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The Origin, History, and Distribution of Water and its Relation to Life in the Universe

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1 Executive Summary

Intellectual Focus & Proposed Research –

Water is the medium in which the chemistry of all life on Earth takes place. Water is the habitat in which life first emerged and in which all of it still thrives. Water has modified Earth's geology and climate to a degree that has allowed life to persist to the present epoch. We propose to create a research and education framework that links the biological, chemical, geological, and astronomical sciences to better understand the origin, history, distribution, and role of water as it relates to life in the universe. We focus on scenarios involving the sources and distribution of water in planetary systems and the delivery and incorporation of water into rocky planets that orbit within the "habitable zones" of their parent stars. Our framework will include and connect research on major aspects of planetary water – in effect we aim to understand the terms of a "watery Drake equation":

- Observations and modeling of the abundance and distribution of water in the interstellar medium, molecular clouds, and circumstellar disks;
- Surveys and studies of the numbers, water content, D/H ratio and dynamics of icy outer solar system bodies such as comets, Centaurs and Kuiper Belt objects;
- Laboratory experiments on complex molecule trapping and formation on interstellar water-rich grain mantles and planetary ices;
- Cosmochemical studies of meteorites that record the incorporation of water into silicate material in the primordial Solar System as an early step in its eventual inclusion in larger bodies, including planets;
- Models of the escape of water (as hydrogen) from the atmospheres of Earth-sized planets;
- Spacecraft- and meteorite-based research and theoretical studies on the role of water in forming the diversity of rocks and sediments on Earth, Mars, and Venus.
- Biological exploration of ice-covered habitats in Iceland, Antarctica, and North America with potential application to the search for life on Mars and Europa.
- Biological and chemical exploration of extreme aquatic habitats in and around the Hawaiian islands including the deep-sea, Kauhako Lake crater on Molokai and Lake Waiau near the summit of Mauna Kea.
- Development of concepts and prototype hardware for instruments that could be used to detect and characterize life on other planetary bodies.

Distinguishing Features –

By developing and testing models and exploring the outcomes of alternative scenarios we seek to determine what controls the abundance and distribution of water and hypothetical aqueous habitats in other planetary systems. This research will directly support the NASA search for past or present life on Mars and efforts (such as the NASA Terrestrial Planet Finder) to directly detect and characterize Earth-sized exoplanets. The proposed framework of our research will support a group of postdoctoral scholars who will carry out independent, interdisciplinary research spanning two or more of the investigators' (or affiliated investigators') research specialties. The island setting and the unique facilities of the University of Hawaii offer an environment conducive to these investigations. The University of Hawaii houses world-class research groups active in astronomy, and in the chemical, geological and biological sciences. It is home to a substantial array of scientific facilities, including the telescopes of Mauna Kea Observatory, a fleet of research vessels for oceanographic and deep-sea investigations and facilities for exploration of the extreme environments found on the volcanoes and in the lakes and oceans around Hawaii. Through this Astrobiology proposal we aim to combine and capitalize on these many areas of research excellence to craft a new, interdisciplinary study of water and its relation to life.

Management Approach –

The UH-NAI PI will meet once a week with the Co-Investigators to discuss research progress, discuss any technical, financial or management issues, and to involve everyone in the E/PO activites. The timelines and status of the projects will be reviewed and updated at these meetings. In addition the UH-NAI will offer an astrobiology seminar series which will involve the entire local community. Additionally the development of our collaborative visualization tool will help foster interdisciplinary communications and highlight areas of new development which can be discussed at these regular meetings.

Education/Public Outreach Activities –

Our group has a strong record in education and public outreach, and we intend to build on that experience by providing innovative laboratory-based learning opportunities for teachers and engaging the public in our research. We intend to develop a program that trains teachers in the science of astrobiology, how to incorporate astrobiology into their classes, and in how to use the activities we will develop as part of the program. The focal point of our teacher-training program will be a summer professional development program. Using the summer workshop and research experience as a base, we will also develop a course for pre-service teachers. All projects will involve development of standards-based classroom activities. We also intend to actively engage the public in our discoveries.

Institutional Commitments –

The University of Hawaii and the Institute for Astronomy are strongly committed to the success of this project, and have commited a total of $4.5 million in faculty positions, in-kind salary support and cash contributions to the project.

Collaborative Networking Concepts –

We will design, implement and evaluate a software visualization tool to interface with the NAI ScienceOrganizer knowledge management tool.

2 Research and Management Plan

2.1 Water and Life in the Universe

"If there is magic on this planet, it is contained in water." – Loren Eiseley, *The Immense Journey*

We humans, and all life on Earth, are aqueous beings. Our cells are mostly water that has been exquisitely packaged in lipid membranes. They are cytoplasmic solutions of solvable molecules whose aqueous chemistry is responsible for cellular maintenance, growth, and reproduction. Water's chemical and thermodynamic properties make it an ideal medium for biological activity, so much so that it is considered essential for recognizable life. It has been called the "ultimate solvent" because of its ability to form multiple hydrogen bonds with solutes and its strongly polar character. It is also capable of serving as both an acid and a base. Strong hydrogen bonding between water molecules stabilizes the liquid phase over a wider range of temperatures compared to other cosmically abundant molecules, and it endows water with a high latent heat of vaporization. Unlike many compounds, water expands upon freezing and its ice floats, a property that is crucial for the persistence of aquatic habitats under freezing surface conditions. In addition to its direct role in biology, water is also a predominant determinant in the geology, geochemistry, and climate of our planet. It influenced the structure and early evolution of the Solar System itself, aspects of which dictate the habitability of Earth. Water and life are connected at many scales, from the interstellar medium to microbial habitats, and through many processes; astrophysical, geological, geochemical, and biological. We propose an Astrobiology research consortium that seeks to better understand these connections and their implications for the distribution, nature, and signature of life throughout the universe.

Water has been involved in life since its first appearance on the early Earth. The leading theories of the origin of life invoke prebiotic chemistry in low-temperature aqueous solutions, *e.g.*, a "warm little pond"[42] supplied with prebiotic molecules by atmospheric chemistry[143], or in the hydrothermal brines produced by high-temperature water-rock interactions[35]. The first three billion years of the drama of life on this planet was played out entirely in aquatic environments. The world's oceans and freshwater bodies remain the home for a large fraction of species at the present era and life has invaded and adapted to nearly every environment on the Earth's surface where there is some liquid water, almost regardless of temperature, pH, or chemistry.

Water is also involved in geochemical reactions that maintain surface conditions permissive of life. For example, aqueous weathering of silicate minerals in the presence of a CO_2-containing atmosphere produces alkalinity, which in turn allows CO_2 in the ocean-atmosphere system to precipitate as carbonate minerals and eventually become sequestered as carbonate rocks. Without these reactions, the buildup of volcanic CO_2 in the atmosphere would lead to intense greenhouse conditions similar to those on Venus. Instead, temperature-sensitive weathering and the concomitant deposition of carbonates constitute a negative feedback that may have regulated atmospheric CO_2 levels to compensate for the Sun's luminosity evolution over 4.5 billion years[214]. Water vapor itself is the most active greenhouse gas in the present-day atmosphere, amplifying the effects of other, incondensible gases by a factor of 2-3. Water also modifies the amount of solar radiation reflected by the Earth back to space, either as relatively absorbent oceans, as reflective ice, or as scattering clouds. These warm or cool the Earth and can create positive or negative albedo-temperature feedbacks. "Snowball Earth" epochs of runaway glaciation thought to have been driven by such a feedback may have provoked major crises in the history of life[85, 111].

Finally, the presence of volatiles such as water significantly alters the rheology and thermodynamics of silicate minerals in Earth's crust and mantle. The presence of water in the mantle has a profound effect on its internal convective motions and the melting behavior. The formation of magmas involved in volcanism at hot spots and island arcs is thought to be driven by, or at least influenced by, the ability of fluxing water to depress the solidus of silicate rocks. Water may be responsible for a low viscosity zone beneath the brittle lithosphere[104] and may weaken faults, giving lithospheric plates increased flexure[168]. These last two may be critical to the operation of plate tectonics. Plate tectonics is responsible for much of the geologic activity on Earth's surface, including mid-ocean ridge and island arc volcanism at the margins of oceanic plates, uplift of mountain ranges by tectonic forces at converging continental plates, and deepening of basins where continental plates diverge. These geologic processes in turn drive many of the biogeochemical cycles important to Earth's habitability, particularly the weathering of uplifted silicate and carbonate rocks, the revolatilization and release of CO_2 from carbonates at subduction zones, and the burial of organic carbon in sediments and concomitant release of molecular oxygen.

Water is abundant on present-day Earth. Three-quarters of its surface is covered by oceans and models suggest that crustal and mantle rocks contain an even greater amount of water[200]. What was the origin of this water and how did it become incorporated in the Earth? The deuterium to hydrogen ratio (D/H) of seawater (1.56×10^{-4}) (and a similar value for mantle water) offers a constraint on the origin and subsequent history of Earth's water[119]. The total inventory and distribution of water on Earth was probably determined early in the planet's history and may have consisted primarily of water dissolved into a magma ocean in equilibrium with a dense steam atmosphere[174]. The D/H of seawater is similar to that found in certain primitive water-rich chondritic meteorites. This suggests that Earth's water was evolved from dehydration of hydrous minerals during the accretion of chondrite-like planetesimals (not necessarily represented by any of the extant classes of meteorites). Thus it is possible that Earth's water was evolved from dehydration of hydrous minerals during or after the accretion of chondrite-like planetesimals (not necessarily represented by any extant classes). The seawater D/H ratio is significantly lower than ratios measured in three long-period comets. While this appears to rule out long-period comets as primary contributors of Earth's water, the D/H ratios of other cometary types have not been measured. In particular, the short-period comets formed further from the sun and at lower temperatures than the long-period comets. Their nebular processing and resultant D/H ratios may have been significantly different from those of their long-period cometary counterparts. In addition, as we discuss later, the terrestrial planet abundances of the noble gases such as Ar, Kr and Xe are not easily explained by delivery from the asteroid belt, but more compatible with a cryogenic, presumably cometary source. For these reasons, it is too early to rule out a cometary source for Earth's water and other volatiles.

Water in precursor planetesimals could have derived either from hydration of silicate grains by water molecules in the primordial solar nebula, or at greater distances from the proto-Sun, by aqueous alteration of larger bodies composed of a rock/ice mixture[77] and their dynamical transport to accretion zone of the proto-Earth. Nebular water in turn traces its ancestry to the chemistry of the interstellar medium at temperatures of 10-20 K. The enrichment of Solar System water in deuterium with respect to the protosolar nebula (D/H = 2.5×10^{-6}), was the result of isotopic fractionation in the protosolar nebula, perhaps involving irradiation and ion-molecule reactions[186]. Irradiation of gas-phase or solid-phase water could also process organic material, enriching it in deuterium, in the interstellar medium and proto-solar nebula. This processing may take the form of gas-phase reactions in the solar nebula, irradiation of icy grains, and aqueous alteration in the parent bodies of meteorites. Important prebiotic molecules such as amino acids and sugars could have been produced in these environments. This material would have been later brought to the Earth in comet-like bodies.

Earth has hosted surface waters throughout most of its history. The rock record preserves water-lain sediments at least as old as 3.5 billion years and the oxygen isotopes of zircon crystals support the existence of a hydrosphere as early as 4.4 billion years ago[223]. How has the total inventory of terrestrial water changed with time and how has it exchanged between reservoirs at the surface and in the interior? The current escape rate of water (as hydrogen) to space would have a negligible impact on the total inventory, even over 4.5 billion years, and is small compared to the fluxes between the surface and interior[119]. However, higher rates of escape may have accompanied an anoxic atmosphere and higher ultraviolet radiation from a younger Sun. The elemental and isotopic abundances of rare gases seem to require that a significant amount of hydrogen (perhaps some from water) was lost in a non-fractionating hydrodynamic wind[174]. Additional water (as hydrogen) could have been sequestered into Earth's core[169]. Because of volcanism, weathering, and the subduction of lithospheric plates, water is continually exchanging between the surface and mantle. A secular decrease of surface water (and uptake by the mantle) with time has been suggested, although this conclusion is highly model-dependent[18].

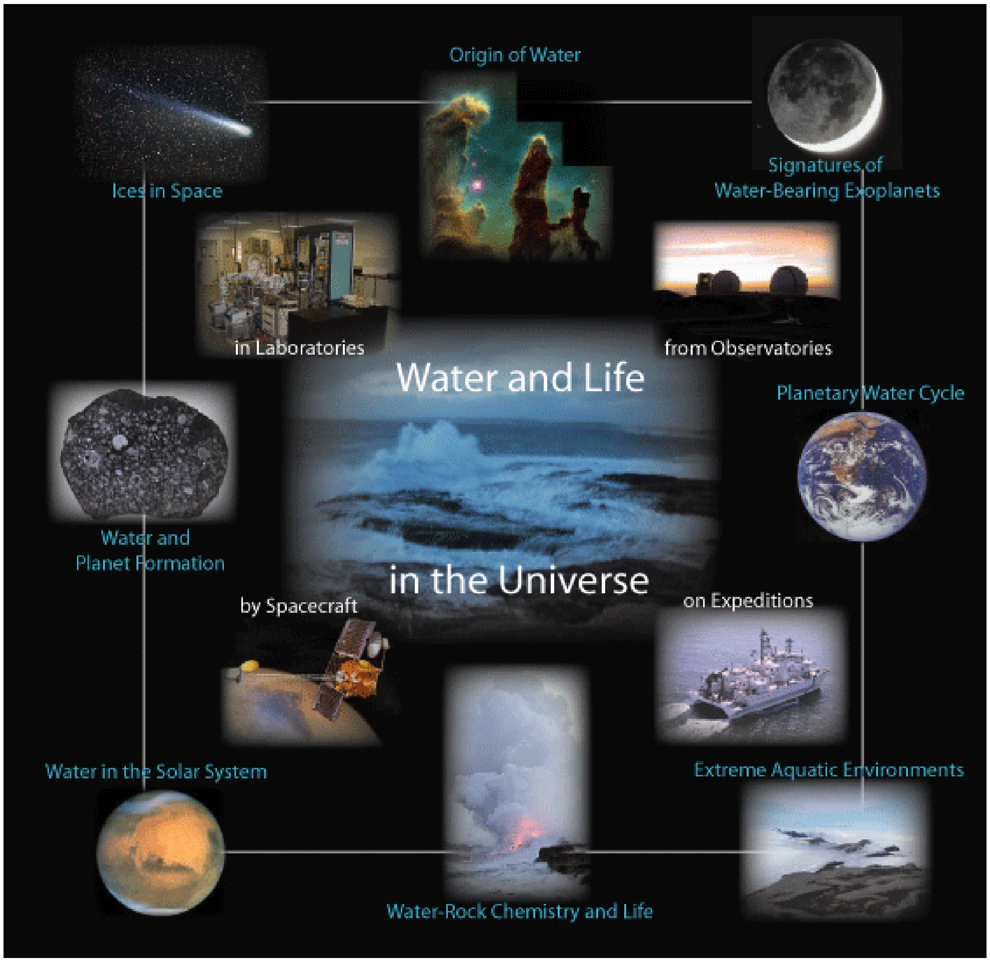
Like liquid water, life has a lengthy history on this planet. It is possible that for nearly as long as aquatic environments have been stable at the surface, life has been present to inhabitat them. Carbon isotopic fractionation in apatite grains from the 3.85 billion-year old Isua supracrustal belt (Greenland) has been interpreted as the product of biological carbon fixation, and microforms from Australian cherts have been described as the oldest microfossils[194]. Both of these interpretations have been challenged in the light of new geologic data[122, 19], and the exact temporal relationship between water and life on the early Earth remains unresolved. Though these early origins remain obscure, it is clear that life has subsequently expanded into, and adapted to, the entire range of aquatic habitats on the Earth, from anoxic seas to the extremely nutrient-poor open ocean, from seafloor hot springs to low-temperature brines in sea-ice, from highly alkaline lakes (pH $\sim$ 10) to the extremely acidic (pH $\sim$ 0) streams draining metal ore bodies. How has water physically and chemically interacted with the silicate component of the Earth over 4.5 billion years to create a physically and chemically diverse habitats for life? How has life evolved to adapt to those environments?

Humanity is extending its search for life beyond the Earth to other bodies in the Solar System, and that quest has been largely framed in terms of a search for water, especially water in its liquid state. Although the surface of present-day Mars is extremely cold and dry, a series of orbiting spacecraft have returned images containing geomorphic evidence for the presence of ground ice, and high concentrations of ice have now been detected in the uppermost meters of martian soil[57]. Spacecraft imagery has also revealed giant outflow channels and valley networks incised in ancient terrain, evidence that this water once flowed as a liquid[57]. Whether these landforms indicate that Mars once possessed a temperate climate, oceans and an Earth-like hydrological cycle is actively debated[33, 195, 71], yet it is clear that aqueous habitats existed, perhaps only transiently, near or at the surface of the planet. The more recent identification of small "gullies" on the walls of some craters and canyons[126], perhaps carved by expelled groundwater[69] or melting ice[36] has prompted speculation that suitable habitats for microbial life may persist to the present day. The search for water is an integral piece of the NASA program of Mars exploration: current and future missions will use high-resolution and multi-spectral imaging to identify sites of past or present aqueous activity from orbit to be investigated by robotic landers and rovers.

The icy Galilean satellites of Jupiter, especially Europa, exhibit features indicative of active geologic resurfacing that may be related to the presence of interior liquid water maintained by tidal frictional heating in addition to heat released by the radioactive decay of long-lived isotopes[170]. The *Galileo* spacecraft's detection of an induced magnetic field around both Europa and Callisto can be explained by global interior oceans or layers of partially molten ice[226]. It is widely speculated that interior oceans could support life, assuming a suitable chemical source of energy replaces sunlight[184, 66, 130, 31]. The tidal-driven tectonics of the icy crust of Europa may allow liquid water to penetrate close to the surface[67]. Missions to orbit Europa, precisely measure the tidal flexure of its ice crust and probe its interior with radar have been considered. Longer-term concepts include plans to land on its surface and penetrate the crust to explore any ocean.

The scope of the search for life will expand dramatically as space observatories are developed to detect and characterize Earth-size planets around other stars[121, 11]. Current ground-based methods such as Doppler velocimetry are capable of detecting only giant gas planets[40]. Future, space-based searches will be based on the direct detection of a planet's reflected or emitted light. This will also allow their surfaces and/or atmospheres to be characterized both spectroscopically and photometrically (changes in full-disk light as the planet revolves around the parent star and rotates on its axis). Planets within the "habitable zone" of their parent star (the range of orbital semimajor axes where surface temperatures permit liquid water) will be of particular interest. Searches for potential atmospheric biosignatures (*e.g.*, methane or molecular oxygen)[47] will be accompanied by observations to determine the physiochemical conditions on the planet's surface and especially the thermodynamic state of water. The latter can be elucidated by searching for the spectral signature of atmospheric water vapor and the photometric variability produced by the planet's rotation and albedo differences between water, land masses, water vapor clouds, and ice. Further into the future, giant space observatories may perform a census of thousands of nearby stars and image the closest Earth-like planets to determine directly if they have oceans and continents, clouds and polar caps, a hydrological cycle and aquatic habitats like those on Earth.

Cosmically, water is not uniformally abundant, its incorporation into Earth-sized planets not necessarily constant, nor is its planetary manifestation as aquatic habitats suitable for life a given. The search for life in the universe must account for these variations and the uncertainties that accompany them. Water is formed in the interstellar medium and in the denser molecular clouds that give rise to star-forming regions. Differences in elemental abundance, gas-phase chemistry, and grain chemistry will result in measurable variation in the abundance of water in those regions. Water is a significant source of infrared opacity in collapsing cloud cores and protostellar disks; the efficiency at which the collapsing gas cools may control the stability against gravitational fragmentation and the formation of binary or multiple systems (including brown dwarf companions). The abundance of water in protoplanetary disks is a sensitive function of the oxidation state of the nebula and, to first order, the elemental ratio of carbon to oxygen: the C/O ratio has been observed to vary significantly from star to star, implying that there may be very "wet" as well as "dry" planetary systems[67]. Furthermore, the cosmochemical record in meteorites shows that a large range in oxidation states and water abundance existed in the early Solar System, perhaps as a result of removal of water from the warm interior of the primordial nebula and its condensation at greater distances[41]. Presumably, planets formed from different mixing ratios of this primitive material would be endowed with different initial inventories of water. The total planetary inventory of water may also depend on the presence of giant planets and the efficiency of its dynamical transport as icy bodies from the outer regions of a planetary system[150].



The efficiency of incorporation of water into planets will also depend on the accretion history and subsequent escape of water back into space via hydrodynamic flow powered by the extreme ultraviolet radiation of the young parent star. Stars of different mass, metallicity (heavy-element abundance) and initial rotation rates will emit different levels of EUV radiation. The convection of planetary silicate mantles as they reject the heat from long-lived radioisotopes and the gravitational energy of formation will manifest itself as geologic activity and will drive the exchange of water between the surface and the mantle of these planets. Depending on the size and composition of a planet, that exchange will result in different partitioning of water between the surface and interior with obvious consequences for habitability. Further, the thermodynamic state of water on the surface (*i.e.*, liquid, vapor or ice) will depend on surface temperatures and atmospheric pressures which are determined in large part by the geochemical cycling of volatiles such as carbon driven by geologic activity and, ultimately, mantle convection. The tempo and mode of mantle convection appears to be sensitive to the amount of volatiles, particularly water, stored in the mantle itself. Finally, the process of biological adaptation may allow life to colonize and flourish not only in a variety of temperate aquatic environments, but also extreme environments such as low-nutrient oceans, high UV exposure lakes, high temperature deep sea vents, low temperature subglacial lakes without sunlight, and even ice or settings where the only stable phase of water is steam. These adaptations will ultimately constrain the limits, distribution, and history of life relative to that of water in the universe.

We seek to investigate the astrophysical, cosmochemical, geological, and biological processes that link the history and distribution of life in the universe to that of water. This research will have eight interdisplinary foci:

- *The origin of water and the formation of stars and planetary systems*: This research will focus on mapping the distribution of water in the molecular clouds and cloud cores that are the precursors of stars and planetary systems; understanding the role of water as active molecule and potential tracer in the evolution of collapsing cloud cores, protostars, and protoplanetary disks, and measuring and modeling the participation of water in the protoplanetary disk chemistry that is recorded in pristine meteoric and cometary material.

- *Observational and experimental investigation of water ices in space*: Comet ices preserve a chemical record of the interstellar medium and early Solar System that can be explored by spectroscopy and imaging as the ices volatilize near orbital perihelion. Interpretations of these observations, however, requires laboratory measurements that include solid-phase reactions. Water ice serves as the energy-transfer medium and active participant in a variety of radiation-driven organic chemistry reactions thought to be important in either the interstellar medium or the primordial solar nebula.

