ELSI 3rd international symposium
"Life in the Universe"
- List of abstracts for oral presentations -

Day 1 (Tuesday, January 13, 2015) - Planets as Cradles of Life

Planetary Diversity

David Stevenson (Caltech)

The remarkable richness of exoplanets and planetary systems (radius, mass, location, orbital spacing and configuration) is already evident from the data. I will focus on a less obvious but important question: To what extent are planets diverse in internal structure and behavior even when their outward characteristics (e.g., mass and radius) are similar. I will argue that diversity is expected and that the astronomical prejudice born of stellar studies (defining classes of bodies by common characteristics) can be expected to miss the essence of exoplanets as indeed it misses the remarkable (but incomplete) richness in our own solar system. The sources of diversity include variations in composition as well as the accidents of evolution.

Planet formation and origins of H_2O, C and N on the Earth

Shigeru Ida (ELSI)

With the equilibrium temperature determined by solar radiation, H_2O icy grains condense beyond 3AU and CO_2/NH_3 condense beyond 15AU. It means that H_2O, C and N must be delivered from cold regions during planet formation stages, either by (1) inward radial migration of dust grains due to disk gas drag, (2) that of planetary embryos due to disk-planet gravitational interactions, or (3) inward scattering of planetesimals (asteroids or Kuiper belt objects) by giant planets. I will review previous theoretical simulations on this issue. I will also present the result of our new simulation related to (1), based on a new concept of planetary accretion called "pebble accretion," which is now intensively discussed in the community of planet formation theory.

The potential importance of Mg/Si ratio in terrestrial planet evolution

John Hernlund (ELSI)

The ability for a planet to maintain chemical disequilibrium at the surface may be a key ingredient for the origin of life, and a usual suspect is tectonic resurfacing that maintains gradients in free energy that could provide a nursery for incipient living systems. Recent models for creation and sustenance of rheologically weak zones that accommodate plate tectonic behavior in the otherwise cold and stiff rocky lithosphere of the Earth involves a mixture of Mg_2SiO_4-olivine and $MgSiO_3$-pyroxene in roughly equal proportions, or Mg/Si~1.5. Deep inside planets at pressures above ~25 GPa this mixture of olivine and pyroxene is converted to periclase and bridgmanite, the former of which is up to 4 orders of magnitude weaker than the latter. Thus the rheology of the deep interiors of terrestrial planets should be highly sensitive to Mg/Si ratio since its variation from 1 to 2 can yield effective rock viscosity variations of more than 3 orders of magnitude in the deep interior, and values close to Mg/Si~1 or Mg/Si~2 may not permit sustenance of plate tectonics. Thus it is quite possible that a planet with Mg/Si=1 will undergo a completely different evolution than one with Mg/Si~1.5, as will be the case for Mg/Si~2. These considerations suggest that a planet's ability to sustain plate tectonics and deep convection currents may be more sensitive to Mg/Si ratio than almost any other factor, and therefore deserves particular attention in assessing the behavior of general planets in which this parameter should vary significantly.

Early Earth vs. Origin of Life

Steve Mojzsis (Univ. of Colorado)

In origins of life discussions, are there some ideas we can rule out?

1. Earth's primordial atmosphere was not fed by a more reduced mantle that in turn could have generated a "Prebiotic Soup". Over the timescale of primary accretion, Earth-like mantles tend to become more oxidized via a combination of such things as metal sequestration in Fe-Ni cores, Fe-disproportionation and Si-partitioning in core growth, and the relatively late arrival of volatile-rich planetesimals. Hadean zircon Ce*/Ce compositions show that the mantle has been close to its present oxygen fugacity (buffered at FMQ) for the past 4.37 Gyr. As such, volcanic gases have long been dominated by CO_2, H_2O, SO_2, N_2 with minor H_2.

