JPY 499,400,000 (2014-2019)

(3) Grant-in-Aid for Scientific Research on Innovative Areas "Interaction and Coevolution of the Core and Mantle" JPY1,091,100,000 (2015-2020)

(4) Grant-in-Aid for Scientific Research on Innovative Areas "Aqua planetology" JPY 69,988,322 (2017-present)

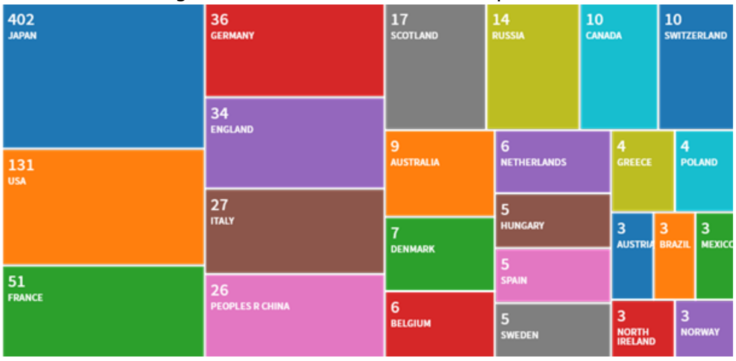
(5*) The research fund from the John Templeton Foundation "ELSI Origins Network (EON) for Research into the Origins of Life" JPY670,000,000 (2015-2017)

(6*) Research fund from the Department of the Interior "Testing the Hypothesis of Magnetite-Mediated Radio Wave Reception and Possible Transmission in Human and Animal Neurophysiology" JPY5,400,000 (2017-present)

(7*) Research Grant from the Human Frontier Science Program (HFSP) for "Exploration of the structure/function space of prebiotic to biological proteins" for Kosuke Fujishima and other co-researchers JPY 116,550,000 (2019-2021)
(8) "FirstLogic", Inc. Endowed Professorship donation for Kosuke Fujishima JPY 24,000,000 (2019-2020)

2-4. State of joint research

Describe the results of joint research conducted with other research organizations both in and outside Jap



ELSI's collaborative reach penetrates all of Japan and the world, a fact that is clearly revealed by examining co-authorship affiliations in our publications (top collaborations are shown in the right figure) which presently includes at least 44 countries. In addition to the collaborations with researchers at ELSI satellites, ELSI has been carrying out joint research with scientists at other institutes under formal mutual agreements, and beyond with informal collaborations made by individual researchers. In addition to the satellite institutes at the beginning of ELSI (Ehime University, Institute for Advanced Study in Princeton, Harvard University's Origin of Life Initiative), two new satellites have been established; the Department of Earth and Planetary Science, University of Tokyo, in 2017, and Columbia Astrophysics Laboratory of Columbia University in 2018. The former is collaborating with research on the Earth's interior and surface conditions and solar system objects, and the latter in the field of astrobiology and material physics. Y. Sekine joined ELSI as PI from the University of Tokyo in June 2018, and Mary Voytek joined ELSI as Executive Director and PI from Columbia University in August 2018, and the relationship with satellites has become even tighter. Renata Wentzcovitch is one of ELSI's founding PIs, who couldn't previously relocate to Tokyo owing to family constraints, but will now re-join as a PI based at our Columbia University satellite in New York.

ELSI has a close relationship and formal research cooperation agreement with the Institute of Space and Astronautical Science (ISAS/JAXA), and contributes to the solar system exploration plan of ISAS from the theoretical and scientific planning side. T. Usui moved from ELSI to ISAS as a professor in July 2018, and maintains a close relationship. Two original ELSI PIs, M. Fujimoto and H. Kuninaka (presently ELSI Fellows), are now in leadership positions at ISAS/JAXA and maintain a close relationship with ELSI members. ELSI Assoc. Prof. H. Genda is a primary science team member for the upcoming MMX sample return mission to one of Mars's moons. ISAS/JAXA Prof. E. Tasker is an affiliated scientist of ELSI (spending 1 day/week at Tokyo Tech) and collaborates on joint PR/outreach efforts between ELSI and JAXA, enhancing the visibility of ELSI and JAXA together.

ELSI also has a research cooperation agreement with Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and original ELSI PI K. Takai of JAMSTEC is an ELSI fellow (PI until FY 2016) and collaborating with ELSI researchers. He recently joined with ELSI Endowed Prof. K. Fujishima in a deep sea submersible to study vent environments. In 2019, Y. Kuruma and N. Kitadai moved from ELSI to JAMSTEC and joined Takai's group as tenure-track researchers, which further strengthens the joint research between the two institutes.

The National Astronomical Observatory of Japan (NAOJ) and the Astrobiology Center (ABC) of the National Institutes of Natural Sciences (NINS) are collaborating with ELSI in the study of extrasolar planets. ELSI and NINS Astrobiology Center have established the Japan Astrobiology Consortium (JABC), and JABC has a research cooperation agreement with NASA Astrobiology Institute. ELSI members such as Prof. S. Ida have been involved in international projects involving the Subaru telescope aimed at exoplanet studies, and discussions are taking place for collaborations with the ALMA telescope which has heavy investment from NAOJ.

The EON project (2016-2018) supported 12 postdocs who actively collaborated with overseas research institutes on the origin of life studies, hosted 9 internationally attended workshops, and supported visitorships to host 25 graduate students and 63 senior researchers from around the world to come to ELSI to work. EON also awarded 8 Seed Grants, many of which had collaborative components involving ELSI members.

2-5. Appraisal by society and scientific organizations

Describe how society and/or scientific organizations in and outside Japan have recognized the Center's research achievements.

- To substantiate the above evaluation, list the main awards received and invitational/Keynote lectures given by the Center's researchers in Appendix 1-3.

(1) Awards and fellowships

ELSI's researchers from different career stages are held in high esteem at their respective levels. Senior researchers such as PIs have received awards including the Medal of Honor with the Purple Ribbon and the JSPS prize. They have also become fellows of notable societies such as the Royal Institute of Navigation, JpGU, and AGU. Meanwhile young researchers have also received awards that target young professionals, such as the IUPAC-SOLVAY International Award for Young Chemists, JpGU Nishida Prize, and Geo-Chemical Journal GJ.

(2) Invitations for Lectures

ELSI researchers, both senior and early-career, have been invited to deliver a total of 78 presentations at international academic conferences.

(3) Collaborative workshops with domestic and international institutions

Along with satellite institutions including Harvard University and Ehime University, ELSI has held a total of 25 research conferences such as collaborative workshops. The details are discussed in 4-2-1.

(4) Competitiveness of ELSI's young researchers

ELSI's young researchers are transitioning into widely visible early-career research scientists during their time at ELSI. This can be witnessed through their being invited to give prominent talks at major international conferences in their field as well as through their continuing employment after ELSI (see Appendix 4-4). This success is partly due to ELSI's high profile and ability to attract researchers of the very highest caliber who are already likely to become academic leaders later in their careers. It is also partly due to efforts by senior ELSI PIs in mentoring, feedback, and career guidance. We take advantage of our International Advisory Board members when they visit and organize meetings for young researchers to interact. ELSI provides opportunities for young researchers to lead study groups, operate committees, and apply for funds to organize workshops, which helps to raise their international profile and attract recruiters and job offers from around the world. Finally, compared to others in their cohort, ELSI researchers are far more exposed to interdisciplinary discourse and research, which builds an important skill of communicating their science clearly to others. ELSI experience makes them more confident in presenting their science even in a more specialized context, and is an important asset in their career growth.

(5) Long-term visits by senior scientists

Another sign of international recognition is through the number of senior scientists who want to take time out of their busy schedules to come spend an extended amount of time at ELSI. ELSI is growing its reputation as an exciting institute with world-class scientists. 22 visitors of a professor level have come to spend over 1—3 months at ELSI since our inception. Separate from long visits, ELSI also has been able to attract world-renown scientists to come to ELSI as speakers and to interact with our researchers. Some big names in ELSI's domain are: George Whiteside, Simon Conway Morris, Andrew Knoll, Robert Blankenship, David J. Stevenson, Steven Benner, Loren Williams, James Kasting, to name a few.

(6) External review of PIs

In FY2018, for the first time, ELSI conducted an external review led by our International Advisory Board (IAB) of our senior PIs. From the review reports, it is clear that the international community regards our PIs highly. Method of external review was as follows: 14 PIs submitted their self-evaluation report by 2018 December, and IAB (6 members) assigned one member to each PI. The IAB recommended three referees per PI; those referees are world renowned researcher in the field of each PI. The task force for review led by Executive Director Mary Voytek sent the self-evaluation report of the PIs to the referees for review. The review was made on the following five points: (1) contributions to the WPI mission, (2) scientific contributions, (3) innovativeness and originality, (4) interdisciplinarity and collaborations, and (5) overall assessment. The review reports were collected by 2019 January, and the IAB produced the evaluation summary in February. <u>The full evaluation material will be disclosed to the Working Group overseeing ELSI upon request</u>. Such external reviews are an important part of building a robust institute with strong scientific leadership as well as a form of networking that gains ELSI credibility from its scientific communities.

2-6. Feeding Research Outcomes Back into Society

2-6-1. Applications of research results

Describe the applications created from research results, their effect in spawning innovation, intellectual properties (IPs) obtained, and joint research activities conducted with corporations, etc.

(1) A. Kobayashi's discovery that nanocrystals of magnetite are among the most potent ice nucleation sites in nature has broad applications for: use of magnetite's passive ability to nucleate ice in the field of climate control, design of industrial technologies to exploit the bulk control of supercooling, and engineering methods to minimize the damage on plant and animal food products by ice crystals during freezing. This is an important discovery that will improve the quality and capacity for food preservation and storage, an important issue facing the global food supply chain.

(2) With funding from pharmaceutical companies, Y. Kuruma and K. Fujishima studied the cell-free protein expression system to establish high-throughput screening and evolution of random polymers (including peptides and RNA) for the purpose of understanding the function and evolvability of primitive biopolymers with regards to the origin of life study. Their research is applicable to design various evolvable peptide/RNA aptamers targeting various macromolecules or even chemical compounds, allowing potential application in the pharmaceuticals and therapeutics industries.

(3) ELSI is connecting with Tokyo Tech's Office of Research and Innovation, Industry Liaison division to get their input on which companies might be best fits to ELSI research's industrial applications and what possible funding opportunities might be established with industry.

2-6-2. Achievements of Center's outreach activities

* Describe what was accomplished in the center's outreach activities during the period from 2012 through March 2019 and how the activities have contributed to enhancing the center's "globally visibility." In Appendix 5, describe the concrete contents of these outreach activities and media reports or coverage of the activities.

ELSI PR Office actively coordinates outreach activities: (some major highlights)

(1) "The Miracle of Hakuba and Science" (FY2014): a public lecture to connect with local community in Hakuba to share the ELSI field research conducted in the area.

(2) Kavli IPMU-ELSI-IRCN Joint Annual Public Lecture (FY2015-2018): initiated in 2015 between Kavli IPMU and ELSI, later IRCN joined, is an effort to enhance collaboration between WPI institutes.

(3) Research reading for students (FY2016): students of Fukushima Prefectural Iwaki High School, a Super Science High School (SSH) practiced their comprehensive reading in English and analytical thinking abilities with ELSI's T. Mochizuki by reading research papers in English.

(4) 'Creators Meet Scientists' project (FY2016-FY2018): a science-art collaborative project among 9 creative artists and 3 ELSI researchers to create artistic outcomes inspired by ELSI science.

(5) Study on accuracy-readability trade-offs (FY2016-FY2017): the study researched differences in accuracy and readability of scientific information in the areas of education, public relation and science communication, and proposed a new methodology on Accuracy-Readability Index.

(6) Video interviews of ELSI researchers to present interdisciplinary science (FY2016-FY2017): an interviewer presented the same set of questions to several ELSI researchers to convey the interdisciplinary aspect of ELSI by highlighting how ELSI research is connected.

(7) The movie, "The Whole History of the Earth" (both in English and Japanese), was created by Hadean Bioscience project. A series of 9 movies have been uploaded on You Tube. Total views of movies are about 232,000.

(8) 29 popular literature books have been written/co-written by ELSI members. Notable mentions are: PI E. Smith's book "Origin of Life" which won the 2017 Marsh Award for Best Earth Science book, PI J. Kirschvink's book "A New History of Life" (2015) published in 3 languages and was on the Japanese best-seller list, and H. Cleaves' "A Brief History of Creation" (2015) has sold over 50,000 copies to date.

3. Generating Fused Disciplines (within 3 pages)

3-1. State of strategic (or "top-down") undertakings toward creating new interdisciplinary domains

(1) Efforts to acquire external inter-disciplinary research funding

Raising funds for inter-disciplinary research is absolutely necessary for ELSI science. However, most traditional funding is targeted to specialized subjects rather than broadly integrative fusion. An exception is the "Shingakujutsu" category of JSPS Kakenhi grants, which offer large scale funding for broad collaborations (involving many fields, investigators, and multiple institutions). ELSI has been successful in raising funds from this program following 3 proposal efforts:

●*Hadean Bioscience* (FY2014-2019) was proposed by PI (and Vice Director at the time) Ken Kurokawa. About 500 million yen was allocated for ELSI members. The aim of this research project

was to create a new academic area to identify when, where, and how life was created through a combination of cutting-edge planet earth science, life science, and organic chemistry, with a focus on the Hadean era (i.e. the earliest era following the birth of the Earth).
●*Co-evolution of the Core and Mantle Toward Integrated Deep Earth Science*, (FY2015-2020) led by ELSI-Ehime satellite Affiliate Faculty Tsuchiya as the PI (approx. 1.09 billion yen for five years). This area aims to constrain the evolution of both the core and mantle as the system that dominates the dynamics in deep Earth.
●*Aquaplanetology* (FY2017-2022) was launched under the leadership of ELSI Professor and PI Y. Sekine. The proposal effort also involves members at ISAS/JAXA and aims to constrain how volatile delivery and history to a planet/moon influences the early environment and possibility for organic processes leading to life.

ELSI's greatest success in external fundraising for inter-disciplinary research was the launch of the *ELSI Origins Network* (EON), which began in July 2015 with support from the US-based John Templeton Foundation (33 months, total $5.6 million USD). Founding PI and Councilor Piet Hut helped to develop the proposal and used his longstanding network to negotiate with the foundation and establish the program at ELSI. This program came at a critical time, when ELSI's early stages of WPI funding was not increasing at the levels we previously planned.

(2) Internal funding mechanisms for inter-disciplinary science

ELSI also established the "Directors Fund" to help fulfill funding needs within the institute that could not be covered by other large grants. This is particularly helpful to the large number of ELSI's junior non-Japanese researchers, who are not well known inside Japan, in obtaining JSPS Kakenhi funds. The Directors Fund has experimented with several different kinds of proposal procedures, and typically targets fusion research or particular needs that are not easy to fulfill using other funding mechanisms. This fund has been used to launch some of ELSI's most promising laboratory experiments, and helped lift the careers of many young scientists who would not otherwise be able to fund their work.

3-2. State of "bottom-up" undertakings from the center's researchers toward creating new interdisciplinary domains

Describe the content of measures taken by the Center to advance research by fusing disciplines. For example, measures that facilitate doing joint research by researchers in differing fields.

Study Groups: Early on ELSI established interdisciplinary study groups that focused on various aspects of Earth-Life science. The "magma oceans" group focused on unifying planetary accretion and early geological environments, "cycles of life on planets" (CycLoPs) examined bio-geochemical cycles involving both geological and biological processes, "mineral selection" brought together organic chemists and mineralogists, while "origin of life" brought together all fields represented in the institute to tackle our biggest unifying question. ELSI researchers were able to learn the best strategies to communicate and collaborate across discipline boundaries, which helped ELSI to achieve a very broad and open-minded science culture. All graduate students of ELSI faculty are required to regularly attend at least one study group.

ELSI Youchien: The "kindergarten" (youchien) concept was launched entirely on the initiative of junior researchers at ELSI who saw the need to explain our broad science to one another in the very simplest terms, and to cement the learning process by using hands-on demonstrations. Hands-on demonstrations were presented in fields ranging from chemistry to fluid dynamics, helping young researchers to understand one another's fields.

ELSI All-Hands Institutional Strategy Meeting: In February 2017 we organized our most ambitious internal strategy meeting by bringing all researchers together to consider fusion science directions across all of our science domains. A key outcome of this effort was the "cross-fertilization" that takes place between different fields when researchers begin to understand the common hurdles to progress in each domain. Once they achieve this realization they can swap strategies, tools, and insights between domains in ways that unlock new ideas and catalyze advances across multiple fields simultaneously.

ELSI International Symposia: ELSI has held 7 international symposia to showcase our research in broadly inter-disciplinary themes and to bring world-leading scientists together to share our perspectives and insights. This is one of our best opportunities to bring famous researchers to ELSI, both to join in our inter-disciplinary conversations as well as to showcase ELSI to global leaders. Their impressions of ELSI, shared with all of their colleagues and networks, have been a key ingredient to ELSI's recognition as an inter-disciplinary institution of unprecedented breadth and scope.

ELSI Workshop Series: ELSI has leveraged WPI support to host dozens of smaller scale workshops with the aim of addressing particular questions relevant to our science and/or to generate a specific product (strategy, book, journal issues, etc.). A good example of an inter-disciplinary meeting is the "Planet Diversity" workshop. It brought together a small group (~30) of international researchers in different fields related to planet formation, evolution, and astronomical observations to discuss the topic of varieties of planets and environments that could exist in our galaxy. The workshop rebooted some of the conventional wisdom in light of the wealth of new exoplanetary data, and began working to understand how this dataset could revolutionize our understanding of planetary science. This was a true working workshop with only two formal talks in the five days, with the remaining time dedicated to discussions and formulation of collaborative projects. The workshop produced a Nature Astronomy paper that re-defined our views on the question of "habitability." The workshop reflects ELSI's institutional efforts: support for early-career scientists, cultivation of a new network of the next leading generation of scientists, and achieving gender balance (50/50) in both its organizing team as well as attendees.

Open Research Labs at Tokyo Tech: As described previously by former President Mishima, Tokyo Tech was inspired by ELSI to launch inter-disciplinary fusion center, Tokyo Tech World Research Hub Initiative (WRHI), in the broader university.

Inter-Disciplinary Courses: Earth and Planetary Science and Materials and Chemical Technology. This allows those faculties to access students in those departments, and allows them to teach courses in those departments, such as the "Earth and Life" course on topics in Astrobiology for third year undergraduate students in the EPS department co-taught by multiple ELSI researchers including Shigeru Ida and John Hernlund. Starting in April 2019, all Tokyo Tech graduate-level courses will be taught in English. As such, ELSI members have been solicited to teach a course in the Department of Life Science and Technology on the origin and evolution of life (Kosuke Fujishima, Shawn McGlynn, Irena Mamajanov, Tony Jia). Traditionally, ELSI members have had strong ties with the EPS department, but this new course will allow biology and chemistry-focused researchers the opportunity to build stronger ties with those in the life sciences. Additionally, ELSI recently organized two research/education collaboration meetings in the Ookayama and Suzukakedai campuses in 2018 in order to catalyze new interdepartmental and interdisciplinary collaborations with members of the Materials and Chemical Technology School and the newly formed (in 2016) Institute of Innovative Research (IIR), a Tokyo Tech research center whose goal is to synthesize new collaborations that will create new interdisciplinary fields. Kristin Johnson and Tony Jia (of ELSI) are currently planning a collaborative workshop with researchers in IIR to continue the dialogues that were started at 2 prior joint research/education collaboration meetings.

3-3. Results of research in fused research fields

Describe the Center's record and results by interdisciplinary research activities yielded by the measures described in 3-1 and 3-2.

- In Appendix 1-2, list up to 10 of the Center's main papers on interdisciplinary research that substantiate the above record of results, and describe their content.

Interdisciplinarity within ELSI and Tokyo Institute of Technology

ELSI was founded on the idea that origin(s) of life is not a challenge that can be tackled by any single discipline of natural science, because life emerges and evolves as an open system and the questions that need to be addressed therefore span many fields. Our original idea was to expand our approach to consider a planet and its life as a collaboration of myriad processes spanning enormous scales of space, time, matter, and complexity. Life did not emerge on Earth in a clean laboratory beaker. The geological context is critical for understanding the conditions under which biological processes could take off from an initially abiotic environment. An additional benefit of our big approach is that we can simultaneously learn how life can emerge in other planetary contexts, which is timely given the rapidly expanding discovery of potentially habitable exoplanets in our galaxy, which will undoubtedly remain one of the hottest science topics of the 21st century. However, following this plan requires fusion between fields ranging from astrophysics to microbiology, and the intersection of different research cultures, languages, tools, and strategies. In fact, the scope is so broad that we also needed to assemble the right people from around the world, since no single nation has the right combination of expertise and social chemistry to enable the dramatic levels of fusion the ELSI sought to achieve. Creating a broadly inter-disciplinary environment at ELSI also required reform of administrative procedures and work customs to encourage collaboration. Thus achieving fusion in our case was not independent of the other pillars of the WPI program, all were necessary to advance our ambitious science goals.

ELSI's interdisciplinary research results

Kurokawa et al. (2018) assembled a broadly inter-disciplinary team consisting of an atmospheric scientist, an isotope geochemist, a geophysical modeler, a seismologist, and a cosmo-chemist to generate a unique new constraint on the origin and circulation of water in the Earth since formation.

Aono et al. (2013) rallied micro-biologists, mathematicians, and chemists to find a novel way of using a living amoeba as a virtual computer to solve chemistry problems that are otherwise impossible to solve using conventional computers.

Brasser et al. (2017) brought together astrophysicists and isotope chemists to show that Mars likely formed rapidly in the early solar system and relatively far from the Sun in comparison to the other terrestrial planets, helping to explain many of Mars' distinct features.

Kimura and Kitadai (2015) combined thermal evolution models of icy moons with organic chemical modeling to show how the kinds of polymerization necessary for the building blocks of life can be assembled in these unique and potentially habitable environments.

Scharf et al. (2015) brought together a team ranging from astrophysicists, geologists, chemists, planetary scientists, biologists, artificial life researchers, and philosophers to formulate a new approach to studying origin of life.

Ballmer et al. (2017) proposed a biology-inspired model for the Earth's formation, composition, long-term evolution, and deep circulation. Their so-called BEAMS hypothesis promises to solve many paradoxes in the Earth sciences and unifies the fields of geophysics and geochemistry.

Rein et al. (2014) brought together atmospheric chemists and astronomers to show that the range of possible interpretations of spectrally characterized chemical disequilibrium (a proposed biosignature) on exoplanets can be a false positive, and provided a model to show how a better search for such biosignatures might be conducted.

Laneuville et al. (2018) included a microbiologist, a planetary scientist, and a geochemist who modeled how nitrogen cycling would proceed on terrestrial planets without life, a seminal study to establish the baseline for one of the bio-essential elements.

Yamamoto et al. (2018) unified important ideas around the geochemical and geoelectrical output of deep sea vents and how they power life in a deep marine environment.

Moore et al. (2017) explored how the geochemical availability of various metals in the early Earth environment facilitated a variety of chemical pathways for biological metabolism.

4. Realizing an International Research Environment (within 4 pages)

4-1. International Circulation of Best Brains

4-1-1. Center's record of attracting and retaining top-world researchers from abroad

Describe the participation of top-world researchers as PIs and their stays as joint researchers at the Center.

- In Appendix 3-2, give the number of overseas researchers among all the Center's researchers, and the yearly transition in their numbers. In Appendix 4-2 give the achievements of overseas researchers staying at the center to substantiate this fact.

ELSI's management has been fanatical about meeting the requirements to be a WPI research center, including (1) establishing an attractive research environment capable of attracting the world's best minds, (2) mandating English in all communications involving ELSI researchers, and (3) recruiting the majority of our junior and senior researchers from outside Tokyo Tech (and abroad). Today, 7 out of 17 PIs are world-class foreign researchers recruited from overseas. Four of these seven foreign PIs are currently based in Japan full-time. This number is a testament to ELSI's quality as a research center at which the world's top-class scientists gather, rather than a mere fulfillment of number requirements (which ELSI easily exceeds). Recruitment of talented bilingual secretarial staff was also crucial to assist ELSI researchers in handling official paperwork and documents, purchasing items for research, and supporting our numerous visitors from abroad.

4-1-2. Employment of young researchers at the Center and their job placement after leaving the Center

Describe the Center's employment of young researchers, including postdoctoral researchers, and the positions they acquire after leaving the Center.

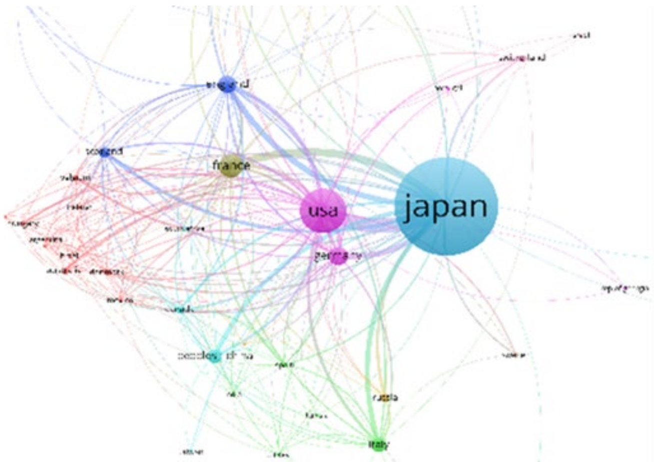
- Enter the following to substantiate the facts provided above:
  - In Appendix 4-3, describe the Center's state of international recruitment of postdoctoral researchers, the applications received, and selections made.
  - In Appendix 3-2, give the percentage of postdoctoral researchers employed from abroad
  - In Appendix 4-4, describe the positions that postdoctoral researchers acquire upon leaving the Center.

ELSI has pursued a targeted strategy for the recruitment of internationally competitive young researchers that is unique in Japanese universities. A recruitment committee headed by a foreign PI put in place an active solicitation of applicants and a review system that incorporates feedback from experts from various areas of research covered at ELSI. In ELSI's initial recruitment, international advertisements were placed in journals including JST (JREC-IN), Nature, and Science as a way to get our new institute global visibility. In addition to announcements in mailing lists of relevant academic societies and communities, ELSI PIs constantly communicate with their outside colleagues to source top quality graduate students and postdocs as potential candidates. Recruitment efforts are also carried out in key meetings of ELSI's fields such as the American Geophysical Union Fall Meeting, the Gordon Research Conference on the Origin of Life, and Astrobiology Science Conference to name a few. ELSI's esteemed visitors bring their students and postdocs to ELSI's annual International Symposium and events are organized for them to get to know ELSI researchers. When world-renowned speakers are invited but decline, ELSI uses this as an opportunity to ask them to send top early-career researchers they know to speak. This is also an effective way to achieve gender balance and give opportunities to young scientists. ELSI's winter and summer schools have brought a number of successful applicants. These coordinated efforts including detailed support by ELSI's administrative staff to assist to questions about relocating to Japan have led to maximizing the quality of recruitment. As shown in Appendix 4-3, ELSI received 363 applications from more than 30 countries around the world, most of which (75%) were from young foreign researchers. The employment period at ELSI is typically three years. However, young researchers with exceptional results may extend their stay by two years based on the outcomes of the annual evaluation. As shown in Appendix 4-4, 33 out of 43 young researchers hired by ELSI have been promoted at the world’s top research institutions following their research experience at ELSI. This is a proof that ELSI is recognized as a career-path institution.

4-1-3. Overseas satellites and other cooperative organizations

・ In Appendix 4-1, describe the state of cooperation with overseas satellites and other cooperative organizations. In Appendix 4-5, describe the state of the Center’s agreements concluded with these organizations.

In 2012, in addition to our domestic satellite center at Ehime University, ELSI established formalized international satellites with the Institute for Advanced Study and Harvard University. For all three satellites we have shared post-doctoral positions (examples: Ichikawa, Cleaves, Fahrenbach.) More recently we established two additional satellites. One at the University of Tokyo was established in 2017 and links researchers at ELSI, particularly those led by Director Hirose, with researchers at U. Tokyo. Hirose’s collaborations with U. Tokyo focus on Fractionations of W, Hf, and Lu during crystallization of a magma ocean at the beginning of the Earth and their implications for a distinct geochemical reservoir in the lower mantle, and the search for evidence for early (>4 billion years old) life in Canada. The satellite has also connected ELSI to U. Tokyo’s Artificial Life and Complex Systems group, ELSI co-hosting a workshop on Komaba campus and attended by top experts of the community. Director Hirose spends 20% of his time at U. Tokyo. The second recent satellite at Columbia University, established in 2018, connects the Astrophysics Laboratory (in particular Executive Director Mary Voytek, Caleb Scharf the Director of the Astrobiology Center, and Renata Wentzcovitch, Professor of Materials Science and Applied Physics, and Earth and Environmental Science) to ELSI. NASA’s Goddard Institute for Space Studies (GISS) is housed on the Columbia Campus and their researchers are engaged in the Astrobiology activities at Columbia. These satellites have provided intellectual engagement and support in a wide range of fields involving astronomy and astrophysics, Earth and planetary sciences, microbiology, synthetic biology, cosmochemistry, prebiotic chemistry, and astrobiology. Through these overseas alliances, we have developed collaborations in areas of research, education, and other scholarly activities. Specifically, we have exchanged researchers and students (total 29) and co-hosted workshops (5) and symposia in order to advance the understanding of the origin of life on Earth and the possibility of life elsewhere in the universe. Furthermore, as a result of the Satellites’ activity, 17 collaborative papers have been published in 2018 with our overseas satellites and another 15 from our domestic satellites.



We have also established formalized

collaborations with cooperative organizations from 23 research institutes and universities around the world, and are in discussion or in the process of formalizing Memorandums of Understandings with at least 7 more. These ongoing collaborations have grown from the initial 5 Satellite and Partner institutions. The strength of these interactions can be measured not only by the number of joint papers that have published but by the number of individual from these institutions that have applied for our internationally advertised research scientist positions and from the number of successful applicants (5) who came from either our satellites or cooperative organizations. Most notably, Tony Jia from our Harvard satellite and a postdoc of PI Jack Szostak, Harrison Smith and Kristin Johnson from Arizona State University, our Cooperative Organization.

In the case of satellite International Advanced Study (IAS), an institute known for its excellent operation and support for international researchers, cooperation extended beyond research to the sharing of administrative know-how (fund-raising, outreach, visitor support).

4-2. Center's record of holding international symposia, workshops, research meetings, training meetings and others

・ In Appendix 4-6, describe the main international research meetings held by the Center.

(1) Annual international symposium

Annually, ELSI holds an international symposium on the origin of life research and its related fields. This year, we held the seventh international symposium. Every year, more than 100 researchers from more than 10 countries participate in presentations and debates. During the event, a lecture for the public was also held in the evening, and more than 100 attendees attended.