- *The origin and distribution of planetary water*: The distribution of water in planet-forming disks, its incorporation of water into planet-forming material, and its eventual inclusion in planets such as the Earth is a fundamental cosmochemical problem. The D/H ratio of planetary atmospheres and potential sources such as meteorites and comets is a powerful means of constraining models of early Solar System water and continued measurement of D/H in additional comets and primitive meteorites will aid that effort. The record of aqueous activity in the parent bodies of chondritic meteorites provides information about the abundance and distribution of water in the primordial solar nebula and its subsequent conversion into the hydrous minerals that are a likely source of most of Earth's water.

- *Water and aqueous alteration on Mars*: Mars is the planet most resembling Earth, it contains unambiguous evidence for the activity of past and present water, and is probably the most likely to host or have hosted extant or extinct life. Studies of the history and action of water on this body compared to Earth are thus of great importance in this regard. These include understanding the potential for the hydrothermal and low-temperature alteration of crustal minerals and rocks by water, and the mechanisms whereby liquid water might be generated on, or brought to the surface of the planet at different epochs.

- *Water-rock chemistry and habitats for life*: The reaction between silicate rocks and water, particularly at high temperature, produces aqueous fluids and altered mineral surfaces whose thermodynamic disequilibria are potential energy sources for life. The role of both subaerial and submarine hotsprings influenced by such water-rock reactions has been well established, but the diversity of potential chemistries – and concomitant biological communities – has only begun to be explored. These include subseafloor hydrothermal systems in the oceanic crust near mid-ocean ridges, low-temperature systems further from the ridge axis, cool springs generated by interaction of water with ultramafic rocks at subduction zones, and the interaction of lava and seawater at the surface of the earth.

- *Extreme aquatic habitats on Earth and their analogy to potential habitats elsewhere in the Solar System*: Evidence for water near the surfaces of Mars and Europa suggests there are potential aquatic habitats for life waiting to be explored. Yet these habitats may be very different from those typically found on Earth in terms of lack of sunlight, nutrient levels, high UV levels, or even the state of water itself. Approximate terrestrial analogs to such habitats do exist and will be explored to determine if and how communities of organisms have adapted to those conditions, and to evaluate strategies for the detection of life in those environments.

- *An integrated model of planetary water and its early history on Earth-like planets*: The processes of impacts, atmospheric escape, volcanic outgassing, weathering, and burial or subduction of hydrous minerals result in changes in the total inventory of planetary water as well as the exchange of water between surface and interior reservoirs. The importance of each process, and its effect on the time-dependent abundance of surface water (and hence the planet's ability to support life) will depend on the initial inventory of water, the astrophysical environment of the planet (*i.e.*, late rate of accretion, ultraviolet radiation from the parent star), its size, and its composition. A model of planetary water can be constrained using known or estimated fluxes and reservoirs of water on the present-day Earth, and can be used to explore the time-evolution of water on the early Earth, as well as Earth-size planets whose space environment or composition differ.

- *Signatures of water-bearing exoplanets*: The search for life – and water – will expand outside the Solar System with the eventual deployment of space observatories capable of detecting and characterizing Earth-size exoplanets and their environments. The escape of water from such bodies in young planetary systems may be directly detectable. In addition to searching for signatures of life on a planet, it will be desirable to measure the abundance, distribution, and state of water on its surface using photometric and spectroscopic data. Earthshine, the light from Earth reflected from the dark side of the Moon, provides a practical means of evaluating our capability to identify and describe similarly water-covered worlds around other stars.

With regards to the theme of Water and Life in the Universe, the University of Hawaii is unique in (1) having personnel whose research encompasses the role of water over the entire range of astrophysics, planetary science, chemistry, geology, and biology; (2) having unequaled access to the telescopes of the world's premier astronomical observing site to carry out water-related observations; and (3) being located near a variety of aquatic habitats, many found nowhere else near a major research university, (*e.g.*, the open ocean, a high-altitude lake, fumaroles, and a shoreline where lava enters the sea). To carry out our research on Water and Life in the Universe, we propose to create an interdisciplinary network of investigators and a core community of postdoctoral fellows. This organization will be based at the University of Hawaii but will have collaborators in several other countries. Each postdoctoral fellow will carry out independent, interdisciplinary research that connects two or more of the areas of expertise of the individual investigators involved in this proposal. The fellow will not be based with any one investigator but will instead be physically located in their own group, which we call the "Water Hole".

2.1.1 Origin of Water and the Formation of Stars and Planetary Systems

Objectives – (1) quantify the presence of water ice in the interstellar clouds, out of which stars form. (2) understand the structure, kinematics, composition, and physical properties of the circumstellar disks out of which planets form, thus defining the general environment in which water will exist. (3) determine the specific role of water ice in these chemical and physical processes.

Connections – §2.1.3
Astrobiology Roadmap Links – Goal 3; Objective 3.1
Researchers – Reipurth, Williams, Ceccarelli

Background – The interstellar medium contains the basic material out of which stars and new planetary systems form. Molecular clouds contain cores of gas and dust, which are cold and dense, and which can collapse, leading to the formation of a protostar and a surrounding rotating disk. By studying star and planet formation as it occurs at present in nearby dark clouds, we open a window on the processes that shaped our own solar system 4.6 billion years ago. The Institute for Astronomy at the University of Hawaii has just inaugurated the Center for Star and Planet Formation in order to develop and strengthen interdisciplinary connections between early solar system studies focusing on comets, Kuiper belt objects, and meteorites, and the analysis of present-day star formation events and newborn stellar objects. One of the prime goals of this effort is to trace the evolution of water from its origins in molecular clouds, its role as a major coolant in the collapse process, its inclusion into and processing within circumstellar disks, to its eventual incorporation into icy solar system bodies such as comets. Ultimately this will lead to planetary water reservoirs such as the oceans on Earth, thus forming the basis for the development of life as we know it.

Interstellar Chemistry and the Origin of Water

In the cold environment of dense interstellar clouds, volatile molecules freeze out onto dust grains and form icy mantles surrounding the silicate and carbonaceous cores. Grain surface chemistry allows for the formation of more complex molecules than is possible in the gas phase. These molecules, including water, are then liberated from the grain surfaces through heating by a young star. Determining the solid state processes in dense clouds is thus essential for an understanding of the chemistry and evolution of water ice. Observationally, there are three closely related approaches to explore the role of water ice in the star formation process.

Mapping the Distribution of Water Ice in Dense Cloud Cores

Water ice exists in the interior of molecular clouds; it is estimated that about 10% of oxygen atoms in molecular clouds are bound up as water ice[4]. For visual extinctions of less than $A_V \sim$ 2 - 5 mag, UV radiation from the interstellar radiation field destroys water molecules. For higher extinctions, the UV field gradually becomes sufficiently attenuated for ice to survive, and a linear relation is found between the optical depth of water ice τ_{ice} and A_V[221, 157]. Such observations can be carried out by observing background stars in the near-IR wavelength range thanks to a strong water ice absorption band at 3.1 μm (Fig. 2.1.1a).

Few studies have been made, since terrestrial water absorption interferes with observations. We will launch a major infrared study extending the early water ice studies between $5 < A_V < 20$ mag (Fig. 2.1.1b) to the much higher extinctions (up to $A_V \sim 100$) in the dense cores out of which solarlike stars are forming. This requires the superior high-altitude dry conditions at Mauna Kea and the availability of 8 - 10 m class telescopes, and the Institute for Astronomy is thus ideally positioned to successfully carry out such a project. Nothing is currently known about water ice absorption at such high column densities, and we will for the first time determine if the linear relation found at low extinctions continues.

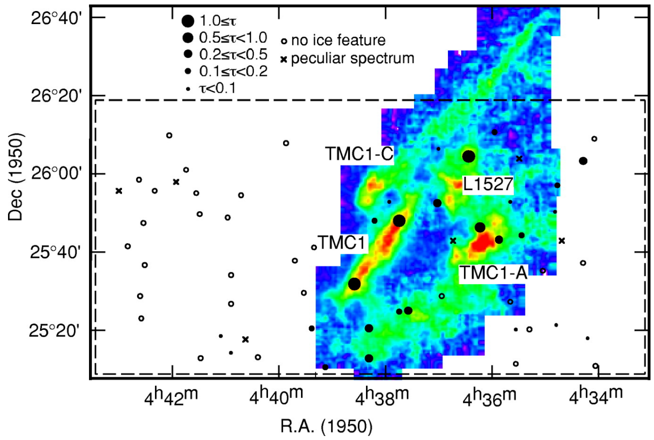


Fig 2.1.1a–Water ice map overlaid on a $C^{18}O$ map of parts of the Taurus molecular clouds[157]. Both filled and open circles show the position of observed field stars and the diameter of filled circles is proportional to the value of τ_{ice}.

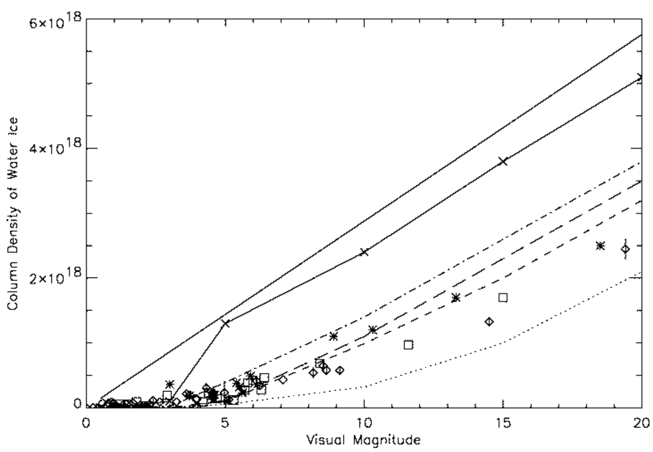


Fig 2.1.1b–Calculated and observed column densitiesof water ice as a function of visual extinction over the range $0 \leq A_V \leq 20$ for Taurus. The models are discussed in[167].

One may expect that the slope changes as the UV field decreases and molecules increasingly condense onto grain surfaces. Physical conditions in the cloud cores can be determined by mapping them with heterodyne detectors and sub-mm continuum arrays at Mauna Kea facilities like the JCMT and the SMA, for direct comparison with the water ice maps. Since the C/O ratio differs between various molecular clouds, we will also explore if the abundance of water ice changes in different star forming regions. If so, the eventual incorporation into planets may not necessarily be constant.

The Physical and Chemical Properties of Circumstellar Disks

It is possible to learn much about water chemistry via observations of related species such as CH_3OH, HCO^+, and their deuterated counterparts, which have observable line emission outside of the broad terrestrial water bands. A rich chemistry has been observed in star forming cores at (sub-)millimeter wavelengths[116]. The next step is to extend the study of chemistry in protostellar envelopes to protoplanetary disks. Dutrey[50] have surveyed a variety of molecules in a nearby disk in Taurus but there are few other observations to date due to the weakness of the line emission. Observations of molecules in disks are technically more challenging than in cores because of the low resolution of single-dish telescopes operating at millimeter wavelengths and the consequent beam dilution. To achieve higher resolution requires operating multiple antennas as an interferometer. Interferometers also have the advantage of automatically filtering out uniform emission from unrelated molecular gas in the cloud. The first such array of telescopes operating at sub-millimeter wavelengths has recently started operations on Mauna Kea. Once it reaches its targeted specifications in late 2003, the Sub-Millimeter Array (SMA) will provide the ability to map molecular line emission in disks and study their chemical state.

Through the UH access to telescopes on Mauna Kea, it is possible to dedicate large quantities of time to survey for sub-millimeter line emission from water related species in nearby protostellar cores and protoplanetary disks and follow their chemical evolution. The single dish Caltech Submillimeter Observatory (CSO) and James Clerk Maxwell Telescope (JCMT) telescopes have a resolution in the range 10-20″ and are well suited to line surveys in protostellar cores. Even in the closest stellar nurseries in Taurus, protostellar disks have radii of only a few arcseconds so line detection is very challenging with these single dish telescopes. The SMA will be a unique resource for imaging at arcsecond resolution in the sub-millimeter regime. By matching the beam and source size more closely, many lines are expected to be detectable and it will become possible to explore the structure, dynamics, and chemistry of protostellar disks. A pioneering study of chemistry in the LkCa 15 disk was made at millimeter wavelengths using the OVRO interferometer[180]. Our proposed observations are at shorter wavelengths than this work and target warmer gas where both line and continuum emission are stronger. In addition to the line observations, the thermal dust emission provides information on the grain mass opacity and thereby the composition of the (icy) mantles.

The combination of the single dish observations of cores and interferometer measurements of disks will show the chemical evolution from the early stages of star formation in cores to the beginning of planet formation in disks. This is a challenging project that will require large amounts of telescope time due to the multitude of species and relative weakness of emission. UH is in a unique position of being able to bring three sub-millimeter telescopes to bear on this problem, including the only one able to image at arcsecond resolution. Therefore, this survey can be expected to make a significant contribution to our knowledge of the initial chemical conditions of star-forming clouds. The SMA will be dedicated in November 2003. It will be linked to the JCMT and CSO in 2005, thereby doubling the sensitivity and resolution. These telescopes are a unique resource both for research and for training. The skills that students and postdocs learn in carrying out this work will prepare them to take full advantage of the Atacama Large Millimeter Array (ALMA). Scheduled for completion in 2011, this 64-element sub-millimeter interferometer will revolutionize the field of astrobiology by imaging the formation of stars in unprecedented detail. It will have, for example, the capability to image the gaps in disks formed by protoplanets and to study chemical gradients at AU scales.

Hot Water Emission and the Chemistry of Circumstellar Disks

Water is found in the form of water ice at temperatures below about 150 K, but it exists as water vapor at temperatures up to the thermal dissociation limit around 2500 K. Whereas the interiors of dark clouds are always below the ice condensation limit, circumstellar disks around newborn sun-like stars are within the temperature range of water vapor between roughly 0.1 and 5 AU. In this region of a disk, water is a strong and efficient molecular coolant (Fig. 2.1.1c). Furthermore, not only is water abundant in circumstellar disks, but it has a large number of radiative transitions sampling a wide range of temperatures. Water is therefore an excellent diagnostic of the properties of circumstellar disks at radii relevant for planet formation[159].

Groundbased observations of water are complicated by the presence of water in the Earth's atmosphere, causing telluric absorption. Observations from dry high-altitude observatories like Mauna Kea greatly reduce this problem. Additionally, because higher excitation states of water have transitions far from the vibrational band centers, it is possible to make groundbased low-resolution spectroscopic observations of water, if it is much hotter than the Earth's atmosphere, when observing in the wings of the telluric water bands at near-infrared wavelengths. Najita *et al.*[159] have demonstrated that it is possible to use high spectral resolution to study individual, resolved near-infrared lines far from the vibrational band centers.

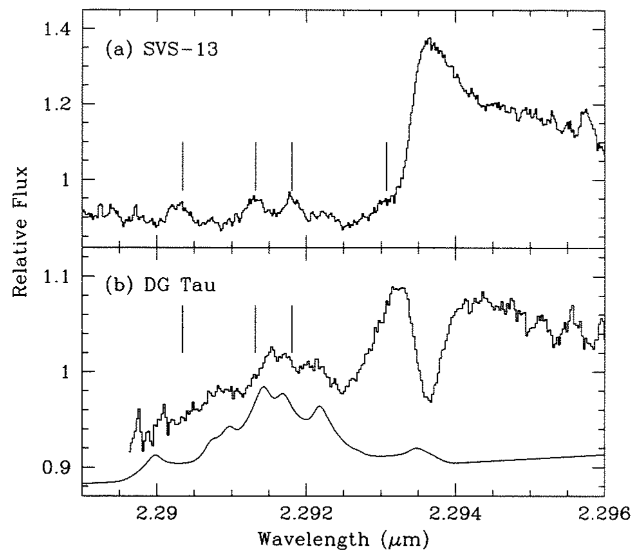


Fig 2.1.1c–Hot water emission (vertical lines) in two young solar-type stars near a CO bandhead[159]. A synthetic spectrum is included for DG Tau.

They find that the water lines are narrower than the CO lines (as expected for a rotating Keplerian disk since water has a lower dissociation temperature than CO) and therefore extend further out into more slowly rotating parts of a disk. Such spectroscopic studies require very high signal-to-noise in order to define the broad weak molecular features, and we envisage to employ the 8-10m telescopes at Mauna Kea for the first detailed and comprehensive study of water vapor emission in the circumstellar disks of newborn sun-like stars.

Water Masers in the Protostellar Environment

Many ortho and para rotational levels of water lie close to each other and thus tend to be easily inverted. Accordingly, if these levels correspond to allowed radiative transitions they can give rise to maser amplification. The strongest water maser emission is that of the $6_{1,6} - 5_{2,3}$ transition which is easily detected from the ground at 22 GHz[25]. The strong 22 GHz maser emission can be explained by the collisional pumping of dense neutral gas which has been heated by shocks.

In recent years a number of surveys have demonstrated that water masers are commonly observed around newborn stars, with detection rates of 40% for the youngest Class 0 sources, 4% for slightly more evolved (50,000 to 100,000 yr older) Class I sources, and 0% for still older, optically visible Class II sources[64, 65]. This dramatic decrease in water maser detection over a relatively short evolutionary time span is likely to be caused by the rapid dissipation of dense gas around the central objects. In most cases the masers appear to align along the axis of outflow from the newborn stars[32], supporting other evidence suggesting that water is efficiently and abundantly produced within warm gas, heated by shocks that are converting gas-phase oxygen into water[164]. The high spatial resolution of the Very Large Array (VLA) interferometer (0.08 arcsec at 1.3 cm in the A configuration, corresponding to 10 AU in the nearest star forming regions) is thus providing insights into the launch of protostellar jets which may be the source of chondrules and CAI's in the early solar nebula[199]. This offers a unique connection between the formation of other young stars and the study of our own origins through meteoritic analysis. In rarer cases, the masers appear to trace the distribution of gas in circumstellar disks, see Fig. 2.1.1d[211, 98, 171].

Recently, proper motions of water masers have been determined by studies with Very Long Baseline Interferometry. Such observations represent an improvement of two orders of magnitude with respect to the best angular resolution achieved with the VLA in its A-configuration[210]. Interferometric water maser observations are the *only* observations with sufficiently high spatial resolution to allow a detailed determination, on solar system scales, of physical conditions and kinematics in the circumstellar disks out of which planets will form. For the last decade, we have used the VLA extensively to study deeply embedded, newborn, sun-like stars[181]. We will employ this facility to study the distribution and temporal evolution of water masers, using the water maser emission as a tool to explore physical conditions in protoplanetary disks versus of age.

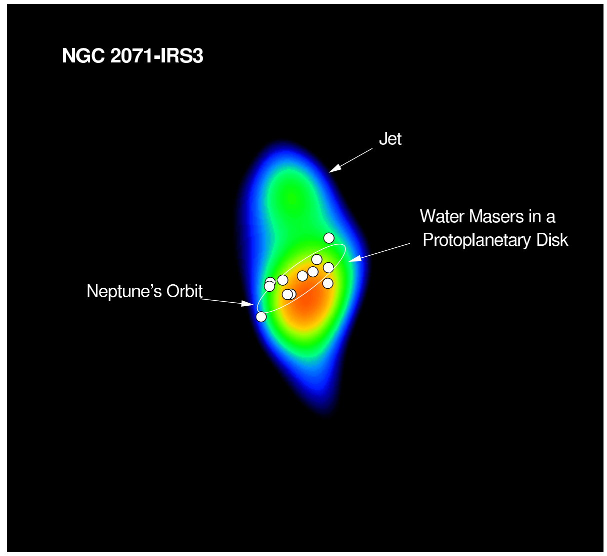


Fig 2.1.1d–A 1.3 cm radio continuum image from the Very Large Array[210]. Dots indicate the position of the water masers. The ellipse shows the size of Neptune's orbit for comparison purposes.

Analysis of Water in Star Forming Regions with Space Missions

Water vapor is so abundant and so rapidly variable in the Earth's atmosphere that detailed observations are rather difficult. The Infrared Space Observatory (ISO) and the Submillimeter Wave Astronomy Satellite (SWAS) opened mid- and far-infrared windows with numerous strong water lines[24, 128, 140], and indicated the advances we can expect in this area of research from future missions. Two major projects, the Stratospheric Observatory for Infrared Astronomy (SOFIA) and the Space Infrared Telescope Facility (SIRTF), are in the final stages of preparation, and will soon be available to the astronomical community. Later this decade we will get the Herschel mission, a 3.5 m mid- and far-infrared telescope that will be placed in a solar orbit at the L2 point. It will be extremely sensitive, and will permit detailed studies of the relation of water ice to circumstellar chemistry in newborn stars[25]. Meanwhile SIRTF, due to be launched this year, will have far higher sensitivity and resolution than ISO and SWAS, although it, too, will be unable to resolve circumstellar disks. We will use SIRTF to measure the global water content in young star forming cores and disks as a constraint on modeling our resolved ground based observations of water related molecules.

2.1.2 Interstellar Ices $\longrightarrow$ Comets

Objective – We would like to understand the volatile (especially water ice) abundances of comets and related bodies and to know to what extent cometary water has been processed since its accretion in the precursor molecular cloud. As ice-rich bodies, the nuclei are thermodynamically stable against sublimation only at heliocentric distances > 5 AU. Therefore, we must address the compositions of objects in the middle and outer solar system in order to understand the sources and delivery mechanisms. This requires the application of astronomical techniques using the largest telescopes. As the cometary ices are likely to have been altered by prolonged irradiation by energetic particles, we must also use laboratory experiments to understand the nature and rates of chemical reactions occuring in exposed ices. We will mount a systematic program to study irradiated ices both astronomically and in the laboratory.

Connections – §2.1.4 §2.1.3
Astrobiology Roadmap Links – Goal 3; Objective 3.1
Researchers – Bar-Nun, Jewitt, Kaiser, Meech, Owen, Prialnik

Background– Until the late 1980's, the standard paradigm held that comets were pristine relics, "planetesimals", from the era of planet formation. Indeed, the inventory of species detected to date in the ISM is very similar to that found in the comets[156], broadly consistent with this paradigm. However, we now understand that comets can have different sources. Dynamical evidence suggests that the short-period comets (SP) must have had a low-inclination source in the trans-Neptunian region (beyond 30 AU), while long-period comets (LP) formed at smaller distances (*e.g.* the Jupiter-Neptune zone), were perturbed outwards and are now stored in the Oort Cloud[49, 58]. The different comet dynamical types have experienced different thermal, collisional and irradiation histories; it is natural to expect that these differences will be reflected in their compositions.