2. Dry land is a primordial phenomenon; Earth was never a pure Ocean World. Work combining $^{147,146}Sm$-$^{143,142}Nd$, ^{182}W-^{184}W, ^{176}Lu-^{176}Hf and $^{235,238}U$-$^{207,206}Pb$ on the oldest rocks places strict constraints on the longevity and residence time of Hadean crust. Model outputs show that the oceanic:continental dichotomy began ca. 4.45 Gyr, but what if its proportion (now ~2.4) was greater in the Hadean (~50)? Continental crust volume at 2% present translates to 10 Japan arcs. A more unimodal Hadean hypsometry means shallower average ocean depths of ~2 km and areas around ridge axes were subaerial (e.g. Sts. Peter and Paul archipelago), as would volcanic islands emerging above mantle plume heads (e.g. Hawai'I; Samoa, Iceland, Canary, Galapagos, Cocos). Doubling the hydrosphere hardly changes things. The above-mentioned landmasses exist now with an average ocean depth of 3.9 km.

3. Comets are an unsatisfactory source of water to Earth. Neither the Late Heavy Bombardment (LHB) nor the Late Veneer (LV) brought Earth's oceans in the form of comets. Evidence exists for a hydrosphere well before the LHB. The cumulative delivered mass of the LHB was less than about 10^{-3} % of Earth's mass. This is too little to account for the hydrosphere. If the odds of a comet striking Earth are around $1:10^6$, something like 10^5 comets are required to account for one ocean's worth of seawater. At least 10^{11} comets (~5 $M_\oplus$) have to be in the source region to explain one ocean volume. If Earth's crust-mantle inventory holds about 10 ocean volumes, this leads to a cometary reservoir of 50 $M_\oplus$ just to explain Earth. Mars and Venus make this idea even less feasible. Both, D/H and $^{15}N/^{14}N$ isotopes are a poor match for comets, but generally right for chondrite building blocks.

4. Subsequent to the LV, it is probably not possible to eradicate microbial life on Earth with bombardment. To do so requires that the whole surface be heated to sterilization (>130°) to depth all at once. Cooling

times between large impacts (asteroids 300 km diameter) during the LHB were far shorter than the recurrence interval of individual large impacts. The oldest terrestrial rocks pre-date the terminus of the LHB. Evidence exists for both sedimentary rocks and a biosphere at LHB time.

Splashed Hadean Seawater Hypothesis

Hidenori Genda (ELSI)

We propose that the information about the Hadean Earth's seawater was recorded on the Moon's surface. Hadean Earth experienced a lot of asteroid and/or comet bombardments, and some amount of seawater should be splashed into the space. Some fraction of salt dissolved in Hadean seawater should spread over the Moon's surface. Here, we investigate the feasibility of this hypothesis, and discuss how to test this hypothesis.

The Early Atmospheres of Terrestrial Planets inferred from Impact Experiments and Asteroid Missions

Seiji Sugita (Tokyo Univ.)

The early atmospheres of terrestrial planets have importance influence on the origin of life. In particular, their redox state changes organic production rate greatly. Recent geochemical analyses have revealed that endogenic atmospheres may be redox neutral (CO_2 rich) rather than reducing; chemical reactions within such composition of atmospheres do not produce organics efficiently. Thus, the potential roles of impact delivery of organics and reducing agents have become increased greatly. However, both numerical and experimental studies shown that organic delivery mechanisms are extremely inefficient; the vast majority of impact delivered meteoritic organics from the space would be destroyed upon impacts or subsequent aerodynamic heating. Organic compounds delivered by meteoritic impacts would be mostly vaporized and incorporated into the atmosphere. However, both elemental and molecular composition of such atmospheres with large exogenic contributions is not well understood. They depend on both thermodynamic/chemical process during impacts and the composition of impactors. The former is controlled by impact mechanics, which can be investigated both impact experiments most effectively. The latter is more efficiently investigated by studying small bodies in the current Solar System. In this study, we review recent results in laboratory experiments regarding chemical reactions associated with hypervelocity impacts and outlook for upcoming sample-return missions to C-type asteroids, which are among the most important candidates for volatile deliverers to Earth, such as Hayabusa 2.

Expansion of Organic Cosmochemistry in the New Era of Small Body Missions

Hikaru Yabuta (Osaka Univ.)