(2) International Workshops

In 2014, Albert Fahrenbach organized a joint workshop with Harvard University. In 2015, the Phobos, Deimos, and Mars workshop allowed ELSI researchers to join the JAXA MMX mission (Tomohiro Usui and Hidenori Genda), which will launch in 2024. This was followed by a major Strategies for Origin of Life Workshop, which produced a highly cited concept paper about how to go forward with origin of life research. This meeting got ELSI and Tokyo Tech mentioned in the widely circulated popular US magazine, The Atlantic. The Magma Oceanology workshop in 2016 was the first step in a significant change in the field of magma oceanology, and resulted in high profile papers in Nature and Science. In 2017 ELSI hosted a young researcher day workshop organized by young ELSI researchers for their young researcher visitors. It was a day of sharing their research to one another and networking. Later on in 2017, ELSI hosted workshops in Biosignatures and Life Detection Technology, produced a White Paper on the future of life detection technologies cited by USA National Academies of Science Astrobiology Strategy Roadmap Document, which will be a leading source of inspiration for future astrobiologists.

(3) Conferences

ELSI members have been awarded a number of keynote seminars in major international conferences such as the Goldschmidt Conference, Astrobiology Graduate Conference (AbGradCon), American Geophysical Union Meeting, and the Geochemical Society of Japan. ELSI also has organized a variety of sessions at those conferences, as well as in major domestic scientific society meetings such as the Japan Society of Cell Synthesis Research (Kuruma) and the Biophysical Society of Japan (BSJ) meeting (Kiga). The 2018 ALife conference, the foremost international conference on the topic, was held in Tokyo. Owing to the international acclaim as a global research hub, ELSI has been chosen to be the host of two international astrobiology conferences in 2020: Australasia Astrobiology Meeting, and AbGradCon, a major young researcher-focused conference co-sponsored by NASA and attended by researchers from all six continents. This is the first time ever that AbGradCon will be held outside of the U.S. and ELSI being the first overseas host is a testament to our rise in reputation.

4-3. System for supporting the research activities of overseas researchers

Describe the Center's preparations to provide an environment conducive for overseas researchers to concentrate on their work, including for example living support in various languages or living support for their families.

(1) Relocation and daily life support (including VISA acquisition)

ELSI provides relocation support including VISA acquisition, housing arrangement, and day-care enrollment to enable researchers to concentrate on their work, even before coming to Japan. Once here, we assist in setting up bank accounts and registering in ward offices. In addition, we assist in making necessary arrangements to go back to the researcher's home country, such as tax matters and social insurance. We also provide necessary support to even our visitors to adapt to circumstances including various unexpected problems or challenges.

In addition to start-ups and daily life support, the Revised Immigration Law implemented in 2015 and 2017 has increased the number of researchers continuing research activities with a view to long-term settlement in Japan. Therefore, we provide information and detailed advice on the change of status of residence (permanent residence application), preparation for children's schooling, etc. The know-how of support accumulated from the beginning of ELSI to the present is also used to support these long-term settlers.

(2) Japanese language classes

An important part of life support is to provide Japanese language classes for researchers to learn conversation skills for daily life. ELSI's philosophy is to not only provide support but to do so in ways that foster researchers' integration into Japanese life. ELSI holds 3 classes of different proficiency levels at the institute to meet the abilities of our interested researchers. In addition to Japanese language classes, E-learning teaching materials are introduced to support Japanese language proficiency improvement. Researchers and staff on occasion hold Japanese language lunches where only Japanese is spoken. In addition to the language classes, ELSI contracts with a 24-hour telephone translation service where our international members can call to get translation assistance. This is particularly useful for sudden visits to medical clinics.

(3) Support for acquisition of competitive funds

ELSI hosts Kakenhi seminars in English conducted by a Japanese PI with abundant experience in obtaining Kakenhi. In addition, translation services are made available to assist with application documents. These services are provided by Japanese researchers, graduate students, and fulltime URA whose research fields are similar to that of the applicant. The number of accepted applications has been increasing since 2015, and newly accepted applications were over 10 in 2017. Applications submitted by foreign researchers have been increasing, and 8 to 9 applications on average have been getting accepted since 2015. The total amount of received funds is over 80 million yen per year in 2017 and 2018.

(4) Safety management training

Automated external defibrillators (AEDs) were installed in ELSI-1 and ELSI-2 buildings in 2016. In cooperation with Tokyo Tech's General Safety Management Section of the Office of Campus Management, AED training sessions in English and Japanese are held every year since then.

(5) Cultural diversity training course

Lack of awareness on differences in cultural background can sometimes lead to miscommunication, misunderstanding and even emotional conflicts, also creating work inefficiencies. In order to avoid such situations, ELSI ran mandatory lectures on cultural diversity and awareness by professional lecturers in FY2018. The same lectures were delivered in three sessions and attended by the majority of the ELSI staff. As an institute, ELSI views this shared awareness by its members as an integral part of sustainable internationalization.

(6) Comfortable, confidential method of voicing complaints, feedback, or allegations

ELSI has set up an official way to communicate confidential suggestions, complaints, or allegations more easily, providing a team representing various cultures at ELSI (foreign/Japanese, female/male, researcher/admin staff) from which ELSI members can choose to whom to voice their issues. ELSI is aware of the care and sensitivity needed for setting up a system that is genuinely thoughtful and supportive of taking in complaints, feedback, allegations.

4-4. Others

Describe the Center's policy for sending Japanese researchers overseas to gain international experience, and give examples of how the Center is working to create career paths for its researchers within a global environment of researcher mobility.

(1) GIFT (Global Impact Fund for Travel) Program was established by the Director's Office to strategically disseminate ELSI's research to scientific communities abroad where ELSI's presence is limited. ELSI researchers can apply to get support for an individual or small group to attend to publicize ELSI's research and what ELSI is like as an institution. GIFT is a way for ELSI to support Japanese and other researchers who might not otherwise be able to get travel support for meetings such as through invitations. Last year, GIFT funds were used to send a Japanese researcher to AGU, the first time she had gone to the international geophysical meeting.

The fund is allocated by the leadership of the Director. Even before establishing GIFT program, 9 Japanese non-PI researchers stayed more than 2 weeks in institutions abroad for several times since the beginning of ELSI. Three of them stayed more than 3 months. One of them became a scholar at the Institute for Advanced Study.

(2) ELSI Origins Network (EON) Program Design: EON was funded to create a global network for origins of life research with ELSI as a hub. A key design of the program was to require EON

postdoctoral researchers to spend half of their contracted term at an overseas institution to pursue their planned research. With acceptance from hosting overseas institutions as a prerequisite for the EON postdoctoral application, ELSI was able to secure forward-thinking young researchers with the willingness to gain international experiences as well as collaborative relations with overseas supervisors. One result was early career ELSI members, many of them Japanese, making research visits to EON overseas institutions to continue their collaborations with EON postdocs.

5. Making Organizational Reforms (within 3 pages)

5-1. Decision–making system in the center

Describe the strong leadership that the director is giving on the Center's operation and its effect, and the division of roles and authority between the Center and its host institution.
- In Appendix 3-3, draw a concrete diagram of the Center's management system.

(1) Roles of the institute director and the president of the host institution

Appointment of the ELSI Director is the responsibility of the President of the Tokyo Institute of Technology, but all other important decisions are made by the ELSI Director. The ELSI directors (Director, Executive Director, and Administrative Director) meet monthly with the University executives (President, Vice Presidents in charge of Research and Financial Affairs) in order to maintain close coordination between the University and ELSI.

(2) Executive Director and succession plan to Director

A key decision made by the Director in discussion with the President was to bring on an Executive Director who is a full-time administrator and someone with scientific knowledge in all of ELSI's research to execute the Director's goals. Two strategies embedded in ELSI's Executive Director position are: 1) this person is recruited with plan to succeed to Director after March 2022, giving time to gain ample experience and prove fit for that job, and 2) this person plays the role of Special Advisor to the President, further strengthening collaboration for reform, internationalization, and scientific excellence between ELSI and the University to best achieve the WPI mission.

(3) Decision-making system in the institute

The Director has the right to make decisions on all matters that pertain to ELSI except for the Director's own appointment. The Director is also responsible for the administration and management of the Administrative Division, with support from the Executive Director and the Administrative Director. This system with concentrated functions to the Director guarantees flexible and quick decision-making.

For matters related to the entire institute, the Director's Office, the Operations Committee and other various committees assist the Director's decision-making. The Director manages the institute in a top-down manner, by referring to the reports or recommendations from the committees.

The Director's Office consists of the Director, the Executive Director, two Vice Directors, Administrative Director, and assistants to the Director, and the members meet regularly once a week. The Director's Office makes day-to-day operations of the institute by sharing the latest situation of the institute among the members and by instructing appropriate committees to address various issues in managing the institute.

The Operations Committee is composed of the directors and several PIs, and meets regularly once a month. The Operations Committee discusses personnel affairs and various institutional regulations, and gives advice and support to the Director.

ELSI has an International Advisory Board (IAB) whose members are internationally recognized scholars who have leadership and management experience. The Director receives advice from the IAB on important aspects of running the institute, ranging from risk management to research strategy.

5-2. Arrangement of administrative support staff and effectiveness of support system

Describe the assignment of the Center's administrative support staff who have English language and other specialized skills, effort made in establishing the support system, and the system's effectiveness.

Under the leadership of the Director, ELSI has established an Administrative team of 20 staff overseen by an Administrative Director who has extensive experience in international research activities. The staff are: Assistant Administrative Director, Chief of general affairs, Chief of financial affairs and assistant, life-support staff, health and safety officer, five secretaries, PR-office staff (Chief, Communications Director, and two staff), technical staff for computer and network system, International Coordinator, Operations Coordinator, and two URA staff. Majority of ELSI staff are fluent in English, are highly skilled and have abundant experience in meeting the unique challenges of a WPI institute.

5-3. System reforms advanced by WPI program and their ripple effects

Concisely itemize the system reforms made to the Center's research operation and administrative organization, and describe their background and results. Describe the ripple effects that these reforms have on the host institution. (If any describe the ripple effects on other institutions.)

(1) Top-down decision making

As stated in 5-1, ELSI has adopted a top-down system. The President of Tokyo Tech, using ELSI as a model, is initiating and establishing a flexible research system.

(2) Promotion of the "World Research Hub" to develop international research activities

Tokyo Tech had already carried out research reforms, including the establishment of the Institute of Innovative Research (IIR), which integrated the existing four research institutes and several research centers, in April 2016. Furthermore, an organization "Tokyo Tech World Research Hub Initiative (WRHI)" has been established in IIR, aiming at promoting interdisciplinary research and creating innovative science and technology. WRHI uses ELSI as a model case and utilizes its know-how, and has been trying to invite top-level foreign researchers and to promote fusion in research. Tokyo Tech plans to propagate the success of ELSI's system to WRHI and IIR, and to further extend it to the entire university, in order to realize its goal of becoming a "global research hub".

(3) Introduction of performance-based pay system

ELSI adopts its own performance-based pay system to recognize and incentivize excellence. This is also necessary when trying to competitively recruit from an international pool of high-caliber applicants. In ELSI's Annual Evaluation, all researchers report their research activities and are evaluated on the criteria of scientific value as well as contribution to ELSI's WPI goals. Researchers who are recognized as having performed particularly excellent research, especially of an interdisciplinary nature, are given the Incentive Award and a salary raise in the next year. Incentives are essential in running a world-class institute that can bring the best out of its researchers while focusing on its goals.

(4) Introduction of cross appointment system

In order to acquire top level researchers, ELSI working with Tokyo Tech established a cross appointment system. Tokyo Tech applied this system for the first time to an ELSI PI. Since then Tokyo Tech has hired 22 researchers by January 2019 using the cross appointment system.

(5) Reduction of work-related payments by ELSI researchers

ELSI negotiated with Tokyo Tech to allow travel insurance for business travel to be paid by the institute's budget, not by the individual researchers as the rule had been. In response, Tokyo Tech changed the accounting rule for travel insurance for work trips. Another move towards efficiency and reduction of credit burden to our researchers was to work with Tokyo Tech to change the university's regulation to allow for a corporate credit card, of which ELSI was its first case. For an international institute as ELSI, a credit card for efficient overseas payment is particularly valuable.

(6) University notifications and services in Japanese and English

As a result of ELSI's feedback and requests to Tokyo Tech about the necessity of making important university notifications in English as well as Japanese to accommodate the university's international members, most notification mail from Tokyo Tech administration are now both in English and Japanese. Tokyo Tech has also established an English-language consultation desk for personnel matters and a counseling service using English. The General Safety Management Section of the Office of Campus Management delivers a lecture on campus safety in English bi-annually to non-Japanese staff and students engaged in lab work. These highlight the outcomes of ELSI administrative staff's efforts in sharing the hurdles of internationalization with Tokyo Tech. There are frequent interactions between various personnel from Tokyo Tech and ELSI staff and researchers to exchange ideas on how to improve various issues concerning better support for foreigners at the university.

5-4. Support by Host Institution

The following two items concern the support that the host institution provides the Center. Describe the functional measures that the host institution has taken to sustain and advance the Center's project. That include those items of support that it committed to at the time of the initial project proposal submittal or in its revised commitment following the project's interim evaluation.

5-4-1. Record of host institution support and its effects

・ In Appendix 6-1, describe the concrete measures being taken by the host institution.

(1) Human resource support to ELSI

Tokyo Tech had already assigned six tenure positions to ELSI until 2017, and one more tenure post was given to ELSI in FY 2018, with a total of seven tenure posts. In addition, the President has promised one more tenure post. This reflects Tokyo Tech's strategic mid- and long-term plan to promote education and research in Tokyo Tech with ELSI playing a vital role.

At the start of ELSI in 2012, tenured professors assigned to ELSI were exempted from undergraduate education duties. In order not to hinder undergraduate education, three faculty posts were provided to the original divisions of three ELSI professors by the President's discretion. Currently a scheme has been established so that professors from other departments can participate in ELSI's research. Tokyo Tech has assigned two administrators to ELSI at the beginning, and in addition assigned one more administrator to ELSI in 2018, supporting ELSI even stronger.

(2) Provision of research spaces

Tokyo Tech provided the existing building (2,670 m^2) on the campus to ELSI at the beginning (ELSI-2). In addition, the university provided a site and completed a new research building (ELSI-1: 5,000 m^2) in FY2014. These two buildings represent the idea of WPI centers strongly supported by Tokyo Tech.

(3) Financial support

ELSI receives 90 million yen annually from Tokyo Tech, which was the same amount of budget the former GCOE program that led to the conception of ELSI had received. Tokyo Tech also covers the salary of three PIs and two full-time administrative staff. In 2018, Tokyo Tech increased the support for one more additional administrative staff.

(4) Accommodations for international staff and set up of daycare service

As mentioned in 4-3, ELSI reserves priority on 20 rooms in Tokyo Tech's International House for foreign researchers. In addition, Tokyo Tech continues its efforts to secure accommodations for foreign researchers, and also opened a nursery school in April 2017 within the International House.

(5) Support for research fund acquisition

Responding to ELSI's request, Tokyo Tech established a new, more flexible and smaller-scale system of donation program to enhance education and research through donations from private companies. ELSI received JPY 24 million donation from a private company and established the "FirstLogic Astrobiology Donation Program". Utilizing this new system, we will continue to increase research fund acquisition from corporate donations. The Office of Research and Innovation also supports our researchers in various ways for external fund applications.

5-4-2. Position of the Center within the host institution's mid-term plan

・ To Appendix 6-2, excerpt the places in the host institution's "Mid-term objectives" and/or "Mid-term plan" that clearly show the positioning of the WPI center within its organization.

Tokyo Tech clearly defined ELSI in its Second Mid-term Plan. In its Third Mid-term Plan starting from FY2016, Tokyo Tech stated "By providing the Presidential discretionary resources, we will promote research in ELSI, focusing on the early earth, and aiming to link and unravel the origin and evolution of the earth and life." And the President recognized ELSI as a "strategic and ambitious organization". In addition, in the organization management rules of the National University Corporation Tokyo Institute of Technology, ELSI is defined as a leading member of the Strategic Research Hubs directly under the President.

5-5. Others

Describe efforts advanced to foster young researchers (e.g., start-up funding, autonomous research environment) and to enlist female researchers.

・ In Appendix 3-1, 3-2, give the transition in the number and ratio of female researchers.

(1) Efforts to foster young researchers

ELSI provides start-up funds to young researchers so that they can begin their research while acquiring external funds. ELSI requires young researchers to apply annually to at least one external grant. This requirement is a form of professional training to grow capabilities necessary for acquiring competitive funds: to manage grant application calendars, to plan one's budgetary needs, and to build proposal writing skills. Young researchers are encouraged to engage in outreach activities when they can. Communicating clearly and dynamically of one's science to a broader audience is a valuable part of a researchers' training. ELSI also believes that it is important to instill the responsibility to share knowledge of the science that is being funded by the public.

(2) Appointment of female researchers

ELSI has steadily increased our appointment of female early career researchers. ELSI has been successful for various reasons: we look for potential top candidates even before a search is open. Our senior scientists speak with their colleagues about promising candidates who will be on the recruitment market. We encourage long-term visits, providing comprehensive staff support to visitors to show that relocating to ELSI/Japan is feasible and exciting. We sponsor conferences and outreach tables to promote ELSI and connect with potential applicants. Our summer and winter schools are also great recruitment opportunities. ELSI has a Gender Equality Team (GET) that tracks our performance in achieving gender balance in invited speakers, visitors, organizing committees, and recruitment. GET works with the university's Gender Equality Office for exchange of information and feedback to meet international standards for gender equality and awareness. As shown in Appendix 3-2, the gender ratio today is 22%.

6. Others

In addition to the above 1.-5. evaluation items, note any of the Center's leading activities, distinctive features or other important points that denote its status as an "internationally visible research center."

(1) Participation in graduate-course education

ELSI has made a significant contribution towards nurturing the next generation of researchers by having our world-renowned scientists supervise graduate students. Currently, six researchers are supervising 19 students (including 5 foreign students) participating in graduate and undergraduate education in the schools of Science, Life Science, and Material Science; another two graduate students will join ELSI from abroad in September 2019. ELSI is in discussion with schools in Tokyo Tech so that ELSI can more actively participate in giving lectures in English, supervising graduate students and 4^{th} grade undergrads; in particular, taking the role of primary or secondary supervisor to individual PhD students. To increase our connections to other schools, ELSI has hosted two events, an Education Symposium at ELSI and a Research Collaboration Symposium at Suzukakedai campus, inviting deans and heads of schools and departments as well as professors and researchers to increase knowledge of one another and find collaborative opportunities.

ELSI has also been contributing to the internationalization of Tokyo Tech and the development of postgraduate education programs by accepting excellent foreign exchange students gathered through ELSI's overseas network (ETH in Switzerland, University College London, National University of Singapore, University of Hong Kong.)

(2) Acquisition of global funds (ELSI Origins Network project)

In July 2015, ELSI acquired research funds totaling JPY670 million (USD1=JPY122) from the John Templeton Foundation in the United States. The purpose of the grant was to build an international network of origins of life research with ELSI as a hub and to progress the science. The fact that the John Templeton Foundation chose to award ELSI to be a key player in origins of life research is testament to ELSI's international reputation. This grant was larger in amount than what all the national universities combined raised from overseas in the previous year. Based on this success, ELSI requested Tokyo Tech to set up overseas presence that would enhance acquiring funds abroad. In May 2017, ELSI helped to incorporate "Tokyo Tech USA, Inc.", a non-profit entity that could provide tax deduction for donations. We are building our activities to obtain donations and research funds from overseas companies, foundations, and private donors.

(3) Leadership in science communication

As an integral part of our internationalization efforts, ELSI is focused on playing a leadership role in transforming science communication conducted in English in Japan. Sharing research progress across the world increases visibility and recognition for domestic scientists, leads to a faster up-take of new ideas and produces opportunities for productive collaborations. Understanding our own challenges to promote our science to a global community using our limited PR human-and-funding resources, we hosted the Japan Scicom Forum 2018 as an event to bring together communicators, writers, scientists, journalists and selected experts from abroad to share ideas and to inspire and boost the cohesion of science communication in Japan. 117 attendees from institutions across Japan gathered together to learn from each other. In addition to building ELSI's communications, our new Communications Director (joined Nov. 2018), meets with Tokyo Tech PR to join efforts on increasing effective output. Finally, to follow on last year's success, ELSI will host Japan Scicom Forum 2019 this year.

(4) Streaming Lectures Online

From 2015, Tokyo Tech has started distributing "Introduction to Deep Earth Science-Part 1 (GeoS101x) outer" by Tokyo Tech's first MOOC (https://www.edx.org/course/introduction-deep-earth-science-tokyotechx-geos101x). Professor Kei Hirose, the Director of ELSI, gave the first and second lectures in English. 5,402 students from 159 countries worldwide registered to learn about the world's top-level research contents on the Internet.

(5) Collaboration with other WPI centers

ELSI holds an annual public event co-hosted with other WPI centers. In Jan. 2019, we held the 4th Joint Public Lecture "A Question of Origins" with Kavli IPMU and International Research Center for Neurointelligence (IRCN). In fall 2018, ELSI invited Dr. Takahiro Watanabe Nakayama from WPI

Nano Life Science Institute (NanoLSI) to give a mini symposium and to begin discussions with ELSI researchers about future collaborations. In December 2018, ELSI then sent researchers who were most interested to establish a joint project on the application of nanotechnologies to the study of prebiotic chemical reactions and to investigate affinities for metal reaction surfaces to visit NanoLSI in Kanazawa.

7. Center's Response to Results of FY 2018 Follow-up (including Site Visit Results)

* Describe the Center's response to results of FY 2018 follow-up. Note: If you have already provided this information, please indicate where in the report.

1)ELSI research and achievements has been steadily increasing over the past several years. It is now time to take stock of what the progress has achieved and set goals for the years ahead. This can best be done by revising and updating the ELSI's roadmap. Both in terms of reviewing ELSI's achievements and clarifying its future direction, making a revised version of the roadmap will be helpful in advancing the progress of individual projects and in developing new research fields by fusion.

ELSI's roadmap laid out an approach towards fusing disciplinary studies in planetary science, chemistry, and biology into an interdisciplinary field which would encompass an understanding of the joint origins of life and of the planets which support it. Specific questions as to the origins of the Earth and the history of Earth life provided us deeper understanding of the one example of life which we currently have access to for study: how did the Earth form, how did its geological and atmospheric evolution shape the formation and evolution of life on its surface, what sorts of environments on the early Earth support the necessary chemical precursors for life, and how did life on Earth proceed from that point? These questions are best answered by generalizing beyond Earth life into thinking about life as it could be elsewhere in the universe:

How could we detect life on other planets?
Is the Earth unique?
What are the fundamental principles of life as a phenomenon, such that we could compare life's emergence on Earth with how it might emerge on other planets?

ELSI's first ten years were dedicated to understanding the origin of life on Earth. In our next decade we will use solutions to fundamental problems derived in Earth's context to understand the conditions for life to exist anywhere in the universe. We will focus on four novel interdisciplinary research themes; 1. A Reference Earth Model for major nutrient cycles, 2. Combinatorial planetary systems chemistry, 3. Comparative planetology, and 4. Universal Biology. Within each, we will explore new synergies, develop new techniques and tools, and combine theory, observation, and experiments to produce world-class results in understanding how planets work, what is the potential diversity of planets beyond our solar system, realistic prebiotic chemistry, and characterizing the fundamental principles of life. This highlights ELSI's unique position as a rare institute in which the breadth of expertise is represented within the Institute and collaborators from other institutes come to ELSI to work on research problems under "one roof", as opposed to being distributed geographically and working together virtually.

The number of publications in Earth and planetary sciences have been very strong at ELSI but over the years. It is important to note that we are steadily increasing those in chemistry and biology, showing our progress in achieving the "life" part of our research. In the early years of ELSI (2013), 8 out of 51 (8%) publications represented life sciences. In 2015, that number increased to 36 out of 168 (21%) publications. Now in 2018, it is 54 out of 193 (28%) publications. This trend will continue and these numbers will undoubtedly increase significantly once we hire our new recruitment in chemistry and/or biology.

2) It would be interesting if ELSI could provide illustrations showing the current results of ELSI research and establish figures on how these research results have developed in various fields since the center's establishment.

We are grateful for the opportunity to showcase our scientific achievements, and this suggestion has guided how we have chosen to present our extension proposal. In this extension proposal (Section 1), we have labelled our updated roadmap with numbers corresponding to our selected research highlights (Section 2) and examples of interdisciplinary fusion (Section 3), corresponding to the specific areas that are addressed in each study. This acts as a virtual "table of contents" for ELSI to highlight its past achievements and simultaneously show the overall strategy and context of our science.

3) The origin of earth and life is an exceedingly complex and difficult issue, so it may be unlikely that a conclusion will emerge soon. Thus, the construction of a narrative on the appearance of life on earth incorporating new findings at ELSI, perhaps termed "ELSI model," will be a worthwhile goal, as was emphasized by the Working Group two years ago.

The overarching research result from ELSI's first seven years of operation has been a formulation of what a theory of the origin of life must be like. It is also a way of framing the broad problems in the origins of planets and life, which not only defines our own goals and criteria for success, but is meant to guide the approach to Origins Research in the worldwide scientific community.

A theory of the origin of life is not a reconstruction of an event or a series of events. Rather, its main subjects must be processes. **A complete theory of the origin of life** will be an account of the cascade of processes, acting between low-level chemistry and physics, and entire biospheres, that expand the diversity of spaces of possibilities, interleaved by other criteria or processes that selectively reduce diversity in hierarchical and robust systems.

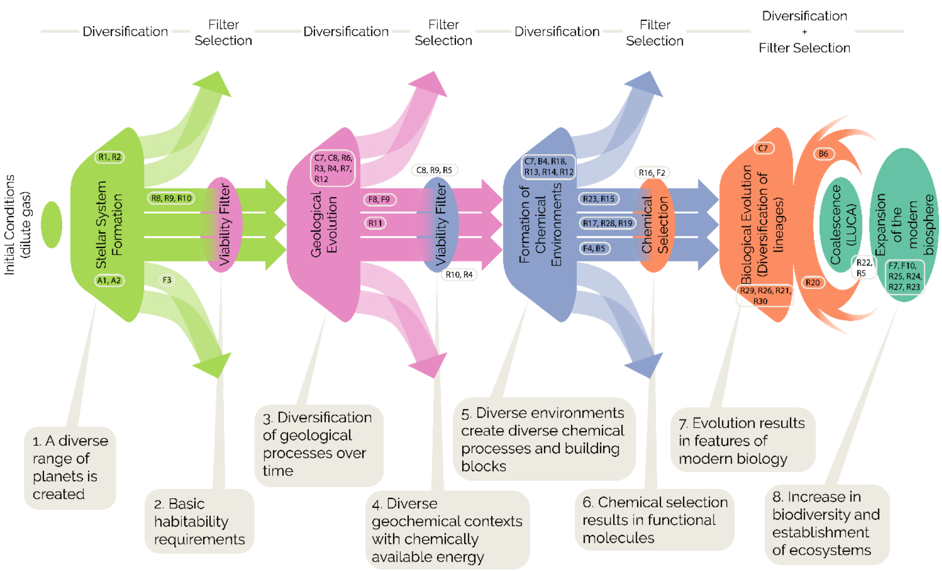
The **ELSI Model** builds on established methods of historical reconstruction, comparative analysis, modeling, and synthesis. It departs from many traditions in Origins Research, however, by lowering the importance given to scenarios-- detailed chains of inference about particular molecular motifs or planetary locations in which continuity of the chain is meant to lend plausibility to claims about individual steps.

In relation to chance and necessity -- studies of the origin of life that emphasize scenarios exaggerate the role of chance, because arguments based on chains of specific motifs or locations are fragile to missing knowledge. The ELSI formulation frames question of life's likelihood in terms of ways in which a biosphere gradually becomes a distinct phenomenon within the complex and interwoven chemical environment of an active planet.

In planetary science -- rather than emphasizing the history of a particular body in a planetary system, we seek to understand the distribution of possibilities, the processes by which the distribution diversifies, and bottleneck stages or criteria that limit the forms capable of generating downstream complexity.

In prebiotic chemistry -- rather than pursuing the chemical history of a succession of particular molecular motifs as the core problem of biogenesis, we seek to characterize the distributions of compounds associated with generating processes [e.g. the products of messy chemistry] and to understand which complex chemical states feedback dynamically either to expand the underlying distribution or contract it onto specific motifs.

In evolutionary biology -- rather than casting the evolutionary history of life in terms that mainly emphasize an ascending sequence of discoveries, we think of biological variety at any time as reflecting the interplay of available diversifying mechanisms and continuously-acting filters from the abiotic environment or from within the biosphere that select for properties, behaviors, and abilities.



The figure shows the phenomenon of origins of planets and life, and how we have structured ELSI's scientific activities to reflect it.
-- The numbers refer to the publications for the results highlighted in Sec. 2 and in 3-3 and Appendix 1-2.
-- The letters refer to the goals of the original proposal.

4) Education is very important in ELSI. In particular, interdisciplinary research has many benefits for young graduate students. It is expected that the university's executive will support the educational *relationship between ELSI and Tokyo Tech's departments.*

ELSI faculty are now actively mentoring over 24 talented graduate students in a variety of fields and departments, including Earth and Planetary Sciences, Material Chemistry, and Life Sciences. When necessary, ELSI faculty also supervise students who are based in other universities (in Japan and abroad). Many of our students come from the top universities and programs around the world, and could instead have chosen to study at any other leading university in the world. Our rapid success mirrors the growth of our purely research efforts in the past, and is ultimately a measure of ELSI's high profile and reputation around the world, the attractiveness of the ELSI environment for bright ambitious scholars, and the opportunity to study subject areas in a broadly inter-disciplinary context that is unique to our institute.

We have also spent considerable efforts on hosting short schools, with over 100 students attending since our institute's founding. We also launched an effort to support the travel of graduate students of our keynote symposium speakers to visit and stay at ELSI, and supported young researcher-led meetings like Astrobiology Graduate Conference (AbGradCon, which will be hosted at ELSI in 2020, the first time ever to be held outside of Europe or North America). ELSI has also maintained exhibit booths at conferences in related fields around the world, at which our researchers in attendance invite students to discuss our institute and opportunities for them in the future. This not only led to a stunningly high rate of highly qualified applicants for our research scientist positions, but it also led to word about ELSI being spread broadly among young scientists and students. Current students who have come to ELSI from abroad heard about us through colleagues or other students, and contacted us directly to inquire about the possibility of graduate study. Owing to our limited capacity for mentoring students, we have turned away the vast majority of such inquiries, and only invited the most talented students to formally apply. Most of our students from abroad have won scholarships from MEXT or other sources.