The Comet – ISM Connection

The inventory of species detected to date in the ISM is very similar to those found in comets[53], leading to the suggestion that much of the interstellar material is incorporated unaltered into comets. However, during the earliest stages of the evolution of the planetary disk, infalling interstellar material may have been heavily processed due to shock-induced sublimation from icy grain mantles and subsequent volatile re-condensation[124]. At the low ambient temperatures expected in the nebula, the water ice would recondense in an amorphous form, trapping other more volatile species. Nevertheless, observations of recent bright comets have shown that there is evidence for preservation of an interstellar ice component within nuclei, yet at the same time the cometary material has undergone processing during its formation. Measurements of the D/H ratio in P/Halley[10, 52], in C/1996 B2 Hyakutake[17] and in C/1995 O1 Hale-Bopp[139] show an enrichment by a factor of ten in water compared to the protosolar ratio. The enrichment is a result of ion-molecule and grain-surface reactions in molecular clouds. Laboratory experiments have shown that this ratio cannot have been re-equilibrated in the solar nebula[118].

The Oort Cloud, the Kuiper Belt and Related Bodies

The Oort Cloud contains about 10^{12} comets, with a combined mass probably comparable to that of Neptune. The planetesimals grew collisionally until they were big enough to decouple from the nebular gas (at sizes of 10's to 100's of meters)[218]. Planetesimals ejected to the Oort Cloud may have undergone collisional evolution en-route, but have since been stored in a collision-free environment at only 10K temperature[201]. They have been subject to the full intensity of ionizing galactic cosmic rays for the past 4.6 Gyr. The Kuiper Belt, contains perhaps 10^5 bodies larger than 100 km in diameter and $\sim 10^{10}$ larger than the typical cometary nucleus ($\sim$ 1 km: Jewitt and Luu 2000). The current total mass is only $\sim$ 0.2 $M_\oplus$ but this is thought to be only about 1% of the initial Kuiper Belt mass. Material has been lost from the Kuiper Belt through dynamical erosion and through collisional shatteriing and ejection. It has been conjectured that the late heavy bombardment of the solar system, most clearly recorded in the cratering history of the Moon, might have been caused by the clearing out of the massive initial Kuiper belt.

Presently, objects escape from the Kuiper belt through dynamical chaos, and are scattered amongst the planets. Those that are not ejected from the solar system to the interstellar medium are scattered inwards to fall under the gravitational control of Jupiter. Once inside Jupiter's 5 AU radius orbit, water ice in the surface layers begins to sublimate, giving rise to an atmosphere or "coma", and these objects are observationally relabelled as "comets". It is thus appropriate to think of a stream of objects emanating from the Kuiper belt and being scattered between the planets, leading sometimes to the appearance of active comets near the earth and, on rare occasions, to collisions with the Earth and terrestrial planets. Bodies that have left the Kuiper belt but which are not yet warm enough to strongly sublimate are known as "Centaurs". About 50 such objects are currently known. In contrast to the Oort Cloud objects, comets from the Kuiper belt are thought to be collisionally produced chips from larger bodies. They have been in a warmer thermal environment (50K), have been at least partly protected from cosmic rays by heliospheric shielding, and may have been heated and shocked during ejection from their parent bodies.

Spectral Properties

Observational evidence for the effects of irradiation of the comets is found in their remarkably low albedos. Even though they are known to be ice-rich, the cometary nuclei are amongst the darkest objects in the solar system, with albedos typically of only $\sim$4%. Albedos of Kuiper Belt Objects and Centaurs, although few are known with confidence, also fall in the few to 10% range. Such low albedoes, together with the reddish colors measured in the optical spectral region, are consistent with hydrogen-depeleted, carbon-rich organics.

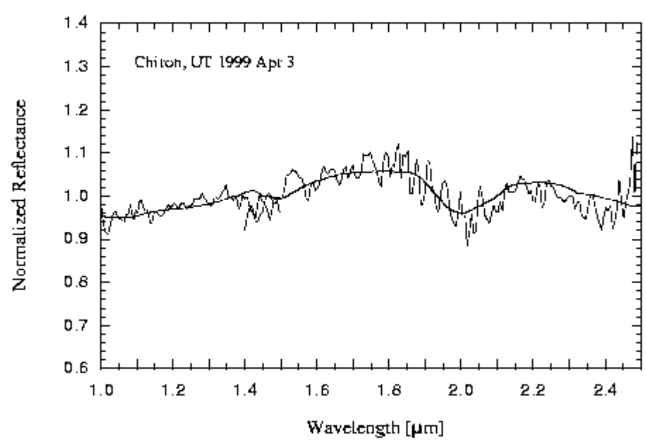


Fig 2.1.2a–Water ice bands at 1.5 and 2.0μm in the reflection spectrum of Centaur 2060 Chiron[?].

Spectral features on these bodies have proved difficult to find, indicating the low abundance of bonds capable of generating measurable vibrational features in the near infrared. In one spectacular counter-example to this claim, telescopic observations have revealed the presence of several near-infrared absorptions in the spectrum of Centaur 5145 Pholus. One model can fit these features using a surface composition including complex organics ("tholin"), water ice and a light hydrocarbon (possible methanol[39]). Water ice is seen also in the reflection spectra of other Centaurs and KBOs (see Fig. 2.1.2a). The existence of organics in comets is known from optical spectroscopy of radicals (C_2, C_3) and from near infrared and radio spectroscopy of molecules (HCN, H_2CO). In-situ measurements of dust grains in P/Halley detected grains composed largely of the elements CHON.

Whether the processed organics are confined to a meter-thick surface layer or "mantle", or are to be found throughout the bulk of the cometary nucleus remains unknown (see Fig. 2.1.2b). Cosmic rays have a stopping length of only meters but irradiation of solid matter prior to incorporation in the cometary nucleus could lead to this matter being found at all depths[138]. Observations of amorphous ice in comets[44] show that the comets cannot have been heated much above 137K. This places limits on the allowable abundance of ^{26}Al and on timescales from chondrule formation to comet formation to allow the ^{26}Al to decay by 2 orders of magnitude from the abundance inferred in the Allende meteorite. The heating from ^{26}Al would occur in the first few $\times 10^6$ to 10^7 years, or possibly longer for larger bodies[176]. Delayed formation is a feature of accretion in the low density Kuiper Belt, so that it seems natural that ^{26}Al would be largely absent in these bodies.

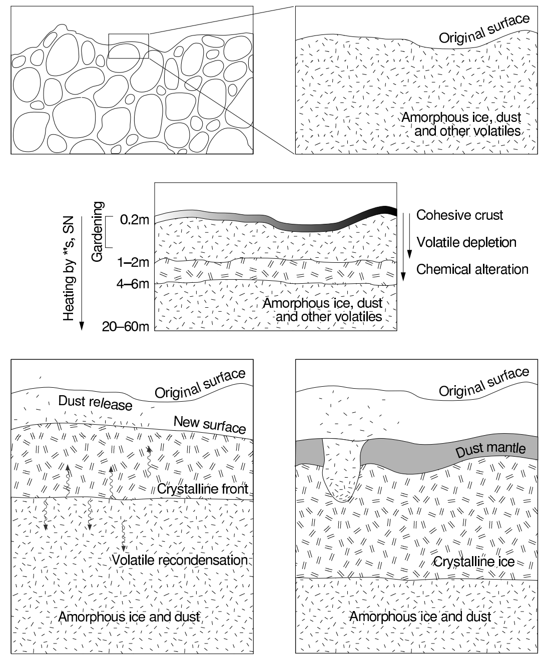


Fig 2.1.2b–Sequences of aging in the upper layers of a comet nucleus from the pristine state, through alterations undergone from heating in the Oort cloud from bright stars, supernovae and decay of ^{26}Al to the active phase of volatile loss.

Comets formed closer to the sun at higher densities could have grown more rapidly and might have incorporated a larger fraction of ^{26}Al and other short-lived isotopes, possibly with important consequences for thermal and chemical processing histories. Organic molecules when exposed to charged particle and UV radiation produce radiolysis and photolysis. Laboratory evidence shows that carbon-containing frozen mixtures will form complex organics when exposed to radiation and that complex organics will break down under irradiation (see §2.1.3). The effects of progressive irradiation include weakening of the IR bands owing to CH bonds, a change in the slope of the visible reflectance spectra (0.4-0.8μm) and a progressive lowering of the albedo. Hence there is much speculation that red outer solar system materials result from these processes[204], and that bright, neutral-blue surfaces correspond to newly exposed icy surfaces. The technology has just become advanced enough to begin to study a statistically meaningful sample of comets and Centaurs to look for the water-ice signature, and the chemical composition of the surface, including organic materials.

Proposed Observations

We aim to capitalize on University of Hawaii access to Mauna Kea to undertake a systematic investigation of the abundances and abundance differences in the ice-bearing bodies of the solar system. Such a study is timely because (*i*) new surveys have revealed a large number of observable but currently unobserved target Centaurs and Kuiper belt Objects and (*ii*) new telescopes and new detector technologies allow high quality observations that were previously impossible to secure. As a counterpart to the acquisition of astronomical spectra, we will obtain laboratory reflection spectra of relevant ice-dirt mixtures, all subject to appropriate degrees of irradiation damage by high energy particle sources. See §2.3.4 for details.

2.1.3 Role of Water in the Formation of Biologically Important Molecules in Space

Objective – To use ultra-high vacuum scattering lab experiments to investigate the charged particle versus photon induced formation of interstellar $C_2H_4O_2$ isomers in astrophysically important, water-rich ice mixtures.

Connections – §2.1.1
Astrobiology Roadmap Links – Goals 3, 4; Objective 3.1, 4.3
Researchers – Kaiser, Ehrenfreund, Bar-Nun, Owen

Background – Cutting-edge laboratory experiments present a unique opportunity to address for the very first time the important questions of how the basic life ingredients can be formed abiotically in extraterrestrial environments such as molecular clouds and the crucial role that water has played in their formation. Water ice presents the main constituent not only of interstellar grain material, but also of cometary matter[146]. Due to its high abundance, it plays a vital role in the underlying physicochemical processes which lead to the formation of astrobiologically significant molecules like carbon hydrates (sugars) in the interstellar medium and in our solar system.

Basic processes of ice formation and destruction in interstellar clouds

There are four basic processes which influence the ice chemistry in the ISM. Figure 2.1.3a shows a schematic overview of an icy grain and its catalytic surface. Accretion is a very efficient process in cold environments because most of the gaseous species (with the exception of H_2 and He) stick onto the grains with almost 100% efficiency. This accretion process occurs on a timescale of $\tau \sim 2 \times 10^9/n(\mathrm{H_2})$ yr, assuming a sticking efficiency of unity. The accretion process occurs to specific grain sites, known as binding sites. Water ice acts as a matrix which embeds complex organic molecules such as freshly synthesized sugars and amino acids. Due to this matrix isolation, ionizing radiation (nuclei, electrons, photons) from the galactic cosmic radiation field and the solar wind interact predominantly with the main constituent of these ices: water molecules. Therefore, water molecules protect astrobiologically significant molecules inside the icy grain material from being destroyed by ionizing radiation. Without this water ice, no organic molecule can survive neither on interstellar grains nor on comets.

Secondly, the actual formation of astrobiologically important molecules generates chemical energy, which is stored as vibrational energy in the newly formed molecules. This excess energy must be diverted from the molecules; otherwise organic molecules fragment and cannot be stabilized. The water matrix can divert this excess energy via phonon coupling. Without this energy transfer of water ice, the astrobiological evolution of extraterrestrial environments would stop right at the beginning. However, the actual effect of both processes and the role of water on the formation of astrobiologically important molecules has never been investigated in laboratory experiments. Here, we unravel for the very first time how these astrobiologically relevant building blocks are actually formed in water rich ices (via ionizing radiation, charged particles, and photons). The formation of the sugar glycolaldehyde and its isomers acetic acid and methyl formate in water ice acts as a prototype example with fundamental astrobiological implications. The production routes are explored quantitatively as a function of temperature (10 K – 300 K) to simulate the chemical processing in cold clouds and hot molecular cores. We also account for the different chemical reactivities in various water ice phases (crystalline versus amorphous). By coupling these laboratory investigations and the production routes of glycolaldehyde, acetic acid, and methyl formate with sub-mm observations, we will then infer conditions in the cores and cold clouds where the chemistry in water-rich ices is occurring.

Untangling the synthetic routes to form basic sugars, which are the building blocks of RNA, in water rich extraterrestrial ices is particularly significant because they serve as an energy source to living organisms (glucose) and as a structural skeleton (cellulose)[51]. Carbohydrates also play a role in vital amino acid producing chemical reactions. These species may have formed on early Earth via the polymerization of two formaldehyde (H_2CO) molecules. However, the validity of whether or not these conditions were likely on a primitive Earth has been seriously questioned, because under any conditions where monosaccharides will form, they would subsequently degrade or react on short time-scales.

Early in Earth's history, it experienced a period of heavy bombardment during which fragile carbon-based life could not have survived[30]. Geological surveys have found 3.5Gy old cyanobacteria fossils and evidence of chemical processing dating to 3.8Gy. Thus, the evolution of pre-biotic molecules on Earth took less than 300 million years, suggesting that these biologically important molecules might have been already available. Astrobiologically important molecules such as glycolaldehyde, a monosaccharide sugar, could have been produced in extraterrestrial environments and then subsequently survived solar nebular processing or were introduced to the Earth during the period of heavy bombardment.

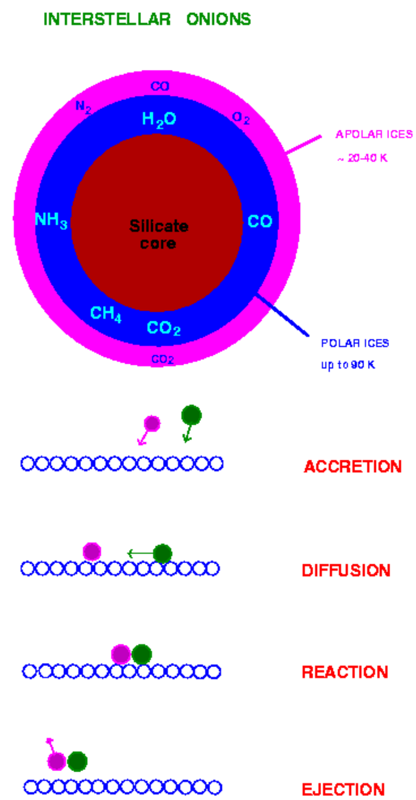


Fig 2.1.3a– A schematic view of an interstellar grain covered with polar (water-dominated) and/or apolar (highly volatile, H-deficient) ice layers. Four major processes act to form and equilibrate interstellar icy grain mantles. A more detailed explanation is given in the text.

An analysis of meteorites such as Murchison and Murray also indicates a large proportion of complex organic matter including amino acids, lipids and sugars to support this claim. In addition, several interesting organic molecules (such as methyl formate and acetic acid) have been tentatively identified in comets.

Hot molecular cores and star forming regions provide a rich laboratory for understanding complex molecular evolution. The transition from the cold molecular cloud to the hot core phase depends strongly on the molecular composition. A detailed understanding of the synthesis of three $C_2H_4O_2$ isomers [acetic acid (CH_3COOH), methyl formate ($HCOOCH_3$), and glycolaldehyde ($HCOCH_2H$)] is of particular pertinence since they play a key role in astrobiology. Acetic acid, a precursor to the simplest amino acid glycine, was first detected in the hot core Sagittarius B2(N) (Sgr B2) , and later also toward W51e2[89]. The second isomer, methyl formate, is ubiquitous in the interstellar medium and has been observed not only in hot cores like Sgr B2 but also in molecular clouds such as OMC-1. The recent detection of glycolaldehyde in Sgr B2 is a significant astrobiological milestone since it represents the first member of monosaccharide sugars and denotes an important biomarker.

Despite the key role of these $C_2H_4O_2$ isomers in astrobiology, their formation is not understood. Chemical reaction network models of pure gas phase chemistry which focus on ion-molecule reactions with methanol and formaldehyde yield abundances 50-100 less than observed. Grain-surface reactions on sub-micrometer sized silicate- and carbonaceous-based nanoparticles at $T \sim 10K$ in cold molecular clouds have been proposed as an alternative formation mechanism. The molecules can be liberated into the gas phase via sublimation in hot cores when the surrounded matter is heated above 100 K by the embedded protostar. Millar & Hatchell[142] extended previous reaction networks to simulate these grain sublimation processes, however, the models could not adequately fit the observed abundances. This suggests that key production routes to form $C_2H_4O_2$ isomers involving interstellar grains are still missing.

Understanding Grain Chemistry

The crucial role of the grain mantles to produce molecular hydrogen (H_2) and simple hydrides such as water and methane has been recognized explicitly, but no consensus has been reached whether complex astrobiologically important molecules are actually formed on grain surfaces or inside icy grains[120, 142]. In the cold molecular clouds, interstellar grains have temperatures of 10K. Thus, grain particles trap all molecules and atoms except H, H_2, and He with unit efficiency upon collision. This results in the formation of nm-thick icy layers which consist predominantly of water (H_2O), methanol (CH_3OH), carbon monoxide (CO), carbon dioxide (CO_2), and of minor components like ammonia (NH_3), formaldehyde (H_2CO), hydrogen cyanide (HCN), carbonyl sulfide (OCS), and methane (CH_4). These ice mantles are processed chemically by MeV cosmic-ray (CR) induced internal UV radiation which is present even in the deep interior of the dense clouds. Because current reaction models assume that this frozen grain mantle material is chemically inert, they have limited validity.

Despite the importance of high energy particle and photon induced chemical formation of molecules in extraterrestrial ices, these processes have never been comprehensively included into astrophysical reaction networks modeling the formation of $C_2H_4O_2$ isomers in cold clouds and hot cores. Studies (including the NASA decadal survey) investigating the effects of charged particle processing of interstellar ices to form heavy hydrocarbons in molecular clouds call for extensive laboratory investigations of the underlying elementary processes.The interstellar medium modeling communities are also calling for laboratory experiments. Novel laboratory experiments on the CR and UV triggered formation of $C_2H_4O_2$ isomers in extraterrestrial ices are clearly desired. Once the prebiotic synthetic routes to form these molecules have been exposed quantitatively in laboratory experiments, we can then predict where sugars and their isomers (or their precursors) can be formed, searched for, and ultimately be observed spectroscopically (via telescopes) or in situ (via space missions).

Experimental Objectives

We will use ultra-high vacuum scattering lab experiments to investigate the charged particle versus photon induced formation of interstellar $C_2H_4O_2$ isomers in astrophysically important, water-rich ice mixtures. These experiments will generate quantitative data under controlled conditions and provide temperature, kinetic energy, and wavelength-dependent synthetic routes to form acetic acid, methyl formate, and glycolaldehyde in water-rich ices as present in cold molecular clouds, hot cores, and in cometary ices. This unique approach addresses for the first time specific mechanisms and generalized concepts on photon versus particle induced formation of complex molecules in astrophysical ices rather than attempting solely to reproduce infrared spectra of astronomical observations.

Production rates of $C_2H_4O_2$ isomers will be explored systematically as a function of ice temperature in molecular clouds and hot cores (10 to 100-300 K), ice composition, photon wavelength, nature of the charged particles (electrons, hydrogen, helium, oxygen, and carbon ions), and flux and kinetic energy of the irradiating particles. Since photons penetrate only the outer layers of the grain, whereas cosmic ray particles can penetrate deep inside, a depth-dependent molecular differentiation is expected. The laboratory experiments combined with kinetic models predict the existence of these isomers quantitatively in various extraterrestrial environments. Using JCMT, CSO, and SMA at Mauna Kea (§2.1.1), we can then attempt to observe these isomers in molecular clouds and star forming regions in the microwave region; the microwave transitions of all three isomers are well known. It will be possible to compare the T – dependent production rates and outputs of the kinetic models with results from astronomical observations.

These experiments may also be important for understanding the data from future space missions (*e.g.* Deep Impact Mission) and spectroscopic observations with telescopes (Stratospheric Observatory for Far Infrared Astronomy; Space Infrared Telescope Facility). This unique synergistic approach combines for the very first time sophisticated laboratory experiments, electronic structure theory, kinetic models, and actual astronomical observations to address generalized concepts in understanding the formation of astrobiologically important molecules in water rich ices in our solar system and in the interstellar medium.

Chemical Processing in the Clouds – Physical processes

An understanding of the chemical processing of ices by photons and charged particles, will enable us to predict the nature of the ice mixtures where $C_2H_4O_2$ isomers might be synthesized. Dictated by optical selection rules, a photon can be absorbed by a single molecule in the ice. This process can be followed by a selective bond rupture. If a hydrogen atom is released in the photodissociation process, it may have kinetic energies up to a few eV. The corresponding radical formed is internally excited and might react with a neighboring molecule. Since the internal energy can be coupled into the reaction coordinate, entrance barriers can be passed and endothermic reactions are feasible.

UV photons are absorbed within about 100Å of the surface, but CR particles (such as 10 MeV H^+) can penetrate deeper and deposit up to 1 MeV inside the icy mantle. This exceeds the chemical bond strength (1 eV) and the stability of the molecule. Upon absorption, a CR can interact inelastically or elastically with either the electronic or nuclear part of molecules, respectively. Consequences of this interaction include the electronic excitation, ionization, and/or bond ruptures. The energetic species thus formed are not in thermal equilibrium with the surrounding 10K ice. Once particles are slowed down in successive collisions to kinetic energies of a few eV – energies in the order of chemical bond strengths – they can react with a molecule in the ice via one of three mechanisms to form new molecules: (*i*) hydrogen abstraction, (*ii*) insertion into a single bond, or (*iii*) addition to an unsaturated bond or to a non-bonding orbital.

The power of suprathermal reactants is based on the ability to impart their kinetic energy into the reaction coordinate. Reaction barriers can be overcome, and endothermic reactions are open resulting in rate constants up to 16 orders of magnitude larger than thermal reactions. Most importantly, calculations show that although the CR flux in dense molecular clouds is two orders of magnitude below the internal UV flux, each MeV particle generates about 100 suprathermal species in a 0.1 μm thick icy layer. Hence the flux advantage of the UV field is eliminated by the ability of one CR particle to generate multiple suprathermal species.

2.1.4 Origin and Distribution of Planetary Water

Objective – Mineralogical, geochemical and isotopic studies of aqueously-altered meteorites will help to understand, firstly, the time and physico-chemical conditions of aqueous alteration in the asteroids, and secondly, how and when the water accreted into asteroids and planets from these diverse sources.

Connections – §2.1.1 2.1.2
Astrobiology Roadmap Links – Goal 3, 5; Objective 3.1
Researchers – Owen, Jewitt, Keil, Krot, Scott

Comets to Earth: Isotopes

The origin of the Earth's water is one of the key issues that we will address under this investigation. It is likely that the Earth formed too hot for much water to have been incorporated directly, or as chemically bound water in minerals, into the body of the planet. The presence of $\sim 10^{-6}$ $M_{\oplus}$ of water on our planet instead indicates delivery from an external source or sources. The other terrestrial planets are likewise thought to have harbored substantial water inventories.