The study on extraterrestrial organic molecules has started with an interest in origin of life in the Universe since 1970 when the indigenous amino acids were identified from Murchison meteorite (Kvenvolden et al., 1970), and has mainly focused on the search of bio-related compounds such as amino acids and their homochirality till 1990s (e.g., Cronin and Pizzarello, 1997). In 2000s, the research field on organics in meteorites has increased its significance to unveil the chemical history of the early Solar System by linking with astronomy (e.g., Ehrenfreund and Charnley, 2000) and by investigating the organic molecular and isotopic variations within and across meteorite groups and petrologic types (e.g., Alexander et al. 2007; Cody et al. 2008). The recent developments of *in-situ* analytical techniques has enabled the detections of D and ^{15}N enrichments in organic macromolecular solid from meteorites (e.g., Busemann et al. 2006) and the submicron-sized organic materials in comet Wild 2 dust particles collected by Stardust spacecraft (e.g., Sandford et al. 2006), tracing back to more primitive stage of organic chemical evolution than meteorites. The great pioneers' achievements have been transmitted to our generation and now opened up to a next stage. The small body missions around the world, such as Rosetta, Hayabusa-2, and OSIRIS-Rex, are targeting organic molecules in the early Solar System, for elucidating the small body surface chemistry that has been difficult to study by Meteoritics and for deepening our understanding of the origin and evolution of life's building blocks. A ground-based experiment of space weathering effect on organic molecules is a pressing need. Moreover, combination of these space explorations with the cosmic dust studies such as micrometeorites from Antarctic snow and cosmic dusts that will be collected at International Space Station ("Tanpopo") after 2015 would expand our knowledge on the generality and diversity of chemical evolution of organics as well as the molecular species which were delivered to the Earth. In particular, observation of the chemical relationships between organic and inorganic components within the primitive small body materials is an important clue to place constraints on the Solar System history.

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Busemann et al. (2006) Science 312, 727-730.
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Chemical compositions of the mantle transition region and the lower mantle of the Earth

Tetsuo Irifune (ELSI/GRC)

We have developed techniques to precisely determine the elastic properties of high-pressure phases relevant to mantle mineralogy by a combination of in situ X-ray and ultrasonic measurements in multianvil apparatus, as well as those for synthesis of high-quality sintered polycrystalline samples suitable for such measurements. Based on these techniques, sound velocity measurements have been made on high-pressure minerals relevant to the mantle and subducted slabs, which provides tighter constraints on the chemical compositions of the mantle transition region and the lower mantle. The results indicate that the mantle transition region is made of a pyrolitic composition except for its bottom region, where the existence of materials with higher sound velocities is suggested to account for one-dimensional seismological models such as PREM. Our sound velocity measurements on bridgmanite also demonstrate that the lower mantle should have a pyrolitic composition, rather than the more silicon-rich composition close to pyroxene stoichiometry as concluded in a recent work based on Brillouin scattering measurements (Murakami et al., 2012). Our result is also consistent with the prediction based on ab initio calculations and suggests the bulk mantle of the Earth is significantly depleted in Si relative to CI chondrites.

Day 2 (Wednesday, January 14, 2015) - Towards Universal Biology

A Self-Assembly Approach to Proto-RNA

Nicholas Hud (Georgia Tech)

The RNA World hypothesis is still popular among many origins of life researchers. However, a prebiotic synthesis of RNA has not been demonstrated. Significant challenges facing the prebiotic formation of RNA polymers include nucleobase selection, nucleoside bond formation, and nucleotide polymerization. As possible solutions to these challenges, we are investigating the hypothesis that RNA was preceded by a polymer that would have assembled more easily than RNA (i.e., pre-RNA), being comprised of a different backbone and different nucleobases. In support of this hypothesis, recent advances in our laboratory have revealed that alternative, plausibly prebiotic nucleobases can self-assemble in water and readily form nucleosides with ribose, two properties not observed with the nucleobases currently found in RNA. Mechanisms by which such assemblies could have facilitated the formation of RNA polymers, as well as their replication, will also be discussed.