ELSI members also contribute to lecture courses in departments at Tokyo Tech, including undergraduate and graduate courses in the Earth and Planetary Sciences department as well as a newly launched course in Life Sciences. ELSI members also regularly teach special lectures at other universities, and perform outreach educational events for high school students in Japan.

Four of the tenured full-time faculty members of ELSI (Genda, Hernlund, Ida, Sekine) have teaching affiliations with Earth and Planetary Sciences (EPS), a productive collaboration that has been designed in collaboration with EPS Chair T. Nakamoto to serve as a role model and prototype for ELSI affiliations with other departments across the university. Associate Professor Shawn McGlynn has been in discussions with Material Chemistry, and we have received notification from the Dean of the school (Professor Y. Wada) that his affiliation and ability to mentor graduate students may officially begin on 1 April 2020. These advances have been discussed and managed by the Education Committee established in ELSI in 2018.

The world's top graduate students can pursue graduate degrees in any of the leading universities around the world, in countries that have long-established systems for concrete stipend support and tuition waivers. On the other hand, Japan has no equivalent system for supporting graduate students in the sciences with the exception of competitive scholarship programs having relatively low acceptance rates. This poses a country-level problem by making Japan less competitive in attracting the best students from around the world. In FY2019 Tokyo Tech started a fellowship program for doctoral course students (Tsubame Scholarship for Doctoral Students) for which all students who do not receive other fellowships are eligible. We would like to continue to suggest to MEXT the idea of launching regular graduate student support and for upgrading their procedures suitable for top world class students.

5) Continued effort needs to be made toward increasing the number of women in senior research positions at ELSI.

ELSI has met with a relatively high success rate in recruiting women to research scientist positions, at times exceeding our target critical mass (one-third) of the research staff. To support female scientists and staff, Tokyo Tech opened a nursery school on campus in 2017 as stated in 5-4-1(4), and two ELSI buildings have women's resting and nursing rooms.

Since our last site visit, we have recruited new PIs from our satellites. For example, we reinstated Renata Wentzcovich from our Columbia University Satellite as a PI. Professor Wentzcovich is a long time ELSI collaborator (co-authoring many papers) and was one of our founding PIs, who was unable to relocate to ELSI owing to family constraints.

Several years ago ELSI also established the Gender Equality Team (GET), which functions as a committee to advance the promotion of management best practices that help us to achieve the best success possible in gender parity. GET tracks our performance in achieving gender balance in recruitment, invited speakers, visitors, and organizing committees. GET reminds members running these efforts to keep our gender balance targets in mind and also asks afterwards what the reasons for being successful or unsuccessful in achieving the targets were. GET works with the university's Gender Equality Office for information sharing and exchange of feedback and ideas to raise international standards for gender equality and awareness. The existence of such efforts enhances the credibility of ELSI as an international institute, hence increases the interest of women to our recruitment calls.

A common challenge in attracting mid-career women to ELSI from abroad is the expense and difficulty of moving families overseas. Compensation is not ordinarily competitive in Japanese universities when compared with the typical salaries of leading world class senior scientists at other universities around the world. Tokyo Tech plans to introduce a flexible salary system as was already adopted in ELSI, but the success of such a system relies on the availability of sufficient funding, which is another challenge.

It is known that the majority of women in science (~70%) have spouses who are also scientists. However, both of them may not be able to find employment opportunities in the same institution or geographical area, and hiring married couples is unusual in traditional Japanese work places. So far ELSI was able to employ 5 married couples, which shows the success of ELSI in establishing work environments capable of attracting and supporting world class scientists.

Appendix 1-1 List of Papers Underscoring Each Research Achievement

* List papers underscoring each research achievement [1] ~ [15] listed in the item 2-1 "Research results to date" of 2. "Advancing Research of the Highest Global Level" (up to 30 papers) and provide a description of the significance of each (within 10 lines).
* For each, write the author name(s); year of publication; journal name, volume, page(s), and article title. Any listing order may be used as long as format is the same. If a paper has many authors, underline those affiliated with the Center.
* If a paper has many authors (say, more than 10), all of their names do not need to be listed.
* Place an asterisk (*) in front of those results that could only have been achieved by a WPI center.

*1. Ida S, Guillot T, Morbidelli A. 2016. The radial dependence of pebble accretion rates: A source of diversity in planetary systems-I. Analytical formulation. Astronomy & Astrophysics, 591:A72.

The paper studies "pebble accretion", a recent alternative to planetesimal accretion in which centimeter-to-meter sized icy grains migrating in planetary disks can control the early phases of planet formation. This analytical treatment shows that pebble accretion occurs in different regimes and can produce diverse planetary systems, consistent with the diversity observed in exoplanet surveys. Therefore, disk structure must be specified, and pebble growth, sublimation/destruction and migration must be considered, to predict the effects of pebble accretion as a planet-forming process.

2. Matsumura, S, Brasser, R, Ida, S. 2017. N-body simulations of planet formation via pebble accretion. I. First results. Astronomy and Astrophysics 607, A67.

This is the first paper that examines exoplanet formation through pebble accretion. It presents an integrated formation model incorporating all of: pebble accretion, gas accretion, eccentricity and inclination damping, type I and type II migration, and the effects of sublimation. Disc parameters on which the process depends, including stellar metallicity, the disc mass, and the disc's viscosity, are all surveyed. Important results include measures of the sensitivity of type-I migration to details of the disc model, and predictions of the dependence of formation efficiencies of planets on the stellar metallicities, not only for giant planets, but also for Earths (Es) and Super-Earths (SEs). A surprising prediction is of more ejected Es/SEs than has been expected – as many as one per every two low-mass ejected planets comparable to Mars – with implications for observations by WFIRST.

*3. Nomura R, Hirose K, Uesugi K, Ohishi Y, Tsuchiyama A, Miyake A, Ueno Y, 2014. Low core-mantle boundary temperature inferred from the solidus of pyrolite. Science 343, 522-525.

The precise relationship between temperature and melting of the lowermost mantle constrains the structure and heat flow across the core-mantle boundary, and is key to the thermal structures of both the mantle and the core. Using high-pressure, high-temperature three-dimensional x-ray microtomographic imaging experiments, the authors found that the temperature of the core-mantle boundary should be about 400 K lower than was previously estimated. Such a large depression is impossible without hydrogen in the core, suggesting that a large amount of H may have been incorporated into metals from a hydrous magma ocean at the time of core formation. The experimentally determined maximum melting point of 3570 K also suggests that some phases typically thought to lose stability in the lowermost mantle, such as $MgSiO_3$-rich post-perovskite, may be more widely distributed than expected.

*4. Hirose K, Morard G, Sinmyo R, Umemoto K, Hernlund J, Helffrich G, Labrosse S. 2017. Crystallization of silicon dioxide and compositional evolution of the Earth's core. Nature 543(99).

This was the first high-pressure/temperature experiment showing that SiO2 crystallizes first from a Fe-Si-O liquid. The resulting buoyancy force would strongly stir the core and expand the parameter range producing a geodynamo. This is a flagship work addressing questions about how to power magnetic fields in general, and more specifically Earth's magnetic field history. Because the presence or absence of a terrestrial magnetic field affects the retention or loss of planetary atmosphere due to the early energetic solar wind, expanding the parameter range in which a geodynamo is expected affects our understanding of whether the Earth's condition is uncommon or normal.

*5. Lin W, Paterson GA, Zhu Q, Wang Y, Kopylova E, Li Y, Knight R, Bazylinski DA, Zhu R, Kirschvink LJ, Pan Y. 2017. Origin of microbial biomineralization and magnetotaxis during the Archean. Proceedings of the National Academy of Sciences, 114:2171-2176

Although magnetotactic behavior is known in many groups of organisms, its evolutionary origin is obscure. This paper presents evidence that magnetotaxis evolved in bacteria during the Archean, before or near the divergence between the Nitrospirae and Proteobacteria phyla, suggesting that magnetotactic bacteria are one of the earliest magnetic-sensing and biomineralizing organisms on Earth. An early origin of magnetotaxis would have provided evolutionary advantages in coping with environmental challenges faced by microorganisms on early Earth; its persistence in separate lineages implies the temporal continuity of geomagnetic field, providing a biological constraint on the evolution of the geodynamo.

6. Hamano K, Abe Y, and Genda H. 2013. Emergence of two types of terrestrial planet on solidification of magma ocean. Nature 497, 607-610.

The paper develops an evolutionary model of magma ocean crystallization to show how cooling rate governs loss or retention of water delivered early in planet formation. Because the timescale for crystallization depends sensitively on stellar irradiance, a strong divergence can arise between Venus-like and Earth-like fates, demonstrating the existence of critical orbital thresholds for habitability.

*7. Kurokawa H, Foriel J, Laneuville M, Houser C, and Usui T. 2018. Subduction and atmospheric escape of Earth's seawater constrained by hydrogen isotopes, Earth and Planetary Science Letters, Volume 497, 149-160

The hydrogen isotopic deuterium/hydrogen (D/H) ratio reflects the global cycling and evolution of water on Earth as it fractionates through planetary processes. This paper reconstructs the early Earth’s ocean volume as a function of time using D/H ratio constraints in the mantle and oceans. It models the combined effects of seafloor hydrothermal alteration, chemical alteration of continental crust, slab subduction, and hydrogen escape from the early Earth, as well as degassing at mid-ocean ridges, hot spots, and arcs. Improved fractionation models suggest that in order to produce observed isotope ratios, secular net regassing and/or early fast plate tectonics are needed, and that the volume of Earth’s initial oceans could have been 2 to 3 times larger than those on Earth today.

*8. Genda H, Brasser R, Mojzsis SJ. 2017. The terrestrial late veneer from core disruption of a lunar-sized impactor. Earth and Planetary Science Letters 480:25-32

This work shows that the late veneer impact on Earth, which occurred around 4480 Myr ago, most likely resulted in a temporary 90-bar H_2 atmosphere on the Earth that lasted about 200 Myr. Such an atmosphere would have produced a highly reducing surface environment that facilitated accumulation of reduced organics, more similar to the conditions in the original Miller-Urey atmosphere models of prebiotic synthesis than would have held on the same planet without the veneer-forming impact. The paper was a focal topic in a 2018 conference in the United States concerning connections between planet formation conditions and prebiotic organosynthesis.

*9. Genda H, Sasaki T, Ueno Y, Iizuka T, Ikoma M. 2017. Ejection of iron-bearing giant-impact fragments and the dynamical and geochemical influence of the fragment re-accretion. Earth and Planetary Science Letters 470: 87-95

The paper conducts a numerical simulation of late giant impacts including fragment dynamics of the impactors and the effects on orbital evolution of protoplanets. The simulations show that the mass fraction of metallic iron in giant-impact fragments of differentiated bodies ranges from ~1 wt% to ~25 wt%. It solves problems concerning the eccentricity of Earth's orbit, the excess of Highly Siderophile Elements in the crust following core differentiation, and possible strong early reduction of the Earth's CO2-H2O atmosphere.

*10. Brasser R, Mojzsis SJ, Werner SC, Matsumura S, Ida S. 2016. Late veneer and late accretion to the terrestrial planets. Earth and Planetary Science Letters 455, 85-93.

The paper shows that the late veneer on Earth - a phase of late accretion that occurred when the Earth's crust was mostly molten and which therefore delivered the highly-siderophile elements to the mantle – is best explained by the impact of a single, lunar-sized object that struck Earth around 4480 Myr ago. The large size of the impactor, implying differentiation, also implies core fragmentation and a massive pulse of reduced iron at Earth's surface, with large consequences for atmospheric redox as well as the element abundances explained directly. Consequences for redox are developed in Genda et al. 2017 EPSL 470 and 480).

*11. Endo Y, Ueno Y, Aoyama S, Danielache SO. 2016 Sulfur isotope fractionation by broadband UV radiation to optically thin SO2 under reducing atmosphere. Earth and Planetary Science Letters 453: 9-22

The paper succeeds in reproducing the Archean sedimentary S-Mass-Independent-Fractionation record including 36S, and demonstrating that the early Earth's atmosphere should not have been a simple CO2 atmosphere but must have contained more reducing gasses, most likely CO. A CO-rich atmosphere may have been critical for prebiotic synthesis, and provides a key constraint for earlier Earth's environment/ecosystem. The mechanism responsible for such moderately reducing conditions for a long interval in the Archean remains to be solved, but part of the answer may come from the earlier strongly-reducing conditions derived by (Genda et al. 2017 EPSL 470) in connection with the late veneer.

*12. Maruyama S, Ikoma M, Genda H, Hirose K, T Yokoyama, M Santosh. 2013. The naked planet Earth: most essential pre-requisite for the origin and evolution of life. Geoscience Frontiers 4:141-165

The paper argues that no single local environment or process should be sought for the emergence of life, but that it likely depended on diverse planetary environments and an extended period in early Earth's maturation. The argument reflects ELSI's earliest emphasis that highly interdisciplinary science is required to sensibly address the Origin of Life problem, and refers to essential bottlenecks including sources of chemical activation such as solvated electrons which may be generated in several ways on a young planet.

*13. Kitadai N, Nakamura R, Takai K, Li Y, Gilbert A, Ueno Y, Yoshida N, and Oono, Y. 2018. Geoelectrochemical CO production: Implications for the autotrophic origin of life. Science Advances 4:eaao7265

The paper addresses a requirement in many autotrophic Origin of Life hypotheses for high pressures of CO as a source of carbon and reducing potential for prebiotic organic synthesis. Simulating a geoelectrochemical environment in deep-sea hydrothermal fields, the authors demonstrate CO production with up to ~40% Faraday efficiency on CdS in CO2-saturated NaCl solution at ≤−1 V vs. Standard Hydrogen Electrode. Such potentials would readily have been generated in the H2-rich, high-temperature, and alkaline hydrothermal vents that were probably widespread on the early komatiitic and basaltic ocean crust.

*14. Adam ZR, Hongo Y, Cleaves HJ, Yi R, Fahrenbach AC, Yoda I, Aono M. 2018. Estimating the capacity for production of formamide by radioactive minerals on the prebiotic Earth. Scientific Reports 8:265

The paper investigates the plausibility of formamide accumulation on early Earth, as a more favorable solvent than water for the synthesis and stabilization of organic compounds. It reports the conversion of aqueous acetonitrile (ACN) via hydrogen cyanide (HCN) as an intermediate into formamide by γ-irradiation under conditions mimicking exposure to radioactive minerals. The authors estimate that a radioactive placer deposit could produce 0.1-0.8 mol formamide per square kilometer per year, whereas a fission zone like the Oklo reactors could produce 0.1-1 mol per square meter per year. Radioactive mineral deposits may have been favorable settings for prebiotic compound formation through emergent geologic processes and formamide-mediated organic chemistry.

*15. Chandru K, Guttenberg N, Giri C, Hongo Y, Butch C, Mamajanov I, Cleaves HJ. 2018. Simple prebiotic synthesis of high diversity dynamic combinatorial polyester libraries. Communications Chemistry 1:30

The paper presents an experimental study of oligomerization of alpha-hydroxy acids, a class of plausibly abundant prebiotic monomers, to form vast, likely sequence-complete libraries that are stable for significant amounts of time. These libraries contain trillions of unique oligomer sequences, and are the largest deliberately prepared to date. Dependence on temperature, concentration, salinity, and presence of congeners are studied, to survey geochemical settings on the primitive Earth and other solar system environments.

*16. Guttenberg N, Virgo N, Chandru K, Scharf C, Mamajanov I. 2017. Bulk measurements of messy chemistries are needed for a theory of the origins of life. Philosophical Transactions of the Royal Society A 375:20160347

The paper addresses the disconnect, between Origin of Life research using restricted and controlled chemical models, and the likelihood that the kinds of chemical systems involved in the origins of terrestrial life produced a wide range of compounds via a wide range of mechanisms. The authors propose that experimental approaches to the origins of life should be expanded to include the study of 'functional measurements', which means inclusively studying bulk properties of chemical systems and their interactions with other compounds, structure-formation and other behaviours, even in cases where the precise composition and mechanisms are unknown.

*17. Fahrenbach AC, Giurgiu C, Tam CP, Li L, Hongo Y, Aono M, Szostak JW. 2017. Common and potentially prebiotic origin for precursors of nucleotide synthesis and activation. Journal of the American Chemical Society, 139: 8780-8783.

The paper demonstrates a prebiotic synthesis pathway for 2-aminoimidazole, a superior activating group in non-enzymatic RNA polymerization, which shares a common mechanism with that for 2-aminooxazole, a key intermediate in prebiotic nucleotide synthesis. Inputs consist of only glycolaldehyde, cyanamide, phosphate and ammonium ion, while pH and ammonium concentration determine which product is favored. The common synthetic origin of 2-aminoimidazole and 2-aminooxazole and their distinct reactivities are suggestive of a reaction network that could lead to both the synthesis of RNA monomers and to their subsequent chemical activation for reactions such as ligation.

*18. Kitadai N, Oonishi H, Umemoto K, Usui T, Fukushi K, Nakashima S. 2017. Glycine polymerization on oxide minerals. Origins of Life and Evolution of Biospheres 47:123-143

The paper combines an experimental study of polymerization of glycine on nine oxide minerals (amorphous silica, quartz, α-alumina and γ-alumina, anatase, rutile, hematite, magnetite, and forsterite), with molecular dynamics simulations of the determinants of amino acid affinity and orientation on the surfaces. Catalytic affinity was shown to decrease in the series rutile > anatase > γ-alumina > forsterite > α- alumina > magnetite > hematite > quartz > amorphous silica. Direct comparison of minerals' catalytic efficiencies and polymerization mechanisms elucidates the role of minerals in the process of abiotic peptide bond formation.

*19. Ilardo, M, Meringer M, Freeland S, Rasulev B, and Cleaves HJ. 2015. Extraordinarily adaptive properties of the genetically encoded amino acids. Scientific Reports 5:9414

The paper uses computational chemistry methods to assess how thoroughly the biologically coded amino acids cover a range of physico-chemical properties associated with adaptedness. The biological amino acid alphabet is compared to random sets of amino acids drawn from a computationally generated compound library containing 1913 alternative amino acids that lie within the molecular weight range of the encoded amino acids. The results of the property comparison indicate that the set of 20 genetically encoded amino acids has been selected as a largely global optimum, suggesting that any aqueous biochemistry would use a very similar set.

*20. Froese T, Campos JI, Fujishima K, Kiga D, Virgo N. 2018. Horizontal transfer of code fragments between protocells can explain the origins of the genetic code without vertical descent. Scientific Reports. 8:3532

The paper refines a widely-held view originally due to Carl Woese, that early cellular evolution was dominated by horizontal exchange of cellular components among loosely organized protocells collectively termed a "progenote". Using an iterated learning model, the authors simulate communal evolution based on horizontal transfer of code fragments, possibly involving pairs of tRNAs and their cognate aminoacyl tRNA synthetases or a precursor tRNA ribozyme capable of catalyzing its own aminoacylation. This model is the first to show explicitly that regularity, optimality, and (near) universality of a genetic code could have emerged entirely via horizontal interactions, without presupposing some form of vertical inheritance.

*21. Kuruma Y, Ueda T. 2015. The PURE system for the cell-free synthesis of membrane proteins. Nature protocols 10:1328

This paper describes how membrane protein complexes, which are essential to the viability of cells, can be artificially synthesized starting from gene expression in a cell-free system. Using a reconstructed cell-free extract known as the PURE system, ATP synthase and the Sec Translocon were artificially synthesized and their activities were determined. The demonstrated technique improves the possibility of making functional membranes in artificial cells, on the way to reproducing the emergence of cellular life in the laboratory.

*22. Giovannelli D, Sievert AM, Hügler M, Markert S, Becher D, Schweder T, Vetriani C. 2017. Insight into the evolution of microbial metabolism from the deep-branching bacterium, Thermovibrio ammonificans. Elife 6:e18990

The paper performs a phylogenetic and functional reconstruction of the core metabolism of the thermophilic, chemoautotrophic bacterium Thermovibrio ammonificans. The authors identify two distinct groups of genes: one encoding enzymes that do not require oxygen and use substrates of geothermal origin; the second apparently a more recent acquisition reflecting adaptations to cope with the rise of oxygen on Earth. They also report the first bioinformatic evidence for joint presence of enzymes from the two oldest carbon fixation pathways -- the Wood-Ljungdahl and reductive TCA pathways -- in a single organism. They infer that the ancestor of the Aquificae was a hydrogen oxidizing autotroph with a hybrid pathway for CO2 fixation, and that as more efficient terminal electron acceptors became available, this lineage acquired genes that increased its metabolic flexibility while retaining ancestral metabolic traits.

*23. Sim MS, Ogata H, Lubitz W, Adkins JF, Sessions AL, Orphan VJ, McGlynn SE. 2019. Role of APS reductase in biogeochemical sulfur isotope fractionation. Nature communications 10 (1), 44

This paper reports the sulfur kinetic isotope effect of the enzyme adenosine phosphosulfate reductase (APR), which is present in all known organisms conducting microbial sulfate reduction, and catalyzes the first reductive step in the pathway. The authors use these measurements to reinterpret the sedimentary sulfur isotope record over geological time. Archean sediments lack fractionation exceeding the Apr value of 20‰, indicating that sulfate reducers had access to ample electron donors to drive their metabolisms.

Large fractionations in post-Archean sediments suggest a decline of favorable electron donors as aerobic and other high potential metabolic competitors evolved. These findings link cellular biochemistry and physiology with the rock record of life on Earth.

*24. Johnson JE, Webb SM, Thomas K, Ono S, Kirschvink JL, Fischer WW. 2013. Manganese-oxidizing photosynthesis before the rise of cyanobacteria. Proceedings of the National Academy of Sciences 110:11238-11243

To illuminate the evolutionary history of biological water-splitting photosynthesis, this paper examines the behavior of the ancient Mn cycle using drill cores through an early Paleoproterozoic succession (2.415 Ga) preserved in South Africa. The cored strata contain substantial Mn enrichments (up to ~17 wt %) well before strata associated with the rise of oxygen at ~2.2 Ga, and the enrichments are hosted exclusively in carbonate mineral phases derived from reduction of Mn oxides. Independent proxies for O2 show that the original Mn-oxide phases were not produced by reactions with O2 but with some other strong oxidant, suggesting that the oxidative branch of the Mn cycle predated the rise of oxygen and was a transitional photosystem from which the water-oxidizing complex of photosystem II evolved.

*25. Rensen EI, Mochizuki T, Quemin E, Schouten S, Krupovic M, Prangishvili D. 2016. A virus of hyperthermophilic archaea with a unique architecture among DNA viruses. Proceedings of the National Academy of Sciences 113:2478-2483

This paper reports the isolation and characterization of a filamentous archaeal DNA virus, Pyrobaculum filamentous virus 1 (PFV1), infecting the hyperthermophilic archeon Pyrobaculum, which has striking structural similarity to the human RNA ebolavirus. PFV1 exhibits a type of virion organization not previously observed in DNA viruses, but superficially similar to that of negative-sense RNA viruses of the family Filoviridae, including Ebola virus and Marburg virus. Its genome, containing 39 predicted ORFs, most of which do not show similarities to sequences in public databases, forms a new viral family and suggests convergent evolution of virus structure. The results provide new insights into the diversity of architectural solutions used by filamentous viruses.

*26. Petrie KL, Palmer ND, Johnson DT, Medina SJ, Yan SJ, Li V, Burmeister AR, Meyer JR. 2018. Destabilizing mutations encode nongenetic variation that drives evolutionary innovation. Science 359:1542-1545

Evolutionary innovations are often achieved by repurposing existing genes to perform new functions; however, the mechanisms enabling the transition from old to new remain controversial. This paper shows that the mutations in bacteriophage λ's host-recognition gene J that confer enhanced adsorption to λ's native receptor, LamB, along with the ability to access a new receptor, OmpF, do so by creating conformational bistability of J. They thus function by generating multiple phenotypes from a single genotype. The results show how nongenetic protein variation can catalyze an evolutionary innovation, a mechanism that may have been even more important in the early stages of life when genome length and replication accuracy were limited.

*27. Cuthill JFH, Morris SC. 2017. Nutrient-dependent growth underpinned the Ediacaran transition to large body size. Nature ecology & evolution 1:1201-1204

The paper seeks to explain the enigmatic fractal growth patterns of the Ediacaran fauna known as rangeomorphs, as a result of the way the most primitive developmental programs interacted with environmental resource flows and constraints. Using micro-computerized tomography and photographic measurements, alongside mathematical and computer models, the authors demonstrate that growth of rangeomorph branch internodes declined as their relative surface area decreased, suggesting that frond size and shape were directly responsive to levels of oxygen and other nutrients. The results show that a scale-invariant growth algorithm can generate both complex and adaptive shapes by using physiological and ecological feedbacks.

*28. Meringer M, Cleaves HJ, Freeland SJ. 2013. Beyond terrestrial biology: Charting the chemical universe of α-amino acid structures. Journal of Chemical Information and Modeling 53:2851-2862

This paper uses computer software based on graph theory and constructive combinatorics in order to conduct an efficient and exhaustive search of the chemical structures for possible α-amino acids consistent with two definitions of relevance to biological coded proteins. The paper presents two virtual libraries of α-amino acid structures corresponding to these different approaches, comprising 121 044 and 3 846 structures, respectively. This demonstration of functionally defined and exhaustive molecule sets suggests a simple approach to exploring much larger, as yet uncomputed, libraries of interest.

*29. Guttenberg N, Laneuville M, Ilardo M, Aubert-Kato N. 2015. Transferable Measurements of Heredity in Models of the Origins of Life. PLoS One. 10:e0140663.

The paper proposes a measure of the amount of heritable variation that can be passed through time in any dynamical system, based on the degree to which the system's state can vary among fixed points in response to different selective pressures. The measure is equivalent across systems with different structure, and agrees with standard measures of memory capacity for transition-matrix models and the Graded Autocatalysis Replication Domain (GARD) model of compositional inheritance by Segre and Lancet. Neither GARD nor the transition-matrix model employs a concept corresponding to that of a genome, so both are testbeds for defining heredity functionally rather than in terms of specific and possibly historically-contingent mechanisms used by life on Earth.

*30. Virgo N, Guttenberg N. 2015. Heredity in Messy Chemistries. Artificial Life Conference Proceedings 13. MIT Press.

This paper makes a connection between the distribution of independent autocatalytic sets in random chemical networks and percolation phase transitions in connected graphs. The number of distinct autocatalytic sets that offer escape from a fixed chemical profile determines the capacity of a chemical system for hereditary dynamics. Maximizing the number of such escape routes identifies a critical density of interactions between reactants, which maximizes the evolutionary capacity of an autocatalytic chemical system. The evolutionary capacity at criticality in random networks scales logarithmically with their total chemical diversity. Autocatalytic chemistries likely supported an early phase of chemical evolution, and the hereditary capacity of this phase should have determined whether a transition to later, more complex, sequence-based mechanisms was achievable.

Appendix1-2 List of Papers of Representative of Interdisciplinary Research Activities

* List **up to 10 papers** underscoring each interdisciplinary research activity and give brief accounts (within 10 lines).
* For each, write the author name(s); year of publication; journal name, volume, page(s), and article title. Any listing order may be used as long as format is the same. If a paper has many authors, underline those affiliated with the Center.
* If a paper has many authors (say, more than 10), all of their names do not need to be listed.

1. Kurokawa H, Foriel J, Laneuville M, Houser C, Usui T. 2018. Subduction and atmospheric escape of Earth's seawater constrained by hydrogen isotopes, Earth Planet. Sci. Lett., 497, 149-160.

   The hydrogen isotopic deuterium/hydrogen (D/H) ratio reflects the global cycling and evolution of water on Earth as it fractionates through planetary processes. This paper reconstructs the early Earth's ocean volume as a function of time using D/H ratio constraints in the mantle and oceans. It models the combined effects of seafloor hydrothermal alteration, chemical alteration of continental crust, slab subduction, and hydrogen escape from the early Earth, as well as degassing at mid-ocean ridges, hot spots, and arcs. Improved fractionation models suggest that in order to produce observed isotope ratios, secular net regassing and/or early fast plate tectonics are needed, and that the volume of Earth's initial oceans could have been 2 to 3 times larger than those on Earth today.

2. Aono M, Naruse M, Kim SJ, Wakabayashi M, Hori H, Ohtsu M, Hara M. 2013. Amoeba-Inspired Nanoarchitectonic Computing: Solving Intractable Computational Problems Using Nanoscale Photoexcitation Transfer Dynamics. Langmuir 29:7557-7564.

   Machine learning, artificial intelligence, neural networks, etc., are among the most significant advances in modern technology, and already these novel approaches are changing the world and opening new opportunities. These techniques are rooted in mimicry of real natural processes, utilizing the tools that nature used to produce life from non-life, or to cause major revolutions in the history of life. Aono et al. take this approach even further, using actual biological functions to perform computational tasks that are impossible to solve on today's massive computers. This is an ELSI-inspired way of thinking, in that the way to solve challenging questions is to find inspiration in the natural world.

3. Brasser R, Mojzsis SJ, Matsumura S, Ida S. 2017. The cool and distant formation of Mars. Earth and Planetary Science Letters 468:85-93.

   The presence of Mars has long presented an enigma for planet formation models, in reconciling its distant orbit with the proximity (and early migration) of the gas giants. Some models proposed Mars formed closer to the Sun, and was later scattered outward to its present position, which predicts that it should have a similar chemical composition to the Earth. This collaboration combines planetary formation theory and cosmo-chemical constraints to argue that Mars could have formed at orbital radii similar to its present day position in the solar system, and offers new constraints on the dynamical conditions in that must have prevailed in the early solar system.

4. Kimura J, Kitadai N. 2015. Polymerization of building blocks of life on Europa and other icy moons. Astrobiology 15:430-44.

   Icy moons such as the Galilean satellite Europa are heated internally by tidal forces driven by orbital dynamics, instead of relying on solar radiation. This may significantly expand the "habitable" zone by producing environments conducive for life. This collaboration between planetary and thermodynamical modelers examined the energetics of polymerization that could be driven in these environments. They find that polymerization of complex organics (building blocks of life) should be energetically favored in moons like Europa.

5. Scharf C, Virgo N, Cleaves HJ, Aono M, Aubert-Kato N, Aydinoglu A, Barahona A, Barge LM, Benner SA, Biehl M, Brasser R, Butch CJ, Chandru K, Cronin L, Danielache S, Fischer J, Hernlund J, Hut P, Ikegami T, Kimura J, Kobayashi K, Mariscal C, McGlynn S, Menard B, Packard N, Pascal R, Pereto J, Rajamani S, Sinapayen L, Smith E, Switzer C, Takai K, Tian F, Ueno Y, Voytek M, Witkowski O, Yabuta H. 2015. A Strategy for Origins of Life Research, Astrobiology 15:1031-1042

   A major challenge in origin of life studies is how to frame the problem in a way that allows for practical strategical decisions to be made, such as establishing key priorities and grand challenges as a target for researchers across many disciplines. This paper was the result of a workshop held at ELSI, combining scholars from artificial life, planetary science, life science, chemistry, astrophysics, and philosophy. Numerous key roadblocks were identified, and strategies for addressing these were mapped out and implemented as part of ELSI's organizational strategy.