Mars might still do so in the form of permafrost ice. For a long time, the water-rich nuclei of comets have been suspected as major carriers of planetary water. Measurements of the D/H ratio in comets P/Halley, C/Hyakutake and C/Hale-Bopp have indicated a problem with the simplest version of this idea, however. The D/H ratio in these comets averages $D/H = 3{\times}10^{-4}$, which is twice the value for Standard Mean Ocean Water, $D/H_{SMOW} = 1.6 \times 10^{-4}$. The three measured comets are from dynamical classes thought to derive from the Oort Cloud, and to have originated in the middle solar system. The comets in the Kuiper Belt, (so-called short-period, Jupiter-family comets), remain unmeasured. The figure at the right shows the D/H ratios of Hale-Bopp, P/Halley and Hyakutake as a function of the (current) inverse semimajor axis, a.

Accordingly, the strongest conclusion that can be drawn from the available data is that the Earth's water does not consist only of melted comets from the middle solar system. There could be other contributions from cometary sources with D/H ratios quite different from the 3 measured so far. It has been specifically suggested that the measured comets are not representative of the isotopic compositions to be found in the outer solar system. It has also been suggested that Earth's water could have come from the outer asteroid-belt. Measurements of planetary noble gas abundances cannot be easily reconciled with "hot" sources from the outer belt, and a cometary carrier still seems likely. However, we lack the data to definitively understand the origin of the Earth's water.

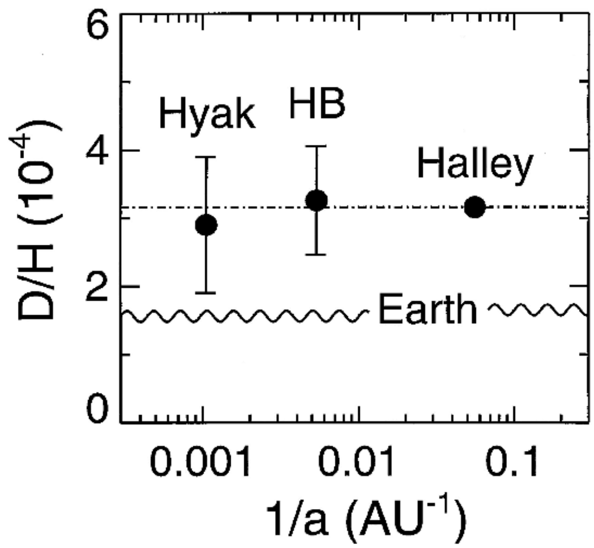


Fig 2.1.4a– D/H ratio of Hale-Bopp (HB), Halley, and Hyakutake (Hyak) versus semi-major axis. The wavy line shows the SMOW value, and the dashed-dotted line, the in situ value for Halley. Depicted are 1σ standard deviations. Figure from [139].

Comets to Earth: Isotopes

There is a long tradition of assuming the Earth is made of matter that is identical to or at least closely resembles the chondritic meteorites. Starting from the observation that the value of Kr/Xe in the Earth's atmosphere is 20 times greater than the value in the meteorites, and that

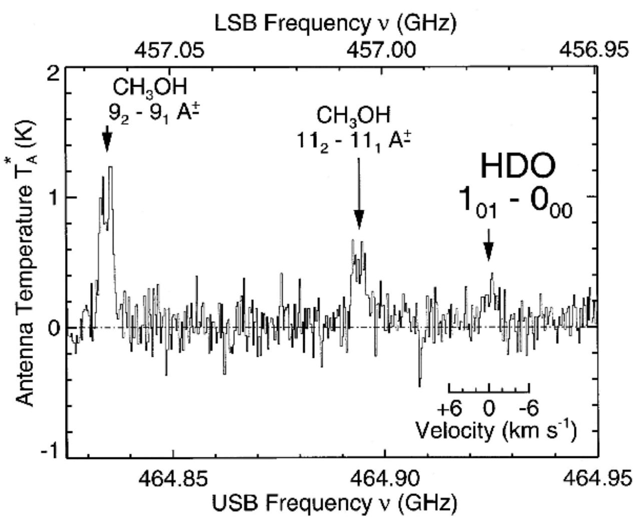


Fig 2.1.4b–Mauna Kea spectrum of Hale-Bopp showing the HDO 101-000 line together with two methanol transitions. The CH_3OH 112-111 A transition originates in the lower sideband (LSB) (top frequency scale); all other lines belong to the upper sideband (USB). The double-peak structure of the lines is caused by the velocity distribution in the comet[139].

the Xe isotope abundances in our atmosphere are also fundamentally different from those in meteoritic xenon, the term "planetary component" for noble gases in meteorites is a misnomer. If meteorites – and by extension asteroids – did not deliver the noble gases, they cannot have brought in the water, nitrogen and carbon either. If they had, we would have a very different situation for xenon in our atmosphere. Fractionation does not help.

This leads to the suggestion that comets may have played some role. Amorphous ice could trap noble gases in the proportion that we find them on Earth, but the isotopic pattern in atmospheric xenon cannot be duplicated. Furthermore, we now know that the water in Oort cloud comets has twice the value of D/H that we find in seawater on Earth. Hence we cannot make the oceans out of melted Oort cloud comets alone.

Suppose comets indeed are a minor carrier of water to Earth, even though they may have brought the noble gases. Then what brought in the water? Presumably it was the rocks that formed the planet, which may have been significantly different in composition from the chondritic meteorites. Mars is an important test bed for this idea, because there is very little mixing between the surface and the interior, and the atmosphere is very thin. Hence external contributions of volatiles will be likely to stay on or near the surface, while internal volatiles should retain their original properties.

Records of Aqueous Activity on Meteorite Parent Bodies

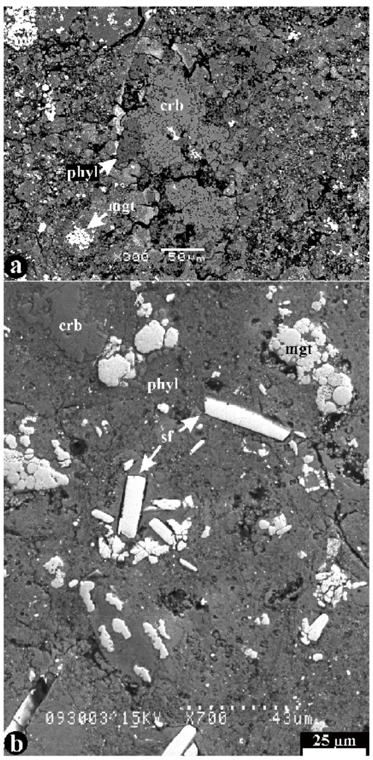


Fig 2.1.4c–Backscattered electron images of the Tagish Lake carbonaceous chondrite (a) and QUE94411 carbonaceous chndrite. Both contained secondary minerals produced during aqueous alteration, including carbonates (crb), magnetite (mgt), FeNi-sulfides (sf), and phyllosilicates (phyl).

Chondritic meteorites (chondrites) are fragments of mineralogically and chemically diverse asteroids that formed at 2-3 AU from the Sun prior to accretion of the planets in the inner solar system (Mercury, Venus, Earth, Mars). They are considered to be analogs for the building blocks for these planets. Asteroids, like planets, formed by aggregation of solids and gas from the protosolar disk. Remote sensing of asteroids and laboratory studies of chondrites show that asteroids at 2 AU largely consist of anhydrous silicates, metal and sulfides, whereas at distances $\sim$3 AU most asteroids are largely composed of hydrated silicates like clay minerals, organic materials, carbonates, sulfates, magnetite, and other iron oxides (Figs. 2.1.4c, 2.1.4d). Experimental studies and studies of meteorites suggest that the hydrated minerals, carbonates, sulfates, magnetite, etc. were not produced in the protosolar disk, but resulted from aqueous activity on asteroidal bodies. The water on asteroids is thought to have multiple sources, including interstellar ice, hydrous silicates from asteroidal and cometary fragments that formed further away from the Sun, and minor amounts of ice condensing in the solar nebula (Fig. 2.1.4e). Mineralogical, geochemical and isotopic studies of aqueously-altered meteorites will help to understand, firstly, the time and physico-chemical conditions of aqueous alteration in the asteroids, and secondly, how and when the water accreted into asteroids and planets from these diverse sources. In order to address these questions, we propose to study secondary mineralization (*e.g.*, phyllosilicates, magnetite, halite, carbonates, nepheline, sodalite, fayalite, andradite) that resulted from asteroidal aqueous alteration of various chondritic meteorites (H, L, LL, CI, CM, CO, CR, CH, CV).

We will conduct this work through detailed mineralogic, petrologic and isotopic studies using optical, scanning and transmission electron microscopy (SEM, TEM), electron probe microanalysis (EPMA), ion probe microanalysis (SIMS), Raman and IR-spectroscopy, thermal ionization and inductively coupled plasma-mass spectrometry (TIMS, ICP-MS).

We will carefully characterize secondary mineralization in chondritic meteorites using optical microscopy, SEM, EPMA, and TEM. Using X-ray elemental mapping and backscattered electron imaging (Figs. 2.1.4c, 2.1.4d), we will identify phyllosilicates, magnetite, halite, carbonates, nepheline, sodalite, fayalite, andradite, and search for fluid inclusions in carbonates and salts. Chemical composition of the identified phases will be measured using EPMA. Based on the occurrences of the secondary phases, their chemical compositions and textural relationships with primary minerals of high-temperature chondritic components (*e.g.*, chondrules and Ca, Al-rich inclusions), we will infer setting (nebular or asteroidal) and chemical changes resulting from aqueous alteration.

Physico-chemical conditions of aqueous alteration will be estimated using thermodynamic modeling[113]. The identified fluid inclusions will be studied using Raman and IR spectroscopy, and SIMS to define composition (pH, D/H, oxygen isotopes) and redox conditions (Eh) of a fluid phase phase[227]. In order to understand sources of water in aqueously-altered asteroids, we will study hydrogen isotopic compositions of their phyllosilicates[?]. As a result of this complex mineralogical, petrological and isotopic studies of aqueously altered chondritic meteorites, we will be able to infer environment, temperature, pressure, water/rock ratio, and other physicochemical conditions (Eh, pH, fluid composition) of aqueous alteration. Our recent results show that aqueous activities on the chondrite asteroids started within 1-2 Myr after formation of Ca, Al-rich inclusions ($\sim$4567$\pm$.6 Myr[5]) and lasted for at least $\sim$15 Myr[207, 55, 93, 94, 95, 87, 113, 115, 90, 20, 21, 175].

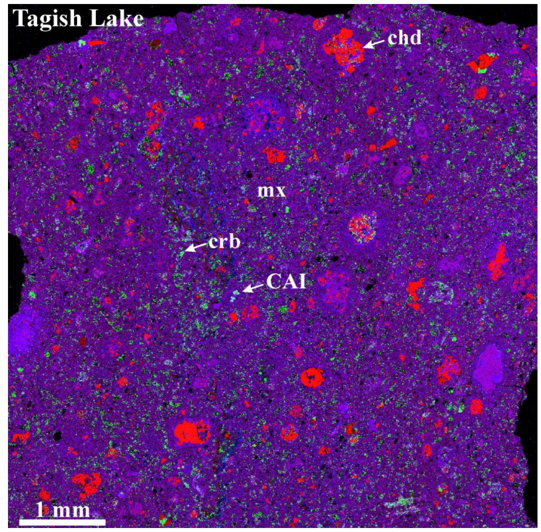


Fig 2.1.4d–Combined X-ray elemental map in Mg (red), Ca (green) and Al Kα (blue) of the Tagish Lake carbonaccous chondrite, which experienced extensive aqueous alteration that resulted in formation of abundant carbonates (crb), magnetite and phyllosilicates. These secondary phases replace chondrules (chd), Ca, Al-rich inclusions (CAIs) and matrix (mx) materials.

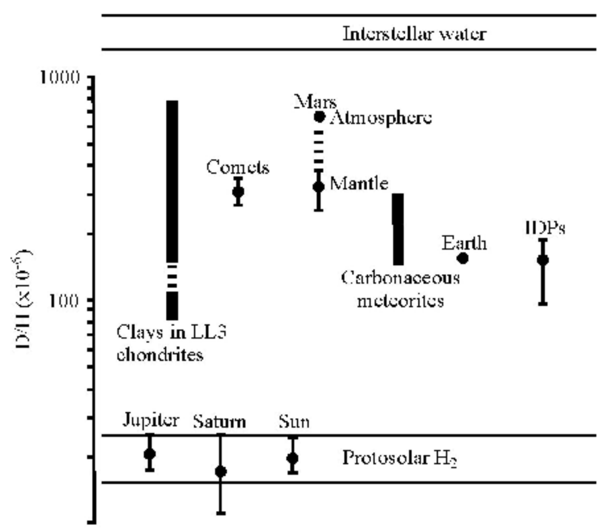


Fig 2.1.4e–Distribution of the hydrogen isotopic composition in solar system bodies.

Physico-chemical conditions of aqueous alteration will be estimated using thermodynamic modeling[113]. In order to constrain timing of aqueous alteration of H, L, LL, CI, CM, CO, CP, CH, and CV chondrites, we will date some of the secondary minerals (carbonates, fayalite, magnetite, phyllosilicates) using SIMS and TIMS based on short-lived radionuclide systems such as ^{26}Al-^{26}Mg ($t_{1/2} \sim 0.7$ Myr), ^{53}Mn-^{53}Cr ($t_{1/2} \sim 3.7$ Myr), and ^{129}I-^{129}Xe ($t_{1/2} \sim 16$ Myr).

Dating of carbonate and fayalite formation will be done *in situ* using SIMS[95]. Dating of magnetite and phyllosilicates formation will be done using TIMS on mineral separates[175]. If we find that aqueous alteration of chondritic meteorites occurred within the first few Myr of the solar system, it would indicate that accretion of the planets in the inner solar system (Mercury, Venus, Earth, Mars) must have involved aqueously altered asteroidal bodies. This would provide important information on the sources of water in the inner solar system planets.

2.1.5 Water and Aqueous Alteration on Mars

Objective – Develop predictive models for the transport and state of water in the Martian crust, its alteration of crustal rocks, and the production and deposition of sediments.

Connections – §2.1.6, 2.1.7
Astrobiology Roadmap Links – Goal 2; Objective 2.1
Researchers – Taylor, Gaidos

Aqueous Processes on Mars

The Martian crust was constructed by igneous processes and subsequently modified by aqueous and aeolian processes. The products of this geologic activity contains the record of the early differentiation of Mars, the evolution of magma composition and production rates, the nature of interactions among the atmosphere, hydrosphere, and lithosphere, and, perhaps, a history of (microbial) life. The Martian crust preserves extremely ancient material but it also records very recent events. Combining data returned from spacecraft instruments with geochemical models it is possible, in principle, to reconstruct the history and importance of these processes, particularly those involving water, over 4.5 billion years of Mars history.

We propose to continue an extensive project (funded largely by other sources) that combines theoretical calculations and published data on terrestrial analogs to develop predictive models for the transport and state of water in the Martian crust, its alteration of crustal rocks, and the production and deposition of sediments. We will make predictions that can be tested by data from past, present, and future orbital and landed missions. Specifically, we intend to make detailed predictions about what assemblages of minerals will be diagnostic of a given aqueous process. This will be coupled with predictions of the effect of these processes on the chemical composition of the surface (including trace element concentrations). A good example of this approach is predictions based on terrestrial analogs of how the large hematite deposits on Mars form[28, 97]. The hematite problem can be tackled by modeling as well, including modeling reaction rates to determine the likelihood of hematite formation by aqueous reactions. For geochemical modeling we will use Geochemist's Workbench[14], which allows thermodynamic based geochemical reaction modeling. Finally, we will use these models to study possible aqueous activity on present-day Mars, its chemical signature, and its potential for hosting extant life. This research will have three foci, as described briefly below.

Products of Past Hydrothermal Alteration

Hydrothermal processes might have pervasively altered the ancient highlands of Mars[165, 166]. The Noachian was marked by active hydrologic systems, vigorous magmatism that would have provided heat to drive hydrothermal systems, and a high impact rate that would also have provided heat for hydrothermal processes. Later magmatism and impacts would also have produced localized hydrothermal systems. These products might have ended up deep in the crust, as sedimentary rocks, or in a global soil/dust layer.

- Products produced by hydrothermal activity – Hydrothermal systems produce some specific types of minerals, depending on physical-chemical conditions and the composition of the starting rock. This is testable by geochemical modeling. The suspected igneous rocks will serve as input into assessing the likely products that would be produced by hydrothermal processes.

- Changes in the nature of hydrothermal systems with time – Because of changing atmospheric composition and pressure and possibly less water being available through time, the nature of hydrothermal alteration might change dramatically. This can be assessed by modeling rock alteration under varying CO_2 pressure and water/rock ratio.

- Mars volatile inventory trapped in hydrothermal deposits. Griffith & Shock[75, 76] have drawn attention to the possibility that much of the H_2O and CO_2 on Mars might be sequestered in the crust. The mineral assemblages produced depend in part on the activities of these volatiles during alteration. More extensive modeling is called for to map out the compositional space of starting rocks and the conditions under which the hydrothermal alteration took place.

- Hydrothermal deposits – effects on compositions / oxidation states of magmas – Hydrothermal mineral assemblages are likely to be assimilated readily by ascending magmas. This process has been proposed for chemical and isotopic properties of Martian meteorites[213, 137, 81]. This would alter magma compositions, water contents, and possibly oxidation state. This process can be modeled by assimilating the alteration products suspected to be made in hydrothermal systems on Mars. This also illustrates that igneous and alteration processes are intimately related.

Ancient Weathering and Sedimentation

There is clearly a gradation from low-temperature alteration at the surface to hydrothermal alteration. We separate them here largely for convenience and include all low-temperature, water-driven processes operating within a few tens of meters of the surface. Weathering is the process in which rocks react with water and atmosphere to form new minerals. The new minerals may be eroded, transported, and deposited as part of sedimentary deposits.

- Assessing the weathering products of the major igneous rocks on Mars – The starting rock composition greatly affects what weathering products are made, so we also will work extensively on determining the full range of possible compositions of igneous rocks on Mars to guide the choice of starting rock compositions[74]. This is an important question because many remote-sensing instruments will analyze weathered rock. We might be able to determine the nature of the unweathered rock from characteristic weathering products. Terrestrial analog studies will be very useful in this aspect of our study[163], as will be considerations of production of alteration products in the Martian regolith[74, 136, 216]

- The weathering products of hydrothermal deposits – Hydrothermal deposits can be weathered when exposed to the Martian atmosphere and surface or near-surface water. If hydrothermal deposits are as widespread as suspected, then their weathering products will be, too. Thus, it will be useful to determine the nature of the mineral assemblages for a suite of hydrothermal deposits produced under different conditions.

- Martian sedimentary mineral production – When sediments were deposited on Mars, they would have reacted with water for however long it was still present. Diagenetic processes would have operated to produce lithified sedimentary rocks. These processes will likely be the most difficult to model, but it is important to do so because sedimentary rocks will be prime targets for exploration. Water-rock reaction rates are slow and the loss of water was probably relatively rapid, so evaporation might be the major process that produces cementing minerals in the sedimentary environment[134].

- Fractionation during sedimentary transport – An intriguing and important possibility is that heavy minerals might be deposited before less dense minerals, forming distinct patterns in sedimentary basins. This can be examined by knowing the mineral assemblages present after weathering or partial weathering and applying depositional models to them to see the extent to which fractionation is possible. Fractionation by sedimentary transport has been proposed to explain aspects of the Martian soil[133].

- The effect microorganisms might have had on sedimentary mineral assemblages – In principle, a vigorous microbial population could influence what minerals are produced during alteration. In many ways organisms act as catalysts for reactions, but unique, nonequilibrium phases are also produced. This work is speculative but still worth doing, especially if it helps set limits on the role of organisms in producing the observed characteristics of the Martian soil. Geochemists Workbench allows a certain limited amount of modeling, but most of this effort will concentrate on the extensive literature of terrestrial soils.

Water, Aqueous Chemistry, and Habitats on Present-Day Mars

The detection of copious ground ice[57] and recently carved gully-like landforms[126] raises the possibility that liquid water is appearing close to or at the surface of present-day Mars. Continued aqueous activity on Mars has implications both for the geochemical evolution of the surface as well as the potential for discovering life[71]. Detailed and integrated modeling of liquid water formation, transport, and aqueous geochemistry is needed to understand these phenomena:

- Expulsion of groundwater by permafrost processes – Groundwater may be expelled from deep, freezing aquifers and rapidly erupted to the surface of Mars[69]. A mechanical and geochemical model of groundwater expulsion[69, 71] will be improved and applied to realistic Martian geologies.

- Melting of ground ice and ice fields on present-day Mars – Melting ground ice or ice fields during periods of high obliquity is currently a favored mechanism for the formation of the gullies seen on the walls of many canyons and craters[36]. However, the frost point of the Martian atmosphere (the temperature above which ice is unstable) has probably never reached the melting point of water, and melting must compete with surface sublimation and refreezing at depth to produce significant liquid water. We will further develop the model of Clow[34] to examine these issues.

- Martian hydrothermal systems at low ambient pressure The presence of ground ice and evidence for recent geologic activity (*i.e.*, young crystallization ages for some Martian meteorites) suggests that hydrothermal systems may still be active on present Mars. However, the atmospheric pressure on Mars is near the triple point of water and liquid water boils at a very low temperature (or is unstable entirely): Water driven to the surface at sites of hydrothermal circulation is most likely to boil below ground and reach the surface as steam. Nevertheless, such fumarolic systems will produce geochemical signatures and be important targets of exobiological exploration: We will model a hydrothermal/fumarole system in a Martian regolith to determine its likely physical and chemical characteristics.

2.1.6 Water-Rock Chemistry and Habitats for Life

Objectives – (*i*) to understand the role of microbially mediated reactions in diverse seafloor environments that may exist on other planets, including hot springs along the mid-ocean ridge axis, warm springs on ridge flanks, and ultramafic-hosted springs in subduction zones, and (*ii*) to assess the interplay between these reactions and the transfer of water between mantle, crust, oceans.

Connections – §2.1.5, 2.1.7, 2.1.8
Astrobiology Roadmap Links – Goals 4, 5; Objectives 4.2, 5.1
Researchers – Cowen, Mottl, Gaidos

Background – Chemical reactions between water and silicate minerals, particularly at high temperature, produces fluids that are in thermodynamic disequilibrium which, if quenched at low temperature, provide a source of free energy for life. Microbial life also accelerates mineral dissolution reactions whose effect is to release important nutrients such as phosphorus. Also, rock-water interfaces provide surfaces that can be colonized by structured communities of microorganisms. Water-rock chemistry, some of it catalyzed by microorganisms, is involved in much of the geochemistry of the Earth's crust and oceans. It also plays an important role in the formation of hydrous minerals and the planetary water cycle. On the early Earth before the appearance of substantial continental crust, the chemical reaction of water with basaltic rocks was the dominant geochemical process, and it is still important in much of the seafloor of the present-day Earth. Such submarine settings, shielded from high levels of solar radiation and the thermal insults of impacts, were likely to have been important for early life. They may also be critical to the sustenance of subsurface ecosystems, if they exist, on Mars or Europa. The role of microorganisms in subaerial weathering reactions and the production of hydrous minerals [162] and their ability to exploit the chemistry of high-temperature water-rock reactions have been clearly established. However, the role of biology in the geochemistry of seafloor alteration is only beginning to be explored. Most alteration of seafloor crust takes place within the first few$\times 10^6$yr [185].