Open-Ended Evolution Revisited

Chrisantha Fernando (Google DeepMind)

Why have we been failing to produce open-ended evolution since Tom Ray failed with Tierra and Chris Adami failed with Avida? Why is Koza's genetic programming and Miller's cartesian genetic programming limited to evolving relatively simple programs? Why can Stephanie Forrest's bug fixing program that works on C parse trees only fix bugs and not write programs itself? How does this relate to problems in the origin of life and the evolution of evolvability? I classify a tree of solutions that all my Facebook friends came up with and talk a bit about my own approach to evolving programs in the framework of Darwinian Neurodynamics.

Towards a Universal Biology

Mary A. Voytek (NASA)

How did life begin on earth and is there a universal biology that would predict that life arose elsewhere? These are inspiring and far-reaching questions that started as philosophical queries as early as 500 BC and moved into the scientific realm during the 19th century.

Once scientists began to appreciate the genetics and physiological complexity of life, the easiest way to explain where life came from was to assert that life didn't simply emerge, but that it was eternal and had always been an inherent part of the universe, with sperms of life wandering the universe and taking root in any planet with the appropriate conditions. While there may be movement of life between celestial bodies, it is clear that life, like our universe, begins with a process of steps that often blurs the line between life and not-life. Several proposed scenarios explore the planetary environmental conditions or early mechanisms that lead to the emergence of life.

All of these theories arise from the intimate links between Earth's biological and physical histories, connections which will lead us to a Universal Biology. Freeman Dyson, professor emeritus of physics at Princeton University reminds us that "the solution of a mystery [as profound as the origins of life] … is totally unpredictable. It might happen next week or it might take a thousand years." Regardless of the timing, current scientific thinking indicates the solution will almost certainly be a universal theory. This talk highlights the inspiring and far-sighted NASA roadmap. It starts with the development of general principles, grounded in raw materials and chemical evolution – on planets and in space. Based on that framework, it covers lines of inquiry focusing on protobiological properties of molecules and systems, including emergent behavior, information transfer and issues of scale and complexity.

Toward a bioinformatic theory of living systems

Palien Hogeweg (Utrecht Univ.)

Living systems as we know them today are complex evolved multilevel information processing systems harbouring at least 2 billion years of molecular memory (information) in their genome, which is maintained by self-reproduction. This information is processed into a phenotype which may involve an up-scaling of a minimum change at the genome level (one nucleotide substitution) 10 orders of magnitude and yet is robust against noise.

In our view it is these bioinformatic properties which are universal of 'living systems' and go beyond their physical/chemical implementation.

To understand how such systems emerged from 'humble beginnings' is the aim of a bioinformatic theory of the origin and complexification of life [1].

The RNA world hypothesis is the most commonly evoked as "humble beginning" ("It is the worst theory of the early evolution of life (except for all the others)" [2]).

RNA-like molecules are capable of information storage (the polymer sequence), as well as information processing (by being a catalyst) in one single molecule.

Here we will review some features of the evolutionary dynamics of RNA-like worlds which lead to the emergence of new levels of selection and the progressive decoupling of information storage and information processing.

[1] Evolutionary dynamics of RNA-like replicator systems: A bioinformatic approach to the origin of life. <http://www.ncbi.nlm.nih.gov/pubmed/22727399>*Takeuchi* N, *Hogeweg* P.Phys Life Rev. 2012 Sep;9(3):219-63. doi: 10.1016

[2] The RNA world hypothesis: the *worst* *theory* of the *early* *evolution* of life (except for all the others)(a). <http://www.ncbi.nlm.nih.gov/pubmed/22793875> Bernhardt HS. Biol Direct. 2012 Jul 13;7:23. doi: 10.1186/1745-6150-7-23.

Detecting the signatures of heredity in generative chemistries

Nicholas Guttenberg (ELSI)

In studying the Origins of Life, we must consider 'what came before?' - before cells, ribosomes, and other highly controlled elements of living systems, proto-biological systems may be hard to recognize from a biological viewpoint. Instead, chemistry is often used to bridge the gap - for example, we consider autocatalysis as a precursor to replication. However, replication is only part of the picture. An important ingredient for the onset of evolution is that variations are heritable. Yet, it is unclear how one would detect that in a complex chemical system.