6. Ballmer M, Houser C, Hernlund JW, Wentzcovitch RM, Hirose K. 2017. Persistence of strong silica-enriched domains in the Earth's lower mantle. Nature Geoscience 10:236-240.

   Mantle convection is the flow and circulation of rock through the Earth's deep mantle, a process that is intimately connected to plate tectonics. While fluid-like models of this process have been used extensively in the past, there are many inconsistencies between the predictions and both geochemical and seismological observations. This study introduces the idea of memory effects in deep mantle dynamics by a combination of chemical heterogeneity and its feedbacks on rock rheology. The Bridgmanite-Enriched Ancient Mantle Structures (BEAMS) model can resolve all of the outstanding paradoxes in deep Earth science, including seismically imaged stagnant slabs of subducted lithosphere, persistence of an unmixed reservoir rich in primordial noble gases, and the fixed geographical positions of hot mantle plumes that trace out volcanic hot spots like Hawaii.

7. Rein H, Fujii Y, Spiegel DS. 2014. Some inconvenient truths about biosignatures involving two chemical species on Earth-like exoplanets. Proceedings of the National Academy of Sciences 111:6871-6875

   Chemical disequilibrium in a planetary atmosphere is commonly invoked as a potential biomarker in a planet, since abiotic processes alone are thought to run close to equilibrium and only biological processes can maintain a perpetually reactive state. This study shows that this approach can be fooled by the presence of a moon orbiting a planet, which has its own atmosphere with a distinct composition. Since it is impossible to rule out the presence of a moon using currently available observations, such a biomarker is not reliable.

8. Laneuville M, Kameya M, Cleaves HJ. 2018. Earth Without Life: A Systems Model of a Global Abiotic Nitrogen Cycle. Astrobiology.

   Nitrogen plays a major role in biotic processes and is the main component of Earth's atmosphere. This paper develops a kinetic mass-flux model of nitrogen cycles on early Earth before the emergence of life. The model suggests that significant concentrations of reactive nitrogen species, including nitrate and ammonia, would have been present in the early oceans, with implications for prebiotic chemistry and metabolic reactions of early life.

9. Yamamoto M, Nakamura R, Takai K. (2018) Deep sea hydrothermal fields as natural power plants. ChemElectroChem 5 (16), 2162-2166.

   Deep sea hot springs are special environments with abundant heat, chemical, and (it turns out) electrical energy. This collaboration between geobiologists and an electrochemist analyzed these energy flows and the possibility to create new kinds of chemical reaction networks and a new hypothesis of electricity-sustained life.

10. Moore EK, Jelen BI, Giovannelli D, Raanan H, Falkowski PG. 2017. Metal availability and the expanding network of microbial metabolisms in the Archaean eon. Nature Geoscience 10 (9), 629.

    The chemistry of life is driven by redox (electron transfer) which is catalyzed by enzymes that contain transition metals. As Earth's environmental conditions have changed, so have the availability of transition metals to operate specific metabolic processes. This study found that the diversity of metals used in enzymes has increased over time, suggesting that such changes in environmental conditions strongly influenced life on Earth.

Appendix 1-3
Major Awards, Invited Lectures, Plenary Addresses (etc.) (within 2 pages)

*Prepare the information below during the period from the start of the center through March 2019.

1. Major Awards

*List main internationally-acclaimed awards received/unofficially announced in order from the most recent.
*For each, write the recipient's name, the name of award, and the date issued.
In case of multiple recipients, underline those affiliated with the center.

Date	Recipient's name	Name of award
2018	Naohiro Yoshida	Medal of Honor with Purple Ribbon
2018	Henderson Cleaves	President, The International Society for the Study of the Origin of Life
2018	Naohiro Yoshida	Elected American Geophysical Union Fellow
2018	Hiroko Nagahara	Elected JpGU Fellow
2018	Tetsuo Irifune	Ehime Shinbun Prize
2018	Norio Kitadai	Incentive award for young scientist, the geochemical society of Japan
2017	George Helffrich	American Geophysical Union Fellow
2017	Henderson Cleaves	Elected Fellow of the International Society for the Study of the Origins of Life (ISSOL)
2017	Hidenori Genda	Geochemical Journal Award
2017	Taku Tsuchiya	JpGU Nishida Prize
2017	Tetsuo Irifune	JpGU Fellow
2017	Kei Hirose	JpGU Fellow
2016	Tetsuo Irifune	Robert Wilhelm Bunsen Medal
2016	Masashi Aono	The Young Scientists' Prize, Commendation by the Minister of MEXT, Japan
2016	Kei Hirose	57th Fujihara Award
June 2016	Yutetsu Kuruma	SFS Research Award 2015
2016	Kosuke Fujishima	iGEM 2016 Best Measurement project (Participated as a team advisor for the Stanford-Brown University team hosted by Lynn Rothschild lab at NASA Ames)
2016	Kosuke Fujishima	WIRED Audi INNOVATION AWARD
2016	Daisuke Kiga	Japan Society for the Promotion of Science Prize
2016	Yuka Fujii	Inoue Research Award for Young Scientists
2015	Tetsuo Irifune	R.W. Bunsen Medal (EGU)
2015	Tetsuo Irifune	Medal of Honor with Purple Ribbon
2015	Joseph Kirschvink	Geological Society of America Fellow
2015	Joseph Kirschvink	Royal Institute of Navigation Fellow
2015	Hiroki Ichikawa	Minister of Education, Culture, Sports, Science and Technology Prize, Science and Technology Award
2014	Ryuichi Nomura	Inoue Research Award for Young Scientists
2014	Masayuki Nishi	The Japan Society of High Pressure Science and Technology Award
2014	Ryuichi Nomura	Spring-8 Seeds Research Award
2014	Joseph Kirschvink	George P. Woollard Award
2014	Taku Tsuchiya	Japan Association of Mineralogical Sciences Award
2014	Shigenori Maruyama	GSA Honorary Fellow
2014	Ryuichi Nomura	SPRUC 2014 Young Scientist Award
2014	Tetsuo Irifune	A. E. Ringwood Medal

2014	Albert C. Fahrenbach	IUPAC-SOLVAY International Award for Young Chemists
2014	Joseph Kirschvink	Fellow of the Japan Geoscience Union
2014	Shigenori Maruyama	Fellow of the American Geochemical Society
2014	Shigenori Maruyama	Fellow of the Japan Geoscience Union
2014	Kei Hirose	Fellow of The European Association for Geochemistry
2014	Kei Hirose	Fellow of the American Geochemical Society

2. Invited Lectures, Plenary Addresses (etc.) at International Conferences and International Research Meetings

*List up to 10 main presentations in order from most recent.
*For each, write the lecturer/presenter's name, presentation title, conference name and date(s)

Date(s)	Lecturer/Presenter's name	Presentation title	Conference name
Jan. 14-19, 2018	Shigenori Maruyama	Nine Requirements for the Birth Place of Life and Three-Step Evolution of First Life [Invited talk]	Gordon Conference "Origin of Life. The Prebiotic Milieu Building the Evolution of Early Life", Galveston, TX, USA
Aug. 21, 2017	Piet Hut	When Will Science Become Fully Empirical? [invited keynote speech]	International Society for Theoretical Psychology, Tokyo, Japan
Jul. 16-21, 2017	Jack Szostak	The Nonenzymatic Copying of RNA Templates [Plenary Opening Lecture]	18th ISSOL Meeting, La Jolla, CA, USA
Jun. 26 – Jul. 1, 2016	Kei Hirose	Mantle Melting in Earth and Planetary Interiors [Keynote talk]	Goldschmidt 2016, Yokohama, Japan
Jan. 19, 2016	Masashi Aono	Oligopeptide formation in geysers [Invited talk]	Gordon Research Conference on Origins of Life, Galveston, TX, USA
Dec. 20, 2015	Daisuke Kiga	Simplification of the genetic code: Restricted diversity of genetically encoded amino acids [Invited talk]	Chemical approaches to astrobiology, Pacifichem 2015, Honolulu, HI, USA
Dec. 14-18, 2015	Kirschvink, J.L. & Kobayashi, A.	Biophysical Puzzles Concerning Magnetite-Based Magnetoreception in the Common Nematode, *Caenorhabditis elegans* [Invited talk]	AGU Fall Meeting, San Francisco, CA, USA
Nov. 15, 2015	David Eric Smith	Phase transitions in the origin of the biosphere [Keynote talk]	Carnegie Workshop "Reconceptualizing the Origin of Life", Washington DC, USA
Jul. 7-10, 2014	Tetsuo Irifune	Multi-anvil high-pressure technology and mineralogy of the deep mantle [Keynote, invited]	Australian Earth Sciences Convention 2014, Canberra, ACT, Australia
Jan. 12-17, 2014	Yuichiro Ueno	Archean geology [Invited talk]	Gordon Research Conference, Galveston, TX, USA

Appendix 1-4 2018 List of Center's Research Results

Refereed Papers

- List only the Center's papers published in 2018. (Note: The list should be for the calendar year, not the fiscal year.)

(1) Divide the papers into two categories, A and B.
 A. WPI papers
 List papers whose author(s) can be identified as affiliated with the WPI program (e.g., that state "WPI" and the name of the WPI center (WPI-center name)). (Not including papers in which the names of persons affiliated with the WPI program are contained only in acknowledgements.)
 B. WPI-related papers
 List papers related to the WPI program but whose authors are not noted in the institutional affiliations as WPI affiliated. (Including papers whose acknowledgements contain the names of researchers affiliated with the WPI program.)

 Note: On 14 December 2011, the Basic Research Promotion Division in MEXT's Research Promotion Bureau circulated an instruction requiring paper authors to include the name or abbreviation of their WPI center among their institutional affiliations. As some WPI-affiliated authors of papers published up to 2011 may not be aware of this requirement, their papers are treated as "WPI-related papers." From 2012, the authors' affiliations must be clearly noted.

(2) Method of listing paper
- List only refereed papers. Divide them into categories (e.g., original articles, reviews, proceedings).
- For each, write the author name(s); year of publication; journal name, volume, page(s), and article title. Any listing order may be used as long as format is consistent. (The names of the center researchers do not need to be underlined.)
- If a paper has many authors (say, more than 20), all of their names do not need to be listed.
- Assign a serial number to each paper to be used to identify it throughout the report.
- If the papers are written in languages other than English, underline their serial numbers.
- Order of Listing
 A. WPI papers
 1. Original articles
 2. Review articles
 3. Proceedings
 4. Other English articles

 B. WPI-related papers
 1. Original articles
 2. Review articles
 3. Proceedings
 4. Other English articles

(3) Use in assessments
- The lists of papers will be used in assessing the state of WPI project's progress.
- They will be used as reference in analyzing the trends and whole states of research in the said WPI center, not to evaluate individual researcher performance.
- The special characteristics of each research domain will be considered when conducting assessments.

(4) Additional documents
- After all documents, including these paper listings, showing the state of research progress have been submitted, additional documents may be requested.

A. WPI papers

1.Original articles

1. Adam, Z.R., Fahrenbach, A.C., Kacar, B., Aono, M., 2018. Prebiotic Geochemical Automata at the Intersection of Radiolytic Chemistry, Physical Complexity, and Systems Biology. Complexity. vol. 2018, Article ID 9376183, 21 pages, 2018. https://doi.org/10.1155/2018/9376183.
2. Adam, Z.R., Hongo, Y., Cleaves, H.J., II, Yi, R., Fahrenbach, A.C., Yoda, I., Aono, M., 2018. Estimating the capacity for production of formamide by radioactive minerals on the prebiotic Earth. Scientific Reports 8.
3. Afrin, R., Ganbaatar, N., Aono, M., Cleaves, H.J., II, Yano, T.-a., Hara, M., 2018. Size-Dependent Affinity of Glycine and Its Short Oligomers to Pyrite Surface: A Model for Prebiotic Accumulation of Amino Acid Oligomers on a Mineral Surface. International Journal of Molecular Sciences 19.
4. Alberto Hernandez-Hernandez, L., Yi, R., James Cleaves, H., Fuentes-Cabrera, M., Sumpter, B.G., Hernandez-Hernandez, A., Rangel, E., Vallejo, E., 2018. Theoretical and experimental evidence of conformational transformation in stereoisomers of nucleoside analogues. International Journal of Quantum Chemistry 118.
5. Andersen, J.L., Fagerberg, R., Flamm, C., Kianian, R., Merkle, D., Stadler, P.F., 2018. Towards Mechanistic Prediction of Mass Spectra Using Graph Transformation. Match-Communications in

Mathematical and in Computer Chemistry 80, 705-731.

6. Andersen, J.L., Flamm, C., Merkle, D., Stadler, P.F., 2018. Rule Composition in Graph Transformation Models of Chemical Reactions. Match-Communications in Mathematical and in Computer Chemistry 80, 661-704.
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13. Berliner, A.J., Mochizuki, T., Stedman, K.M., 2018. Astrovirology: Viruses at Large in the Universe. Astrobiology 18, 207-223.
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3.Proceedings

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4.Other English articles

NIL

B. WPI-related papers

1.Original articles

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2.Review articles

NIL

3.Proceedings

252. Bose, R., Meringer, M., Ilardo, M., Cleaves, H.J., 2018. Adaptive Properties of the Amino Acid Alphabet and its Subsets. The 2018 Conference on Artificial Life: A Hybrid of the European Conference on Artificial Life (ECAL) and the International Conference on the Synthesis and Simulation of Living Systems (ALIFE), 459-460.

4.Other English articles

NIL

Appendix 2 FY 2018 List of Principal Investigators

NOTE:

*Underline names of principal investigators who belong to an overseas research institution.

*In the case of researcher(s) not listed in the latest report, attach a "Biographical Sketch of a New Principal Investigator"(Appendix 2a).

<Results at the end of FY2018> **Principal Investigators Total: 18**

Name	Age	Affiliation (Position title, department, organization)	Academic degree, Specialty	Effort (%)*	Starting date of project participation	Status of project participation (Describe in concrete terms)	Contributions by PIs from overseas research institutions
Kei HIROSE	51	Director, Tokyo Institute of Technology, Earth-Life Science Institute Professor, The University of Tokyo, Department of Earth and Planetary Science	Ph.D., High-pressure Geoscience	90	From start	Main stays at the center, other than that, at Tokyo University Satellite.	
Mary VOYTEK	60	Executive Director, Tokyo Institute of Technology, Earth-Life Science Institute Professor, Columbia University Senior Scientist, NASA	Ph.D., Biology and Ocean Science	67	From August,2018	Main stays at the center, other than that, at Columbia University Satellite.	・Collaborative research promotion with Columbia Univ.
Shigenori MARUYAMA	69	Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D., Geology, Tectonics, History of Life and the Earth	80	From start	Usually stays at the center	
Shigeru IDA	58	Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D., Planetary Sciences, Planetary Physics	80	From start	Usually stays at the center	
<u>Piet HUT</u>	65	Full professor, Institute for Advanced Study, Princeton, Program of Interdisciplinary Studies Professor, Tokyo Institute of Technology, Earth-Life Science Institute	Ph.D., Theoretical Astrophysics, Interdisciplinary Studies	50	From start	Stays at the center for five months, other than that, at Princeton Satellite	・Accept young ELSI scientists to the Satellite (5 months, 7 months) ・Facilitate interdisciplinary research - Organize Workshops - Recruit young scientists
Naohiro YOSHIDA	64	Professor, Tokyo Institute of Technology, School of Materials and Chemical Technology	Doctor of Science, Environmental Chemistry, Global Change Analysis	80	From start	Stays at the center three times a week	
Tetsuo IRIFUNE	64	Professor, Ehime University, Geodynamics Research Center	Ph.D., High-pressure geosciences, Materials sciences	66	From start	Usually stays at Ehime Satellite	

Joseph Lynn KIRSCHVINK	65	Professor, California Institute of Technology, Division of Geological and Planetary Sciences Professor, Tokyo Institute of Technology, Earth-Life Science Institute	Ph.D., Geobiology, Paleo-magnetism, Biophysics, Neurobiology	50	From start	Stays at the center for five months, regularly communicates with us by email	・Research fieldwork and prepare customize equipment for research
Jack William SZOSTAK	66	Investigator, Howard Hughes Medical Institute Professor of Genetics, Harvard Medical School Professor of Chemistry and Chemical Biology, Harvard University Alex. A. Rich Distinguished Investigator, Department of Molecular Biology, Massachusetts General Hospital	Ph.D., Molecular biology Synthetic biology	60	From start	Usually stays at Harvard Satellite	・Accept a young ELSI scientist to the Satellite (5 months) ・Mutual dispatch of young scientists between two institutes
John HERNLUND	46	Professor, Tokyo Institute of Technology, Earth-Life Science Institute	Ph.D., Geophysical Modeling, Fluid and Solid Dynamics	100	From August, 2013	Usually stays at the center from August 2013	
George HELFFRICH	66	Professor, Tokyo Institute of Technology, Earth-Life Science Institute	Ph.D., Geological Sciences	85	From July, 2014	Usually stays at the center from July 2014	
Eric SMITH	53	Professor, Tokyo Institute of Technology, Earth-Life Science Institute External Professor, Santa Fe Institute Senior Research Scientist, Georgia Institute of Technology	Ph.D., High-energy/particle Physics	80	From February, 2015	Stays at the center for Six months, regularly communicates with us by email	・Research fieldwork and prepare customize equipment for research
Irena MAMAJANOV	43	Professor, Tokyo Institute of Technology, Earth-Life Science Institute	Ph.D., Physical Chemistry	100	From January, 2016	Usually stays at the center from January 2016	
Yuichiro UENO	44	Professor, Tokyo Institute of Technology, Department of Earth and Planetary Sciences	Doctor of Science, Geochemistry	60	From April, 2016	Usually stays at the center from April 2016	
Shawn McGLYNN	35	Associate Professor, Tokyo Institute of Technology, Earth-Life Science Institute	Ph.D., Evolutionary biology, Microbial biochemistry	80	From April, 2016	Usually stays at the center from April 2016	
Ryuhei NAKAMURA	42	Professor, Tokyo Institute of Technology, Earth-Life Science Institute	Doctor of Science, Electrochemistry	80	From April, 2017	Usually stays at the center from April 2017	
Hidenori GENDA	44	Associate Professor, Tokyo Institute of Technology, Earth-Life Science Institute	Ph.D., Planet formation	80	From April, 2018	Usually stays at the center from April 2018	
Yasuhito SEKINE	40	Professor, Tokyo Institute of Technology, Earth-Life Science Institute	Ph.D., Planetary Science, Astrobioloby, Evolution of Earth and planets	80	From June, 2018	Usually stays at the center from June 2018	

*Percentage of time that the principal investigator devotes to his/her work for the center vis-à-vis his/her total working hours.

Principal investigators unable to participate in project in FY 2018

Name	Affiliation (Position title, department, organization)	Starting date of project participation	Reasons	Measures taken
Not applicable				

Appendix 2a Biographical Sketch of Principal Investigator

(within 3 pages per person)

Name (Age) Hidenori Genda (44)

* Place an asterisk (*) by the name of the principal investigators who are considered to be ranked among the world's top researchers.

Affiliation and position (Position title, department, organization, etc.)

Associate Professor, Earth-Life Science Institute, Tokyo Institute of Technology

Academic degree and specialty

Doctor of Science, planetary science

Effort **100 %**

* Percentage of time that the PI will devote to his/her work for the center vis-à-vis his/her total working hours (total time for whole working activities including education, medical services, and others as well as research).

Research and education history

Education

1999	B.S. (Physics)	Keio University
2001	M.S. (Planetary Science)	The University of Tokyo
2004	Ph.D (Planetary Science)	The University of Tokyo

Research

2001.4 – 2004.3	Research Fellowship of JSPS (DC1), The University of Tokyo
2004.4 – 2007.3	Research Fellowship of JSPS (PD), Tokyo Institute of Technology
2007.4 – 2009.10	Project Assistant Professor, Tokyo Institute of Technology
2009.10 – 2013.3	Project Assistant Professor, The University of Tokyo
2013.4 – 2016.3	Researcher / Project Associate Professor, ELSI
2016.4 – 2018.3	A-PI / Project Associate Professor, ELSI
2018.4 – present	PI / Associate Professor, ELSI

Achievements and highlights of past research activities

* Describe the PI's qualifications as a top-caliber researcher if s/he is considered to be ranked among the world's top researchers.

Genda has been conducting research on how characteristics of planets and satellites were formed. What made Earth and Venus evolve so differently? What determined the existence of satellites, their numbers, and their sizes? Genda expects that those fundamental features were characterized during planet formation and their early evolution. Here are some highlights of Genda's past research.

Origin of atmospheres and oceans on terrestrial planets:

In 1990s, it was generally believed that a giant impact that happened during the late stage of Earth's formation can erode all pre-existing atmosphere and oceans (Ahrens 1993). Thus, volatile elements were supplied after the last giant impact. We quantitatively showed that this was totally wrong, and revealed that a significant amount of pre-existing atmosphere and oceans can survive giant impacts (**Genda** & Abe 2003 *Icarus*). This work brought a paradigm shift for the origin of atmosphere and oceans on Earth. Moreover, we further investigated this issue focusing on the difference between Earth and Venus. We found that the existence of ocean on protoplanets orbiting around 1 AU can enhance atmospheric loss (**Genda** & Abe 2005 *Nature*), which solved the compositional difference in noble gas abundance between Earth and Venus, which was a 20-year mystery.

Origin of wet Earth and dry Venus

Giant impacts lead to global and deep magma ocean. We investigated cooling process of a magma ocean by developing a radiative-convective atmosphere model. We found that Earth's magma ocean quickly condenses, and almost all water dissolved in a magma ocean was degassed into atmosphere, and ocean was finally formed. On the other hand, Venusian magma ocean cannot cool down until almost all hydrogen in water molecules escape into the space (~100Myrs). Remaining massive amount of oxygen can disappear in a long-lasting magma ocean, and very dry Venus was naturally formed in a framework of recent planet formation theory (Hamano, Abe & **Genda** 2013 *Nature*). A subtle difference of the distance from Sun can divide the fates of Earth and Venus.

Surface environment on Hadean Earth

After Earth's formation, Earth entered the stage of heavy meteoritic bombardment, which is often called late veneer and explains the excess of iron-loving highly siderophile elements in the current Earth's mantle. We investigated the effect of a late veneer on the early Earth's environments. Since accreting materials would have metallic iron (Dauphas 2017 *Nature*, **Genda**, Iizuka, Sasaki, Ueno & Ikoma 2017 *EPSL*), the very reduced surface environment should be formed during a Hadean era (**Genda**, Brasser & Mojzsis 2017 *EPSL*). Such a reduced surface environment on early Earth has obvious implications for biopoesis (e.g., Urey 1952, Miller 1953).

Origin of satellites

Regarding the origin of our Moon, the giant impact hypothesis is the most promising. Based on this hypothesis, we investigated the volatile loss from a proto-lunar disk. We found that the volatile elements at the outer part of the disk can be easily lost due to the shallow gravity potential, but the inner part of the disk survives (**Genda** & Abe 2003 *EPS*). At that time in 2003, this paper did not attract much attention. However, water was recently found in Apollo lunar samples (Hui *et al.* 2013), which means that volatile elements should be kept in the proto-lunar disk. Our paper has started to attract attention.

Among the terrestrial planets, only Earth and Mars have moon(s). In terms of comparison, the origin of Martian moons is interesting. There are two leading hypotheses about their origins: a capture origin and a giant impact origin (e.g., Rosenblatt 2011). Recently, we succeed in making Martian moons in a framework of a giant impact origin (Rosenblatt, … **Genda** et al. 2016 *Nature Geoscience*). We also predicted the compositions of the building blocks of Martian moons, which are a mixture of impactor's and Martian materials from its crust and mantle (Hyodo, **Genda** *et al.* 2017 **ApJ**). These theoretical predictions will be tested by a JAXA's future sample return mission from Martian moons, which is called MMX (Martian Moons eXploration) mission. Genda is involved in this mission as a core member of the Science Board.

We also investigated a research on Pluto-Charon system. We revealed that the dark and reddish whale-shaped region—named "Cthulhu Regio"—observed by NASA's New Horizons spacecraft is the smoking gun of a giant impact on Pluto (*Sekine, ***Genda** *et al.* 2017 *Nature Astronomy* <*equal contribution>). Though the investigation of the moons' origin, we have revealed how characteristics of planets were formed and what kind of constraints can be given to the processes of planet formation in the whole solar system.

Achievements

(1) International influence * Describe the kind of attributes listed below.

a) Guest speaker or chair of related international conference and/or director or honorary chairman of a major international academic society in the subject field

Genda, H., Origin of Earth's Oceans: An Assessment of the Total Amount, History and Supply of Water, Goldschmidt Conference 2017, Le Palais des Congrès de Paris, Paris, France, August, 2017. **(Medal)**

Genda, H., Planet Formation, UK-Japan Frontiers of Science Symposium, The Royal Society at Chicheley Hall, Buckinghamshire, U.K., November, 2016. **(Invited)**

Genda, H., Hamano, K. and Abe, Y., Formation and Early Evolution of Atmosphere and Ocean, Goldschmidt Conference 2014, Convention Center, Sacramento, California, USA, June, 2014. **(Keynote)**

Genda, H., Giant Impacts and Terrestrial Planet Formation, Goldschmidt Conference 2014, Convention Center, Sacramento, California, USA, June, 2014. **(Invited)**

Genda, H., N-body and SPH Simulations of the Formation of the Terrestrial Planets and Moon, Origin of the moon: challenges and prospects, The Royal Society at Chicheley Hall, Buckinghamshire, U.K., September, 2013. **(Invited)**

b) Member of a scholarly academy in a major country

N/A

c) Recipient of international awards

N/A

d) Editor of an influential journal, etc.

N/A

(2) Receipt of large-scale competitive funds (over the past 5 years)

Title: Modeling of water and material cycles in solar system bodies
Agency: MEXT
Category: KAKENHI, Scientific Research on Innovative Areas
Award: JPY 84,000,000
Period: FY2017–FY2021
Role: PI

Title: Impact spallation: Application to material delivery among planetary bodies
Agency: JSPS
Category: KAKENHI, Scientific Research (B)
Award: JPY 13,600,000
Period: FY2017–FY2019
Role: PI

(3) Major publications (Titles of major publications, year of publication, journal name, number of citations)

Genda, H., and Abe, Y. (2005) Enhanced atmospheric loss on protoplanets at the giant impact phase in the presence of oceans. *Nature* 433, 842–844. **<citation 157>**

Hamano, K., Abe, Y., and **Genda, H.** (2013) Emergence of two types of terrestrial planet on solidification of magma ocean. *Nature* 497, 607–610. **<citation 143>**

Ikoma, M., and **Genda, H.** (2006) Constraints on the mass of a habitable planet with water of nebular origin. *The Astrophysical Journal* 648, 695–706. **<citation 114>**

Genda, H., and Abe, Y. (2003) Survival of a proto-atmosphere through the stage of giant impacts: the mechanical aspects. *Icarus* 164, 149–162. **<citation 104>**

Genda, H., and Ikoma, M. (2008) Origin of the ocean on the Earth: Early evolution of water D/H in a hydrogen-rich atmosphere. *Icarus* 194, 42–52. **<citation 93>**

Number of papers published in 2003-2019: 40
Sum of the Times Cited: 1448
Average Citations per Item: 36.2
h-index: 18

(4) Others (Other achievements indicative of the PI's qualification as a top-world researcher, if any.)

N/A

Appendix 2a Biographical Sketch of Principal Investigator

Name (Age): Yasuhito Sekine (40)

Affiliation and position: Professor, Earth-Life Science Institute, Tokyo Institute of Technology

Academic degree and specialty: Doctor of Science, Planetary Science and Astrobiology

Effort: 100%

Research and education history

2006-2007. Research Associate, Dept. of Earth & Planetary Sci., The University of Tokyo

2007- 2011. Assistant Professor, Dept. of Complexity Sci. & Engr., The University of Tokyo

2011-2014. Lecturer, Dept. of Complexity Sci. & Engr., The University of Tokyo

2014-2018. Associate Professor, Dept. Earth & Planetary Sci., The University of Tokyo

Achievements and highlights of past research activities

Yasuhito Sekine has tried to develop "chemistry" on the formation and evolution of surface environments of planets and satellites. This is the case because understanding of chemical reactions and geochemical cycles occurring on planets/satellites would be one of the necessary steps toward development of "biology" in the Solar system and to answer a long-standing, fundamental question — *Is there life beyond Earth in the Solar system?*

To this end, Yasuhito Sekine focuses on the following four topics in the last decade; 1) to quantify chemical reactions into planetary surface processes, 2) to expand understanding of surface processes on Earth to other planets, 3) to understand the feedback among the atmosphere, climate, and life on Earth, and 4) to apply the above understanding for interpretations of spacecraft data.

The remarkable achievements of the topic 1) include to reveal the origin of Titan's N_2 atmosphere based on the Cassini's new observation [Sekine et al., 2011; *Nature Geosci.*], to explain a variety in surface materials on Pluto and Kuiper belt objects as a result of giant impacts in the Solar system [Sekine et al., 2017; *Nature Astron.*], and to reveal feedbacks among the atmospheric chemistry and climate on Titan [Sekine et al., 2008; *Icarus*]. In especially, the first two have proposed that a variety in surface compositions among the outer Solar system bodies would have been caused by gas and ice giants' migrations based on a recent planet formation theory.

Regarding the topic 2), Yasuhito Sekine has performed geological survey for impact craters [Komatsu et al., 2011, *PPS*], caldera, and cold arid deserts [Sekine et al. In prep] on present-day Earth. These terrestrial analogs provide essential constraints for interpreting and modeling hydrological and geochemical cycles on a planet/satellite, especially on early Mars.

The remarkable achievements of the topic 3) include to constrain detailed timing of a rise in atmospheric O_2 [Sekine et al., 2011a; *EPSL*; Sekine et al., 2011b, *Nature Comm.*]. We show that a rise of O_2 would have occurred in the aftermath of a large-scale glacial event. Biogeochemical modeling explains this linkage quantitatively [Harada et al., 2015]. Under greenhouse conditions immediately after a large-scale glaciation, intense chemical weathering and consequent nutrient inputs would have caused a transition of a steady-state of O_2 level.

The remarkable achievements of the topic 4) include the discovery of ongoing hydrothermal activities within Enceladus [Hsu et al., 2015; *Nature*]. In a follow-up paper, Yasuhito Sekine also shows that Enceladus' hydrothermal activities occur in a chondritic core, which would provide sufficient H_2 to support chemoautotrophic life [Sekine et al., 2015; *Nature Comm.*]. These researches have first revealed the presence of requirements for life—liquid water, organic matter, and energy—beyond Earth.