The microbiota place a significant role in geochemical transformations within the oceanic crust both at mid-ocean ridges[206] and in cooler, off-axis crust[37]. Known biology ($T < 115°$) could persist as deep as 4 km in off-axis oceanic crust. We propose to investigate several environments dominated by water-basaltic rock chemistry, including some that are particularly accessible from Hawaii.

Hot springs along the mid-ocean ridge axis

Basaltic magma crystallizes along the mid-ocean ridge axis to form the oceanic crust. This magma also supplies heat to drive hydrothermal circulation of seawater through the crust, producing spectacular "black-smoker" springs at temperatures up to about 400°C. UH scientists who are Co-Is for this proposal have active field programs at several such sites on the seafloor, including the Endeavour main vent field on the Juan de Fuca Ridge and the Lau Basin behind the Tonga volcanic arc. The former is a typical basalt-hosted system with some evidence for sediment input, whereas the latter has systems in rocks ranging from basalt to rhyolite. The range in rock type has a large effect on the chemistry of the springs, particularly their metal and volatile content, which are doubtless important for the microbial communities in the different settings. These field programs will provide a range of opportunities for post-doctoral researchers within the proposed NAI.

One particularly unique opportunity to study the adaptation of microbial life to extreme hydrothermal environments and to freshly emplaced but rapidly evolving basalts is offered by a program headed by UH to detect and respond to mid-ocean ridge eruptive events. Ridge axis diking and eruptive events are episodic perturbations that trigger a sequence of interrelated and rapidly evolving physical, chemical, and biological processes associated with the formation of ocean crust. Dikes and lava flows develop rapidly and instantly alter the local hydrothermal flow regime. Volcanic activity produces hydrothermal discharge with a distinct geochemical signature and triggers specific geochemical and microbial responses in the adjacent crust and overlying water-column. Significant change in a variety of processes can be expected to take place over limited time spans. In effect, diking-eruptive events offer short-term natural "experiments" unachievable in the laboratory. Observing and quantifying co-variation among related processes provides opportunistic time-zero points for observations of water-basalt reactions and the development and role of microbial communities in low water/rock environments.

Diking and eruptive events dramatically alter the intensity of hydrothermal discharge from the seafloor, epitomized by the generation of so-called event plumes (Fig. 2.1.6a)[9], which involve the near instantaneous release of enormous volumes of hydrothermal fluids. Event plumes appear to form only during the short-lived period of intense seismic activity and the event-associated chronic discharge can attenuate quickly. Furthermore, the chemical and biological characteristics within hydrothermal plumes change rapidly, with the steepest rate of change occurring over seconds to days following their discharge and subsequent mixing in the deep sea. Because of these rapid changes, early on-site investigation of event plumes and associated chronic venting is essential to derive the wealth of information that they can provide, including:

- Chemical, biological, and physical constraints on subseafloor chemistry, biology and hydrology; in effect opening a window to the subsurface. It is important to take advantage of this information before aging processes degrade the initial signals.

- A unique opportunity to study and isolate subseafloor extremophiles, perhaps discharged from otherwise inaccessible regions of the crust.
- Knowledge of the heat and chemical fluxes also provide insight into the potential production and physiological diversity of subseafloor microbial communities.

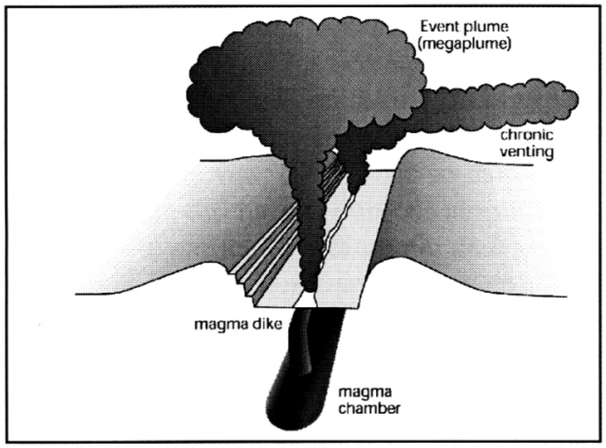


Fig 2.1.6a–Active mid-ocean ridge showing formation of event plume at location of magma dike extrusion. Continuous "chronic" style venting also indicated [37].

Diking-eruptive events provide unique opportunities to detect and characterize subseafloor microbial communities that are ejected from the ocean crust[88]. Models of the response of hydrothermal systems to a magmatic event indicate that the flux of heat and volatiles increases enormously at the time of an intrusion and then decays slowly with time. In addition, the output of subsurface bacterial biomass undoubtedly also changes. Presumably, the hydrological (*e.g.*, hydrothermal circulation) changes induced in the oceanic crust by diking-eruptive events tap pre-existing microbial crustal habitats as well as create new ones. Massive bacterial output from the associated fissures and vents created during diking/eruptive activity has accompanied the early stages of all three eruptive events studied to date[80, 88, 205]. The so-called snow blower vents associated with some of the events which discharged copious amounts of microbially-derived sulfur-based particulate matter were particularly dramatic demonstrations of potential subsurface microbial activity and biomass. Both familiar and new species and genera of hyperthermophilic anaerobic Archaea were also detected and isolated at each event studied.

Volatile output has been very high in the early phases of most diking events observed. Ratios of He, H_2S, H_2 and CO_2 to heat were all relatively high in the venting fluids during the early period of an event, recovering to lower, more steady-state levels over weeks to several years. The subsurface microorganisms are subjected to these changing, intense chemical and thermal conditions. The most intensely affected parts of the hydrothermal system are probably sterilized and would subsequently have to be recolonized. These processes are likely analogous on a small scale to sterilizing events during early Solar System bombardment of the terrestrial planets.

The unpredictability of these research opportunities accentuates the value of a sensitive and reliable event detection tool. Directed rapid response to volcanic events depends on remote real-time detection of seismic events. In 1993, the T-phase Monitoring System was developed by NOAA-PMEL to access the U.S. Navy's Sound Surveillance System (SOSUS) and allows real-time monitoring of acoustic T-waves generated by seafloor seismic activity[61].

The T-phase Monitoring System depends on U.S. Navy hydrophone arrays located off the coast of Oregon, Washington, and British Columbia and covers the northeast Pacific ridge system from the southern limit of the Gorda Ridge (GR) to the northern limit of Explorer Ridge (Fig. 2.1.6b).

Since the real-time T-Phase Monitoring System was brought on-line in June, 1993, three major eruptive episodes have been documented on the northeast Pacific spreading centers (1993 CoAxial, 1996 North GR, and 1998 Axial Volcano). Another likely magmatic event, the 2001 Middle Valley event, apparently did not penetrate the thick sediment cap overlying that ridge valley. In total, at least 6 eruptive events have occurred along the Juan de Fuca/Gorda Ridges over 15 years, or 4 remotely detected events over 6 years. Given this recent record, there is a very high probability that at least one major eruptive event will be detected along the Juan de Fuca/Gorda Ridges during the lifetime of this proposed NASA program; UH is the lead institution on the response team which is funded by NSF to maintain readiness for rapid response to SOSUS detected events through 2007.

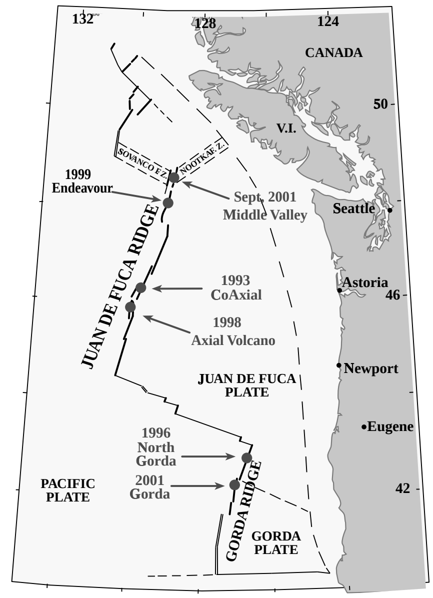


Fig 2.1.6b–Map of Juan de Fuca and Gorda Ridges (and Explorer Ridge to north). SOSUS system covers the entire MOR shown.

The close involvement and leadership of the University of Hawaii in this Event Response program will insure excellent opportunities for participation by Institute postdoctoral associates who are interested in pursing research into the identification/isolation/functionality of mesophiles, thermophiles, hyperthermophiles, halophiles and other “extremophilic” microorganisms, as well as into water(fresh) basalt interactions. Rapid and follow-up field response efforts (including submersible) will provide abundant water, fluid, and rock sampling opportunities over and at the new eruption sites.

Warm springs along mid-ocean ridge flanks

The possibility of a significant biosphere extending throughout the immense volume of aging crusts under the global system of mid- ocean ridge flanks and ocean basins is controversial. Since most ridge flank and ocean basin crust is buried under a thick, impermeable layer of sediment, the fluids circulating within the underlying oceanic crust are usually inaccessible for direct studies.

However, CORK (Circulation Obviation Retrofit Kit) observatories[45] (Fig. 2.1.6c) affixed to over-pressured Ocean Drilling Program (ODP) boreholes[46] on the flanks of the Juan de Fuca Ridge, offer unprecedented new opportunities to study biogeochemical properties and microbial diversity in circulating crustal fluids with very low water/rock ratios over a range of temperatures ($\sim$1.5 to $>$ 100°C). Basement waters collected from one such hole (ODP Hole 1026B) are chemically similar to fluid venting from nearby rocky outcrops[153, 219, 220]; the chemical characteristics and temperature (65°C) of the fluids escaping from Hole 1026B are conducive to microbial growth, supporting a diverse community of bacteria and Archaea[37].

Small subunit rRNA genes cloned from microorganisms collected on BioColumn filters (Fig. 2.1.6c) revealed a diverse assemblage of phylogenetic groups (including both Archaea and Bacteria) that are often most closely affiliated with cultured thermophiles, many that are known for their metabolic capacity to reduce sulfate or nitrate[37]. Though speculative, the data suggest that microbial processes with these electron acceptors (nitrate and sulfate) may play an important role in this region of the oceanic crust. However, stoichiometric inconsistencies in the crustal fluid chemistry remain unexplained. Critical questions remain regarding the age and flow rate of the crustal fluid[59], and the potential presence of novel metabolic pathways that may sustain microbial life in low water/rock, slow recharge environments. To what extent does H_2 production as well as organic compound synthesis via abiotic reactions between seawater and basalt[198] fuel this deep subsurface biosphere? The opportunities are great for Institute postdoctoral researchers to uncover new insights into "low water/rock" microbial communities and to discover new organisms and novel metabolic pathways.

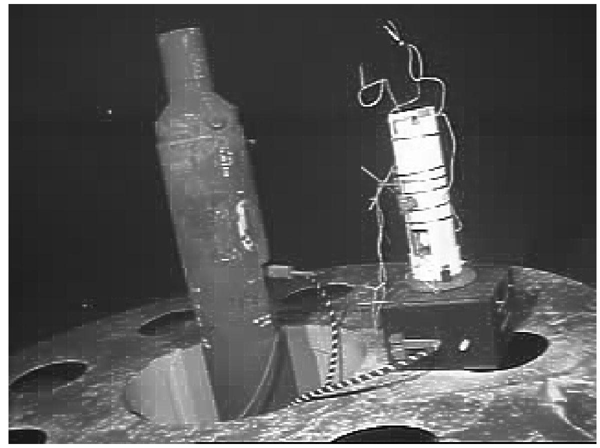


Fig 2.1.6c– Circulation Obviation Retrofit Kit (CORK) structure on top of ODP borehole 1026B. Cylinder and box to right are sampling device "plumbed" into the fluid access port of the CORK.

Ultramafic-hosted springs in subduction zones

Ultramafic rocks make up the mantle of most rocky bodies in the Solar System. When ultramafic rocks come in contact with liquid water they are altered to serpentinite over a wide range of temperatures, from freezing to about 500°C. On Earth, new crust is primarily mafic basalts, however plate tectonics still provides opportunities for the reaction of water with ultramafic rocks: 1) along the mid-ocean ridge axis, especially where the basaltic crust is thin such as at fracture zones in slow-spread crust; 2) in subduction zones, where dehydration reactions in the subducting slab release water that ascends into and serpentinizes the mantle wedge of the overriding plate; 3) most controversially, in the outer rise just seaward of the trench, where the plate flexes upward as it begins to bend before plunging into the mantle[173]. On planets around other stars with somewhat different compositions or where mantle melting is less efficient, considerable more ultramafic rock may come in contact with water.

Recent work in the Mariana forearc by a Co-I[154], including manned submersible dives and deep drilling by the Ocean Drilling Program, indicates that slab dehydration and the resulting serpentinization produce unusual habitats for extremophilic microbes, including both Bacteria and Archaea, that may be a model for some extraterrestrial environments. The Mariana subduction complex is formed between the northwestward subducting Pacific plate and the overriding Philippine plate. Volatiles released from the downgoing Pacific plate hydrate the overlying mantle wedge of the Philippine plate and convert depleted harzburgite to low-density serpentinite. The resulting serpentinite mud, containing variably serpentinized harzburgite clasts, ascends buoyantly along fractures and extrudes at the seafloor, where it forms large (30 km diameter, 2 km high) mud volcanoes along the outer Mariana forearc, in a band that extends from 50 to 120 km behind the trench axis[63]. These mud volcanoes are built from flows of poorly consolidated sedimentary serpentinite fed through a central conduit. Cold ($\sim$2°C) spring waters fresher than seawater have been sampled on several of these mud volcanoes.

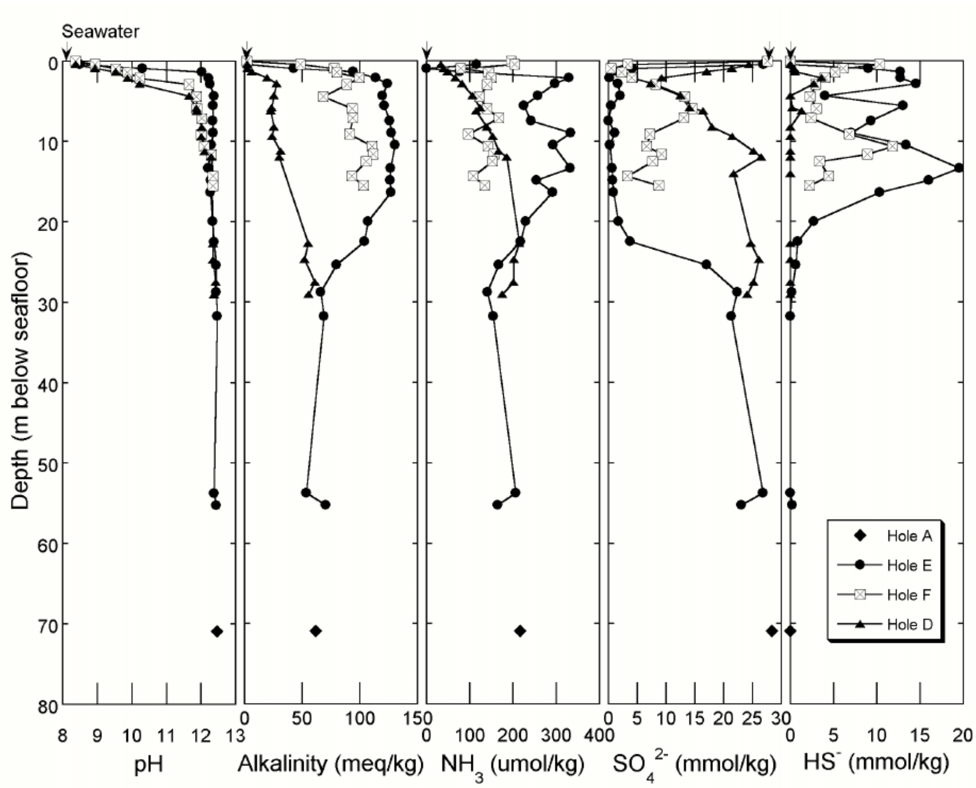


Fig 2.1.6d–Composition of pore water squeezed from serpentinite mud at ODP Site 1200, summit of South Chamorro Seamount, an active serpentinite mud volcano in the Mariana forearc at 13°47.0N, 146°0.2E[154]. Holes A and E were drilled at a cold (2°C) spring and Holes F and D are 20 m and 80 m to the north, respectively. Sulfate reduction at 1 to 3 and 13 mbsf, mainly by Archaea as indicated by the concentration of phospholipid-derived diphytanyl diethers (DE), produces alkalinity, bisulfide, and ammonia, all at pH 12.5. The carbon source is methane, which is present at 2 mmol/kg in the fluid ascending from the top of the downgoing plate, which is about 27 km below the seafloor at this site.

The chemistry of these springs is highly unusual: they are among the least saline waters ever recovered from the deep sea and have the highest pH, 12.5, which results from ongoing serpentinization. Relative to seawater, these springs have higher to much higher sulfate, alkalinity, pH, Na/Cl, K, Rb, B, light hydrocarbons, ammonia, δ^{18}O, and δD; and lower to much lower chloride, Mg, Ca, Sr, Li, Si, phosphate, and Sr isotopic ratio. Ba, Mn, Fe, and bisulfide are low[152]. Within the upper 20 m below seafloor in the vicinity of these springs, a microbial community operating at pH 12.5, are made up overwhelmingly of Archaea, is oxidizing methane from the ascending fluid to carbonate ion and organic carbon, while reducing sulfate to bisulfide and probably dissolved nitrogen to ammonia (Fig. 2.1.6d). There is essentially no sedimentary organic carbon in this setting. The microbial community that feeds the macrobiota at the summit of S. Chamorro Seamount is therefore not only extremophile, but subsists on a source of chemical energy delivered from as deep as 27 km below the seafloor. Additional cruises to the Mariana forearc during the period of this grant will permit Institute scientists, including post-doctoral researchers, to characterize these unusual microbial communities and to assess the likelihood that similar communities might have evolved in extraterrestrial habitats. We will culte these organisms in the laboratory at high pH in a serpentinite matrix.

Microbial "colonization" of lava-seawater-generated plumes

Direct entry of lava into the ocean on the shoreline of Kilauea Volcano, Hawaii, creates a surface hydrothermal plume enriched in dissolved F, Cl, Fe, Al, Ti, Mn, Si, V, certain rare earth elements, dissolved gases such as H_2 and even sulfate[190, 191, 182, 183]. The plumes are acidic and contain high levels of suspended silicate glass particles produced by the explosive disintegration of lava as it is quenched from temperatures near 1400 K to that of boiling water. Surface waters are also influenced by input of aerosols generated in the resulting steam plume[192]. These plumes are a unique biological habitat because of the high concentrations of biologically important elements, particularly P and Fe, which were measured at 2 and 5 orders of magnitude, respectively, above average seawater concentrations[183], extremely high concentrations of potentially toxic metals (Al, Co, Cu, Pb, Cd, V), the high density of suspended glass particles available for colonization (up to 65 mg L^{-1}[191]), *and* they are within the photic zone (unlike deep-sea hydrothermal vents). Strong thermal and chemical gradients are produced by entrainment of ambient water into the plume[191]. These could represent analogs to aquatic microbial "oases" on the early Proterozoic Earth when rising oxygen levels and the insolubility of iron in surface waters deprived photosynthetic organisms of critical nutrients[111]. They also may be representative of processes occuring on a wider scale during the emplacement of large igneous provinces[222] during the Phanerozoic.

Although large zooplankton blooms have been observed, the biology of these plumes has remained unexplored. We propose to survey the microbiology associated with the plume water column and that attached to the glass particulates, using the ambient seawater as the basis of comparison. We are especially interested in tracing the dynamics of both populations as the plume waters are a dynamic entity, being mixed out over a distance of about 1 km. We will carry out spectrophotometric analyses of the plume waters to identify potential photosynthetic pigments. Filtered particulates and water samples will be analyzed separately with microscopy, including low-vacuum scanning electron microscopy for the former. DNA will be extracted and amplified using polymerase chain reaction (PCR) and analyzed both at the community level , *e.g.*, denaturing gradient gel electrophoresis (DGGE), and at the individual sequence level. We predict that because of the high levels of H_2 and ferrous iron in the plume, gnallgas and iron-oxidizing bacteria will be well-represented in these communities.

2.1.7 Extreme Aquatic Environments on Earth and their Analogy to Potential Habitats in the Solar System

Objective –In this project we will focus on a comparative study of microbial biodiversity, biomass and metabolic activity in a variety of "extreme" aquatic habitats.

Connections – §2.1.5, 2.1.6

Astrobiology Roadmap Links – Goal 5; Objective 5.3
Researchers – Gaidos, Karl, Thorsteinsson

Background – Life, especially microbial life, has successfully radiated into nearly all the aquatic habitat space on Earth. It is usually assumed that life as we know it absolutely requires liquid water and that the fundamental constraint for growth is the activity of water or the availability of free water. Besides water, life also requires a source of carbon and nutrients, and an environment that is conducive to the propagation of genetic information, *i.e.*, the error-free replication of DNA. Many aquatic environments on Earth are challenging or "extreme" from the point of view of these other requirements. By studying these we can better understand what may limit the origin and persistence of life in aquatic habitats elsewhere in the universe.

The scope of potential habitats is expanded further when one considers indications of possible aquatic environments elsewhere in the Solar System. There is significant geomorphological evidence for past (or even present) flowing water on Mars, and geophysical evidence for an interior ocean beneath the crust of Europa (and possibly Callisto). Ground ice is abundant on present-day Mars[57] and the outflow channels and valley networks carved in ancient terrains show some of that water was liquid, at least transiently, in the past[23]. Apparently much more recent gullies carved in the walls of canyons and craters raise the exciting possibility that surface or shallow groundwaters occur at the present epoch[126],[69],[36]. The geomorphic evidence for a subsurface ocean on Europa[170] has been strengthened by the detection of an eddy current-induced magnetic field around the satellite[226].

However, these extraterrestrial aquatic environments may be far more extreme than most encountered on Earth: Liquid water is not, and may never have been stable on Mars, and any long-lived bodies of water were probably covered with thick ice crusts that isolated the surface from sunlight and the atmosphere [71]. During episodes of high martian obliquity, summer surface temperatures on poleward facing slopes on Mars can exceed the melting point of water ice, but mean surface pressures and temperatures will limit the amount of liquid that can be generated. Martian meteorites with young crystallization ages[135] and low crater counts on some martian terrains[79] suggest that magma is still reaching relatively shallow depths on Mars. The near-ubiquitous presence of ground ice[57] supports speculation that hydrothermal systems may still be active on present Mars and are potential targets for exobiological exploration. However, the atmospheric pressure on Mars is near the triple point of water and liquid water boils at a very low temperature (or is unstable entirely): Water driven to the surface at sites of high planetary heat flow is most likely to boil and reach the surface as a vapor. Europa's ocean is isolated from sunlight by an ice crust between 10 and 100 km thick and the amount of free energy for chemotrophic organisms will be meager [66, 31]. Tide-driven shear and viscous dissipation can warm the shallow crust of Europa and create liquid water within reach of sunlight[67] , but the melt fraction will be low[168] and any aquatic habitats will probably consist of brine channels within an ice matrix.