We have been developing ways to look for signs of heritability in the response of arbitrary dynamical systems to perturbative 'selection' pressures. Taking individual replicators and expanding them into a population tends to cause a single dominant species to emerge for a given selection pressure. We hypothesize that the the distribution of such species provides information about what information can and cannot be preserved by the replicative dynamics at the individual level, and extend this idea to an algorithm which may be able to detect this kind of information capacity in simulated and experimental systems.

A study of a boids model at large scale

Takashi Ikegami (Tokyo Univ.)

A boids model originally proposed by C. Reynolds in 1986, shows a various swarm behavior. Its individual motion is controlled by three simple rules; separation, attraction and alignment with other boids. Its dynamic coordinated structure has been well studied in the orders of hundreds of boids. But what happens if we further increase the number of boids? In this talk, by using the GP-GPU and simulating the number of boids up to one million, we will report the emerging behavior at a large scale swarms.

Engineering the Transition to Evolvable Chemistry: Inorganic Biology

Leroy (Lee) Cronin (Univ. of Glasgow)

The development of inorganic systems capable of evolution as a fundamentally less complex ‘emergent’ model of prebiotic evolution is proposed as a solution to the information catastrophe that sets unreasonable limits of complexity on the spontaneous emergence of life. Further, by developing a new paradigm for evolution outside of biology, we propose a roadmap to engineer, discover or emerge the minimal evolvable inorganic chemical entities that could eventually make the transition from dead to living matter. This new experimental approach not only requires developments in theory, but automation of experiments, robotics, and algorithmic programming. Thus this area defines an intrinsically multidisciplinary field requiring contributions from chemistry / chemical engineering, molecular biology / genetics, robotics and computing science. Success could mean new hints to the origin of life on earth and elsewhere, a new set of criteria that define molecules that originate from universal biological processes, as well as the possibility of developing new types of artificial life based upon chemistries not today found in biology.

References:

Cronin L (2013) Linking Evolution in Silico, Hardware, and Chemistry to discover or engineer Inorganic Biology. Advances in Artificial Life ECAL 12:1066-1067

Cronin L et al (2012) A flow-system array for the discovery and scale up of inorganic clusters. Nature Chemistry, 4: 1037-1043

Coupled Phase Cycles: A Testable Origin of Life Scenario for Fluctuating Inland Volcanic Hydrothermal Fields

Bruce Damer (UC Santa Cruz)

Hydrothermal fields on the prebiotic Earth are candidate environments for biogenesis. We propose a model in which molecular systems exposed to cycles of hydration and dehydration undergo polymerization in a dehydrated surface phase followed by encapsulation in a hydrated bulk phase. Underpinning that model is a set of defined factors, both pre-existing and emergent, that we propose are required for origin of life models and simulations to have sufficient complexity. To determine whether such simulations have the capacity to generate increasing complexity related to the origin of life, we are designing and testing hybrid chemical/computational instruments that incorporate combinations of the defined factors. A successful simulation will not only generate a set of self-assembled protocells containing polymer mixtures, but will also be able to undergo combinatorial selection and thereby evolve.

Some Perspectives on the Origin of Life from Organic Chemical Space

Jim Cleaves (ELSI/IAS)

Life as we know it uses ~ 500 common small molecules (of MW ≤ 1000 AMU) to make every organism, from bacteria to bees. Beyond these ~500, life makes an incredible array of secondary metabolites, now counted at well over 100,000. This number approaches the number of novel organic compounds mankind has now made artificially. However, these numbers of compounds are all dwarfed by the truly super-astronomical number of possible organic molecules of 1000 AMU or less, estimated by some to be a numerous as 10^{60}. Thus biologically-explored chemical space represents an *infinitesimal* subspace of the possible chemical space. Using graph-theory based computational methods, we have now enumerated the plausible (e.g. stable) sub-spaces of two important biological compound classes, a-amino acids and nucleic acid-like compounds. The a-amino acid space up to the formula of tryptophan and the nucleic acid-like chemistry space up to molecules containing seven C-atoms were exhaustively enumerated. Any given compound used in biology has likely been selected by a number of criteria over the course of evolution, some of which can be evaluated *in silico*. By several physico-chemical metrics, the biologically used compounds appear surprisingly optimal, even with respect to the enormousy large numbers of molecules which have never come into existence. The rationale, methods, findings and practical uses of our recent studies in this realm will be discussed.