Achievements

(1) International influence

a) Guest speaker or chair of related international conference and/or director or honorary chairman of a major international academic society in the subject field

Yasuhito Sekine has been invited to more than 20 international conferences and meetings since 2009. He has also worked as a convener in more than 10 international conferences and symposiums.

b) Member of a scholarly academy in a major country

American Geophysical Union, Japan Geoscience Union, The Geochemical Society of Japan, The Japanese Society for Planetary Sciences, Japan Association of Mineralogical Sciences

c) Recipient of international awards

2009. Outstanding Young Scientist Award, the Japan Society for Planetary Sciences

2012. Young Researcher Award, Geochemical Research Association, Japan

2016. Young Scientists' Prize, The Commendation for Science & Technology by the Minister of Education, Culture, Sports, Science, and Technology, Japan

d) Editor of an influential journal, etc.

2013-present. Journal of Geophysical Research–Planets.

(2) Receipt of large-scale competitive funds (over the past 5 years)

Principle Investigator

2017-2021. MEXT Grant-in-Aid for Scientific Research on Innovative Areas (Steering and International Research Groups X01 and Y01), Total JPY 79,300,000 (~$ 710,000)

2017-2021. MEXT Grant-in-Aid for Scientific Research on Innovative Areas (Research Group A02), Total JPY 170,200,000 (~$ 1,500,000)

2016-2018. Satellite Research Project, the Astrobiology Center, National Institutes of Natural Sciences (NINS), Total JPY 14,500,000 (~$120,000)

2016-2017. JSPS Grant-in-Aid for Challenging Exploratory Research, Total JPY 4,000,000 (~$ 36,000)

2014-2016. JSPS Grants-in-Aid for Young Scientists (A), Total JPY 19,000,000 (~$140,000)

2015. JGC-S Scholarship Foundation, Total JPY 2,000,000 (~$18,000)

2015. Ito Science Scholarship, Total JPY 1,000,000 (~$9,000)

Co-Investigator

2015-2018. JSPS Grant-in-Aid for Scientific Research (A), JPY 1,600,000 (~$ 15,000).

2011-2015. MEXT Grant-in-Aid for Scientific Research on Innovative Areas, JPY 10,000,000 (~$ 95,000).

(3) Major publications (Titles of major publications, year of publication, journal name, number of citations)

Hsu, H.-W.+, F. Postberg+, <u>Y. Sekine+</u>, T. Shibuya, S. Kempf, M. Horanyi, A. Juhasz, N. Altobelli, K. Suzuki, Y. Masaki, T. Kuwatani, S. Tachibana, S. Sirono, G. Moragas-

Klostermeyer, R. Srama "Ongoing hydrothermal activities within Enceladus" ***Nature*, 519**, 207-210, 2015. (+*these authors contributed equally to this work*). Citations 168 in Google Scholar

Sekine Y., H. Imanaka, T. Matsui, B.N. Khare, E.L.O. Bakes, C.P. McKay, S. Sugita "The role of organic haze in Titan's atmosphere I: Laboratory investigation on heterogeneous reaction of atomic hydrogen with Titan tholin" *Icarus*, **194**, 1, 186–200, 2008. Citations 51 in Google scholar

Sekine, Y., H. Genda, S. Sugita, T. Kadono, T. Matsui "Replacement and late formation of atmospheric N_2 on undifferentiated Titan by impacts" *Nature Geoscience*, **4**, 359–362, 2011. Citations 37 in Google Scholar

Sekine, Y., S. Sugita, T. Shido, T. Yamamoto, T. Kadono, T. Matsui "The role of Fischer-Tropsch catalysis in the origin of methane-rich Titan" *Icarus*, **178**, 154–164, 2005. Citations 36 in Google Scholar

Sekine, Y., T. Shibuya, F. Postberg, H.-W. Hsu, K. Suzuki, Y. Masaki, T. Kuwatani, M. Mori, P.K. Hong, M. Yoshizaki, S. Tachibana, S. Sirono "High-temperature water-rock interactions and hydrothermal environments in the chondrite-like core of Enceladus" *Nature Communications*, **6**, 8604, 1–8, 2015. Citations 32 in Google Scholar

Total numbers of the peer-reviewed papers since 2002: 54

Total citations: 819

(4) Others (Other achievements indicative of the PI's qualification as a top-world researcher, if any.)

A member of Editor-in-Chief Selection Committee of Geophysical Research Letters, AGU

A member of Japanese-Germany Frontier of Science Symposium (J-G FoS)

Appendix 2a Biographical Sketch of a New Principal Investigator

(within 3 pages per person)

Name (Age) Mary Voytek (60)

Affiliation and position (Position title, department, organization, etc.)

Position: Specially Appointed Professor and Executive Director

Department: Earth-Life Science Institute

Organization: Tokyo Institute of Technology

Academic degree and specialty

Effort 67 %

Research and education history

APPOINTMENTS:

8/18-present Executive Director, ELSI and Special Advisor to the President Tokyo Tech

8/18-present Cross appointment with Columbia University, Astrobiology

12/10-present Senior Scientist for Astrobiology, Planetary Sciences Division, SMD, NASA

12/15-present Lead Scientist for the Nexus of Exoplanet System Science (NExSS)

8/11-present Deputy Program Scientist for the Mars Science Laboratory "Curiosity" Rover

1/16-12/16 Special Detail to the NASA Office of the Chief Scientist

1/98-11/10 Senior Scientist Environmental Microbiology, National Research Program, U.S. Geological Survey, Reston, VA

2000-present Adjunct Associate Professor at University of Maryland, Cambridge, MD

7/97-9/97 Visiting Investigator at the Max Planck Institute for Limnology, Ploen, Germany

1/96-1/98 Postdoctoral Fellow, Inst. Marine & Coastal Sci., Rutgers University, New Brunswick, NJ

DEGREES:

1996 Ph.D., Biology and Ocean Sciences, University of California, Santa Cruz, CA,

1984 M.S., Biological Oceanography, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI

1980 B.A., Biology Honors, The Johns Hopkins University, Baltimore, MD

Achievements and highlights of past research activities

Achievements

(1) International influence * Describe the kind of attributes listed below.

a) Recipient of international awards

b) Member of a scholarly academy in a major country

c) Guest speaker or chair of related international conference and/or director or honorary chairman of a major international academic society in the subject field

Plenary and Keynote Lectures

2018 International Congress of Extremophiles 2018, Ischia, Italy

2018 AGU Fall Meeting, Washington, DC Biogeosciences Centennial Session

2018 UNOLS Deep Submergence Science Committee Community Meeting

2018 Curiosity2018 Future Insight Conference Sponsored by Merck on their 350th year anniversary

2017 Microbiology in the new Millennium: from Molecules to Communities (MNM 2017) Kolkata, IN

2016 4th ELSI Symposium Origins of Life Tokyo, Japan

2016 11th Annual DOE Joint Genome Institute Genomics of Energy & Environment Meeting

2016 Gordon Research Conference Origins of Life

2014 Origins 2014- ISSOL Conference Nara, Japan

2012 COSPAR Planetary Protection Colloquium 2012, Alpbach, Austria

2011 11th European Workshop on Astrobiology EANA'11 Cologne, Germany

2011 International Investigations into Carbon Cycling in the Deep Crustal Biosphere, South Africa

2011 Origins 2011- ISSOL And Bioastronomy Joint International Conference Montpellier, FR

2010 CAREX (Coordination Action for Research Activities on Life in Extreme Environments) Rome, Italy

2010 Gordon Research Conference Organic Geochemistry

2009 ICDP Deep Biosphere Conference, Potsdam, Germany

d) Editor of an international academic journal

2004-2008 Associate Editor, Aquatic Microbial Ecology

e) Peer reviewer for an overseas competitive research program (etc.)

Regular reviewer for multiple programs U.S. NSF, DOE, ONR and NASA (1998-2010)

Member, Committee of Visitors to Evaluate the Ocean Sciences Program, U.S. NSF (2015).

(2) Receipt of major large-scale competitive funds (over the past 5 years)

N/A

(3) Major publications (Titles of major publications, year of publication, journal name, number of citations)

Authored 102 refereed publications. Most highly cited papers are in the areas of nitrogen cycling in aquatic systems, bioremediation of chlorinated compounds, and microbial activity in extreme environments.

Stevenson A, J Burkhardt, CS Cockell, JA Cray, J Dijksterhuis, M Fox-Powell, TP Kee, G Kminek, TJ McGenity, KN Timmis, DJ Timson, **MA Voytek**, F Westall, MM Yakimov, JE Hallsworth (2015) Multiplication of microbes below 0.690 water activity: implications for terrestrial and extraterrestrial life. Environmental Microbiology 17:257–277 **(84)**

Grotzinger JP… MSL Science Team (2014) A Habitable Fluvio-Lacustrine Environment at Yellowknife Bay, Gale Crater, Mars. Science 343(6169):1242777 **(358)**

Groffman PM, MA Altabet, JK Böhlke, K Butterbach-Bahl, MB David, AE Giblin, TM Kana, LP Nielsen, MK Firestone, **MA Voytek** (2006) Methods for measuring denitrification: diverse approaches to a difficult problem. Ecological Applications 16: 2091-2122 **(694)**

Reysenbach A-L, Y Liu, AB Banta, TJ Beveridge, JD Kirshtein, S Schouten, MK Tivey, K Von Damm, **MA Voytek** (2006) A ubiquitous thermoacidophilic archaeon from deep-sea hydrothermal vents. Nature 442(7101): 444-447 **(208)**

Wallenstein MD, DD Myrold, M Firestone, **MA Voytek** (2006) Environmental controls on denitrifying communities and denitrification rates: Insights from molecular methods. Ecological Applications 16:2143-2152 **(367)**

Priscu JC, E Adams, WB Lyons, **MA Voytek,** DW Mogk, RL Brown, CP McKay, CD Takacs,

KA Welch, CF Wolf, JD Kirshtein, R Avci (1999) Geomicrobiology of subglacial ice above Lake Vostok, Antarctica Science 286: 2141-2144 **(465)**

Voytek MA, BB Ward (1995) Detection of ammonium-oxidizing bacteria of the beta-Subdivision proteobacteria in aquatic samples using the polymerase chain reaction Applied and Environmental Microbiology 61(4):1444-1450 **(201)**

Citations	5353
h-index 37	37
i10-index	63

(4) Others (Other achievements indicative of the PI's qualification as a top-world researcher, if any.)

National and International Memberships on Science Advisory Committees in recognition of Scientific Expertise and Stature

Microbiology Advisory Group, International Continental Scientific Drilling Program (2009).

Committee for Biology & Genomics, US Subglacial Antarctic Lake Environments (SALE) Working group for ISC, Scientific Committee on Antarctic Research (SCAR), (2005-2010).

Evaluation Committee UK Centre for Astrobiology, University Edinburgh (2014).

Interagency Committee on Microbiomes, White House Office of Science & Technology Policy (2015-present).

Marine Microbiology Initiative Expert Evaluation Committee, Moore Foundation (2017)

U.S. Department of Energy (BERAC) subcommittee on Natural and Accelerated Bioremediation Research (NABIR) (2002–2003)

NASA Planetary Protection Advisory Committee (2005–2009)

Science Advisory Board, National Center for Ecological Analysis and Synthesis (NCEAS) (2004–2007).

HONORS AND AWARDS:

2017 NASA Distinguished Achievement Award for NExSS
2016 Group Special Act Award for Implementation of OSTP Policy-Public Access
2015 Group Achievement Award to MSL Prime Mission Science and Operations Team
2013 Group Achievement Award to the Agency Grand Challenge Working Group
2013 Group Achievement Award for MSL Launch and Landing-NASA Science Management
2013 NASA Superior Service Award
2012 Cooperative External Achievement Award for FameLab Science Communication
2011 Group Achievement Award to O/OREOS Nanosatellite Science and Engineering Team
2006 USGS Superior Service Award
2001 Scholar, German-American Frontiers of Science
1997 Helmholtz Federation Early Career Fellow
1996 UCSC Outstanding Dissertation Award
1994 Switzer Foundation Fellowship
1993 Distinguished paper in phycology from Phycological Society of America

Appendix 3-1 FY 2018 Records of Center Activities

1. Researchers and other center staffs, satellites, partner institutions

1-1. Number of researchers and other center staffs

* Fill in the number of researchers and other center staffs in the table blow.
* Describe the final goals for achieving these numbers and dates when they will be achieved described in the last "center project."

a) Principal Investigators

(full professors, associate professors or other researchers of comparable standing)

(number of persons)

	At the beginning of project	At the end of FY 2018	Final goal (Date: March, 2023)
Researchers from within the host institution	6	13	13
Researchers invited from abroad	3	4	4
Researchers invited from other Japanese institutions	4	1	1
Total principal investigators	13	18	18

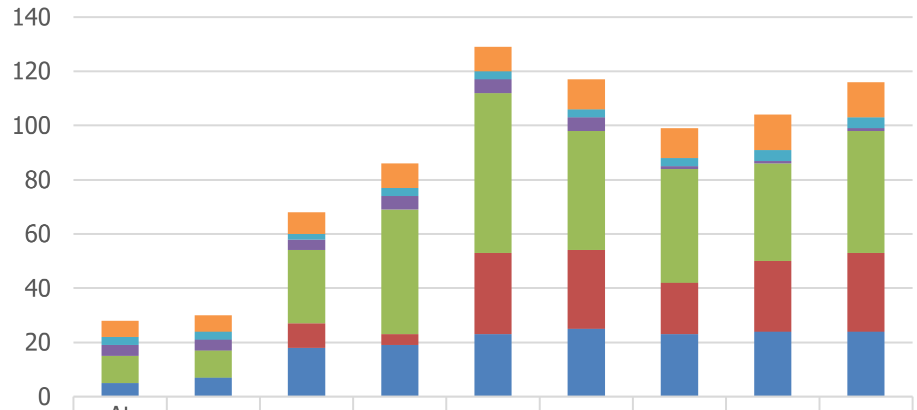
b) Total members

	At the beginning of project		At the end of FY2018		Final goal (Date: March, 2023)	
	Number of persons	%	Number of persons	%	Number of persons	%
Researchers	23		54		63	
Overseas researchers	3	13%	26	48%	32	51%
Female researchers	0	0%	12	22%	15	24%
Principal investigators	13		18		18	
Overseas PIs	3	23%	9	50%	10	56%
Female PIs	0	0%	2	11%	2	11%
Other researchers	10		36		45	
Overseas researchers	0	0%	17	47%	22	49%
Female researchers	0	0%	10	28%	13	29%
Research support staffs	0		26		29	
Administrative staffs	5		24		24	
Total number of people who form the "core" of the research center	28		104		116	

Appendix 3-2 Annual Transition in the Number of Center Personnel

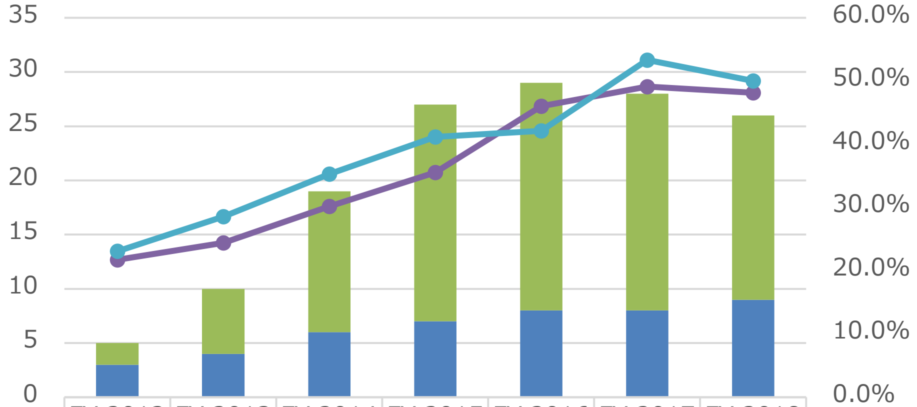
*Make a graph of the annual transition in the number of center personnel since the start of project.

Transition of Personnel



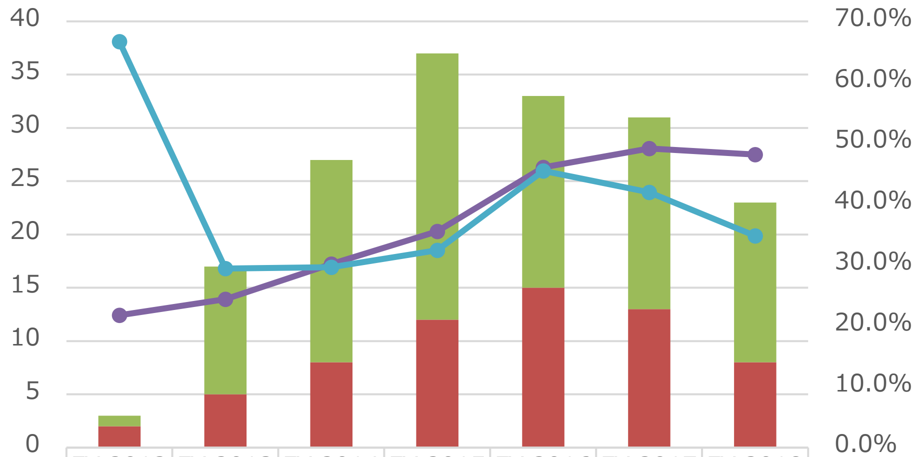
	At beginning	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018	Final goal
PI : Researchers from within host institution	6	6	8	9	9	11	11	13	13
PI : Researchers invited from abroad	3	3	2	3	3	3	3	4	4
PI : Researchers invited from other Japanese institutions	4	4	4	5	5	5	1	1	1
Other researchers	10	10	27	46	59	44	42	36	45
Research support staffs	0	0	9	4	30	29	19	26	29
Administrative staffs	5	7	18	19	23	25	23	24	24

Number/Ratio of Overseas Researchers



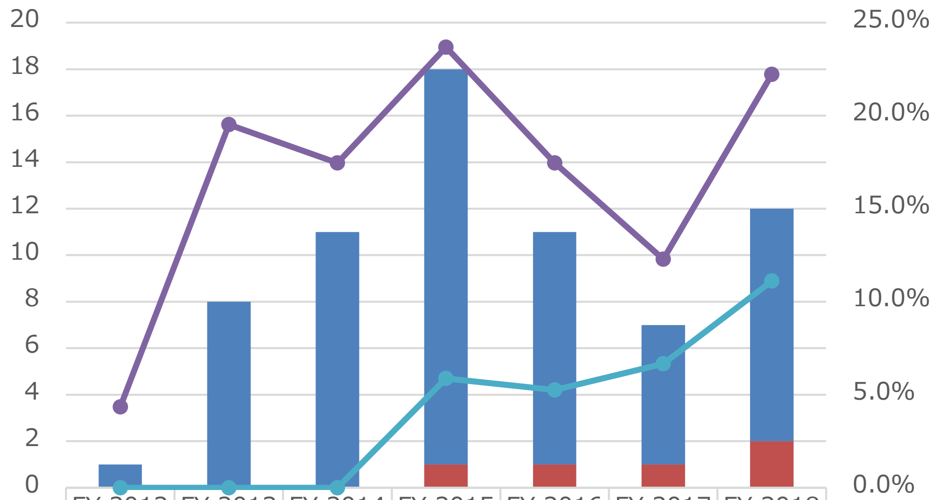
	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018
Other Researchers from abroad	2	6	13	20	21	20	17
PI from abroad	3	4	6	7	8	8	9
Ratio of Researchers from abroad	21.7%	24.4%	30.2%	35.5%	46.0%	49.1%	48.1%
Ratio of PIs from abroad	23.1%	28.6%	35.3%	41.2%	42.1%	53.3%	50.0%

Number/Ratio of Overseas Postdoc



	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018
Japanese Postdoc	1	12	19	25	18	18	15
Overseas Postdoc	2	5	8	12	15	13	8
Ratio of Researchers from abroad	21.7%	24.4%	30.2%	35.5%	46.0%	49.1%	48.1%
Ratio of Overseas Postdoc	67%	29%	30%	32%	45%	42%	35%

Number/Ratio of Female Researchers



	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018
Other Female Researchers	1	8	11	17	10	6	10
Female PI	0	0	0	1	1	1	2
Ratio of Female Researchers	4.3%	19.5%	17.5%	23.7%	17.5%	12.3%	22.2%
Ratio of Female PI	0.0%	0.0%	0.0%	5.9%	5.3%	6.7%	11.1%

Appendix 3-3　Diagram of Management System

- Diagram the center's management system and its position within the host institution in an easily understood manner.
- If any changes have been made in the management system from that in the latest "center project" last year, describe them. Especially describe any important changes made in such as the center director, administrative director, head of host institution, and officer(s) in charge at the host institution (e.g., executive vice president for research).

● New Tokyo Tech President

Yoshinao Mishima, who has energetically supported ELSI since its launch, completed his term as the Tokyo Tech President, and Kazuya Masu succeeded him in April 2018. Masu guarantees that the support from the host institution as promised by Mishima will continue. The executive vice president responsible for research also changed from Makoto Ando to Osamu Watanabe.

● Appointment of Executive Director

Mary Voytek, who founded the Astrobiology Program of NASA and is also a renowned scientist in astrobiology, joined ELSI in August 2018 as PI and Executive Director. At Tokyo Tech, she has the positions of specially appointed professor and Special Advisor to the President. She has rich experience in organizational management and strong international network connections; she is expected to strengthen the management of ELSI and will also advise the Tokyo Tech President in terms of the university's globalization, visibility enhancement, and fund raising. At ELSI she has introduced the "Operations Coordinator" position to facilitate daily management, and hired a "Communications Director" from outside Japan to promote the international PR activities of ELSI.

● Columbia University as a New Satellite

Mary Voytek is currently at Columbia University on leave of absence from NASA, and ELSI has established its satellite center in the Astrophysics Institute of Columbia University. We will conduct joint research in astrobiology and related fields.

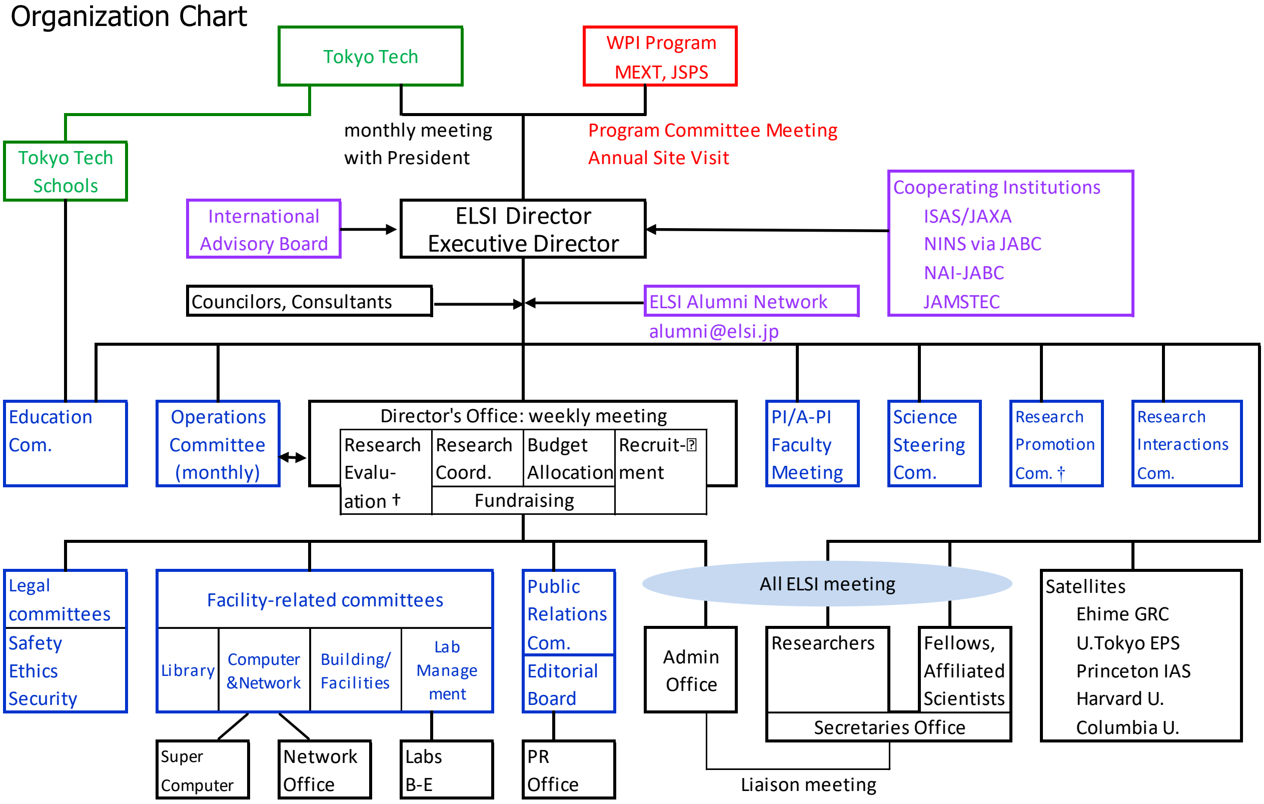
● Establishment of Press Release Editorial Board

The Editorial Board is a subcommittee under the Public Relations Committee and is composed of a PI and a few scientists. The Board will work on identifying or screening new research results that are worth having a press release for.

● Establishment of Education Committee

As the number of graduate students affiliated with ELSI is increasing, the Education Committee has been set up to take care of the educational program, support for fellowships, assignment of desks in the institute, and so on.

● Organization Chart



Appendix 3-4　Campus Map

- Draw a simple map of the campus showing where the main office and principal investigator(s) are located.

Ookayama Campus Map

Earth-Life Science Institute Bldg. (ELSI-2)

Shigenori MARUYAMA
Eric SMITH
Hidenori GENDA

Earth-Life Science Institute Bldg. (ELSI-1)

Kei HIROSE	George HELFFRICH
Mary VOYTEK	Irena MAMAJANOV
Shigeru IDA	Shawn McGLYNN
Piet HUT	Ryuhei NAKAMURA
Joseph Lynn KIRSCHVINK	Yasuhito SEKINE
John HERNLUND	

Suzukakedai Campus Map

G1 Building

Naohiro YOSHISA

PIs in other institutions

Tetsuo IRIFUNE
Jack William SZOSTAK

Appendix 3-5　Project Expenditures in FY2018

1) Overall project funding

* In the "Total costs" column, enter the total amount of funding required to implement the project, without dividing it into funding sources.

* In the "Amount covered by WPI funding" column, enter the amount covered by WPI within the total amount.

* In the "Personnel," "Project activities," "Travel," and "Equipment" blocks, the items of the "Details" column may be changed to coincide with the project's actual content.

(Million yens)

Cost items	Details (For Personnel - Equipment please fill in the breakdown of fiscal expenditure, and the income breakdown for Research projects.)	Total costs	Amount covered by WPI funding
Personnel	Center director and Administrative director	25	10
	Principal investigators (no. of persons):15	139	104
	Other researchers (no. of persons):32	189	156
	Research support staffs (no. of persons):13	53	53
	Administrative staffs (no. of persons):15	75	53
	Research Assistant(no. of persons):7	5	4
	Subtotal	486	380
Project activities	Gratuities and honoraria paid to invited principal investigators	0	0
	Cost of dispatching scientists (no. of persons):1	3	3
	Research startup cost (no. of persons):41	9	4
	Cost of satellite organizations (no. of satellite organizations):2	30	30
	Cost of international symposiums (no. of symposiums):1	1	1
	Rental fees for facilities	83	83
	Cost of consumables	30	7
	Cost of utilities	0	0
	Other costs	71	29
	Subtotal	227	157
Travel	Domestic travel costs	2	1
	Overseas travel costs	15	10
	Travel and accommodations cost for invited scientists		
	(no. of domestic scientists):26	1	1
	(no. of overseas scientists):111	37	30
	Travel cost for scientists on transfer		
	(no. of domestic scientists):0		
	(no. of overseas scientists):1	1	1
	Subtotal	56	43
Equipment	Depreciation of buildings	1	0
	Depreciation of equipment	181	0
	Subtotal	182	0
Research projects (Detail items must be fixed)	Project supported by other government subsidies, etc. *1	87	0
	KAKENHI	336	0
	Commissioned research projects, etc.	31	0
	Joint research projects	13	0
	Ohers (donations, etc.)	30	0
	Subtotal	497	0
Total		1448	580

Costs (Million yens)

WPI grant in FY 2018	594
Costs of establishing and maintaining	2
facilities	0
Establishing new facilities	0
(Number of facilities: , OO m²)	
Repairing facilities	0
(Number of facilities: , OO m²)	
Others	2
Costs of equipment procured	12
Draft chamber	4
(Number of units:1)	
Gas chromatograph	5
(Number of units:1)	
Others	3

*1. Funding sources that include government subsidies (including Enhancements promotion expenses (機能強化促進経費), National university reform reinforcement promotion subsidy (国立大学改革強化推進補助金) etc.), indirect funding, and allocations from the university's own resources.
*2 When personnel, travel, equipment (etc.) expenses are covered by KAKENHI or under commissioned research projects or joint research projects, the amounts should be entered in the "Research projects" block.