The limits to life with respect to temperature have been intensely explored since the pioneering work of Brock[22]. Hyperthermophilic prokaryotic archaea with measurable growth rates at 115°C have been cultured from deep-sea hydrothermal systems and there has been tantalizing evidence of biological activity at still higher temperatures. Accelerated hydrolysis of tri-phosphates above 160°C may constitute an ultimate temperature limit to life based on known biochemistry. What are the limits to life with respect to the activity of water, *e.g.*, can life exist under conditions where the stable phase of water in the environment is vapor? Hyperthermophiles growing above

100° are found in environments where the pressure is well above ambient and the boiling point well above the maximum growth temperature. Certain microorganisms florish in superheated hot springs 1-2°C above the boiling point but their ability to survive in superheated steam conditions is unknown. Any life in these truly extreme conditions must adapt to the limited activity of water. These truly extreme conditions create life that must adapt. By studying analogs of such environments on Earth and their potential biota we obtain basic information on the strategies of, and limitations to, biochemical and physiological adaptation.

In this project we will focus on a comparative study of microbial biodiversity, biomass and metabolic activity in a variety of "extreme" aquatic habitats including: (1) the open sea near Hawaii, (2) Lake Kauhako, Molokai and (3) Lake Waiau, Hawaii, (4) subglacial habitats in Iceland and Antarctica, and (5) fumaroles in Hawaii and South America. Each study area has unique physical and chemical characteristics and each is expected to select for a different assemblage of microorganisms. By studying the similarities as well as the differences we hope to provide basic information on the strategies of biochemical and physiological adaptation and on gene evolution.

1. Scientists in the UH-NAI program will have access to numerous open ocean habitats ranging from the nutrient stressed surface waters of Station ALOHA (22°45′N, 158°W) to the deep abyss. These study areas are visited approximately monthly as part of the ongoing Hawaii Ocean Time-series (HOT) program that uses the university's research vessel as a floating laboratory. Samples collected at sea can either be processed on site or returned to the university for more extensive or sophisticated analyses.
2. Lake Kauhako (Fig. 2.1.7a), Molokai is a deep (248 m) meromictic lake that occupies the crater of an extinct volcano (21°11.5'N, 158°58'W). This lake has the highest relative depth (ratio of depth to surface area) of any lake in the world. The upper 4.5m of the lake is well stratified but below 4.5m the lake is nearly uniform in temperature and salinity (26.25°C, 32 per mil). The lake is anoxic below about 2 m with very high concentrations of hydrogen sulfide appearing below about 6m[48].

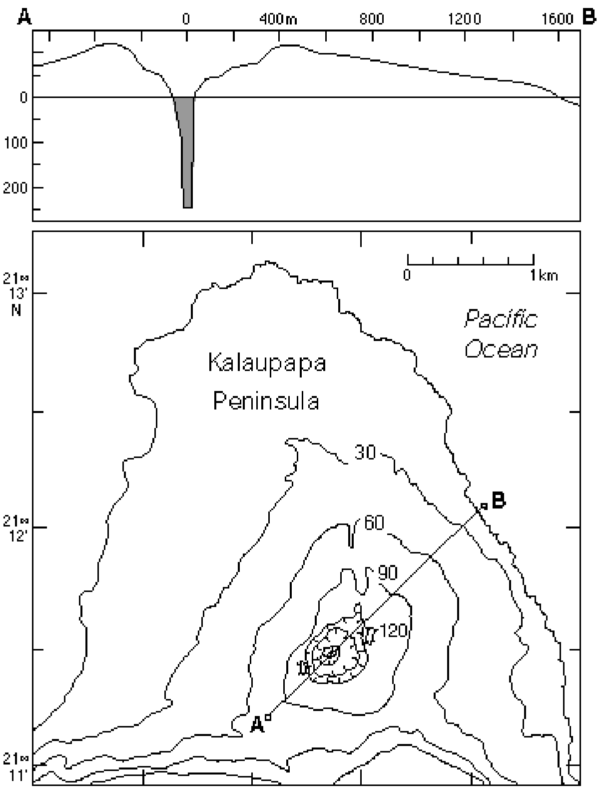


Fig 2.1.7a–Lake Kauhako on Molokai. Upper panel shows a vertical profile along A to B on the bottom map. The shaded portion in the top figure is the lake itself with depth interval in meters. Bottom panel: contour elevation map in meters.

In many respects this lake has conditions that are analogous to the permanently anoxic basin, the Black Sea[158] and thus serves as a convenient and relatively accessible habitat for comparative studies of aquatic microbiology. Kauhako Crater was designated a "special Ecological Area" in 1994.

3. Lake Waiau, Hawaii, is located at an elevation of 3980 m near the summit of Mauna Kea (19°48′N, 155°29′W). The lake lies in a shallow crater and is approximately 90m in diameter and 3 m deep, although its dimensions vary with precipitation patterns. Weather at this site is extreme with especially high winds; the typically isothermal lake temperature ranges annually from 0-13°C, with wintertime ice cover. Lake Waiau ultraviolet radiation levels are about 30% higher than at sea level for comparable latitude and is thus of interest to studies of organismal adaptation to the high radiation environments of the early Earth and on other planets. Like Lake Kauhako, Lake Waiau is located in a restricted conservation area which minimizes human impact and interference. For the open Pacific Ocean, Lake Kauhaku, and Lake Waiau we will make comparative observations and measurements of key indices of microbial biomass (by total ATP, lipopolysaccharide, chlorophyll and epifluorescence microscopy[106] and habitat chemical characteristics) temperature/salinity, dissolved oxygen and CO_2 gas concentrations, inorganic and organic nutrient concentrations, particulate matter carbon/nitrogen and phosphorus content[105] at each site.

   Metabolic activity will be assessed for the total microbial assemblage by measurement of respiration (in vitro oxygen consumption) as well as for specialized physiological functions such as nitrogen fixation (by the acetylene reduction method) and other selected enzyme activities (phosphatase, peptidase). We will also endeavor to isolate representative microorganisms from each site, with a focus on prokaryotes.

4. The existence of a large, deep freshwater lake beneath the ice of central East Antarctica was reported in 1996[103]. The lake was named Lake Vostok because of its proximity to Vostok Station (near 77°S, 105°E). During the same year an inventory of 77 such Antarctic subglacial lakes was published[196] proving them to be a relatively common occurrence. Lake Vostok is located beneath approximately 3800m of ice; below approximately 3500 m the ice appears to be refrozen from Lake Vostok, accreted to the bottom of the glacial ice column (*i.e.*, so-called accretion ice). Although microorganisms have been detected in the accreted ice portion of the 3623 m long Vostok ice core (drilling was terminated at a depth of approximately 120 m from the ice-lake water interface[107, 179]) no samples have yet been recovered from any Antarctic subglacial lake.

   Besides the liquid water in the lake itself, both the glacial ice column and the accreted ice may also provide unique habitats for the growth of microorganisms. For example, bacteria, yeasts, fungi and microalgae at depths ranging from 1500 to 2750 m have been found[2] in Vostok glacial ice. Some of the microbes were claimed to be viable. Price (2000) has also reported viable cells to depths of 3600 m in the Vostok core. He hypothesized that the microorganisms inhabit a microenvironment consisting of interconnected liquid veins along three-grain boundaries in ice wherein psychrophilic, halophilic bacteria can move and obtain energy and carbon from ions and compounds in solution. We plan to test this hypothesis using ice column mesocosms in the laboratory. We will also test the hypothesis concerning the role of brine channels in sea ice as a unique habitat for microbial growth using a laboratory based mesocosm approach similar in design to the one recently described by Mock[147].

5. Iceland is located on the Mid-Atlantic Ridge and at the Arctic Circle, and consequently hosts numerous active volcanoes and glaciers. We are investigating Icelandic subglacial

volcanism as unique terrestrial environments and analogs to potential habitats on Mars and the galilean satellites of Jupiter. Some martian landforms have already been identified as possibly of glaciovolcanic origin[26]. Subglacial systems where volcanic heat drives hydrothermal circulation are more like to support a flourishing subsurface community because (1) liquid water is produced from the melting of the overlying ice by high geothermal heat; (2) free energy is provided by the reducing hydrothermal fluids produced by high-temperature water-rock chemistry mixing with oxidizing gases such as O_2 or CO_2 released by melting of ice; and (3) the extreme thermal gradients between the ice and hot rock or water will create a wide range of habitats. We expect that, because of differences in temperature, geology, and ice flow, subglacial hydrothermal environments will manifest significant physiochemical and biological diversity similar to that seen in the hot springs within the Yellowstone caldera.

Grimsvötn is one of two active volcanoes under the Vatnajökull ice sheet. Intense hydrothermal circulation within the 100 km^2 caldera drives an average heat flow of 50 W m^{-2}, far exceeding the 2 W m^{-2} typical of the Yellowstone caldera and in vent fields on mid-ocean ridges. Glacial melt in a 300 km^2 drainage basin feeds a geothermally sustained lake covering 20 km^2. Continuous geothermal activity and eruptions cause the lake to episodically – and catastrophically – drain, triggering jökulhlaups, the largest floods on present-day Earth. The lake was previously sampled for geochemical analyses in 1991[3]. We carried out a preliminary biological investigation of the Grimsvötn subglacial caldera lake in June 2002 expedition[70]. Self-sterilizing hot-water drilling was used to penetrate the 300 m ice shelf and sample the lake (Fig. 3.1.7b). We sampled the lake water, the tephra at the bottom of the lake, and the ice and snow over the lake. Chemical analyses included pH, alkalanity, and total dissolved solids. Cell counts were made on replicate samples. Lake water samples were incubated with ^{14}C-labeled bicarbonate and acetylene to assay for carbon fixation and nitrogen fixation, respectively. DNA was extracted and amplified using universal bacterial primers and the polymerase chain reaction (PCR). An analysis of the whole community was done using the denaturing-gradient gel electrophoresis (DGGE) technique.

There were significant cell counts in both lake waters and especially high counts in the tephra sediments. We measured significant carbon uptake and nitrogen fixation by lake samples. The DGGE analysis showed that (at the molecular level) the lake community was distinct from the organisms trapped in the overlying snow and ice. We have preliminarily concluded that an endemic, autotrophic, and nitrogen-fixing community of microorganisms exists in the lake, the product of the unique environment selecting on an assemblage of "innoculating" microbes that are released into the lake from melting ice.

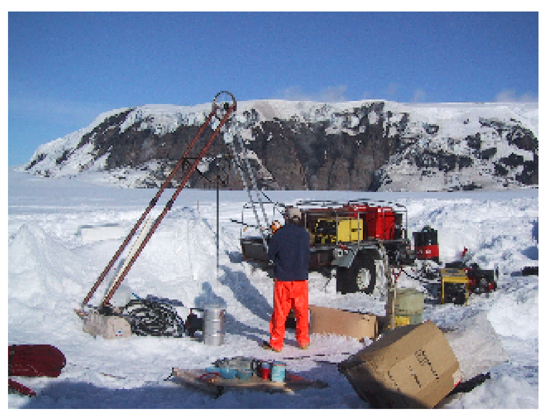


Fig 3.1.7b– Hot-water drilling apparatus in operation on the lake ice shelf within the Grimsvötn volcanic caldera, Iceland.

The discovery of high cell counts in the lake tephra is consistent with findings in many settings that microorganisms preferentially colonize particle surfaces relative to the water column. At Grimsvötn and similar environments in Iceland, volcanic tephra and hyaloclastic breccia is emplaced as extremely hot (900-1400 K) and thus sterile debris during subglacial eruptions. This material is, of course, immediately quenched by melting and vaporization of the surrounding ice, but temperatures are likely to remain at the boiling point (230°C under 300 m of ice) and well above plausible limits for life for a brief period of time that depends on the water to rock ratio and the vigor of subsequent hydrothermal circulation. Eventual cooling will allow organisms released from the surrounding ice to colonize the mineral surfaces on the tephra. Our objective is to understand the mechanisms and sequence of events associated with the establishment and maintenance of a microbial community in an initially sterile, abiotic subglacial environment. The processes of colonization and succession on subaerial[209] and submarine[155] basaltic lavas, particularly involving plants and macrofauna has been extensively studied including on Hawaii. The subglacial process is arguably simpler and better defined because potential colonists must come from the overlying ice and can be surveyed, and plants and macrofauna are absent. The process may be crucial to the continuity of life on planets (such as Mars) with inhospitable surfaces. We are interested in addressing the following question: Is there a single colonization event or continued succession in the microbial community over time? In the absence of sunlight and phototrophy, is the colonization process related to the suite of chemotrophic metabolisms available to, and employed by, microorganisms? Is the process identical at every subglacial site or is it a function of local conditions? Is it deterministic or depends on some stochastic element? What are the important potential biomarkers of colonization that could be used to identify past biological activity at similar sites on other Solar System bodies?

Our plans for future field work include a return to Grimsvötn in the summer of 2004 for additional drilling and sampling close to the caldera rim where normal faulting associated with the collapse of the caldera is expected to permit more intense hydrothermal circulation. We will also investigate the Skáfta "cauldrons", two sites of subglacial geothermal heating whose surface expression are 2 km-wide depression in the Vatnajökull ice sheet. These occupy separate drainage basins adjacent to that of Grimsvötn. Additional cauldrons have been identified on the Mýrdalsjökull ice cap, which occupies the extremely active Katla caldera[16]. Samples will be examined using both epifluorescence microscopy and environmental scanning electron microcopy. DNA will be extracted and amplified for both community-level analysis and the construction of clone libraries for sequencing. Fluorescent probes will be designed to target organisms with DNA sequences of interest and image them in the tephra particle environment. We will remove pristine samples of ice and fresh tephra for use in laboratory microcosm experiments: The tephra is reheated to temperatures sufficient to sterilize and volatilize any organic carbon and then added to the ice. Sampling of these incubations will allow time-dependent phenomenae to be observed.

6. On Earth, high-altitude fumaroles provide natural environments in which temperatures within the known range of biological tolerance exceed the boiling point. For example, water boils at 92°C in Yellowstone (2225 m elevation) and at the Geysers del Tatio in Chile (4321 m elevatio) the boiling point is 85°C. At Sol de Manana, Bolivia (up to 5000 m eleva-

tion) water boils at a “mere” 83°C, well within the range of non-photosynthetic life. Organisms surviving in such environments would have to evolve two adaptations; (1) preventing its cytoplasmic fluid from boiling, and (2) preventing dehydration due to the difference in the vapor pressure between liquid water inside and outside the organism. Microorganisms with cell walls maintain their volume by creating an internal (turgor) pressure. This is done by maintaining a difference in osmolality (equivalent solute concentration) between the internal cell and its environment. Gram-negative bacteria can maintain turgor pressures up to several bars. The corresponding boiling point elevation is approximately 60°C. Cellular cytoplasm is also a briny fluid and the presence of anti-boil compounds could elevate the boiling point. Finally, boiling requires the nucleation of bubbles. The scale of most bacteria is 1 μm, raising the potential of suppression of boiling by suppression of nucleation. Dehydration could be prevented by suppressing the vapor pressure of the cytoplasm (by antiboil compounds), or by expending energy to actively pump water into the organism against the osmotic gradient. In fumarolic environments where steam temperatures are outside the tolerable range of life, microorganisms could adapt endolithic lifestyles and use the insulating properties of the fumarole rock walls to protect them from heat and retain water.

We have developed a program to search for biological activity, and organisms, in low-temperature fumaroles associated with the Kilauea Volcano in Hawaii (1200 m elevation). We will expand our program to identify high-altitude fumaroles in South America, including the Geysers del Tatio (4321 m) and Sol de Manana sites. Past and present fumarolic activity has been identified as high as 6000 m in the Andes, where the boiling point is about 80°C. Fumarole wall samples will be retrieved for optical and electron microscopy, isotopic analysis, DNA extraction for molecular identification of organisms. We will also carry out colonization experiments, leaving sterilized silicate surfaces in place for a period of 1-2 years (Fig. 3.1.7c).

Fig 3.1.7c– Colonization experiments tested in fumaroles at Kilauea Volcano, Hawaii. Basalt sample were thin-sliced, attached to glass slides using high-temperature epoxy, and roughly polished. This provides a natural substrate for potential organisms.

2.1.8 An Integrated Model of the Planetary Water Cycle

Objective – Develop and refine an integrated model of planetary water, including mantle degassing, crustal hydration, dewatering at subduction zones, and escape to space. Use this model to explore the sensitivity of planetary water evolution to planetary mass, composition, and initial inventory of water.

Connections: §2.1.4, §2.1.9

Astrobiology Roadmap Links – Goals 3, 5; Objective 3.1
Researchers – Gaidos

Background – Earth's most visible inventories of water are its oceans, fresh-water bodies, and continental ice sheets, however an additional 40% is present as hydrous minerals in sediments and crustal rocks, and several oceans is contained in the hydrated mantle[200]. Mantle convection and plate tectonics mediates the exchange of water between surface and interior reservoirs. Mantle water partitions into the silicate melts created by the divergence of lithospheric plates and is volcanically outgassed at mid-ocean ridges. Water enters crustal rocks and sediments as hydrated minerals during continental and seafloor weathering and hydrothermal alteration of the oceanic crust. Much of this water is re-released during high pressure metamorphism and arc volcanism at subduction zones, but some fraction is returned to the mantle. The difference in these fluxes controls the evolution of the surface and mantle inventories of water over Earth history.

Although the current escape rate of water to space (as H) by thermal and non-thermal mechanisms is $\sim 10^{-6}$ oceans per billion years[225] and is negligible compared to the geological fluxes, more significant amounts of hydrogen (and equivalent water) may have been lost during the Archean (prior to 2.5 billion years ago) when molecular oxygen did not limit the mixing ratio of molecular hydrogen[108] or biogenic methane[84] in the trophosphere. Greater amounts may also have escaped to space via hydrodynamic space powered by giant impacts or higher solar ultraviolet radition early in Earth's history[92]. Conversely it has been proposed that additional water was brought to Earth subsequent to accretion by carbonaceous chondritic or cometary bodies[29]. These processes would obviously have effected the size of Earth's surface and interior inventories of water.

A minimum reservoir of surface water is probably required for planetary habitability, *e.g.*, to promote the precipitation of atmospheric CO_2 as carbonate minerals and its sequestration as crustal carbonate rocks so as to avoid a runaway greenhouse. In addition, surface water entering the crust can lubricate faults, weakening the brittle lithosphere and possibly enabling plate tectonics itself to function[168, 151]. The abundance of water in the mantle influences its rheology and solidus and thus exerts a powerful control on mantle dynamics and degree of mantle melting[82]. In turn, this affects the exchange of water between the surface and interior. Thus the partitioning of planetary water between mantle and surface reservoirs may be crucial to long-term habitability, especially if the initial surface inventory is removed early on and replenished by degassing of the mantle. In addition, hydrous melting is involved in the production of buoyant felsic crust that serves as the source material for continents. Continental growth is important factor in rates of weathering and atmospheric CO_2 levels, sequestration of organic carbon and stabilization of atmospheric O_2[13]. High oxygen levels and stable continental platforms may be prerequisites for the appearance of complex terrestrial life, and, perhaps, intelligence.

The inventories and cycling of water in Earth-size planets around other stars may be quite different than our own. The initial abundance of water may depend sensitively on the redox chemistry of the planet-forming nebula and water content of the planetary source material[68], the presence of giant planets which facilitate (or impede) transfer of water from the outer to the inner regions of a planetary system[125], and variation in the efficiency of loss processes such as impacts[141] or ultraviolet radiation-driven hydrodynamic escape[217]. The fluxes of water between the surface and interior can differ because of differences in the composition and melting properties of the planet's mantle and the abundance of heat-generating long-lived radioactive isotopes.

We are developing a model of the dynamics of water in and on a solid planet. Our objective is to understand the implications of differences in planetary mass, composition, environment and initial inventory on the long-term evolution of planetary water. Such models will be useful in predicting the potential diversity of Earth-mass companions to stars that might be directly detected by future space-based observatories such as those envisioned by the Terrestrial Planet Finder project[11]. We have developed an initial parametric model of an ideal, perfectly uniform mantle. Similar parameterized convection models include those of[131, 208, 18]. The thermal evolution of the mantle is set by the balance between the heat generated by the decay of long-lived radioisotopes, heat rejected by mantle convection, and mantle cooling. The convection involves a temperature- and water content-dependent viscosity[131] and the usual parametric relationship between heat flow and the mantle Raleigh number is assumed. The total spreading rate of the lithosphere is then calculated as a function of heat flow[131].

The evolution of the surface and mantle water reservoirs (W_s and W_m) is specified by the difference between the outgassing flux and the regassing and escape fluxes;

$$\frac{dW_s}{dt} = F_{out} - F_{recycl} - F_{esc} \tag{1}$$

$$\frac{dW_m}{dt} = -F_{out} + F_{reg} \tag{2}$$

The rate of outgassing is

$$F_{out} = C_{mw}\rho_m SR \int_0^{d_m} X dz, \tag{3}$$

where the concentration of water in the mantle C_{mw} is W_m/V_m, ρ_m is the average mantle density, SR is the spreading rate, d_m is the depth of melting, and X is the melt fraction. We assume that water partitions into the melt fraction X up to a specified solubility limit. We use an empirical melting parameterization to calculate the melt fraction and depth of melting[132].

The rate of recycling of water back into the mantle is the rate of subduction of water in lithospheric slabs corrected by a factor R_{reg} that accounts for the devolatilization and escape of water from unstable minerals;

$$F_{recycl} = (1 - R_{reg})C_{cw}\rho_c d_c SR, \tag{4}$$

where C_{cw} is the concentration of water in crustal minerals, ρ_c is the density of the crust, and d_c is the thickness of the hydrous crust. The amount of water in the crust will depend on the depth at which hydrothermal circulation penetrates, and on the mineralogy of the crust[99].

Fig. 2.1.8a shows the results of initial simulations with three different initial total inventories of water (measured in present-day Earth oceans). In each simulation, the initial surface reservoir is zero and the initial mantle temperature is set so that the mantle is in thermal equilibrium with the initial rate of heat production by long-lived radioactive isotopes. Using these assumptions, we find that the surface reservoir asymptotically increases with time. This result is consistent with the absence of any indication of a dramatic change in continental freeboard in the geologic record. The model (Fig. 2.1.8a) also correctly produces the current mantle potential temperature of the Earth but the estimated global spreading rate must be corrected by a factor of 1.7. Currently the model simulates only planets with contiguous oceanic crust; we will add the formation of continental crust to a later version. We will continue to improve the model, constrain the model parameters using the terrestrial case, and then use the model to explore the effect of varying the abundance of planetary mass, abundance of heat-producing long-lived radioisotopes, mantle composition, initial water inventory, and rate of hydrogen escape on the evolution of the planetary water cycle.