Day 3 (Thursday, January 15, 2015) - Signs of Life on Other Planets

The ExoMars Programme: searching for traces of life on Mars

R.P. de Groot[1], J. L. Vago[1], O Witasse[1], D. Rodionov[2], and the ExoMars Team

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Based on what we knew about planetary evolution in the 1970's, people took more or less for granted the presence of simple life forms on other planets. The 1976 Viking landers can be considered the first missions with a serious chance of discovering signs of life on Mars. That the landers did not provide conclusive evidence was not due to a lack of careful preparation. In fact, these missions were remarkable in many ways, particularly taking into account the technologies available at the time. If anything, the Viking results were a consequence of the manner in which the life questions were posed. The failure to detect organic molecules on Mars had an effect on all subsequent landed Mars missions, which thereafter focused mainly on geology.

In the mid 90's a group of European investigators worked to define what they thought would be necessary to tackle the life-on-Mars issue once again. Their recommendations gave rise to what would become the ExoMars Programme. Today ExoMars is an international collaboration between ESA and the Russian Space Agency Roscosmos - with important NASA contributions - to develop and launch two missions (2016 and 2018).

The 2016 ExoMars mission includes two elements: 1) the Trace Gas Orbiter (TGO) to study atmospheric trace gases and subsurface water with the goal to acquire information on possible on-going biological or hydrothermal rock alteration processes; and 2) the European Entry, Descent, and landing Demonstrator Module (EDM) to achieve a successful soft landing on Mars and demonstrate technologies for the 2018 mission landing. The TGO will also provide data communication services for surface missions, nominally, until end 2022. The mission will be launched in January 2016 using a Proton rocket and arrive to Mars in October 2016.

The 2018 ExoMars mission will deliver a 310-kg rover and an instrumented landed platform to the martian surface. The mission will pursue one of the outstanding questions of our time by attempting to establish whether life ever existed on Mars.

The rover will explore the landing site's geological environment and conduct a search for signs of past and present life. A drill will allow the rover to collect and analyse samples from outcrops and at depth. The subsurface sampling capability will provide the best chance to access and analyse well-preserved sedimentary deposits, possibly containing molecular biosignatures.

The rover's Pasteur payload includes: panoramic instruments (wide-angle and high-resolution cameras, an infrared spectrometer, a ground-penetrating radar, and a neutron detector); a subsurface drill capable of reaching a depth of 2 m to acquire specimens; contact instruments for studying rocks and collected samples (a close-up imager and an infrared spectrometer in the drill head); a Sample Preparation and Distribution System (SPDS); and the analytical laboratory, the latter including a visual and infrared imaging spectrometer, a Raman spectrometer, and a Laser-Desorption, Thermal-Volatilisation, Derivatisation, Gas Chromatograph Mass Spectrometer (LD + Der-TV GCMS). The very powerful combination of mobility with the ability to access subsurface locations where organic molecules may be well preserved is unique to this mission.

After the Rover will have egressed, the Platform will carry out scientific environmental measurements at the landing site. The mission is scheduled to launch in May 2018 on a Proton rocket, and arrive to Mars in January 2019.

Even in case of promising biosignature discoveries, confirmation of the results would require a more thorough analysis than can be performed by remote robotic means. For this reason, the long-term goal of ESA's Mars Exploration Programme remains an international Mars Sample Return (MSR) campaign, sometime towards the end of the next decade. ESA is also considering a Phobos Sample Return mission as a step towards MSR. The ExoMars programme constitutes a fundamental milestone for MSR, as it will make an important contribution toward determining what types of samples to return.

The Aqueous Environments of Early Mars: Where are the Biosignatures and Where Should We Be Looking?