2) Costs of satellites

(Million yens)

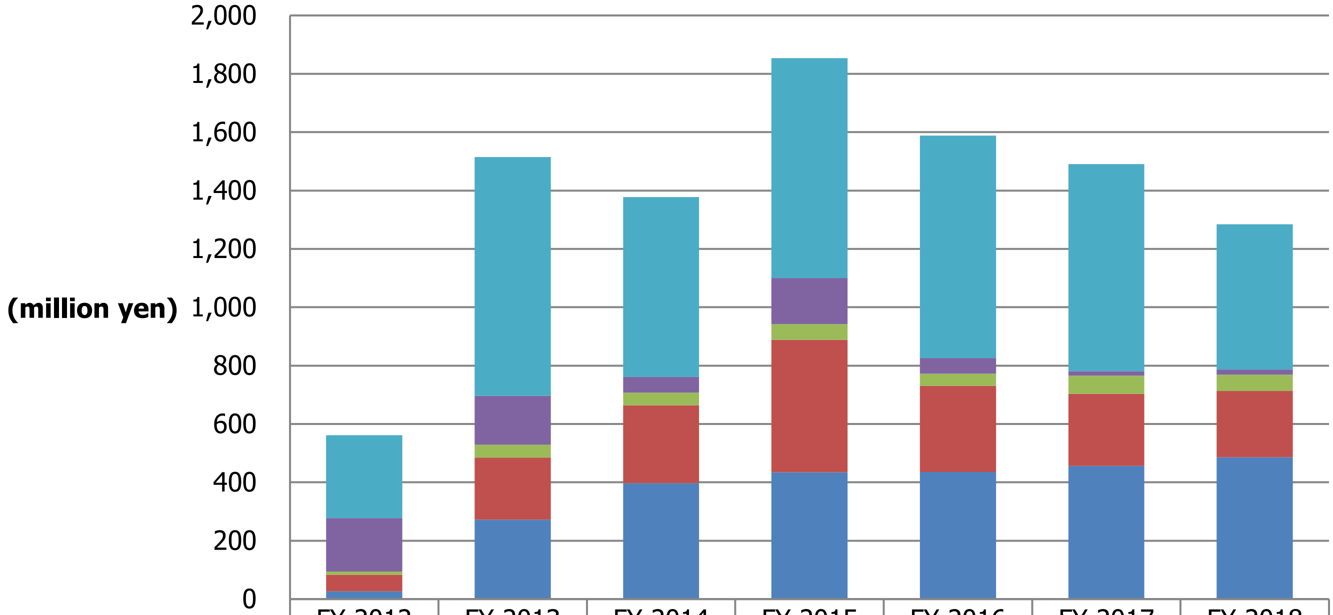
Cost items	Details	Total costs	Amount covered by WPI funding
Personnel	Principal investigators (no. of persons):1		
	Other researchers (no. of persons):2		
	Research support staffs (no. of persons):1		
	Administrative staffs (no. of persons):2		
	Subtotal	0	18
Project activities	Subtotal	0	9
Travel	Subtotal	0	3
Equipment	Subtotal	0	0
Research projects	Subtotal	94	0
Total		94	30

Appendix 3-6　Annual Transition in the Amounts of Project Funding

*Make a graph of the transition in the number of overall project funding.

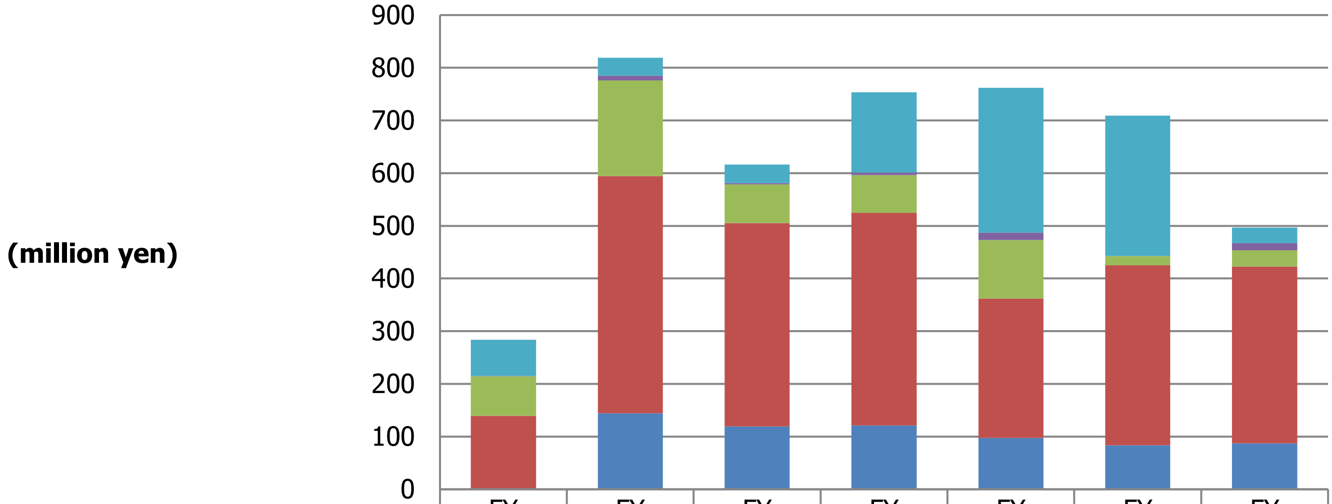
*1 Definition is as shown in Appendix 3-5 (Project Expenditures)

Transition of Project Expenditures



	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018
Research Projects	284	819	616	753	762	709	497
Equipment	183	168	54	159	54	15	18
Travel	11	43	44	53	42	63	56
Project Activities	56	212	266	455	295	247	227
Personnel	27	273	397	434	435	456	486

Transition of Research Project Expenditures



	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018
Ohers (donations, etc.)	68	34	35	152	275	266	30
Joint research projects	1	9	2	5	14	0	13
Commissioned research projects, etc.	75	182	74	72	111	18	31
KAKENHI	140	450	385	403	265	341	336
Project supported by other government subsidies, etc. *1	0	144	120	121	97	84	87

Appendix 4-1 FY 2018 Status of Collaboration with Overseas Satellites

- If satellite and partner institutions have been established, fill in required items of the form below.

1. Satellites and partner institutions

- List the satellite and partner institutions in the table below (including the domestic satellite institutes).
- Indicate newly added and deleted institutions in the "Notes" column.

<Satellite institutions>

Institution name	Principal Investigator(s), if any	Notes
Ehime University	Tetsuro Irifune	
The University of Tokyo	Kei Hirose	
Institute for Advanced Study, Princeton	Piet Hut	
Harvard University	Jack Szostak	
Columbia University	Mary Voytek	Newly added in 2018

< Partner institutions>

Institution name	Principal Investigator(s), if any	Notes
JAXA		
NINS		
NASA		
JAMSTEC		

- If overseas satellite institutions have been established, fill in required items on the form below. If overseas satellite institutions have not been established, it is not necessary to complete the form.

2. Coauthored Papers

- List the refereed papers published in FY 2018 that were coauthored between the center's researcher(s) in domestic institution(s) (include satellite institutions) and overseas satellite institution(s). List them by overseas satellite institution in the below blocks.
- Transcribe data in same format as in Appendix 1-4. Italicize the names of authors affiliated with overseas satellite institutions.
- For reference write the Appendix 1-4 item number in parentheses after the item number in the blocks below. Let it free, if the paper is published in between Jan.-Mar. 2019 and not described in Appendix 1-4.

Overseas Satellite 1 Institute for Advanced Study, Princeton (Total: 5 papers)

1) (2) Adam, Z.R., Hongo, Y., *Cleaves, H.J.*, II, Yi, R., Fahrenbach, A.C., Yoda, I., Aono, M., 2018. Estimating the capacity for production of formamide by radioactive minerals on the prebiotic Earth. Scientific Reports 8.
2) (4) Alberto Hernandez-Hernandez, L., Yi, R., *James Cleaves, H.*, Fuentes-Cabrera, M., Sumpter, B.G., Hernandez-Hernandez, A., Rangel, E., Vallejo, E., 2018. Theoretical and experimental evidence of conformational transformation in stereoisomers of nucleoside analogues. International Journal of Quantum Chemistry 118.
3) (20) Chandru, K., Guttenberg, N., Giri, C., Hongo, Y., Butch, C., Mamajanov, I., *Cleaves, H.J.*, II, 2018. Simple prebiotic synthesis of high diversity dynamic combinatorial polyester libraries. Communications Chemistry 1.
4) (85) Laneuville, M., Kameya, M., *Cleaves, H.J.*, II, 2018. Earth Without Life: A Systems Model of a Global Abiotic Nitrogen Cycle. Astrobiology 18, 897-914.
5) (96) Meringer, M., Giri, C., *Cleaves, H.J.*, II, 2018. Fitting Cometary Sampling and Composition Mass Spectral Results Using Non-negative Least Squares: Reducing Detection Ambiguity for In Situ Solar System Organic Compound Measurements. Acs Earth and Space Chemistry 2, 1256-1261.

Overseas Satellite 2 Harvard University (Total: 8 papers)

1) (1) *Adam, Z.R.*, Fahrenbach, A.C., Kacar, B., Aono, M., 2018. Prebiotic Geochemical Automata at the Intersection of Radiolytic Chemistry, Physical Complexity, and Systems Biology. Complexity. vol. 2018, Article ID 9376183, 21 pages, 2018. https://doi.org/10.1155/2018/9376183.
2) (2) *Adam, Z.R.*, Hongo, Y., Cleaves, H.J., II, Yi, R., Fahrenbach, A.C., Yoda, I., Aono, M., 2018. Estimating the capacity for production of formamide by radioactive minerals on the prebiotic Earth. Scientific Reports 8.
3) (91) Maddamsetti, R., Johnson, D.T., Spielman, S.J., *Petrie, K.L.*, Marks, D.S., Meyer, J.R., 2018. Gain-of-function experiments with bacteriophage lambda uncover residues under diversifying selection in nature. Evolution 72, 2234-2243.
4) (130) Ramirez, R.M., *Levi, A.*, 2018. The ice cap zone: a unique habitable zone for ocean worlds. Monthly Notices of

the Royal Astronomical Society 477, 4627-4640.
5) (155) *Tam, C.P.*, Zhou, L., Fahrenbach, A.C., Zhang, W., Walton, T., *Szostak, J.W.*, 2018. Synthesis of a Nonhydrolyzable Nucleotide Phosphoroimidazolide Analogue That Catalyzes Nonenzymatic RNA Primer Extension. Journal of the American Chemical Society 140, 783-792.
6) (169) *Ward, L.M.*, McGlynn, S.E., Fischer, W.W., 2018. Draft Genome Sequence of a Divergent Anaerobic Member of the Chloroflexi Class Ardenticatenia from a Sulfidic Hot Spring. Microbiology Resource Announcements 6.
7) (179) Yi, R., Hongo, Y., Yoda, I., *Adam, Z.R.*, Fahrenbach, A.C., 2018. Radiolytic Synthesis of Cyanogen Chloride, Cyanamide and Simple Sugar Precursors. Chemistryselect 3, 10169-10174.
8) (200) Agmon, E., *Egbert, M.*, Virgo, N., 2018. The Biological Foundations of Enactivism: A Report on a Workshop Held at Artificial Life XV. Artificial Life 24, 49-55.

Overseas Satellite 3 Columbia University (Total: 5 papers)

1) (126) Qin, T., *Wentzcovitch, R.M.*, Umemoto, K., Hirschmann, M.M., Kohlstedt, D.L., 2018. Ab initio study of water speciation in forsterite: Importance of the entropic effect. American Mineralogist 103, 692-699.
2) (145) Spieker, K., Rondenay, S., *Ramalho, R.*, Thomas, C., Helffrich, G., 2018. Constraints on the structure of the crust and lithosphere beneath the Azores Islands from teleseismic receiver functions. Geophysical Journal International 213, 824-835.
3) (200) *Agmon, E.*, Egbert, M., Virgo, N., 2018. The Biological Foundations of Enactivism: A Report on a Workshop Held at Artificial Life XV. Artificial Life 24, 49-55.
4) Qin, T., Zhang, Q., *Wentzcovitch, R.M.*, Umemoto, K., 2019. qha: A Python package for quasiharmonic free energy calculation for multi-configuration systems. Computer Physics Communications 237, 199-207.
5) van den Berg, A.P., *Yuen, D.A.*, Umemoto, K., Jacobs, M.H.G., *Wentzcovitch, R.M.*, 2019. Mass-dependent dynamics of terrestrial exoplanets using ab initio mineral properties. Icarus 317, 412-426.

3. Status of Researcher Exchanges

- Using the below tables, indicate the number and length of researcher exchanges in FY 2018. Enter by institution and length of exchange.
- Write the number of principal investigator visits in the top of each space and the number of other researchers in the bottom.

Overseas Satellite 1: Institute for Advanced Study, Princeton

<To satellite>

	Under 1 week	From 1 week to 1 month	From 1 month to 3 months	3 months or longer	Total
FY2018	0	2	1	1	4
	0	1	2	0	3

<From satellite>

	Under 1 week	From 1 week to 1 month	From 1 month to 3 months	3 months or longer	Total
FY2018	0	0	3	0	3
	0	0	0	0	0

Overseas Satellite 2: Harvard University

<To satellite>

	Under 1 week	From 1 week to 1 month	From 1 month to 3 months	3 months or longer	Total
FY2018	0	0	0	0	0
	0	1	0	0	1

<From satellite>

	Under 1 week	From 1 week to 1 month	From 1 month to 3 months	3 months or longer	Total
FY2018	0	0	0	0	0
	0	2	1	0	3

Overseas Satellite 3: Columbia University

<To satellite>

	Under 1 week	From 1 week to 1 month	From 1 month to 3 months	3 months or longer	Total
FY2018	0	0	0	0	0
	0	0	0	0	0

<From satellite>

	Under 1 week	From 1 week to 1 month	From 1 month to 3 months	3 months or longer	Total
FY2018	0	0	0	0	0
	0	2	0	0	2

Appendix 4-2 FY 2018 Visit Records of Researchers from Abroad

* If researchers have visited/ stayed at the Center, provide information on them in the below table.

Total: 125

	Name	Age	Affiliation (Position title, department, organization)	Academic degree, specialty	Record of research activities (Awards record, etc.)	Time, duration	Summary of activities during stay at center (e.g., participation as principal investigator; short-term stay for joint research; participation in symposium)
1	Lewis Ward		Harvard Univ.	Ph.D., Geobiology	NSF Graduate Research Opportunities Worldwide Japan fellow, NSF East Asia and Pacific Summer Institutes fellowship, NSF Office of International Science and Engineering travel grant recipient, NASA Earth and Space Science Fellow, Lewis and Clark Fund for Exploration and Field Research in Astrobiology award, Agouron Institute Postdoctoral Fellowship	20180401 to 20180430	short-term stay for joint research and sampling in Japan with ELSI scientists
2	Mary Voytek		NASA	Ph.D. Astrobiology	USGS Superior Service Award, Invited scholar, German-American Frontiers of Science, et al.	20180401 to 20180502	short-term stay for discussion about ELSI research plan
3	Jean-Baptiste SANONER		Freelance VR/AR Unity Developer at Neural Studio LLC, Individual Game Developer	MD	Junior software engineer with graduate degree in astrophysics and strong programming background	20180401 to 20180707	short-term stay for joint research
4	Ankit Jain		CUNY ASRC	Ph.D., dynamic peptide libraries	postdoctoral research associate	20180403 to 20180418	short-term stay for joint research and sampling in Japan with ELSI scientists
5	Patrick M Shih		Lawrence Berkeley National Laboratory	Ph.D.	NIH K99 Award Branco Weiss Fellowship Life Sciences Research Foundation Fellowship Lawrence Berkeley National Lab Director's Award for Exceptional Early Scientific Career Achievement	20180404 to 20180405	short-term stay for joint research
6	Sarah Mojarad		University of Southern California, Educator | Digital Communication Specialist | Public Speaker	social media, misinformation, science communication, and online professionalism	created a number of new initiatives that aim to improve the communication skills of students and researchers in science, technology, engineering, mathematics, and medical (STEMM) disciplines.	20180416 to 20180421	invited lecturer of workshop of ELSI and its preparatory meeting

7	Rachel Harding		University of Toronto	Ph.D.	Harding’s research focuses on understanding the molecular mechanisms of Huntington’s disease, an incurable and devastating neurodegenerative disorder. Dr. Harding is a leader in open notebook science, releasing all of her work through her open notebook, LabScribbles, and sharing reagents she generates in the lab with the wider Huntington’s research community without restriction.	20180417 to 20180423	invited lecturer of a forum
8	Juliana Chan		Editor-in-Chief of Asian Scientist Magazine, CEO of Wildtype Media Group	Ph.D., science communication from Asia	Singapore Youth Award, EmTech Asia’s 10 Innovators Under 35, Young Global Leader of the World Economic Forum	20180419 to 20180421	invited lecturer of workshop of ELSI
9	Markus Reinhard Meringer		German Aerospace Center (DLR), Staff Scientist	Dr. Rer. Nat., computer applications in earth and life sciences	Development of data processors for the atmospheric spectrometer SCIAMACHY on board ESA's environmental satellite ENVISAT	20180421 to 20180520	short-term stay for joint research
10	David Fike		Washington University at St. Louis, Earth and Planetary Sciences	Ph.D., chemical origin of life	Associate Director of InCEES, InCEES professor	20180428 to 20180518	short-term stay for joint research with ELSI scientists and seminar
11	Rasulev Bakhtiyor		North Dakota State University (NDSU)	Ph.D.	His research covers a range of topics in structure-activity relationship for biological activity, toxicity and physico-chemical properties prediction of polymers and nanoparticles.	20180430 to 20180520	short-term stay for joint research
12	Lauren M Seyler		Woods Hole Oceanographic Institution	Ph.D.	AGU Celebrate 100 Grant, Blue Marble Space Institute of Science Internal Research Fund, NASA Astrobiology Early Career Collaboration Award, et al.	20180504 to 20180520	short-term stay for joint research
13	Shephard Grace Elizabeth		University of Oslo	Ph.D., geodynamics	Co-Editor for EGU Geodynamics Blog, Council member or Association of Polar Early Career Scientists (APECS) Norway President	20180504 to 20180531	short-term stay for joint research with ELSI scientists
14	Feng Tian		Tsinghua University	Ph.D., planetology	National Research Council Research Associateship Award, NASA Team Achievement award to the Cassini UVIS team	20180513 to 20180518	participation in workshop and research discussion
15	Theresa Luftinger		University of Vienna, Permanent Senior Scientist	Ph.D., magnetic fields of planetary environments		20180513 to 20180518	participation in workshop and research discussion
16	Jim Kasting		Penn State University, Evan Pugh Professor	Ph.D., Planetary science	Faculty Scholar Award, Penn State, Oparin Medal, International Society for the Study of the Origin of Life, NAS Award in Early Earth and Life Sciences (Stanley Miller Medal)	20180513 to 20180518	participation in workshop and research discussion
17	Tilman Spohn		German Aerospace Center (DLR), HP3 Principal Investigator	Ph.D., Space Science	Runcorn-Florensky Medal, Executive Director of International Space Science Institute (ISSI)	20180513 to 20180518	participation in workshop and research discussion

18	Lena Noack		Freie Universitat Berlin, Junior professor	Ph.D., Geochemistry		20180513 to 20180518	participation in workshop and research discussion
19	Vinciane Debaille		Universite Libre de Bruxelles, research associate	Ph.D., geochemistry		20180513 to 20180518	participation in workshop and research discussion
20	Jean Bedard		Natural Resources Canada, Research Geoscientist	Ph.D., Geochemistry	Howard Street Robinson Award, 10 scientific discoveries in Quebec for 2014	20180513 to 20180518	participation in workshop
21	Dougal Ritson		MRC Laboratory of Molecular Biology, Post-doc	Ph.D., prebiotic chemistry		20180513 to 20180518	participation in workshop
22	Addy Pross		Ben Gurion University	Ph.D., Theoretical and Physical Organic Chemistry		20180513 to 20180518	participation in workshop
23	Andrew Pohorille		NASA, Research Scientist	Ph.D., theoretical physics (with specialty in biophysics)	NASA Award for Astrobiology, NASA Exceptional Scientific Achievement Medal,	20180513 to 20180518	participation in workshop
24	Ulrich Muller		UC San Diego, Associate Professor	Ph.D., Evolution of catalytic RNAs, and the Origin of Life	NASA research award, NASA research award	20180513 to 20180518	participation in workshop
25	Francis Albarede		Ecole Normale Superieure de Lyon, Professor	Ph.D., Geochemistry	V. M. Goldschmidt Award - Geochemical Society, Knight of the Legion of Honor, Knight of the Order of Academic Palms	20180513 to 20180518	participation in workshop
26	Maureen O’ Malley		University of Sydney, senior research associate and affiliate	Ph.D., Philosophy of microbiology		20180513 to 20180518	participation in workshop
27	Sean Raymond		Faculty member, Laboratoire d'Astrophysique de Bordeaux, CNRS	Astronomy (Anthropology of Science), Physics, Astrophysics		20180513 to 20180518	participation in workshop
28	Audrey Bouvier		University of Western Ontario, Associate Professor	Ph.D., Cosmochemistry		20180513 to 20180518	participation in workshop
29	Guillaume Avice		California Institute of Technology, Postdoctoral Scholar	Ph.D., Cosmochemistry, Astrophysics and Experimental Geophysics		20180513 to 20180518	participation in workshop

30	Stephen Mojzsis		University of Colorado, Boulder, Chair, Arts & Sciences Council of the College of Arts & Sciences	Ph.D., Geology	Scholar, Erwin Schroedinger Institute for Mathematics & Physics, et al.	20180513 to 20180518	participation in workshop
31	Mark van Zuilen		INSTITUT DE PHYSIQUE DU GLOBE DE PARIS	Ph.D., Geomicrobiology		20180513 to 20180518	participation in workshop
32	Linda Kah		University of Tennessee, Kenneth G. Walker Associate Professor	Ph.D., Carbonate Sedimentology and Geochemistry	Awarded Roger and Beverly Bohanan Faculty Achievement Award	20180513 to 20180518	participation in workshop
33	Julie Cosmidis		University of Colorado, Postdoctoral Researcher	Ph.D., Geomicrobiology		20180513 to 20180518	participation in workshop
34	Muriel Gargaud		Laboratoire d'Astrophysique de Bordeaux, Universite de Bordeaux, Directrice de Recherche au CNRS	Ph.D., Astrobiology		20180513 to 20180518	participation in workshop
35	Emmanuelle Javaux		University of Liege, full professor and director	Ph.D., biology	Adolphe Wetrems award from the Royal Academy of Belgium, Francqui Foundation Research professor, member of the class of Sciences Royal Academy of Belgium	20180513 to 20180518	participation in workshop
36	Manuel Guedel		University of Vienna, Professor	Ph.D., Astrophysics	theoretical and observational issues related to star formation, stellar environments, and high-energy astrophysics.	20180513 to 20180518	participation in workshop
37	Carlos Briones		Centro de Astrobiologia (CSIC-INTA), Staff Scientist	Ph.D., Biotechnology, Molecular Biology and Virology		20180513 to 20180518	participation in workshop
38	Daniele Pinti		Universite du Quebec a Montreal, Professor	Ph.D., Isotope Geochemistry, Noble Gases, and Astrobiology		20180513 to 20180518	participation in workshop
39	Puri Lopez-Garcia		University Paris Sud	Ph.D., Parasitology	Purificación López-García is a Research Director working for the French CNRS and the leader of the "Microbial diversity, ecology and evolution" research group at the Ecology Systematics Evolution unit (CNRS & University Paris-Sud/Paris-Saclay;	20180513 to 20180518	participation in workshop
40	Herve Martin		University Clermont Auvergne, Professor	Ph.D., Geology, Petrology and Geochemistry	Prix Furon de la Société Géologique de France	20180513 to 20180518	participation in workshop

41	Pierre-Alain Monnard		University of Southern Denmark, Tenured Associate Professor	Ph.D., Origins of Life and Astrobiology		20180513 to 20180518	participation in workshop
42	Eugene Koonin		National Center for Biotechnology Information (NCBI), Senior Investigator	Ph.D., evolutionary and computational biology	member of the National Academy of Sciences	20180513 to 20180518	participation in workshop
43	Sudha Rajamani		Indian Institute of Science Education and Research, Pune, Associate Professor	Ph.D., Biochemistry		20180513 to 20180526	participation in workshop
44	Burkhard Militzer		University of California, Berkeley, Associate professor	Ph.D., Computer Simulations in Earth and Planetary Science		20180518 to 20180527	short-term stay for joint research
45	Renata Wentzcovitch		Columbia University, Professor of Material Science and Applied Physics, and Earth and Environmental Science	Computational Materials Physics	fellow of APS, AGU, MSA, AAAS, and American Academy of Arts and Sciences	20180519 to 20180526	short-term stay for joint research
46	Dimitri Veras		University of Warwick, Proleptic Assistant Professor	Ph.D., Astrophysics		20180528 to 20180602	short-term stay for joint research
47	Tristan Guillot		Observatoire de la Cote d'Azur,Directeur de Recherche C.N.R.S.	Ph.D., Planetary science	Urey Prize of the Division for Planetary Sciences of the AAS, Zeldovich medal of the Committee on Space Research (COSPAR), Bronze medal of the CNRS	20180602 to 20180606	short-term stay for joint research
48	Scott D. Hull		Ohio State University, Graduate Research Assistant	Ph.D., Earth Sciences	His work focuses on human dimensions of natural resources, including collaborative watershed management, coastal storm resiliency, and community-based response to ecological change	20180603 to 20180606	participation in workshop
49	Donato Giovannelli		Institute for Marine Sciences, Assistant Professor	Ph.D., Biology, Ecology and Microbiology		20180603 to 20180609	participation in workshop
50	Christopher Joseph Butch		JSPS fellow	Ph.D., Philosophy, Chemical Engineering		20180603 to 20180616	short-term stay for joint research

51	Olja Panic		The University of Leeds, Royal Society Dorothy Hodgkin Fellow	Ph.D., Planetary Systems; Protoplanetary discs; Exoplanets; Circumplanetary Discs		20180606 to 20180614	short-term stay for joint research
52	Marthe Klocking		University of Cambridge	Ph.D., Earth and Planetary Sciences		20180609 to 20180617	short-term stay for joint research and discussion for future plan of
53	Mary Voytek		NASA	Ph.D. Astrobiology	USGS Superior Service Award (2005). Invited scholar, German-American Frontiers of Science (1997 and 2001); Distinguished paper in phycology (1993). Board member of the American Geophysical Union	20180609 to 20180801	short-term stay for discussion about ELSI management and research plan
54	Harrison Smith		Arizona State University, Ph.D. student	Geological Sciences		20180610 to 20180616	short-term stay for joint research and seminar
55	Joti Rouillard		Institut de Physique du Globe de Paris, PhD student	Geomicrobiology		20180610 to 20180616	short-term stay for joint research and seminar
56	Arnaud Salvador		Universite Paris-Sud, Professor	Ph.D., Biological Analysis by Mass Spectrometry		20180611 to 20180618	short-term stay for joint research and seminar
57	Charitra Jain		ETH Zurich, post doctoral research associate	Ph.D., computational geodynamics		20180611 to 20180619	short-term stay for joint research and seminar
58	Emilie Panek		University Paris Diderot, PhD student			20180611 to 20180812	short-term stay for joint research and seminar
59	Haiyang Wang		The Australian National University, PhD student	astrobiology	the Prime Minister’s Australia Asia Endeavour Award	20180612 to 20180622	short-term stay for joint research and seminar
60	Steven Charnley		NASA Goddard Space Flight Center, Physical Scientist	Ph.D., Theoretical astrochemistry and molecular astrophysics		20180619 to 20180627	short-term stay for joint research
61	Mathilde Kervazo		UFR Sciences et Techniques, Universite de Nantes, PhD student	planetary science		20180709 to 20180827	short-term stay for joint research and seminar

62	Tommaso Pietro Fraccia		San Raffaele University/ University of Milan, Professor	Ph.D., Materials Science, Condensed Matter Physics and Biophysics		20180713 to 20180722	short-term stay for joint research
63	Sina Khajehabdollahi		University of Western Ontario, Master of Science	Ph.D., Biochemistry		20180714 to 20180730	short-term stay for joint research and workshop
64	Alexandra Penn		University of Surrey, research fellow	Ph.D., participatory methodologies and mathematical models	fellow of the Royal Society of Arts, member of the board of directors and Chair for Societal Impact of the International Society for Artificial Life	20180715 to 20181027	short-term stay for joint research
65	Pushkar Kopparla		California Institute of Technology, JSPS Postdoctoral Fellow	Ph.D.		20180717 to 20180728	preparatory meeting and participation in workshop
66	Stuart Bartlett		California Institute of Technology, Affiliated Scientist (PostDoc Position)	Ph.D., Complex Systems Simulation		20180717 to 20180801	preparatory meeting and participation in workshop
67	Rudrarup Bose		National Institute of Science Education and Research, Bhubaneswar, student			20180719 to 20180729	short-term stay for joint research and workshop
68	Frances Westall		Centre de Biophysique Moleculairec, CNRS, Director of Research CNRS	Ph.D., Geobiology		20180721 to 20180726	participation in WPI site visit and meeting of International Advisory Board as member
69	Robert Hazen		Carnegie Institution of Washington, research scientist	Ph.D. Mineralogy, Earth Science	Roebling Medal	20180722 to 20180726	participation in WPI site visit and meeting of International Advisory Board as member
70	Carl Pilcher		Blue Marble Space Institute of Science	Ph.D.	NASA Exceptional Achievement Medal, Group Achievement Awards, and an Ames Honor Award NASA Astrobiology Institute Director (2006-2013)	20180722 to 20180728	participation in WPI site visit and meeting of International Advisory Board as member
71	Douglas Lin		University of California, Santa Cruz, Professor	Ph.D. Astronomy and Astrophysics	Guggenheim Fellow, Otto Schmidt Medal, von Humboldt Fellow, et al.	20180722 to 20180803	participation in WPI site visit and meeting of International Advisory Board as member
72	Erik Hom		University of Mississippi, Assistant Professor Department of Biology	Ph.D., biology	Postdoctoral Fellow, Dept. of Molecular & Cellular Biology and Center for Systems Biology, Harvard University	20180722 to 20180804	invited lecturer of workshop of ELSI and its preparatory meeting

73	Sreejith Jayasree Varma		University of Strasbourg	Ph.D.		20180723 to 20180801	short-term stay for joint research and workshop
74	Bethany EHLMANN		California Institute of Technology, Professor	Ph.D., Planetary Science	Zeldovich Medal for Commission B (Planetary Science) for demonstrated excellence and achievement by a young scientist, et al.	20180808 to 20180817	short-term stay for joint research and workshop
75	Lewis Ward		Harvard Univ.	Ph.D., Geobiology	NSF Graduate Research Opportunities Worldwide Japan fellow, et al.	20180904 to 20181004	short-term stay for joint research and sampling in Japan with ELSI
76	Lizzy Trower		University of Colorado Boulder,USA, Assistant Professor	Ph.D., Geological Sciences		20180922 to 20181006	short-term stay for joint research and sampling
77	Jena Johnson		University of Michigan,USA, Assistant Professor	Ph.D., Geomicrobiology; Geochemistry; Sedimentology		20180922 to 20181006	short-term stay for joint research and sampling
78	Brenna Helene ROETS		Middlebury College, Undergraduate	Molecular Biology & Biochemistry	Janet C. Curry '49 Award in the Biological Sciences	20181001 to 20190331	short-term stay for joint research
79	Jeffrey Michael Dick		Central South University, Geochemistry Researcher	Ph.D., Geochemistry, Geobiochemistry, Thermodynamics, Redox, Cancer	EAR Postdoctoral Fellowship, National Science Foundation et al.	20181014 to 20181027	short-term stay for joint research and seminar
80	Mark Ghiorso		OFM Research	Ph.D., geochemistry	Norman L. Bowen Award from the VGP Section of the American Geophysical Union et al.	20181016 to 20181025	short-term stay for joint research and seminar
81	Yue Zhao		Vrije Universiteit Amsterdam, PhD candidate	Planetary Science and Geodynamical Modelling		20181026 to 20181202	short-term stay for joint research
82	Heenatigala Thilina Nishadh		Leiden University, IAU astroEDU Editor	astronomy educator		20181028 to 20181031	discussion about PR activities
83	Yueh-Ning Lee		Institut de Physique du Globe de Paris, Post-doctoral researcher	Ph.D., Astrobiology		20181101 to 20181103	short-term stay for joint research
84	Charley Lineweaver		ANU College of Science, Senior Fellow	Ph.D., astrobiology, cosmology and planetology	frequent appearance in the media (TV, radio, web)	20181120 to 20181125	participation in symposium
85	Henri Claude NATAF		Conseil de l'0MP, Research Director, CNRS	Ph.D., Geophysics	Paul Doistau-Émile Blutet Prize of the French Academy of Science, Barrabé Prize of the French Geological Society, CNRS Bronze medal, Guinier Prize of the French Physical Society	20181203 to 20181207	short-term stay for joint research and seminar