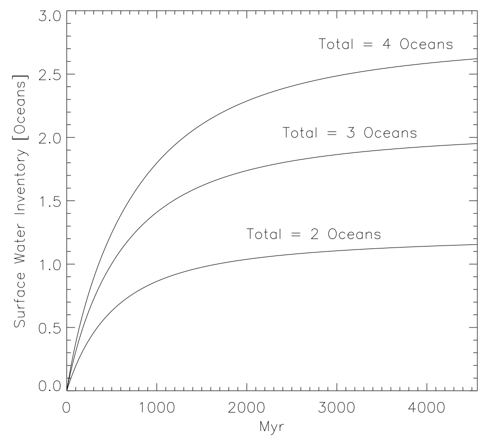


Fig 2.1.8a– Planetary surface water reservoir versus time for an Earth-like planet simulated using an empirical model of mantle convection coupled with a geologic water cycle model. Only the initial total water inventory is varied. See text for details.

2.1.9 Signatures of Water-Bearing Exoplanets

Objective – Model the water-rich comae of super-comets and planets experiencing atmospheric escape and determine their detectability. Evaluate the feasibility of the time-series spectroscopic determination of the abundance, distribution, and state of water on Earth-like planets around other stars using observations of earthshine reflected by the Moon.

Connections – §2.1.1, 2.1.8
Astrobiology Roadmap Links – Goal 1; Objective 1.1, 1.2
Researchers – Gaidos, Meech

Background – Nebular water will be removed with the rest of the primordial disk gas from a young solar system either by a T-Tauri wind or by incorporation into giant planets. However, volatiles, including water, will be retained for much longer periods of time in icy bodies or water-rich planets, depending on their masses and orbits. This water may be subsequently lost to space by direct devolatilization (in the case of an icy body) or by the ultraviolet radiation-driven escape of water-rich atmospheres. This process is still ongoing in our solar system, although it is now important only for comets. In the early Solar System, (dissociated) water would be escaping from the runaway greenhouse atmosphere of Venus[27] as well as from satellite-sized icy planetesimals scattered closer to the Sun by the giant planets. Are the extended, hydrogen/water-rich atmospheres/coma of equivalent objects around other stars detectable? Transient, doppler-shifted absorption lines in the spectrum of β Pictoris, surrounded by a circumstellar disk, have been proposed to be the result of comet-like "falling, evaporating bodies" crossing the stellar disk[15]. We propose to model the comae of "super-comets" and planets with hydrodynamically escaping atmospheres and determine if it is possible to detect them either in absorption or emission.

Space-based observatories have been proposed to directly detect and characterize Earth-sized planets around nearby stars[121, 11]. The ultimate goal of these projects is to ascertain whether a extrasolar planet has life by identifying "biosignatures" in a planet's spectrum, *e.g.*, atmospheric O_2, O_3, CH_4, or biogenic pigments such as chlorophyll. Time-series photometry and spectroscopy of an Earth-like planet may also reveal important physiochemical details about the surface and its habitability. These include the presence of oceans, clouds, ice caps, and deserts[60]. The thermodynamic state of water on a planet and its variability is fundamental to its climate and seasonality. Earth-like planets need not resemble the Earth as it is today: Large continental glaciations, episodes of intense warming (and cloudiness) and so-called "snowball Earth" events[85] would have dramatically altered the albedo and spectrum of the past Earth.

In the absence of known Earth-like extrasolar planets (and a space observatory to observe them), a suitable test of an observational strategy is to observe the Earth itself from a distance. Sagan[189] observed the Earth with the *Galileo* spacecraft and detected the chlorophyll "red edge" of terrestrial vegetation at $\sim$750 Å. A more cost-effective technique is to measure the intensity and spectrum of earthshine reflected by the dark side of the Moon. Two groups have derived the terrestrial albedo as a function of wavelength and report the detection of Rayleigh scattering at blue wavelengths and absorption features of ozone, molecular oxygen, and water[224, 6]. They also report the tentative detection of the chlorophyll red edge. The Earth exhibits significant albedo variations as a consequence of exposure of the Antarctic ice sheet to austral summer sunlight and changes in cloud and vegetation patterns[73]. But with limited temporal and spectral resolution, limited signal-to-noise, and no spatial resolution, how can clouds and ice sheets be distinguished? How can water-ice and CO_2-ice clouds be distinguished, particularly in the absence of independent temperature data? Can seasons be inferred solely by detecting changes in cloud cover patterns or the waxing and waning of ice sheets? These signatures may be subtle and difficult to deconvolve. While the absorption bands of water vapor may be obvious (at least from space), the spectrum of ocean water is blue and resembles that produced by Rayleigh scattering and an atmospheric aerosol component.

To answer these questions we are carrying out a long-term monitoring of the spectrum of earthshine with the UH 2.2 meter telescope and the HARIS spectrograph. The first observations are to be carried out during late March of 2003. The earthshine spectrum, modulo a constant, is obtained by dividing the spectrum of the dark side of the Moon by that of the illuminated portion. Care will be taken to remove from each spectrum the temporally interleaved spectra of the sky (which changes with time) and correcting for detector effects, including CCD fringing.

2.2 Extending the State of the Field – Relevance to Past, Current, Future NASA OSS Programs

We have chosen water, and its relationship to life, as both a unifying paradigm and interconnecting theme. Our consortium will advance the state of the field by placing the research of individual investigators into a framework in which the results in any given field will advance, or serve as the foundation of, research in other fields: Observations of the abundance and chemistry of water in star- and planet-forming regions provides the boundary counditions for experiments on space ices, which in turn are critically important to correct interpretation of observations of comets and the interstellar medium. Modeling of Martian hydrothermal systems is necessary for selection of terrestrial environments as appropriate analogs, exploration of which will help the search for potential habitats for and signatures of life on Mars. Modeling of the planetary water cycle requires information about water in planet-forming material provided by the study of meteorites and comets, and in turn informs searches for the signatures from water-bearing exoplanets.

In addition, the bulk of the funding requested in this proposal will support postdoctoral fellows who will be given access to facilities, the academic freedom, and the independence necessary to pioneer innovative and interdisplinary rsearch that includes, and builds upon, the research described in this proposal. In funding a corps of respected junior colleagues, allowing them to create a unique and independent environment (the "Water Hole") and connecting them to multiple investigators and research facilities, we plan to develop a unique assembly of scientists bonded by a common interdisciplinary research them rather than sometimes-anochronistic disciplinary ties.

Water underpins much of the current research of the Astrobiology Institute and our efforts would support these, as well as other NASA efforts, including the Mars Exploration Program and the Search for Origins. One of the products of this research will be an improved understanding of processes that control the frequency and nature of extrasolar planets with aquatic (*i.e.,* habitable) environments, information that is critical to the design of space observatories such as those envisioned by the Terrestrial Planet Finder project. Finally, much of this research will be carried out in Hawaii, a location where a variety of aquatic environments and their conjugate ecosystems, some unique can be studied. It is also a place where the theme of water has an obvious resonance and deep roots. As inhabitants of the most isolated archipelago on Earth, we will contribute a sense of importance to scienctific ties that span great divides of distance and discipline, and, as dwellers in an ocean, an appreciation both scientific and cultural to that great medium from which we all sprang.

This work is well-aligned with NASA OSS programs, closely following the Astrobiology Roadmap (as noted in each section). In addition, the work is closely related to many upcoming and proposed NASA missions, such as Deep Impact, Pluto-Kuiper Express, and most especially the Terrestrial Planet Finder. Our goal, in effect, is to establish the parameters of a "Watery Drake Equation", to better assess the properties which make a world habitable.

2.3 Technical Approach

2.3.1 Infrared Spectroscopy and Sub-mm Interferometry: Young Stars, Circumstellar Disks, and Molecular Clouds

Objective – Identify process and support instrument design for detection and measurements of ice and water biomarkers.

Connections – §2.1.1
Astrobiology Roadmap Links – Goal 3; Objective 3.1
Researchers – Reipurth, Williams, Ceccarelli

Background – We will determine the water ice distribution in molecular clouds by taking infrared spectra of field stars shining through the molecular clouds being investigated. We will obtain high-quality spectra (S/N of 30 or better in the continuum) of a variety of sources located behind the clouds and cloud cores of interest. For the study of water ice distributions in clouds and to explore differences between clouds we will use several telescope/instrument configurations (SPEX on the 3.5 m IRTF, UIST on the 3.9 m UKIRT) to achieve a resolving power of about 1000 in the K plus L bands. About 200 stars will be targetted, requiring about 20 nights, which over a five year period is about 2 nights per semester. For a study of the denser cloud cores we will observe about 20 - 30 stars using larger telescopes (the 8 m Subaru with IRCS, and the 8m

Gemini with NIRI) totalling approximately 10 nights, which is on average one night per semester if spread over 5 years.

For the study of hot water emission towards young stars with massive circumstellar disks we will use high-resolution infrared spectroscopy in the K-band with a resolving power of about 20,000. Since many of our targets are rather bright (K of 8 - 10), we can use medium sized telescopes (*e.g.*, IRTF with CSHELL, UKIRT with CGS4 or its successor), and only for the faintest objects do we need to go to very large telescopes (*e.g.*, Subaru with IRCS in its echelle configuration). Given that this is a largely unexplored research field, it is difficult to estimate the amount of observing time required, but we envisage using a total of around 6 to 7 nights on a 3-4 m class telescope and a few nights on larger telescopes for this study.

We will explore water masers in circumstellar disks by using the Very Large Array (VLA) in New Mexico. This is a general facility which we have used repeatedly in the past. We will employ the A-configuration at 4.86, 8.46, 22.255, and 107.1 GHz. The A-configuration is available approximately every 15 months, and we intend to submit our proposals for each of these deadlines for the coming years.

Through the UH access to telescopes on Mauna Kea, it is possible to dedicate large quantities of time to survey for sub-millimeter line emission from water related species in protoplanetary disks around young stars in nearby star forming environments using the Caltech Submillimeter Observatory (CSO) and James Clerk Maxwell Telescope (JCMT). The resolution of these data will be $\sim 10''$ which is sufficient only to allow abundance measurements to be made. Followup observations of disks with detectable lines will then be made with the SMA to map the different species at a few arcsecond resolution (few hundred AU). In addition to the line observations, the thermal dust emission provides information on the grain mass opacity and thereby the composition of the (icy) mantles. Millimeter interferometric observations of the LkCa 15 disk show interesting morphological differences at this scale[180]. Our proposed observations are at shorter wavelengths than this work and will target warmer gas closer to the protostar where abundances may be higher and line emission stronger. Progress in learning about protostellar disk chemistry will require large amounts of telescope time due to the multitude of species and relative weakness of emission. UH is in a unique position of being able to bring three sub-millimeter telescopes to bear on this problem, including the only one able to image at arcsecond resolution, and this survey can be expected, therefore, to make a signficant contribution to our knowledge of the initial chemical conditions of the solar nebula.

Atmospheric transmission (Fig. 2.3.1a) versus frequency for a range of precipitable water vapor (pwv) levels. The sky offers several "windows" which allow astronomical observations of the line and continuum radiation from the molecules and dust in star forming cores. There are very few telescopes in the world that operate at sub-millimeter wavelengths (ν > 300 GHz) and three are situated on Mauna Kea, including the only one (SMA) that will produce sub-arcsecond resolution images.

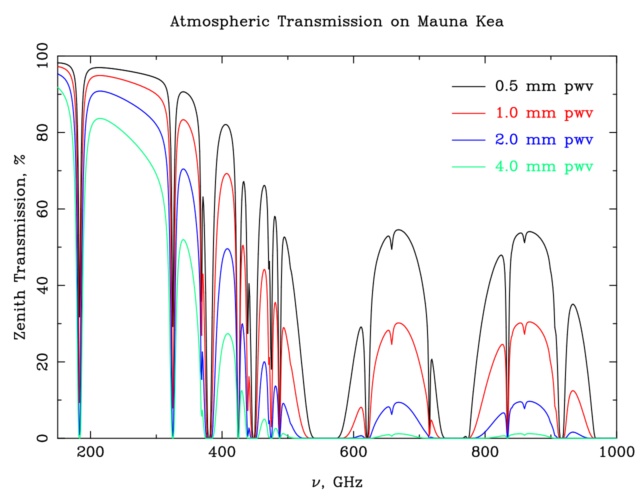


Fig 2.3.1a–Atmospheric transmission in the sub-mm.

Much of the opacity in the atmosphere at these wavelengths is due to water but the extremely dry conditions at the summit of Mauna Kea, pwv$\sim 0.5-1$ mm, allow for observations at frequencies as high as 900 GHz. Other sites with sub-millimeter telescopes in Europe and Arizona have much higher water vapor levels, pwv$\sim 2-4$ mm, and are consequently rarely able to observe at frequencies greater than 400 GHz.

2.3.2 Extraterrestrial Ice Laboratory Experiments

Connections – §2.1.3
Astrobiology Roadmap Links – Goal 3; Objective 3.1
Researchers – Kaise, Bar-Nun, Ehrenfreund

The Experimental Setup

The experiments on the interaction of charged particles and photons with extraterrestrial ice analog bodies are carried out in vacuum chambers which mimic the interstellar or solar system environments. All experiments will be carried out at the University of Hawaii in an existing oil free ultra high vacuum (UHV) vessel which has the following characteristics:

- Contamination-free operation at extreme ultrahigh vacuum conditions (pressures of about 10^{-11} torr),
- Reproducible preparation of thin frost layers ($<$ 500 nm),
- Target substrates which allow a rapid heat dissipation from the irradiated ices to the cold head thus minimizing surface heating and reaction mechanism changes,
- Temperature monitoring of heated ice surfaces and substrates,
- Preparation of clean charged particle beams and operation of monochromatic photon sources,
- Quantitative on line and in situ analyses of the solid state and the gas phase employing low background detection schemes.

This machine consists of an irradiation unit and a stainless steel chamber which can be pumped down to 3x10^{-11} torr by a magnetically suspended turbopump (Fig. 2.3.2a). A rotatable, two stage closed cycle helium refrigerator is attached to the lid of the machine and holds a polished silver mono crystal. This crystal can be cooled to 9.5 K, serves as a substrate for the ice targets and conducts the heat generated from the impinging photons or particles to the cold head. To allow a selection of any target temperature from 9.5 K to the sublimation point of the samples, a temperature sensor and a programmable heater are attached to the crystal. To assist a quick change of the irradiation source and maintain the UHV conditions in the main chamber, the irradiation unit is placed in a removable side chamber which can be separated from the machine through a gate valve. Three irradiation modules are necessary to simulate the CR and UV effects on interstellar ice mixture: the ion module (shown in Fig. 2.3.2a), the electron module, and a tunable photon source. Continuous ion beams are generated by an ion gun via electron impact ionization of a gas precursor, ion extraction, acceleration up to 5 keV, and mass separation of contaminants in a Wien filter. The current of the charged particles is monitored by a Faraday cup. Since the gas load inside the main chamber has to be kept to a minimum during the irradiation to avoid any condensation of contaminants on the ice surface, the ion source is triply differentially pumped by magnetically suspended turbomolecular pumps backed by oil free scroll pumps. This pumping scheme reduces the pressure from 10^{-4} mbar via 10^{-6} mbar, 10^{-8} mbar, and 10^{-10} mbar to $3x10^{-11}$ mbar in the main chamber. Secondly, electrons with kinetic energies up to 5 keV are generated by an electron gun. Due to the modular design of the irradiation unit, the ion source can be simply replaced by the electron gun, which is interfaced then via two differentially pumped regions to the main chamber. Thirdly, photolysis experiments are performed employing a differentially pumped ultraviolet source which is also interfaced together with the differentially pumped monochromator region through two differentially pumped chambers to the main recipient. The advantage of the tunable photon source is the wavelength selectivity. Since experiments are performed at distinct wavelengths, a complete picture of the underlying photochemical processes can be obtained. The main chamber has spare ports, and simultaneous photon/particle irradiation can be also conducted.

To guarantee an identification of the reaction products in the ices and those subliming into the gas phase on line and in situ, two detection schemes are incorporated: (*i*) a Fourier transform infrared spectrometer (FTIR), and (*ii*) a quadrupole mass spectrometer (QMS). The chemical modification of the ice targets are monitored during the irradiation experiments to extract time-dependent concentration profiles and hence production rates of newly formed molecules in the solid state. Since no QMS can distinguish multiple $C_2H_4O_2$ isomers from the raw data alone, the mass spectrometer must be calibrated first for the fragmentation patterns of distinct isomers of interest; hereafter, these raw data are processed via matrix interval arithmetic to extract quantitative information on the isomers formed.

Fig 2.3.2a–Schematic top view of the simulation chamber, ion irradiation unit, quadrupole mass spectrometer (QMS), Fourier transform infrared (FTIR) spectrometer, and the gas condensation unit.

Ice Mixtures–Mechanisms for Formation of $C_2H_4O_2$ Isomers in Interstellar Ices

We elucidate now the mechanisms by which glycolaldehyde, acetic acid, and methyl formate might be formed inside interstellar ices via charged particle bombardment and photolysis. Synthetic routes are derived combining concepts of suprathermal chemistry[102, 187] and photochemistry[212] together with a classical retrosynthetic approach[127]. This will ultimately identify those molecules as potential precursors to the $C_2H_4O_2$ isomers and guide the selection of ice mixtures in our simulation experiments. Note that due to the complexity of the interstellar environments no single experiment can mimic all effects simultaneously, and an understanding of elementary processes must be based on experiments involving binary systems first before extending them to more complex ice mixtures. As evident from the structures of the $C_2H_4O_2$ isomers, the CO_2-unit can be found in acetic acid and methyl formate, whereas the CO-moiety is present in all isomers (Fig. 2.3.2b). Since CO and CO_2 are common in astrophysical ices, we investigate first if binary ice mixtures CO/CH_3OH (mixture 1) and CO_2/CH_4 (mixture 2) synthesize any $C_2H_4O_2$ structure.

Considering a CH_3OH molecule, a photon or particle can split the CH_3-OH (1.1), CH_3O-H (1.2), or H-CH_2OH bond (1.3) to yield [CH_3 ... OH], [CH_3O ... H], and/or [H ... CH_2OH] radical pairs which could react with a CO molecule to acetic acid, methyl formate, and glycolaldehyde (Fig. 2.3.2b). Similarly, a CH_3-H bond in a CH_4 molecule can be broken to form a [CH_3...H] pair; the radicals/atoms might add to a CO_2 neighboring molecule in the ice matrix to give acetic acid (2.1) or methyl formate (2.2). All routes to $C_2H_4O_2$ investigated so far require only one bond rupture in a single molecule; both reacting radicals/atoms originate from the same precursor. However, reactants could emanate from two different molecules, and two bond ruptures prior to the reaction are required. Hence, ice samples with formaldehyde (H_2CO) are studied, as the formyl group (HCO) is present in methyl formate and glycolaldehyde. Binary mixtures of H_2CO/CH_3OH (mixture 3) could form methyl formate (3.1) and glycolaldehyde (3.2).

After binary mixtures have been investigated comprehensively, ternary mixtures with a radical plus an atom precursor, which requires two bond ruptures, will be also studied. These involve mixtures of CO with CH_4/H_2O, CH_4/CH_3OH, H_2O/CH_3OH, and of CO_2 with CH_4/H_2O, CH_4/CH_3OH, and CH_3OH/H_2O. To get information on the reaction mechanism, isotopic substitutions will be performed. For example irradiation of CH_3OH/ CO/H_2O could give CH_3 (from CH_3OH) and OH radicals (from H_2O) which might react with CO to acetic acid. Since CH_3OH can be cleaved to CH_3 plus OH as well, both CH_3OH and H_2O can form OH. The dominating pathway is unraveled using CH_3OD which produces only OD. CH_3COOH and CH_3COOD have different infrared spectra and can be discriminated experimentally. Note that the radical species formed can recombine either in a radical pair cage inside the solid ice even at temperatures as low as 10 K or - if they are separated inside the ice matrix - after annealing of the ice target in the hot core phase to allow the radicals to diffuse. Since the production rates of the $C_2H_4O_2$ isomers are expected to depend on the initial concentration of the ice components, experiments have to be performed at various concentrations of the ice constituents.

Besides simple bond rupture processes followed by atom/radical additions and recombination reactions, we have to investigate also to what extent insertion processes of suprathermal particles can lead to the $C_2H_4O_2$ isomers. Note that in the following considerations, the spin states of the reacting particles are omitted for clarity. Further, the reader should keep in mind that the reaction of a suprathermal particle with a thermal molecule leads to highly internally excited molecules. In the gas phase, the latter fragments, but inside ices, the surrounding matrix might absorb the excess energy of the newly formed molecule via phonon interaction. Acetaldehyde (CH_3CHO) and formic acid (HCOOH) are identified as the key reactants in this scheme.

Here, suprathermal oxygen atoms, which can be formed as knock on species via interaction of the primary implant with water molecules (CH_3CHO/H_2O; mixture 4) as the dominant constituent of extraterrestrial ices, can insert into the carbon-hydrogen bond of the methyl group of the acetaldehyde molecule to form glycolaldehyde (4.1); an insertion into the carbon-carbon and formylic carbon-hydrogen bond leads to methyl formate (4.2.) and acetic acid (4.3.), respectively.

Fig 2.3.2b–Formation of $C_2H_4O_2$ isomers via simple bond ruptures followed by addition of atomic hydrogen and/or a radial and recombination of radicals (left) and via insertion of suprathermal oxygen atoms and carbene radicals (right).

Alternatively, insertion of carbene radicals (CH_2), which can be generated via interaction of charged particles with methane molecules (CH_4/HCOOH; mixture 5), can undergo three distinct insertion reactions into the carbon-hydrogen (5.1.), oxygen-hydrogen (5.2.), and carbon-oxygen bonds (5.3.) to form acetic acid, methyl formate, and glycolaldehyde, respectively. These considerations make it clear that charged particle irradiation of binary ice mixtures of H_2O/CH_3CHO and CH_4/HCOOH could yield all three $C_2H_4O_2$ isomers.

Note that the single insertion process of a carbine radical can be substituted by an insertion of a carbon atom or methylidene radical (CH) followed by two or one hydrogenation steps, respectively. We like to stress, that after binary mixtures have been exposed to high energy radiation in the laboratory, it is crucial to prepare ternary mixtures of these ices into a water-rich matrix. Water is the dominant component of the interstellar and comatary ice component, and the production rates depend strongly on the nature of the ice matrix.