Bethany L. Ehlmann (Caltech)

The last decade of high resolution orbital imaging spectroscopy of Mars, coupled with in situ exploration by Mars rovers and landers, has revealed nearly a dozen distinct aqueous, potentially habitable environments, ranging from acid to alkaline, reducing to basic, and lacustrine to hydrothermal to weathering, preserved in the rock record of early Mars and identified by diverse secondary mineral assemblages. These environments varied in space and time and do not necessarily imply a continually warm early Mars, but rather a warm and wet subsurface with punctuated periods of more clement conditions that allowed liquid water availability at the cold surface. I will review these new discoveries of the last five years, with particular focus on understanding what types of biosignatures we might find and where we should look to find them. Audience discussion will be encouraged.

Search for life on other worlds of our Solar System

Chris McKay (Ames/NASA)

One of the main goals of astrobiology is the search for another type of life in our solar system. The planet Mars, Europa, one of the moons of Jupiter, and Enceladus one of the moons of Saturn, are the most likely targets for this search. In each case the search begins with a search for liquid water, followed by the detection of organic material. If organics are present, the next challenge will be to determine if they are of biological or non-biological origin. On Mars and Europa we still await the detection of organics. For Enceladus, analysis of the plume by the Cassini mission indicates that the steady plume derives from a subsurface liquid water reservoir that contains organic carbon, biologically available nitrogen, redox energy sources, and inorganic salts. Furthermore, samples from the plume jetting out into space are accessible to a low-cost flyby mission. No other world has such well-studied indications of habitable conditions. Thus, the science goals that would motivate an Enceladus mission are more advanced than for any other Solar System body. The goals of such a mission must go beyond further geophysical characterization, extending to the search for biomolecular evidence of life in the organic-rich plume. This will require improved in situ investigations and a sample return.

Generation and transportation of molecular oxygen to sub-ice ocean of Europa

Takeshi Naganuma (Hiroshima Univ.)

Tectonic movement of ice mantle of the Jovian icy moon *Europa* has been a matter of argument, and the tectonics-associated "subsumption" (compared to subduction) of the ice shell was recently reported[1)]. This may suggest transportation of cometary organic matter piled on the ice surface to plausible interior (sub-ice) ocean, which is regarded as an important organic source to possible sub-glacial life from a materialistic viewpoint. From the energetic viewpoint, supply of oxidizing power should be vital to maintain *Europan* life, as reducing materials such as hydrogen and hydrogen sulfide could be readily supplied from seafloor volcanoes. Diverse sources of oxidizing power, *e.g.*, SO_4, NO_3, CO_2, Fe(III), *etc.* other than molecular oxygen O_2, are known for the Earthly life forms. On the *Europan* ice shell, $MgSO_4$ has been detected[2)], which is more likely produced by radiation (solar UV and charged particles) rather than delivered from internal brine water[3)]. Radiation also generates free O_2 by splitting H_2O, and the *Europan* atmosphere hosts O_2 at the feeble pressure as low as 10^{-11} atm[4)]. More or less O_2 could lie in surface of radiated ice since ice H_2O would act as O_2 source. Despite feebleness of the surface O_2, its presence is vital to test presence of sub-surface life, because O_2 is regarded as the realistically ultimate oxidizer to draw enough energy to sustain abundant and/or highly complex life forms, if any, in *Europan* ocean. In this line of the O_2 context, ice tectonics may serves as O_2 conveyor from ice surface to sub-ice ocean. Possible life-forms would attach or settle on the subsumed ice surface, which may look like "ice ceiling", to chew O_2. If *Europan* ice tectonics resembles Earth's plate tectonics, the older the surface ice is, the more O_2 input would be possible; eventually older surface ice subducts to bring more O_2 inside. In addition, it is likely that radiation by charged particles does "etching" or "doping" (as used in material science/engineering) on the ice; I would term the action as "ploughing". The degree of ploughing would correspond to the time of exposure of ice to radiation. If so, degree of ploughing, *e.g.*, roughness (probably in micro-scale) of the ice surface as well as amount of "doped" particles, should be taken as measurable parameters for *Europan* ice chronology.

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2. McKinnon & Zolensky (2003) Sulfate content of Europa's ocean and shell: evolutionary considerations and some geological and astrobiological implications. *Astrobiology*, **3**, 879-897.