86	Zachary Adam		Arizona State University, Associate Staff Scientist	Ph.D., Astrobiology		20181227 to 20190124	short-term stay for joint research and participation in symposium
87	Betul Kacar		University of Arizona, assistant professor	Ph.D., Astrobiology	NASA Astrobiology Postdoctoral Fellowship et al.	20181227 to 20190124	short-term stay for joint research and participation in symposium
88	Alexandra Penn		University of Surrey	Ph.D., participatory methodologies and mathematical models	fellow of the Royal Society of Arts, member of the board of directors and Chair for Societal Impact of the International Society for Artificial Life	20181228 to 20190112	invited lecturer of international symposium of ELSI and short-term stay of joint research
89	Michael James Toillion		NASA Astrobiology Institute			20190102 to 20190121	short-term stay for joint research and participation in symposium
90	Paul Humphreys		University of Virginia, Commonwealth Professor	Ph.D., Philosophy of Science, Epistemology	Co-PI (with S. Hartmann (Tilburg), R. Frigg (LSE), J. Dubucs (Paris), J. Diez (Barcelona)) for Dutch Science Foundation (NWO) grant et al.	20190104 to 20190112	invited lecturer of international symposium of ELSI and short-term stay of joint research
91	Simonetta Gribaldo		Institut Pasteur, Full Professor	Ph.D., Microbiology	Prix Pasteur-Vallery Radot et al.	20190104 to 20190120	invited lecturer of international symposium of ELSI and short-term stay of joint research
92	Lindy Elkins-Tanton		Arizona State University, professor	Ph.D., Planetary Science	the Explorers Club Lowell Thomas prize for Exploring Extinction et al.	20190105 to 20190112	invited lecturer of international symposium of ELSI and short-term stay of joint research
93	Luis Campos		University of New Mexico, Associate Professor	Ph.D., History of Science and Medicine	grants and fellowships from the Library of Congress, the Max Planck Institute for the History of Science, the National Science Foundation, the American Philosophical Society, the National Humanities Center, and NASA	20190105 to 20190113	invited lecturer of international symposium of ELSI and short-term stay of joint research
94	Joseph Lizier		University of Sydney, Associate Professor	Ph.D., Research Cluster on Complex Systems	SUPRA Supervisor of the Year Award -- Faculty of Engineering & IT, University of Sydney et al.	20190105 to 20190113	invited lecturer of international symposium of ELSI and short-term stay of joint research
95	Katie Mack		North Carolina State University, Assistant Professor	Ph.D., astrophysics, particle physics	Discovery Early Career Researcher Award from the Australian Research Council (ARC), et al.	20190105 to 20190113	invited lecturer of international symposium of ELSI and short-term stay of joint research
96	Jake Hanson		Arizona State University, PhD Student	Life vs Nonlife, Causality, Complex Systems, Exoplanets/Biosignatures		20190105 to 20190113	participation in symposium
97	Mark Smith		University of Houston, Cullen Distinguished University Professor	Ph.D., chemistry	organic chemistry of the interstellar media and outer planetary atmospheres and the development of broadly general instrumentation for space mission investigation of complex organic mixtures with a focus on astrobiology	20190105 to 20190114	invited lecturer of international symposium of ELSI and short-term stay of joint research

98	David Alastair Baum		University of Wisconsin Madison, Professor	Ph.D., Botany		20190105 to 20190116	short-term stay for joint research and participation in symposium
99	Harrison Smith		Arizona State University, Ph.D. student	Geological Sciences		20190105 to 20190117	participation in symposium and workshop
100	Francis Heylighen		Free University of Brussels, research professor	Ph.D., Cybernetics, Complex systems,		20190105 to 20190118	invited lecturer of international symposium of ELSI and short-term stay of joint research
101	Caleb Scharf		Columbia University, Director of Astrobiology	Ph.D., Astrobiology	Chambliss Medal/Award for Astronomical Writing, American Astronomical Society	20190105 to 20190118	short-term stay for joint research and participation in symposium
102	Lena Vincent		University of Wisconsin, Graduate Student	complex biological systems		20190105 to 20190118	short-term stay for joint research and participation in symposium
103	Douglas Moore		Arizona State University, Post-doctoral Research Associate	Ph.D., Physics		20190105 to 20190118	participation in symposium and in workshop
104	Jean-Sebastien Gagnon		Harvard University, Alumni	Ph.D., theoretical high energy physics		20190105 to 20190119	participation in symposium and discussion for joint research
105	Arsev Aydinoglu		Middle East Technical University, Assistant Professor	Ph.D., interdisciplinary research, virtual scientific collaborations, emergence, data management	NASA Postdoctoral Program Fellowship	20190105 to 20190120	invited lecturer of international symposium of ELSI and short-term stay of joint research
106	Enrico Borriello		Arizona State University, Postdoc Research Associate	Ph.D., astroparticle physics		20190105 to 20190120	participation in symposium and in workshop
107	Karyn Rogers		Rensselaer Polytechnic Institute, Assistant Professor	Ph.D., Earth and Environmental Sciences		20190106 to 20190112	invited lecturer of international symposium of ELSI and short-term stay of joint research

108	Donna Blackmond		Scripps Research Institute, Professor	Ph.D., Chemical Engineering Chemistry	American Institute of Chemists Chemical Pioneer Award, Gabor Somorjai Award for Creative Research in Catalysis, American Chemical Society et al.	20190106 to 20190112	invited lecturer of international symposium of ELSI and short-term stay of joint research
109	James P. Crutchfield		University of California, Davis	Ph.D., Complexity Sciences	Distinguished Visiting Research Professor of the Beckman Institute at the University of Illinois, Urbana-Champaign, Bernard Osher Fellow at the San Francisco Exploratorium	20190106 to 20190119	short-term stay for joint research and participation in symposium
110	Sara Walker		Arizona State University, assistant professor	Ph.D., Physics of Life, Astrobiology, Abiogenesis	Out-of-the-box-thinking", Foundational Questions Institute Essay Contest, Fellow, ASU-SFI Center for Biosocial Complex Systems, Arizona State University and Santa Fe Institute et al.	20190106 to 20190120	invited lecturer of international symposium of ELSI and short-term stay of joint research
111	Susovan Sarkar		Indian Institute of Science Education and Research (IISER), PhD student	Biology		20190106 to 20190121	participation in symposium and discussion for joint research
112	Stuart Bartlett		California Institute of Technology, Affiliated Scientist (PostDoc Position)	Ph.D., Complex Systems Simulation		20190106 to 20190123	participation in symposium and workshop
113	Marc Kaufman		Many Worlds, journalist	journalism		20190106 to 20190126	short-term stay for joint research and participation in symposium
114	Christopher Joseph Butch		Emory University	Ph.D., Philosophy, Chemical Engineering		20190107 to 20190125	participation in symposium and workshop
115	Steen Rasmussen		University of Southern Denmark, Center Leader; Santa Fe Institute, External Research Professor	Ph.D., artificial life and complex systems	Top-5 Scientific Break-Through in Denmark. Rasmussen, Maurer & Monnard, Top-5 World Technology Network Reward, Biotechnical Category: Protocell Design, et al.	20190108 to 20190118	short-term stay for joint research and participation in symposium
116	Michael Lachman		Santa Fe Institute, Professor	Ph.D., theoretical biology		20190112 to 20190126	short-term stay for joint research and participation in symposium
117	Lee Cronin		University of Glasgow, Professor	Ph.D., complex chemical systems	Japan Society of Coordination Chemistry International Award	20190114 to 20190120	invited lecturer of a workshop
118	Emily Wong		The University of Hong Kong, Student			20190116 to 20190119	short-term stay for joint research

119	Marine Lasbleis		University of Nantes, PD researcher	Ph.D., deep Earth geodynamics		20190211 to 20190310	short-term stay for joint research
120	Robin Wordsworth		Harvard University, Assistant Professor	Ph.D., Environmental Science & Engineering		20190226 to 20190306	lecturer of international school of research project of ELSI and participation in workshop
121	Jeffrey Catalano		Washington University in St. Louis, Professor	Ph.D., Geochemistry, Mineralogy	NSF Faculty Early Career Development (CAREER) Award, et al.	20190226 to 20190306	lecturer of international school of research project of ELSI and participation in workshop
122	Vinciane Debaille		Universite Libre de Bruxelles, research associate	Ph.D., isotope geochemistry		20190227 to 20190307	lecturer of international school of research project of ELSI and participation in workshop
123	Bethany L. Ehlmann		California Institute of Technology, Professor	Ph.D., Planetary Science	Zeldovich Medal for Commission B (Planetary Science) for demonstrated excellence and achievement by a young scientist, Committee on Space Research (COSPAR), et al.	20190228 to 20190304	lecturer of international school of research project of ELSI and participation in workshop
124	Mikhail Zolotov		Arizona State University, Research Professor	Ph.D., Geochemistry		20190302 to 20190310	lecturer of international school of research project of ELSI and participation in workshop
125	Dennis Hoening		Vrije Universiteit Amsterdam, Origins Center Fellow	Ph.D., planetary physics		20190326 to 20190331	short-term stay for joint research

Appendix4-3 Postdoctoral Positions through Open International Solicitations

* In the column of number of applications and number of selection, put the total number (upper), the number and percentage of overseas researchers in the < > brackets (lower).

Fiscal year	number of applications	number of selection
FY2012	N/A	N/A
	< , %>	< , %>
FY2013	134	10
	< 124, 93%>	< 8, 80%>
FY2014	N/A	N/A
	< , %>	< , %>
FY2015	72	8
	< 52, 72%>	< 6, 75%>
FY2016	39	3
	<25 , 64%>	< 2, 67%>
FY2017	60	7
	< 37, 62%>	< 3, 43%>
FY2018	58	4
	< 34, 59%>	< 3, 75%>

Appendix4-4 Status of Employment of Postdoctoral Researchers

* Prepare the information below during the period from the start of the center through March 2019.

* List each researcher in 1 line. If the list exceeds this form, add extra pages.

Japanese Postdocs

Period of project participation	Previous affiliation, position title (Country)	Next affiliation, position title (Country)
2013.4.1-2015.10.31	The University of Tokyo・Graduate Student・Japan	Postdoctoral Program Fellpw・NASA-GISS・USA
2013.4.1-2016.3.31	RIKEN・Researcher・Japan	Tokyo Institute of Technology・Research Staff・Japan
2013.4.1-2016.3.31	Tokyo Institute of Technology・Research Staff・Japan	National Institute of Genetics・Researcher・Japan
2013.4.1-2016.3.31	Tokyo Institute of Technology・Research Staff・Japan	Kyushu University・Researcher・Japan
2013.4.1-2015.8.31	JAMSTEC・Researcher・Japan	Okayama University・Researcher・Japan
2014.4.1-2016.3.31	Tokyo Institute of Technology・Graduate Student・Japan	Ehime University・Researcher・Japan
2014.4.1-2015.9.30	Hiroshima University・Postdoctral Researcher・Japan	JAMSTEC・Technical Scientist・Japan
2014.4.1-2015.7.31	Tokyo Institute of Technology・Graduate Student・Japan	The University of Tokyo・Assistant Professor・Japan
2014.6.1-2015.3.31	Tokyo Institute of Technology・Post-doctoral fellow・Japan	Tokyo Institute of Technology・Research Staff・Japan
2014.4.1-2016.3.31	Tokyo Institute of Technology・Research Staff・Japan	AIST・Researcher・Japan
2014.4.1-2014.8.31	Tokyo Institute of Technology・Research Staff・Japan	RIKEN・Researcher・Japan
2014.4.1-2014.8.31	Tokyo Institute of Technology・Graduate Student・Japan	Carnegie Institution for Science・Postdoctral Researcher・USA
2015.4.1-2016.3.31	Hiroshima University・Graduate Student・Japan	Kyushu University・JSPS Postdoctoral Fellowships・Japan
2015.4.1-2015.6.30	Nagoya University・Graduate Student・Japan	Niels Bohr Institute・Postdoctral Researcher・Denmark
2015.4.1-2015.9.30	Tokyo Institute of Technology・Graduate Student・Japan	JASRI・Researcher・Japan
2014.4.1-2017.3.31	Ritsumeikan University・Visiting scholar・Japan	JAMSTEC・Researcher・Japan
2013.4.1-2016.9.30	Hokkaido University・Researcher・Japan	Osaka University・Assistant Professor・Japan
2015.10.1-2016.10.31	The University of Tokyo・Project Researcher・Japan	The University of Tokyo・Project Researcher・Japan
2015.4.1-2017.8.31	Toyama University・Researcher・Japan	The University of Tokyo・Assistant Professor・Japan
2015.7.1-2018.3.31	Tokyo Institute of Technology・Specially Appointed Assistant Professor ・Japan	Tokyo Institute of Technology・Researcher ・Japan
2015.4.1-2017.7.31	Tokyo Institute of Technology・Graduate Student・Japan	JAMSTEC・Researcher・Japan
2017.4.1-2018.3.31	YHouse・Core membr・USA	Ritsumeikan University・Associate Professor・Japan
2015.10.1-2018.10.31	Riken・Senior Technical Scientist・Japan	Tokyo Institute of Technology・Specially Appointed Assistant Professor ・Japan
2017.4.1-2018.7.31	Ehime University・Researcher・Japan	TADANO LTD.・Researcher・Japan
2018.4.1-2018.5.31	Tokyo Institute of Technology・Graduate Student・Japan	Chiba Institute of Technology・Associate Staff Scientist・Japan
2018.4.1-2018.9.30	Tokyo Institute of Technology・Graduate Student・Japan	Utredht University・Researcher・Nederlands

Overseas Postdocs

Period of project participation	Previous affiliation, position title (Country)	Next affiliation, position title (Country)	Nationality
2013.3.8-2014.3.31	The University of Arizona・Senior Research Scientist・USA	The University of Tokyo・Associate Professor・Japan	USA
2014.9.1-2015.7.31	University of Hawaii・PostDoctral Researcher・USA	Chief research officer・ETH・Switzerland	Germany
2013.11.1-2017.2.28	Tokyo Institute of Technology・Research Staff・Japan	Tokyo Institute of Technology・Specially Appointed Assistant Professor ・Japan	France
2014.8.5-2016.6.30	University of Oregon・Researcher・USA	Araya Brain Imaging・Data Science Manager・Japan	USA
2016.2.1-2017.2.28	Ochanomizu University・Project Assistant Professor・Japan	Ochanomizu University・Assistant Professor・Japan	France
2014.5.1-2017.4.30	Yokohama National University・Graduate Student・Japan	-	Malaysia
2015.5.1-2017.6.30	Georgia Institute of Technology・Graduate Student・USA	Tokyo Institute of Technology・JSPS Postdoctoral Fellowships ・Japan	USA
2015.9.24-2017.9.23	University of Southern Denmark・Graduate Student・Denmark	University of Southern Denmark・Assistant Professor・Denmark	Denmark
2016.2.1-2018.1.31	Max Planck Institute for Solar System Research・Postdoctoral Research Scientist・Garmany	Gateway House・Fellow・India	India
2016.2.1-2018.1.31	UC San Diego・Postdoctoral fellow・USA	University of California, San Diego・Assistant Teaching Professor・USA	USA
2016.3.1-2018.2.28	University of Cambridge・Postdoctoral Research Associate・UK	University of Cambridge・Visiting Researcher・UK	UK
2016.4.1-2018.3.31	University of California, Los Angeles・Graduate Student・USA	Lawrence Livermore National Laboratory・Postdoctoral Research Staff・USA	USA
2016.4.1-2018.3.31	Ecole Polytechnique・Postdoctral Researcher・France	California Institute of Technology・Postdoctoral Researcher・USA	UK
2016.4.1-2018.3.31	Institute of Advanced Studies, Princeton・Visiting Scholar・USA	University of Naples "Federico II"・Assistant Professor・Italy	Italy
2017.9.1-2018.2.28	University of Oxford・Postdoctral Researcher・UK	University of Southampton・Research Fellow・UK	UK
2013.9.1-2018.8.31	Harvard University・Postdoctoral・USA	University of New South Wales・Lecturer ・Australia	USA
2017.4.1-2018.8.28	Tokyo Institute of Technology・JSPS Postdoctoral Fellowships ・Japan	Nantes University・Marie Skłodowska-Curie actions Individual Fellowship fellow・France	France

Appendix4-5　List of the Cooperative Research Agreements with Overseas Institutions

*Prepare the information below during the period from the beginning of the Center through March 2019.

1. Name of an Agreement: Memorandum of Understanding
   Dates of an Agreement: March 31, 2015
   Counterpart of an Agreement: Georgia Institute of Technology
   Summary of an Agreement: Under the umbrella of the Tokyo Tech/Georgia Tech MoU, ELSI is strengthening its collaboration with their Center for Chemical Evolution (CCE), through their PIs Loren Williams and Martha Grover, to expand on 'messy chemistry', ELSI's hallmark approach to studies in origin and evolution of a biotic chemosphere. In recent years, ELSI has laid the groundwork for a broad-based experimental and computational study of combinatorial chemistry in systems that are regulated by geo-energetic boundary conditions and that have limited catalytic support. Collaboration, mutual visitorships, sabbaticals with CCE are planned to strengthen ELSI's efforts. ELSI and CCE are also interested in creating course material for the chemical origin of life.

2. Name of an Agreement: Memorandum of Understanding
   Dates of an Agreement: June 29, 2015
   Counterpart of an Agreement: Prof. Daniel Merkle, Dept. of Mathematics and Computer Science, Univ. of Southern Denmark
   Summary of an Agreement: Prof. Merkle will act as an Affiliated Institute Supervisor to ELSI Origins Network (EON) postdoc Dr. Jakob Andersen as he pursues research on computational chemistry methods for prebiotic chemistry. Academic mentorship and the provision of work space will be provided while Andersen spends half of his two-year EON postdoctoral program at U. of Southern Denmark. As an EON Affiliate Institute Supervisor, Prof. Merkle will attend EON annual meetings at ELSI and share his expertise with other ELSI researchers. Outcomes: Through Prof. Merkle and shared postdoc Andersen, ELSI hosted a computational chemistry workshop that brought experts in computer algorithms together with experts on prebiotic chemistry to identify common goals for research, the first time that this has been done ever, to our knowledge.

3. Name of an Agreement: Memorandum of Understanding
   Dates of an Agreement: July 06, 2015
   Counterpart of an Agreement: Prof. Dennis Liotta, Dept. of Chemistry, Emory University
   Summary of an Agreement: Prof. Liotta will act as an Affiliated Institute Supervisor to ELSI Origins Network (EON) postdoc Dr. Chris Butch as he pursues research on the evolution of nucleic acid polymerase enzymes. Academic mentorship and the provision of work space will be provided while Butch spends half of his two-year EON postdoctoral program at Emory University. As an EON Affiliate Institute Supervisor, Prof. Liotta will also attend EON annual meetings at ELSI and share his expertise with other ELSI researchers. Outcomes: Dr. Liotta's group, which mainly focuses on medicinal chemistry, is building on ELSI researcher K. Petrie's groundbreaking results on protein evolution.

4. Name of an Agreement: Memorandum of Understanding
   Dates of an Agreement: July 17, 2015
   Counterpart of an Agreement: Prof. Constantine Vetriani, Dept. of Biochemistry and Microbiology, Rutgers University
   Summary of an Agreement: Prof. Vetriani will act as an Affiliated Institute Supervisor to ELSI Origins Network (EON) postdoc Dr. Donato Giovannelli as he pursues research on the distribution and ecology of microorganisms deeply rooted in the tree of life. Academic mentorship and the provision of work space will be provided while Giovannelli spends half of his two-year EON postdoctoral program at the Deep-Sea Microbiology Laboratory at Rutgers Univ., a center of expertise in the microbiology of extremophiles. As an EON Affiliate Institute Supervisor, Prof. Ventriani will also attend EON annual meetings at ELSI and share his expertise with other ELSI researchers. Outcomes: this has been a particularly active collaborative relationship, with Prof. Vetriani and Giovannelli inviting ELSI research scientist Nakagawa to spend time at Rutgers to

learn new lab techniques. ELSI and Rutgers members are continuing to submit proposals to develop extremophile models which are the best models for early life.

5. Name of an Agreement: Memorandum of Understanding
Dates of an Agreement: September 12, 2015
Counterpart of an Agreement: Prof. Nicholas Bredeche, Dept. of Computer, Science, Institut des Systèmes Intelligents et de Robotique (France)
Summary of an Agreement: Prof. Bredeche will act as an Affiliated Institute Supervisor to ELSI Origins Network (EON) postdoc Dr. Nathanael Aubert-Kato as he pursues research on the emergence of agency in chemical reaction systems. Academic mentorship and the provision of work space will be provided while Aubert-Kato spends half of his two-year EON postdoctoral program at ISIR. As an EON Affiliate Institute Supervisor, Prof. Bredeche will also attend EON annual meetings at ELSI and share his expertise with other ELSI researchers.

6. Name of an Agreement: Memorandum of Understanding
Dates of an Agreement: September 15, 2015
Counterpart of an Agreement: ETH Zurich
Summary of an Agreement: Under the umbrella of the Tokyo Tech/ETH Zurich MoU, ELSI is in discussion with their Geochemistry/Petrology Institute in areas of High Pressure Geology and Planetary Geochemistry, and the Geophysics Institute in areas of Planetary Magnetism and Seismology/Geodynamics to formally expand our collaborative activities. In addition to ongoing work on Mars core properties at ETH, ELSI would contribute expertise in areas as the coupling of N-body and pebble accretion models to planetary geochemistry, modeling of planetary atmospheres, their signatures in exoplanet observations, and early atmosphere interaction/evolution with magma oceans, the generation and maintenance of early magnetic fields in pre-planetary bodies, and the interaction of early planetary atmospheres with planetary magnetic fields to assess retention and loss of atmospheric components. ETH sends strong applicants to the ELSI research scientist call and a graduate student from ETH is spending time at ELSI on a JSPS fellowship. There is discussion of an ELSI PI spending a few months at ETH to further promote those collaborative activities.

7. Name of an Agreement: Memorandum of Understanding
Dates of an Agreement: October 01, 2015
Counterpart of an Agreement: Dr. Joseph Nuth, Senior Scientist for Primitive Bodies, NASA Goddard Institute for Space Studies
Summary of an Agreement: Dr. Nuth will act as an Affiliated Institute Supervisor to ELSI Origins Network (EON) postdoc Dr. Chaitanya Giri as he pursues research on the nature of organic astromaterials of possible relevance to the origins of life. Academic mentorship and the provision of work space will be provided while Giri spends half of his two-year EON postdoctoral program at NASA Goddard. As an EON Affiliate Institute Supervisor, Dr. Nuth will also attend EON annual meetings at ELSI and share his expertise with other ELSI researchers.

8. Name of an Agreement: Memorandum of Understanding
Dates of an Agreement: October 02, 2015
Counterpart of an Agreement: Prof. Kenneth Nealson, Dept. of Earth Sciences and Biological Sciences, University of Southern California
Summary of an Agreement: Prof. Nealson will act as an Affiliated Institute Supervisor to ELSI Origins Network (EON) postdoc Dr. Nancy Tseng Merino as she pursues research on the identification of novel extremophile microorganisms. Academic mentorship and the provision of work space will be provided while Tseng Merino spends half of her two-year EON postdoctoral program at Univ. of Southern California. As an EON Affiliate Institute Supervisor, Prof. Nealson will also attend EON annual meetings at ELSI and share his expertise with other ELSI researchers.

9. Name of an Agreement: Memorandum of Understanding
Dates of an Agreement: October 18, 2015

Counterpart of an Agreement: Prof. Yuk Yung, Dept. of Planetary Science, California Institute of Technology
Summary of an Agreement: Prof. Yung will act as an Affiliated Institute Supervisor to ELSI Origins Network (EON) postdoc Dr. Stuart Bartlett as he pursues research on the emergence of complexity. Academic mentorship and the provision of work space will be provided while Bartlett spends half of his two-year EON postdoctoral program at Caltech. As an EON Affiliate Institute Supervisor, Prof. Yung will also attend EON annual meetings at ELSI and share his expertise with other ELSI researchers. Outcomes: Prof. Yung's group is now exploring fundamental questions concerning the origin of life and the phenomena of learning in chemical systems in addition to planetary science as a result of the shared postdoc with ELSI, increasing the overlapping activities between them and ELSI.

10. Name of an Agreement: Memorandum of Understanding
Dates of an Agreement: November 30, 2015
Counterpart of an Agreement: Prof. Justin Meyer, Section of Ecology, Behavior and Evolution, University of California, San Diego.
Summary of an Agreement: Prof. Meyer will act as an Affiliated Institute Supervisor to ELSI Origins Network (EON) postdoc Dr. Katherine Petrie as she pursues research on the mode of evolution of bacterial-virus pathogen-host relationships. Academic mentorship and the provision of work space will be provided while Petrie spends half of her two-year EON postdoctoral program at UCSD. As an EON Affiliate Institute Supervisor, Prof. Meyer will also attend EON annual meetings at ELSI and share his expertise with other ELSI researchers. Outcomes: Prof. Meyer said of ELSI's funding for shared postdoc Petrie and its interdisciplinary atmosphere allowed her to pursue controversial ideas, which resulted in a paper accepted in Science that will have significant impact on the fields of evolutionary biology and origins research.

11. Name of an Agreement: Memorandum of Understanding
Dates of an Agreement: December 7, 2015
Counterpart of an Agreement: Prof. Simon Conway Morris, Dept. of Earth Sciences, University of Cambridge
Summary of an Agreement: Prof. Conway Morris will act as an Affiliated Institute Supervisor to ELSI Origins Network (EON) postdoc Dr. Jennifer Hoyal Cuthill as she pursues research on the nature of Precambrian biological evolution. Academic mentorship and the provision of work space will be provided while Hoyal Cuthill spends half of her two-year EON postdoctoral program at the Univ. of Cambridge. As an EON Affiliate Institute Supervisor, Prof. Conway Morris will also attend EON annual meetings at ELSI and share his expertise with other ELSI researchers.

12. Name of an Agreement: Memorandum of Understanding
Dates of an Agreement: January 12, 2016
Counterpart of an Agreement: Prof. Lynn Rothschild, Evolutionary biologist and astrobiologist, NASA's Ames Research Center
Summary of an Agreement: Prof. Rothschild will act as an Affiliated Institute Supervisor to ELSI Origins Network (EON) postdoc Dr. Kosuke Fujishima as he pursues research on the synthesis and selection of amino acid and RNA in prebiotic systems. Academic mentorship and the provision of work space will be provided while Fujishima spends half of his two-year EON postdoctoral program at NASA's Ames. As an EON Affiliate Institute Supervisor, Prof. Rothschild will also attend EON annual meetings at ELSI and share her` expertise with other ELSI researchers.

13. Name of an Agreement: Affiliate international Partner of the NAI
Dates of an Agreement: July 15, 2016
Counterpart of an Agreement: NASA Astrobiology Institute (NAI) with Japan Astrobiology Consortium (JABC)
Summary of an Agreement: ELSI launched the Japan Astrobiology Consortium in cooperation with the National Institutes of Natural Sciences' Astrobiology Center, and signed a partnership agreement with NASA's Astrobiology Institute. The mission of JABC is to develop the field of

astrobiology, establish a community of researchers in astrobiology, to support especially young researchers, and to be the hub for international relationships. The partnership between NAI and JABC will focus initially in (1) the exchange of early career scientists and astrobiology summer schools; (2) the organization of Workshops Without Walls; and (3) research collaborations involving members of NAI and the JABC.

14. Name of an Agreement: Temporary Assignment Contract
Dates of an Agreement: July 17, 2018
Counterpart of an Agreement: Columbia University
Summary of an Agreement: Agreement to forge closer ties to Columbia University as an affiliate institution of ELSI, which will help to enable collaborative activities like joint planning and sponsorship of workshops, symposia or courses and other ELSI or CAL hosted events as well as facilitating the exchange of visiting researchers at all professional stages.

15. Name of an Agreement: Memorandum of Understanding
Dates of an Agreement: March 18, 2019
Counterpart of an Agreement: The Australian Center for Astrobiology/School of Chemistry, University of New South Wales
Summary of an Agreement: To forge closer ties with the Australian Center for Astrobiology (ACA), a powerhouse of geoscience research and also the only astrobiological research institute in Australia. ACA is an associate member of the NASA Astrobiology Institute, of which ELSI is an active Affiliate International Partner through the Japan Astrobiology Consortium. Scientific collaborative opportunities in prebiotic chemistry and early Earth geological scenarios, leveraging ELSI and UNSW's research experiences and resources available at UNSW, will be pursued under coordination with former ELSI associate principal investigator Albert Fahrenbach who is now a Lecturer at UNSW School of Chemistry. Other potential activities include: personnel exchange/visits, jointly organized international workshops, joint development of origins of life curriculum and sharing of pedagogical materials, sabbatical stays between UNSW and ELSI academic staff. There is already a plan for an ELSI researcher to go spend time at UNSW.

16. Name of an Agreement: Joint Appointment Agreement
Dates of an Agreement: March 23, 2019
Counterpart of an Agreement: Max Planck Institute for Mathematics in the Sciences
Summary of an Agreement: To share in the hiring of research scientist Dr. Nathaniel Virgo (50% FTE for ELSI) through which closer ties between MPI MiS and ELSI will be forged in the field of complex systems and the origin of cognition.

Under Preparation

In addition, as our collaborative networks deepen and expand, we are in the process of setting up Memorandum of Understandings with the following institutions below and expect them to be signed in the coming months:

1. Name of an Agreement: Memorandum of Understanding
Dates of an Agreement: in the coming months
Counterpart of an Agreement: Arizona State University (ASU)’s School of Earth and Space Exploration
Summary of an Agreement: Director Lindy Elkins-Tanton has two strong groups of interest for ELSI: the Habitability and Exoplanets group with Drs. Hilairy Hartnett and Steve Desch, both having spent 2 months at ELSI, have numerous collaborations with ELSI researchers; and the Universal Biology group with Dr. Sara Walker, where one of the shared fundamental questions ELSI will explore is whether biology is governed by general principles and not tied to specific chemical instantiations. In addition, ASU’s Center for Meteorite Studies houses the world’s largest university-based meteorite collection. ELSI would like to further build collaborations with those already working on these astromaterials. ASU and ELSI already have strong collaborative research ties, further strengthened by them sending competitive candidates to ELSI's research scientist calls. Two of our recent hires have come from ASU.

2. Name of an Agreement: Memorandum of Understanding
   Dates of an Agreement: in the coming months
   Counterpart of an Agreement: Penn State Astrobiology Research Center (PSARC)
   Summary of an Agreement: PSARC is a part of the NASA Astrobiology Institute. Dr. Katherine Freeman and Dr. Hiroshi Ohmoto (Director of PSARC) will collaborate on developing novel approaches to detecting and characterizing life, investigate biosignatures in mission-relevant ecosystems and ancient rock and evaluate the potential for biosignatures in extraterrestrial settings.

3. Name of an Agreement: Memorandum of Understanding
   Dates of an Agreement: in the coming months
   Counterpart of an Agreement: Heidelberg Initiative for the Origins of Life (HIFOL), Max Planck Institute for Astronomy
   Summary of an Agreement: Dr. Thomas Henning will lead collaborative work with ELSI. HIFOL facilitates a wide range of interdisciplinary theoretical, experimental, and observational research covering the fields of astronomy, physics, geosciences, chemistry, biology and life sciences, overlapping with ELSI. MoU will explore collaborative activities like joint planning and sponsorship of workshops, symposia or courses and other ELSI or HIFOL hosted events as well as facilitating the exchange of visiting researchers at all professional stages.

4. Name of an Agreement: Memorandum of Understanding
   Dates of an Agreement: in the coming months
   Counterpart of an Agreement: University of Illinois at Urbana-Champaign
   Summary of an Agreement: Dr. Nigel Goldenfeld is the director of the NASA Astrobiology Institute for Universal Biology. ELSI's research to date has focused on the molecular systems that realized the principles of life on Earth. ELSI's next phase will seek to define the theoretical and empirical science of a Universal Biology. Dr. Goldenfeld and close collaborator Dr. Kunihiko Kaneko of U. Tokyo are leading the only two existing institutes on Universal Biology worldwide, and will provide valuable guidance to our five research areas looking to define that science.

5. Name of an Agreement: Memorandum of Understanding
   Dates of an Agreement: in the coming months
   Counterpart of an Agreement: University of Arizona
   Summary of an Agreement: with Affiliated ELSI PI Betul Kacar (previously at Harvard, and an active collaborator with ELSI), we will continue to pursue the reconstruction of the deep history of biochemistry and bioenergetics. Collaboration with Dr. Dante Lauretta, PI of OSIRIS-Rex, the asteroid Bennu's sample return mission, and his team will bring further cosmochemistry expertise to ELSI on possible molecular precursors to the origin of life and the Earth's oceans.

Appendix4-6　Holding International Research Meetings

* Indicate up to ten of most representative international research conferences or symposiums held from the start of the center through March 2019 and give the number of participants using the table below.

Date	Meeting title and Place held	Number of participants
March 27-29, 2013	The 1st ELSI International Symposium	From domestic institutions: 116 From overseas institutions: 26
March 24-26, 2014	The 2nd ELSI International Symposium "Origin & Evolution of the Earth-Life System"	From domestic institutions: 102 From overseas institutions: 43
January 13-15, 2015	The 3rd ELSI International Symposium "Life in the Universe"	From domestic institutions: 103 From overseas institutions: 41
January 12-15, 2016	4th ELSI International Symposium "Early Earth, Venus & Mars Three Experiments in Biological Origins"	From domestic institutions: 100 From overseas institutions: 49
July 25-26, 2016	Symposium on the Origin of Consciousness	From domestic institutions: 85 From overseas institutions: 24
January 11–13, 2017	5th ELSI International Symposium "Expanding Views on the Emergence of the Biosphere"	From domestic institutions: 78 From overseas institutions: 89
July 26-28, 2017	EON Workshop "Sensors, Motors and Behavior at the Origin of Life"	From domestic institutions: 19 From overseas institutions: 26
January 9-11, 2018	6th ELSI International Symposium "Building Bridges from Earth to Life: From Chemical Mechanism to Ancient Biology"	From domestic institutions: 80 From overseas institutions: 72
May 14-18, 2018	Workshop "Puzzles and Solutions in Astrobiology"	From domestic institutions: 49 From overseas institutions: 35
January 7-11, 2019	7th ELSI International Symposium "COMPARATIVE EMERGENCE"	From domestic institutions: 69 From overseas institutions: 43

Appendix 5 List of Achievements of Center's Outreach Activities between FY 2012 – 2018

* Using the table below, show the achievements of the Center's outreach activities from FY2012 through FY2018 (number of activities, times held).

*If there are any rows on activities the center didn't implement, delete that (those) row(s). If you have any activities other than the items stated below, fill in the space between parentheses after "Others" on the bottom with the name of those activities and state the numbers of activities and times held in the space on the right. A row of "Others" can be added, if needed.

Activities	FY2012	FY2013	FY2014	FY2015	FY2016	FY2017	FY2018
	(number of activities, times held)						
PR brochure, pamphlet	0	1	4	2	2	2	1
Lectures, seminars for the general public	0	12	15	12	25	20	13
Teaching, experiments, training for elementary, secondary and high school students	0	1	9	10	11	8	4
Science cafe	0	1	1	0	1	4	0
Open house	0	0	7	0	1	1	0
Participating, exhibiting in events	0	1	8	3	3	4	4
Press releases	3	3	13	14	17	8	17
Publications of the popular science books	0	7	4	10	5	3	0
Others（collaboration with creators）	0	0	0	0	0	1	1

Appendix 5 List of Media Coverage of Projects Carried out between FY 2012 – 2018

* Select main items of press releases, media coverage, and reports for FY 2012-2018 (especially by overseas media)

1) Japan

No.	Date	Type of the media (e.g., newspaper, magazine, television)	Description
1	2012/10/31	Newspaper (Yomiuri Shimbun et al.)	Tokyo Institute of Technology to shed light on the environment of the early Earth; Professor Kei Hirose (44) Three university groups selected for the world's most advanced research center, Ministry of Education, Culture, Sports, Science and Technology
2	2013/2/14	Newspaper (Yomiuri Shimbun)	Exploratory research in high-pressure geoscience, Kei Hirose (Director, Tokyo Institute of Technology Earth–Life Science Institute): "Journey to the Center of the Earth."
3	2013/2/18	Newspaper (Nihon Keizai Shimbun)	Saturn probe data were applied to the mystery of the galactic cosmic ray acceleration. The incontrovertible results are announced in Nature Physics. (Fujimoto)
4	2013/3/21	TV (TV Asahi "Morning Bird")	A simulation movie demonstrating the evolution of a gas cloud approaching a black hole located in the center of the Milky Way was introduced in a segment that was about two minutes long. (Makino)
5	2013/3/21	Newspaper (Nikkei et al.)	The evolution of the gas cloud G2 was simulated. The cloud was discovered last year at the center of the Milky Way and is approaching a black hole at the center of the galaxy. It was shown that the gas cloud will shine brightly in the infrared band around the summer of 2013. (Makino)
6	2013/5/2	Newspaper (Mainichi Shimbun)	Maruyama & S, Takai, K "The Origin of Life: The Ocean or the Space."
7	2013/5/12	Newspaper (Nihon Keizai Shimbun)	Hirose, K & Maruyama, S "What is the 'Rock Theory' to Explain the Origin of Life?" Science Section
8	2013/5/14	TV (NHK BS Premium)	Hirose, K "Secrets of Explosion of Planets, the Earth, and Life." Cosmic Front.
9	2013/5/25	Magazine (Nikkei Science)	Saitoh, T "Focusing on the Galactic Center This Fall."
10	2013/7/7	TV (NHK ETV)	Irifune, T "It Is More Than Beautiful! The Birth of Super Diamonds." Science Zero.
11	2013/7/25	TV (NHK BS Premium)	Ida, S "Uranus and Neptune." Cosmic Front.

12	2014/1/17	Newspaper (Tokyo Shimbun)	Hirose, K "The Existence of Large Amounts of Water upon the Birth of Earth." Comprehensive Section No. 12
13	2014/1/31	Newspaper (Mainichi Shimbun)	Ueno, Y "Methane: Providing a Clue to Solving the Origin of Life." Kurashi Navi No. 13
14	2014/4/16	Newspaper (Nihon Keizai Shimbun The Mainichi Shimbun)	Water on Mars—Reduced by half in 400 million years. "Underground Ice." Mars: Water reduced to half in 400 million years since the birth of the planet. Is there a large quantity of ice underground?
15	2014/5/26 2014/6/26 2014/12/27	Magazine (Newton)	Birth and evolution of the solar system Evolution of universe told by colliding galaxies– Exoplanets Grand Prix The complete map of the galaxy
16	2014/5/31 2014/6/6 2014/6/22	Newspaper (Zaikei Shimbun Kagaku Kogyo Nippo Nihon Keizai Shimbun)	Indicates gene evolution from algae to land plants. How did plants evolve from sea to land?
17	2014/6/6 2014/6/23	Newspaper (Chunichi Shimbun Kyoto Shimbun Nihon Keizai Shimbun)	A satellite shines in the shadow. Discovered during observation of Jupiter. National Astronomical Observatory of Japan: Satellite observed shining behind Jupiter.
18	2014/7/3 2014/9/8	Newspaper (Ehime Shimbun The Asahi Shimbun)	Professor Irifune of Ehime University wins Australian Geological Society "Ringwood Award." Winner of Australian Geological Society Ringwood Award, "I followed the footsteps of my heroes."
19	2014/7/16 2014/8/14	Newspaper (The Mainichi Shimbun Nihon Keizai Shimbun)	"The Earth's depth unlocked" from the laboratory. An unknown mineral created under high pressure.
20	2014/8/25 2014/8/26 2014/9/1	Newspaper (Nishi Nihon Shimbun Nihon Keizai Shimbun The Sankei Shimbun)	Waseda University discovers a new mineral in Central Asia —a type of tourmaline. Tourmaline with micro-diamond discovered by Waseda University in Central Asia New mineral discovered in Central Asia: Waseda University and Tokyo Institute of Technology discover a type of tourmaline
21	2014/12/14	Newspaper (Nihon Keizai Shimbun)	Theory: Large amounts of hydrogen in the Earth's core.
22	2015/2/19 2015/2/26	Newspaper (Zaikei Shimbun The Mainichi Shimbun)	Earth-like planets are likely to form around Sun-like stars - Tokyo Institute of Technology runs a simulation. M-type dwarf planet, "different environment from Earth"
23	2015/2/17	TV (NHK World)	The Leading Edge: Not Just a Pretty Face! The Birth of the Super Diamond
24	2015/2/24	Newspaper (Nihon Keizai Shimbun The Tokyo Shimbun)	Understanding the ultra-deep sea ecosystem Unique ecosystem found beyond 6 km depth.

25	2015/4/10	Television (NHK BS Premium)	<Cosmic Front> Virtual Space Tour—Adventure! Milky way galaxy.
26	2015/4/13	TV (NHK "Close-up Gendai")	ELSI's research was introduced in the article "Found at Last!? Scientists Grapple with Life Beyond Earth".
27	2015/5/4	TV (TV Asahi)	<Miracle Earth> Treasure buried in Sahara Desert—The meteorite hunter 1,500 km
28	2015/6/5	Television (NHK BS Premium)	<Cosmic Front> Virtual Space Tour—An unusual planet
29	2015/8/8	Newspaper, Web articles (Mainichi News, Yahoo! News, LabOnline etc.)	Tokyo Institute of Technology: American Foundation Makes 670 Million Yen Donation. Tokyo Institute of Technology Earth-Life Science Institute obtains about 670 million yen in research funding from American charitable foundation! A new search for the origin of life
30	2015/10/1	TV (NHK BS Premium)	Cosmic Front☆NEXT "Mystery of Earth's Birth"
31	2015/12/4	TV (NHK BS1)	Catch! The global perspective: "Why is biohacking spreading around the world?"
32	2016/1/16	magazine (Bungeishunju)	Bungeishunju February Issue <New Leader Conditions> 125 Outstanding Persons Enlivening Japan
33	2016/2/14	TV (NHK E Tele)	Science ZERO "Birth of a Planet! Giant Impact"
34	2016/4/21	TV (NHK BS)	Scientific simulation movie made by Dr. Saito was introduced in the program "Cosmic Front - NEXT "Mystery of Globular Clusters - Ancient Cities of the Universe"
35	2016/5/28	newspaper (The Yomiuri Newspapers)	It was reported that the 57th Fujihara Prize was given to the Center Director, Prof. Hirose.
36	2016/7/3	TV (NHK "Science ZERO")	Scientific simulation movie made by Dr. Saito was introduced in the program.
37	2016/11/28	Newspaper (The Mainichi Newspapers)	It was reported that ELSI had been donated 5.5 million dollars by an US foundation among many universities in Japan suffering from their serious financial situation.
38	2016/12/7	Magazine (WIRED)	It was reported that Dr. Fujishima had won WIRED Audi Innovation Award 2016.
39	2017/4/6	Magazine (Nikkei Science)	It was reported a new hypothesis by Dr. Genda and his colleagues regarding how the marks observed on the Pluto were created.
40	2017/10/27	web article (Newsweek Japan edition)	It reported that Dr. Fujii and her colleagues developed a new method of knowing the possibility of a planet reserving water.
41	2017/12/6	Magazine(web article) (AXIS)	The collaboration project among scientists and creators called 'Creators Meet Scientists' organized by ELSI was reported.

42	2018/4/2 2018/4/23 2018/5/14 2018/7/31 2018/8/22	Magazine(web article) (Kodansha Bluebacks)	Specially appointed associate professor Yutetsu Kuruma was interviewed about his research on synthesis biology.
43	2018/7/25 2018/7/27 (rerun) 2019/1/23 (rerun)	TV (NHK "Matayoshi Naoki No Heureka!")	Prof. Ida, Dr. Fujishima, and Dr. Mochizuki appeared to talk about possibility of extraterrestrials. The ELSI building was also introduced.
44	2018/10/6 2018/10/7 (rerun) 2018/10/27 (rerun)	TV (The Open University of Japan)	Prof. Maruyama appeared to give a lecture about origins of the Earth and life.
45	2018/10/13 2018/10/14 (rerun) 2018/10/28 (rerun)	TV (The Open University of Japan)	Prof. Maruyama appeared to give a lecture about evolution of life.
46	2018/12/26	TV (NHK "Matayoshi Naoki No Heureka!")	Prof. Ida appeared to talk about what life is.
47	2019/3/4 2019/3/5 2019/3/6 2019/3/7 2019/3/8 2019/3/11	web article (NATIONAL GEOGRAPHIC Japanese edition)	Dr. Fujishima was interviewed about his research of astrobiology.

2) Overseas

No.	Date	Type of the media (e.g., newspaper, magazine, television)	Description
1	2013/1/21	magazine (Science & Technology, Concentrates)	Dr. Cleaves's research was introduced in the article "Mass Spectrometry Imaging of Granite".
2	2013/3/14	web article (SCOOP Independent News)	Prof. Hirose's research was introduced in the article "Tokyo Origin of Life Talks: Core of Earth —Beyond".
3	2013/3/22	web article (SCOOP Independent News)	Prof. Hut's research was introduced in the article "Origins of Life and Herding Cats."
4	2013/9/13	Newspaper (The Science News)	Dr. Sekimoto-Sasaki's research was mentioned in the article "Stress Response Control in Plants."
5	2013 Fall	Newsletter (Institute for Advanced Study, Princeton IAS Magazine)	Prof. Hut's research was introduced in the article "Origin of Life."

6	2014/3/22	web article (SCOOP Independent News)	Prof. Hut's research was introduced in the article "Origins of Life and Herding Cats".
7	2014/4/28	web article (Science)	ELSI's research was introduced in the article "False Signs of Life on Alien Worlds".
8	2014/7/14	magazine (U.S. Geological Survey)	ELSI's research was introduced in the article "New Global Geologic Map of Mars".
9	2014/7/15	magazine (INTERNATIONAL BUSINESS TIMES)	ELSI's research was introduced in the article "Mars Interactive Maps Go Beyond Just Data And Visualization".
10	2014/7/23	web article (GIZMODE)	ELSI's research was introduced in the article "Currently the most detailed map of Mars".
11	2014/10/16	Newspaper (LE FIGARO)	ELSI's research was introduced in the article "Des éruptions sur la Lune au temps des dinosaures".
12	2014/10/28	web article (Deutschlandfunk)	ELSI's research was introduced in the article "Junge Vulkane auf dem Mond"
13	2014/10/30	magazine (MEDISTER)	ELSI's research was introduced in the article "Young pioneers in geophysics creating a new experimental system with new technology".
14	2014/11/21	web article (Nature World News)	ELSI's research was introduced in the article "Deep-Earth Carbon Offers Clues to Origins of Life".
15	2014/11/21	web article (Science 2.0)	ELSI's research was introduced in the article "Deep-Earth Carbon Could Have Sparked Origin Of Life On Earth".
16	2014/12/8	web article (Nature Geoscience Online)	ELSI researcher's commentary "Deep water cycle: Mantle hydration" was posted in the media.
17	2014	TV/Radio (France Télévisions)	ELSI's research was introduced in the program “La Compagnie Des Taxi-Brousse: SynBio.”
18	2015/2/16	web article (GlobeNewswire)	ELSI's research was introduced in the article "Mysteries of Cosmic Oceans and Dunes: Planetary Research Shows That Earth-Like Planets are More Likely to Orbit Sun-Like Stars Rather Than Lower-Mass Stars"
19	2015/7/16	TV (GrassRoots Community Network)	Dr. Eric Smith's research was introduced in the program "Aspen Science Highlights - "New Theories on the Origin of Life"".
20	2015/10/5	TV, newspaper, web article (BBC, Huffington Post, Science News etc.)	Dr. George Helfrich's research was introduced in the article "The tsunami that engulfed an island. Ancient Tsunami Was Nearly As Tall As The Eiffel Tower, Scientists Say" of Huffington Post, and other media.
21	2015/11/11	magazine (The Atlantic)	ELSI Origins Network's (EON) roadmapping workshop held at ELSI was covered in detail in this popular magazine article "Inside a New Effort to Discover Life's Origins"
22	2016/1/4	magazine (Scientific American)	ELSI's research was introduced in the article "The Search for the Origin of Life".
23	2016/2/5	magazine (Nature Digest)	ELSI's research was introduced in the article "＜News in Japan＞ Birth of New Site for Searching Space for Key to the Origins of Life!".

24	2016/5/25	newspaper (web article) (Washington Post)	Dr. Jennifer Hoyal Cuthill's research published in the Proceedings of the Royal Society B was introduced in the article "These animals relied on each other for 100 million years. Now climate change is killing them both."
25	2016/7/7	web article (Nature Planetary Science)	Dr. Genda's research about formation of Martian moons was focused in the article "This week's Research Highlights".
26	2017/2/2	web article (Nature's Research highlights)	Dr. Genda's paper was introduced in the article "Pluto's dark equator explained".
27	2017/2/3	web article (Nature Astronomy)	ELSI's workshop about exoplanets was reported in the article.
28	2017/2/3	web article (Huffington Post)	5th ELSI International Symposium was mentioned in the article titled "The New Evolutionary Biology".
29	2017/2/3	web article (Nature Astronomy)	ELSI's workshop about exoplanets was reported in the article.
30	2017/2/3	web article (Huffington Post)	5th ELSI International Symposium was mentioned in the article titled "The New Evolutionary Biology".
31	2017/5/9	web article (NASA Astrobiology website)	ELSI is featured in this article "Research Center a Hub for Origins of Life Studies" as being a hub for Origins of Life research
32	2018/3/20	web article (nature)	Dr. Yuka Fujii's opinion was introduced in the article about exoplanet exploration.
33	2018/3/29	newspaper(web article) (Times of San Diego SAN FRANCISCO CHRONICLE)	Dr. Katherine L. Petrie was reported about her study that discovery of a surprise multitasking gene helps explain how new functions and features evolve.
34	2018/3/31	magazine(web article) (Forbes)	Dr. Ramses Ramirez's research on planets' potential habitable zones was introduced on the Forbes website.
35	2018/4/5	magazine(web article) (Scientific American)	Dr. Ramses Ramirez's opinion was introduced in the article "Are Water Worlds Habitable?"
36	2018/4/18	magazine(web article) (Science)	Dr. George Helffrich's opinion was introduced in the article "By listening for quakes on Mars, NASA lander will prove Red Planet's interior".
37	2018/4/3	web article (Genomics Research)	Dr. Katerine Petrie's research was introduced in the article "Virus Follows New Evolutionary Path".
38	2018/4/18	web article (Cosmos)	Prof. Shigenori Maruyama's research was introduced in the article ""Nuclear geyser" may be origin of life".
39	2018/4/30	magazine(web article) (Forbes)	A graduate student Irene Bonati and Dr. Keiko Hamano's opinions were introduced in the article "Magma Oceans Could be Key To Life In Cosmos".
40	2018/5/2	web article (Science Daily)	Dr. Ramses Ramirez's research was introduced in the article "Recent work challenges view of early Mars, picturing a warm desert with occasional rain".
41	2018/5/8	newspaper(web article) (Boston Business Journal)	Research of Dr. Atsuko Kobayashi and Dr. Joseph Kirschvink was introduced in the article "Oscillating nanophase magnetite controls ice nucleation".

Earth-Life Science Institute

42	2018/6/13	magazine(web article) (R&D Magazine)	Research of Dr. Kuhan Chandru and Dr. Jim Cleaves was introduced in the article "Study Reveals Simple Chemical Process That May Have Led to the Origin of Life on Earth".
43	2018/6/29	magazine(web article) (Forbes)	Dr. Daigo Shoji's study on using artificial intelligence to understand volcanic eruptions from tiny ash was reported.
44	2018/9/20	web article (Evolution News & Science Today)	Dr. Jennifer Hoyal Cuthill's research was introduced in the article "More Excuses for Cambrian Non-Evolution".
45	2018/11/9	web article (Cosmos)	Dr. Chaitanya Giri's research was introduced in the article "The tech we're going to need to detect ET".
46	2019/1/9	web article (Nature NEWS AND VIEWS)	Dr. Gréaux and Prof. Irifune's research was mentioned in the article "High-pressure experiments cast light on deep-Earth mineralogy"
47	2019/1/11	web article (Discover)	Dr. Gréaux and Prof. Irifune's research was mentioned in the article "Recreating the Intense Conditions of the Earth's Mantle Solves A Long-standing Geological Mystery"
48	2019/1/15	magazine (Science)	Dr. Ramone Brasser's research was mentioned in the article "Seeing the Dawn - Evidence lines up to offer a new view of how life on our planet may have emerged"
49	2019/2/19	web article (Nature's Research highlights)	Dr. Mochizuki's research was introduced in the article "The giant Medusavirus turns defenseless cells to 'stone' ".
50	2019/3/3	magazine (Science Magazine)	Dr. Christine Houser wrote the article "Earth's rugged lower mantle"

Appendix6-1 Host Institution’s Commitment (Fund, Personnel)

1. Contributions from host institution

(1) Fund, Personnel

* Regarding "Fund" entry, describe with reference to the items in the Progress Report (Jisseki-hokoku-sho) based on Article 12 of the Grant Guidelines (Kofu-yoko).

* Don’t include competitive funding obtained by researchers (used as research project funding)

(FY 2012-2018)

<Fund> **(million yen)**

Fiscal Year	2012	2013	2014	2015	2016	2017	2018
Personnel	16	82	129	153	114	110	125
Faculty members	14	66	111	132	94	84	103
Full-time	14	66	105	91	72	84	83
Concurrent	0	0	6	41	22	0	20
Postdocs	0	0	0	0	0	0	0
RA etc.	0	0	0	1	0	0	1
Research support staffs	0	0	1	1	1	0	1
Administrative staffs	2	16	17	19	19	26	20
Full-time	2	16	17	18	19	26	16
Concurrent	0	0	0	1	0	0	4
Project activities	0	83	81	241	87	36	45
Travel	0	6	15	8	10	33	11
Equipment	0	6	26	133	29	3	3
Research projects	284	819	616	502	762	709	497
Total	300	996	867	1037	1002	891	681

<Personnel> **(person)**

Fiscal Year	2012	2013	2014	2015	2016	2017	2018
Personnel	9	10	19	28	18	12	14
Faculty members	8	8	16	18	11	9	9
Full-time	8	8	13	11	8	9	9
Concurrent	0	0	3	7	3	0	0
Postdocs	0	0	0	0	0	0	0
RA etc.	0	0	0	2	0	0	2
Research support staffs	0	0	1	4	4	0	0
Administrative staffs	1	2	2	4	3	3	3
Full-time	1	2	2	2	3	2	2
Concurrent	0	0	0	2	0	1	1

Appendix6-1 Host Institution's Commitment

1. Contributions from host institution

(2) Provision of land and/or building(s), lab space, etc.

Tokyo Tech provided the existing building (2,670 m^2) on the campus to ELSI at the beginning (ELSI-2) in FY 2012. In addition, the university provided a site and completed a new research building (ELSI-1: 5,000 m^2) in FY2014.

2. System under which the center's director is able to make substantive personnel and budget allocation decisions

Tokyo Tech has positioned ELSI as a research center that the president specifically recognizes. ELSI reports directly to the president, and aims to establish and develop a flexible research system that does not follow the conventional practices and management system. Furthermore, Tokyo Tech positions ELSI as a front-runner in research and reform that attracts researchers from around the world while raising international recognition. In ELSI, the Director has the authority to make decisions on important management and operation issues of the institute. As a result, the Director can carry out organizational reform, recruitment of young researchers through international recruitment, personnel management of staff, and budget allocation efficiently and effectively.

3. Support for the center director in coordinating with other departments at host institution when recruiting researchers, while giving reasonable regard to the educational and research activities of those departments

After ELSI was approved as a WPI center, an agreement was set by Tokyo Tech that five full-time professors were assigned to ELSI and they were exempted from the undergraduate education. As a measure to alleviate possible difficulties in the undergraduate education due to this transfer, Tokyo Tech assigned three faculty posts by the president's discretion to the department where the vacancy occurred. This has made it easier for professors from outside ELSI to be able to participate in ELSI's research.

4. Revamping host institution's internal systems to allow introducing of new management methods

(e.g., English-language environment, merit-based pay, cross appointment, top-down decision making unfettered by conventional modes of operation)

(1) Development of support environment in English

In ELSI, administrative tasks, committee meetings, and various training courses are basically conducted in English. ELSI has been requesting Tokyo Tech that some of these internationalization measures should be incorporated within the campus, and as a result most notification mails from Tokyo Tech administration are both in English and Japanese. Tokyo Tech has also established an English-language consultation desk for personnel matters and a counseling service using English. In addition, ELSI has assigned a full-time life support staff member, and has provided various support for foreign researchers to live in Japan even before the day of arrival.

(2) Introduction of performance-based pay system

ELSI adopts its own performance-based pay system. In the Annual Evaluation Meeting, all researchers report their research activities and are evaluated. Researchers who are recognized as having performed particularly excellent research are given the incentive award and salary raise in the next year.

(3) Introduction of cross appointment system

In order to acquire top level researchers, ELSI with the help of Tokyo Tech established a cross appointment system. Tokyo Tech applied this system for the first time to an ELSI PI. Since then Tokyo Tech has hired 22 researchers by January 2019 using the cross appointment system.

(4) Top-down decision making

As stated in (2), ELSI adopts a top-down decision-making system in which the Director decides on management and operation including personnel and budget execution. Tokyo Tech is promoting the construction, establishment and development of a flexible research system that is not tied to conventional practices and operating systems, using ELSI as a model.

(5) Support for fundraising

An NPO "Tokyo Tech USA" was established in the United States in 2017 in order to obtain donations and research funds from overseas companies and research support organizations.

In response to a request from ELSI, Tokyo Tech established a new system of donation program to enhance education and research through donations from private companies. ELSI received JPY 24 million donation from a private company and established the "FirstLogic Astrobiology Donation Program".

(6) Monthly meeting with the President's Office

The ELSI directors (Director, Executive Director, and Administrative Director) meet monthly with the University executives (President, Vice Presidents in charge of Research and Financial Affairs) in order to maintain close coordination between the University and ELSI. Requests from ELSI are seriously considered and often actions are quickly taken.

5. Utilities and other infrastructure support provided by host institution

(*In addition to those listed in the item 1. "Contributions from host institution")

ELSI has secured 20 rooms in the International House close to ELSI with priority to foreign researchers at ELSI. A nursery school was opened in April 2017 in the International House, which will assist researchers who need childcare services.

6. Support for other types of assistance

Tokyo Tech has appointed Dr. Mary Voytek, Senior Scientist at the Planetary Sciences Division of NASA Astrobiology, as Special Advisor to the President and Executive Director of ELSI. She will actively promote system reform, recruitment of talented researchers from around the world, and acquisition of external research funds.

It is the first time for Tokyo Tech to appoint a foreign female researcher as Special Advisor to the President. The appointment of Mary Voytek as ELSI Executive Director is an example of how Tokyo Tech is implementing an international-standard governance system.

Appendix6-2 The Host Institution's Mid-term Plan

* Excerpt the places in the host institution's "Mid-term objectives" and/or "Mid-term plan" that clearly show the positioning of the WPI center within its organization.

Tokyo Tech's Mid-term Plan

[The second term: April 01, 2010 – March 31, 2016]
(Mid-term goal)
2. Research goals
(1) Targets on research level and research accomplishments
I-2-2. Tokyo Tech will enhance the values created at this university and actively develop multidisciplinary and new areas, in order to attract researchers from Japan and all over the world and to lead science and technology researches.
(Mid-term Plan)
(1) Measures to achieve the goals of research level and research results
[25-2] As the World Top-Level Research Center, Earth-Life Science Institute will focus on the early earth to promote research aiming to unravel the origin and evolution of the earth and life, and Tokyo Tech will promote organizational reform to assist the institute.

[The third term: April 01, 2016 – March 31, 2022]
(Mid-term goal)
2. Research goals
(1) Targets on research level and research accomplishments
1-2-2. Tokyo Tech will enhance the values created at this university and actively develop multidisciplinary and new areas, in order to attract researchers from Japan and all over the world and to lead science and technology researches.
(Mid-term Plan)
(1) Measures to achieve the goals of research level and research results
[15] The president will provide resources to ELSI, the WPI center, to promote research to unravel the origin and evolution of the earth and life with focusing on early earth.

In this medium-term goal and medium-term plan, Tokyo Tech positions ELSI as a "strategic and ambitious institute".