3. Brown & Hand (2013) Salts and radiation products on the surface of Europa. *Astrophysics*, arXiv:1303.0894 [astro-ph.EP].

4. Hall *et al.* (1995) Detection of an oxygen atmosphere on Jupiter's moon Europa. *Nature*, **373**, 677-679.

Future Prospects for Characterizing Earth-size Exoplanets

Wesley A. Traub (JPL/NASA)

We live in an exciting time: we're getting ready to search for signs of life beyond the Earth! We have found 7 terrestrial, habitable-zone exoplanets during the past two years, and soon we will be able to characterize the upper atmospheres of the 6 of these that transit their star, using transit spectra from JWST (to be launched in 2018). However to characterize the full atmosphere of an exoplanet down to its surface, we will need direct imaging and spectroscopy. These capabilities will be possible with the coronagraph on WFIRST/AFTA, now in pre-formulation (for launch around 2024), or Exo-C or Exo-S (both currently in a study phase). Each of these direct-imaging missions is capable of carrying out a preliminary reconnaissance, including detection and low-resolution spectra. The likelihood of finding a good target to observe is governed by three major factors: the frequency of exoplanets, the number of suitable nearby stars, and the capability of our observing mission. To address these points respectively, I will present a new (Kepler-based) estimate of the frequency of exoplanets, an application of this estimate to nearby stars, and a sketch of the capabilities of currently-studied direct imaging missions. Taken together, these factors provide a prediction of the number of terrestrial, habitable-zone planets that could be found by each mission, and an estimate of our potential near-term progress in the search for signs of life in the Universe.

Strengths and Limitations of Reflected-light Observations of the Pale Blue Dot

Tyler Robinson (Ames/NASA)

Near-future dedicated exoplanet characterization missions, such as the Exo-C and Exo-S concepts currently under study, will observe their targets in reflected light. As was initially shown by Sagan et al. (1993) with Galileo Earth flyby data, the ultraviolet (UV), visible, and near-infrared (NIR) wavelength regions contain many spectral signatures that can be used to characterize for habitability and life. Of particular relevance to studying Earth-like exoplanets are the UV Hartley and Huggins ozone bands, the atmospheric molecular Rayleigh scattering slope at blue wavelengths, the broad visible-wavelength ozone Chappuis band, the molecular oxygen A-band at 760 nm, the water vapor NIR bands, and the crescent phase glint signature that spans the visible and NIR. However, the utility of these features, in practice, can be severely limited by instrument wavelength coverage, spectral resolution, and the observational signal-to-noise ratio. Here, I will discuss the utilities, strengths, and weaknesses of spectroscopic and photometric reflected-light observations of the Pale Blue Dot, with an emphasis on key observables for detecting surface liquid water and life.

Oxygen as a biosignature, the importance of the geological context

Antígona Segura (UNAM)

Since Lovelock (1965) proposed oxygen (O_2) and methane (CH_4) as good atmospheric signatures of life in other planets, many studies have been focused on understanding which biosignatures are more likely to be detected and possible false positives. The latest debate is focused on molecular oxygen (O_2) after several simulations showed that this compound may be formed by abiotically in amounts that may be detected by future missions dedicated to characterize atmospheres of potentially habitable exoplanets. While some authors found that abiotically formed oxygen may be a detectable false positive others concluded that it can only be detectable in limited circumstances.

On this talk I will review the concept of biosignatures and the research around the couple O_2-CH_4 and abiotic formation of O_2. I will present suggested guidelines for ongoing and future research that may be able to settle the debate about O_2 as a biosignature.

Color variation of planets

Yuka Fujii (ELSI)

Life as we know it is coupled to the ambient planetary environment. It has been argued that the heterogeneous surface of the Earth and the continuous geological evolution of atmosphere-ocean-solid Earth system have played an essential role in the emergence and evolution of life.

Here we will discuss the possible diversity of surface environments of rocky exoplanets along with diagnostic features in planetary colors (low-resolution spectra) and their variabilities, based on the reassessment of Solar system solid planets/moons.