2.3.3 Comet & Centaur Observations

We will obtain JHK ($1.2 \leq \lambda \leq 2.4$ μm) spectra of a sample of ∼50 bright Centaurs and Kuiper belt objects using the Keck, Subaru and Gemini 8-m and 10-m class telescopes. These spectra will be used to determine the surface abundance of water ice from the 1.5 μm and 2.0 μm spectral features, and to search for expected correlations in the water ice abundance with object distance and size. The spectral properties of amorphous and crystalline water ice are measurably different (see reference by John Davies). We will use this fact to place a limit on the abundance of amorphous water ice or to detect it. As noted, this places an upper bound on the temperature experienced by a given body. We will also search for indications of organic and other surface molecules, like those already found in Centaur 5145 Pholus.

The presence of organics is most easily ascertained from the ultra-red optical reflection spectra, of which 5145 Pholus remains the prime example. We will obtain calibrated optical reflection spectra of 100 Centaurs, KBOs and cometary nuclei to examine the incidence of surface organics. We are interested to know whether the organics so prevalent in the outer solar system can survive passage to the hot inner regions. Recent observations, for instance, suggest that they cannot, based on the relative lack of ultrared objects amongst the comets and dead-comets[?].

While detailed compositional studies of the organics are not possible from low resolution spectra alone, we will, with the aid of laboratory experiments, be able to make useful statements about the degree of hydrogenation of the organics. The ability to take comparable spectral datasets for astronomically remote objects and for laboratory samples designed to model those objects constitutes a powerful aspect of our collaboration. Presently, the literature contains irradiated ice spectra from the laboratory that are difficult to compare with real astronomical data. In some cases this is because the spectral resolutions are mis-matched, in others it is because the relevant spectral range has not been sampled or because astrophysically relevant ice mixtures have not been employed. We will have complete control over all these aspects, and will ensure that the laboratory spectra are fully comparable with those obtained at the telescope.

2.3.4 Comet Isotopic Measurements

Comet Observations

In this proposal, we will use the observational facilities atop Mauna Kea to obtain measurements of cometary D/H in comets having a wider range of dynamical characteristics and origins than the 3 already sampled. The James Clerk Maxwell Telescope (JCMT) has been used to study the $1_{01} - 1_{00}$ line of HDO at 464.92452 GHz in comet Hale-Bopp. This high frequency line is challenging because of telluric absorption: Mauna Kea is probably the only place on Earth where it can be studied. In addition, the new Submillimeter Array Telescope (SMA), will have sensitivity and higher angular resolution at the HDO line. The key is to find comets that are bright enough to permit useful signal-to-noise ratio spectra to be obtained. In practice this means comets must be observed when near the sun and at small solar elongation angles. The optically opaque Gore-Tex screen of the JCMT makes such observations routine.

Here the main emphasis, aside from seeing if there are real variations in D/H among these comets will be to test the pristine nature of the comets. How extensive was the mixing of interstellar material with material in the solar nebula? Can we assume that comets in other systems will resemble ours (little mixing) or will the comets of a given system be dependent on the structure and composition of the local circumstellar nebula (extensive mixing)? The answer will determine to what extent we can generalize the transport of water in our system to other systems. The question can be addressed by investigating D/H and $^{15}N/^{14}N$ in more compounds in more comets, and comparing the results with values measured in interstellar clouds.

For Kuiper belt comets, conceivably the D/H in their water could match that in seawater, but they are too faint to investigate from Earth. However, these are the ones that missions can go to. Owen is Co-I on the Rosina mass spectrometer that will be carried on the Rosetta Spacecraft. This instrument will not only measure D/H in the comet's water, it is capable of measuring the noble gas abundances and isotope ratios, including xenon, in the comet, thereby testing the hypothesis that comets might have brought these particular volatiles to Earth. If they did, they obviously would have brought SOME water as well as organic compounds and other sources of nitrogen. Rosina will also measure the nitrogen isotopes in the comet, providing another test of cometary delivery of volatiles to Earth. We now know that the nitrogen in Hale-Bopp's HCN has an isotope ratio close to the telluric value, but HCN is a minor constituent of comets, so we need to evaluate the total cometary nitrogen, and this Rosina can do.

Mars Observations

As a starting proposition, one might expect that Mars had the same sources of volatiles as the Earth. Support for this assumption comes from a study of noble gases in the Martian atmosphere, which shows that Ar/Kr/Xe and the Xe isotopes are virtually identical on Mars and Earth. We can test the water on Mars by remote observations from Earth and by studies of Martian meteorites (SNCs). We find that water in the Mars atmosphere shows the effect of atmospheric escape: D/H is 5.5 times the value in seawater. Water in minerals in the SNCs shows a range of values of D/H extending to the value measured in atmospheric water, showing that some of this water must have become incorporated in the minerals. But the lowest value of D/H in these minerals is not the value in our oceans, it is the twice higher value found in comets.

Finally, the xenon in the rock that comes from the greatest sub-surface depth shows xenon with solar isotope ratios, rather than the atmospheric values that mimic those on Earth. Thus the stage is set to use Mars to test ideas about the origin of volatiles on Earth. To pursue this investigation, a postdoc supported by the present grant could collaborate to investigate the Mars rocks further to unravel the evolution of the Martian atmosphere and to evaluate the water content of the Martian interior. For example, it will be interesting to compare the total water on Mars with the total on Earth, to see if there is a model for water delivery that is compatible with these results.

2.3.5 Instruments for the Identification of Biomarkers

Objective – Identification of processes and instruments relevant to ice and water bio-markers measurements.

Connections – §2.1.6, 2.1.7
Astrobiology Roadmap Links – Goal 7; Objective 7.2
Researchers – Anderson, Gaidos

Background – Detection and identification of biomarkers and bio-molecules in extraterrestrial aquatic environments remains a key challenge for future exploration of planetary bodies[143], *e.g.*, the posited sub ice oceans of Europa[202, 112], the icy polar caps of Earth, Mars, Callisto, and the icy surface of Europa. Our approach will use knowledge of these types of water and ice locales as the basis for testing both vehicles and instruments required to find bio-habitats, as well as the specific measurements that will most rapidly assess the presence of biomarkers in that environment. Our proposal specifically seeks funding to support continued operational testing of a unique Cryobot vehicle for in-situ analysis of ice and water environments, in conjunction with sample handling and biomarker detection studies using simple definitive instruments tested in both the laboratory and in analog sites.

The Cryobot is a tethered vehicle capable of penetrating ice to kilometers of depth using a combination of passive heating and active hot water jetting that has been developed by partners at both the University of Hawaii and the Jet Propulsion Laboratory (Fig. 2.3.5a, b). It has the advantage of being small in size, mass, and power, while providing the capabilities of a hot water drill, while considerably simplifying ice contamination issues from both dangerous drilling fluids and surface biology. The onboard avionics allow the Cryobot to steer, cut side channels to store debris, and transmit real time data to the surface via a tether that spools from the back of the vehicle, allowing it to continue descending following refreeze of the bore hole. The tether supports gigabit communication speeds, enabling realtime high resolution video, mass spectroscopy, and sample handling.

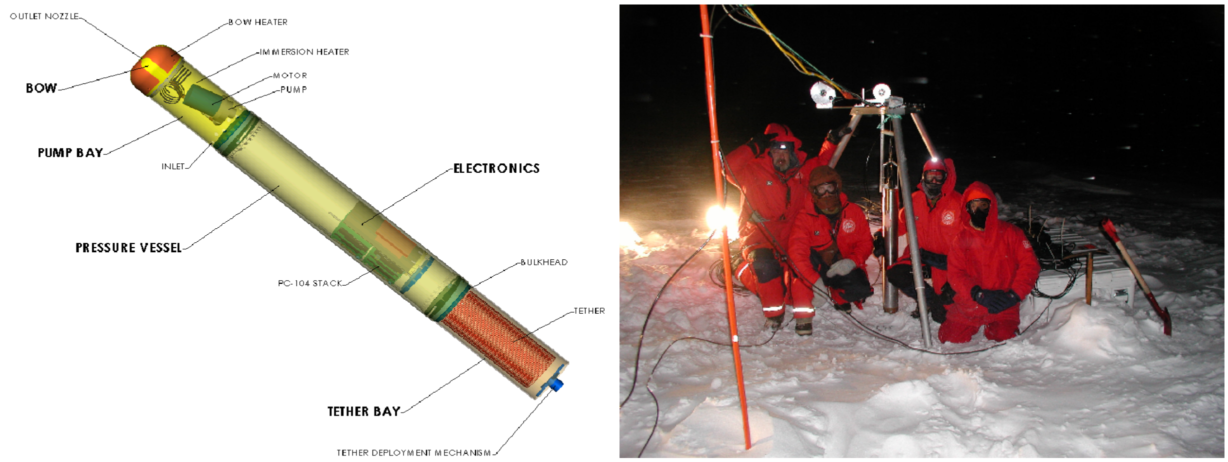


Fig 2.3.5–*a)* Funding from this proposal will aid in linking technology development, such as the ice drilling Cryobot vehicle shown above with astrobiology instruments appropriate for watery and icy environments. The Cryobot is a fully independent robotic vehicle, including: 1) a nose that heats and jets hot water, 2) an instrument and avionics bay containing an advanced computer and control system, including directional control and fault tolerance, as well as on-board analytical capability, and 3) a fiber optic tether capable of transmitting video and gigabits of instrument data in real time. *b)* The Cryobot has been tested in extreme environments, including the northern polar island of Svalbard, Norway, in winter. Additional funding will be used to bridge the existing design with our ongoing science efforts in Iceland and in the laboratory. The system does not use environmentally harmful chemical like many ice drilling methods, protecting the biosignatures that the science effort seeks to measure.

The vehicle has been tested in ice sheets during the harsh winter in Svalbard, Norway, and is ready for integration with instruments, as well as testing of sampling and sterilization technology. It can also be used in the deep ocean to study hydrothermal vents, and other astrobiologically significant targets. Though not selected, the vehicle was one of the most highly rated Scout proposals for exploring Mars, and is under consideration for the ice penetrating studies of other icy bodies in the solar system. Further development of this system by terrestrial analog studies is supports the long term astrobiology infrastructure of searching for life associated with water. Our proposal seeks money to support laboratory tests of the existing vehicle, as well as funds to allow us to use the vehicle in ice and lakes in collaboration with our other projects in Iceland, Antarctica, Kauhako Lake crater on Molokai, and Lake Waiau near the summit of Mauna Kea.

Identification of processes and instruments relevant to ice and water bio-marker measurements is ongoing, and is one of the weakest links in the existing astrobiology infrastructure. While numerous astrobiology detection concepts have been suggested[7, 160, 161, 86, 56], no definitive flight ready astrobiology instrument exists today. To that end our NAI proposal will focus on the provenance and association of life with water to the design and selection of appropriate instruments for planetary use. We will both partially support new instrument designs as well as survey the astrobiology instrument field, as a wide range of possible instruments are planned or are in partial stages of completion throughout the planetary science community. This effort will focus on identifying the most relevant instruments for the ice and water environment, as well as the basic technology hurdles to their broader acceptance within the ASTEP or ASTID programs. Successful interpretation of complex natural environments will require detailed laboratory study of the physical processes that produce a measurable astrobiology signature in water and ice, which we will carry out at the University of Hawaii in our existing labs, as well as in partnership with the National Ice Core Laboratory (NICL), in Denver Colorado. Our proposal effort will focus on processes and related measurement techniques by using samples obtained from terrestrial analogs, including the dry deserts of Antarctica, the relatively wet environments of the desert southwest, and the unique water environments in Hawaii. Hence, the research effort we are proposing has specific strengths in that it builds on:

- The Astronomy and Laboratory portions of this proposal, including the sources, sinks, and history of astrobiologically relevant water.
- The rich history of design, construction, and field use of instruments in the harshest environments by the University of Hawaii, including a range of spectrometers and wet chemistry systems. For example, the University has recently deployed mass spectral systems to 4000 m in hydrothermal vents, and demonstrated stand-off Raman instruments.
- Integrates previous work for identifying biomolecules and markers, both at the University[12], and in the literature.
- Integrates new measurements using instruments currently being proposed by the University of Hawaii for astrobiology by testing them at terrestrial analog sites, as well as supports a inclusive effort to identify the physical processes underlying biologic processes that will produce the definitive instruments of the future.

Definition of Biomarkers

There are two broad classes of environmental signatures that can be interpreted as evidence for life: geochemical fractionation and direct bio-molecule identification. One task of this proposal will support the ongoing development of astrobiology instruments for the direct detection of biomolecules in water or ice enivronmnets. A second will be a feasibility analysis to use the basis for new ASTID, ASTEP, PIDDP, and MIDP proposals. We will demonstrate the practicality of using of a rotating field mass spectrometer (RFMS) currently in our possession at the University of Hawaii to search for biosignatures such as stratified geochemistry both using the Cryobot and samples from hydrothermal vents, Antarctic ice cores, and field-testing in Iceland. What makes the RFMS truly unique is its rotating field approach, which allows us to measure molecules with weights from 1-100,000 daltons, far more than comparable systems, with a length of $\sim$6 cm and no precision parts (Fig. 2.3.5c). Because RFMS uses a semi-soft-ionization technique, this range is sufficient to measure elemental abundance, ions, and large organic molecules. We will calibrate the instrument by measuring the inorganic, organic, and isotopic chemistries of a variety of liquid samples containing biosignatures. These instruments are currently operational, and demonstrated at high-pressures and extreme temperatures (Fig. 2.3.5d).

In addition to supporting lab testing of the instrument, we propose to use funds from this proposal to enable us to test this instrument on currently proposed NSF and future ASTEP ice projects. These bridging funds will allow us to bring along the existing instrument on these additional field proposals to constrain real world sensitivity to biosignatures. The proposed effort will not only return useful science data on the range of environments conducive to life, but provide real world in situ testing of advanced instrumentation that could be used to study oceans, ice sheets, and hydrothermal vents on Europa, or the icy poles of Mars. These technologies enable the science goals of MEPAG, ASTEP, and the Europa Focus Groups, and represent a convergence of science objectives, enabling technologies, and field deployment experience. This technology will enable NASA to directly search for biomarkers, measure the metabolic potential of biota should they be present, and characterize the geologic and climatalogic environment whether or not biosignatures are present.

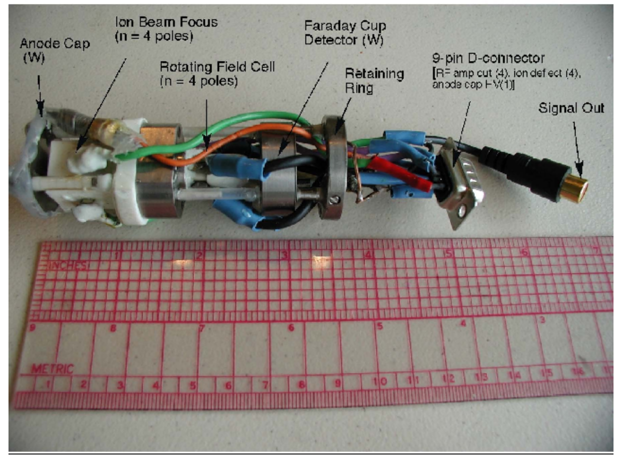


Fig 2.3.5c–The core of the RFMS instrument shown here is small and tolerant of the space-flight environment. Funds from this proposal will be used to test the sensitivity of the existing instruments using lab standard biomolecules from the American Type Culture Collection (ATCC), and bridge the existing technology with ongoing science efforts.

Fig 2.3.5d–The RFMS instrument, shown here in a very large pressure chamber, has been used in high pressure aqueous environments similar to those that may be analogs for life on Mars or on Europa. While the instrument casing shown here is not suitable for ultimate space-flight, we are interested in lab testing, as well as ultimate modification for Cryobot use.

Cellular Membranes (Lipids)

Biosignatures in organic lipids include specific biomarker compounds and other features (stereochemistry, non-random distributions) of the lipid fingerprint that cannot be explained by abiogenetic synthesis[149]. Both lipid distributions and the occurrence of complex molecular structures requiring biosynthesis (biomarkers) are important when screening for organic biosignatures. In screening for biomarkers it may be possible to recognize whether any of the three extant domains, Bacteria, Archaea and Eucarya, were present by including hopanes, head-to-head isoprenoids and steranes, respectively, in the search protocol used to interrogate the mass spectra. Distributions of non-biomarker compounds can amount to a biosignature, *e.g.*, a normal alkane distribution that shows predominance of the even (or odd) carbon numbered compounds, reflecting biosynthetic pathways that homologate by two-carbon increments.

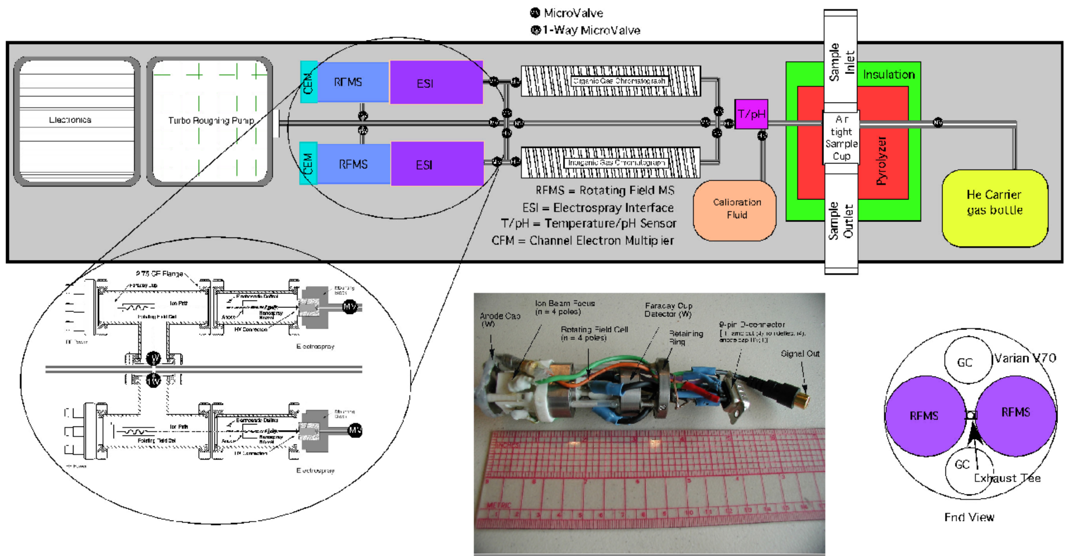


Fig 2.3.5e–New designs for incorporating pyrolysis and gas chromatography into a RFMS system are currently under consideration. We will use funds from this proposal to use the ATCC samples as a test suite for designs like the one shown here, to determine their sensitivity to bio-molecules.

In general, lipids are found as complex mixtures. We can recognize biosignatures in these mixtures when their composition is out of balance with what could be formed from abiotic synthesis alone. Characteristics of a biosignature may include (1) excesses of some structural isomers or homologues over others outside the realm of possible random (abiotic) synthesis, (2) repeating structural sub-units in a molecule, for example, the C_5 isopentene sub-units in isoprenoids, and (3) enantiomeric or other stereochemical excesses that do not reflect relative thermal stability.

The most abundant large lipids produced either by abiogenetic processes or by enzymatic synthesis are the normal alkanes. A large component of these are biosynthetically produced as functionalized compounds, such as fatty acids. Fischer-Tropsch synthesis, an abiotic process, also produces these straight hydrocarbon chains, again mostly with functionality. The smooth distribution (by gas chromatography or gas chromatography-mass spectrometry) of fatty acids or n-alkanes in a Fischer-Tropsch product typifies what would be expected from abiotic synthesis[129]. This distribution of homologs is controlled by conditions of the synthesis, such as temperature, pressure, and catalyses. In contrast, biogenic distributions typically show predominance of the even carbon numbered homologues unless they are obscured by thermal alteration or diagenesis. For example, diagenetic effects of clay can result in decarboxylation and produce an n-alkane distribution with an odd C-number predominance. But the biosignature, though altered, remains legible because it differs from the smooth distribution characteristic of an abiogenic origin. Simple methyl-branched alkanes whose methyl group shows a positional preference along the carbon chain may be a key biosignature, because of the link between these lipids and primitive organisms[110].

Many biomarkers carry taxon specificity in which they show input from various kingdoms, families and even individual species. Examples of taxon specific biomarkers[149] from the three domains, Bacteria, Archaea, Eucarya, are hopanes, head-to-head linked isoprenoids and steranes, respectively. Squalene is a widely used isoprenoid intermediate in the biosynthesis of many polycyclic biomarkers, but the cyclization varies in different domains[172]. Bacteria cyclize squalene to make hopanes while in Eucaryas squalene lies on the pathway that eventually leads to sterols. Archaea have a unique way of joining isoprenoids to form a head-to-head linkage.

Analysis of samples from water or ice environments composed of living or recently living organisms in complex mixtures, *e.g.*, from natural ecosystems, presents a challenge. The challenge is to recognize key biomarkers and biosignatures against a large background of organic debris that is un-interpretable as a biosignature. A primary task is to determine the biomarker detection limits of the RFMS instrument and to recognize any biomarkers or biosignatures by in situ analysis. This ability will be demonstrated by lab tests under various conditions that simulate the kinds of primitive extraterrestrial ecosystems that might exist now or in the past. We further propose to optimize our RFMS system for biosignature detection by integrating a laboratory gas chromatograph and pyrolyzer system, allowing us to determine sensitivity for measurements of key biomarker information such as lipid compounds and isotopic biosignatures, amongst a wide range of other biomarkers (Fig. 2.3.5e).

Other Approaches: Amino Acids & ATP

Amino acids are the building blocks of proteins and enzymes required for life in terrestrial organisms. A capability to engage in direct detection of amines, amino acids, and poly-aromatic hydrocarbons would provide a useful tool for distinguishing between biotic and abiotic organic compounds. For example, homochirality of amino acids provides an unambiguous indicator of a potential biogenesis[8]; D-amino acids would suggest a non-terrestrial origin, while the detection of non-racemic amino acids would favor a biotic origin. ATP is used as an intermediate energy-storage molecule by ll life on Earth. A number of ideas exist for the in-situ identification of ATP, including UV fluorescence, and the labeling of phosphates for uptake and respiration of organisms. These labeled phosphates can then be identified via mass spectroscopy or tunable diode laser spectroscopy (TDLS). While we currently do not have active programs supporting in-situ analysis of these types of biosignatures, we will provide a comparative analysis of the strengths of these types of instruments of use in ice or water as part of our study. Specifically, we propose to study: 1) microchip capillary electrophoresis systems capable of identifying both any amino acids and enantiomeric composition of a compound, following the work of[96], and 2) ATP detection using UV florescence, mass spectroscopy, or TDLS.

2.4 Outline of Work Plan

The proposed research framework will support a group of postdoctoral scholars who will carry out independent, interdisciplinary research spanning two or more of the investigators' (or affiliated investigators') research specialties. The funding for an NAI does not equate to a substantial amount of money per Co-I, and is not intended to fund major new instrumentation initiatives, but is rather a seed to foster collaborations among existing groups. We are proposing an innovative model to maximize the collaborative science output. By supporting a group of postdoctoral scholars we intend both to influence young scientists at a formative phase of their careers, and to provide them with a circle of expert faculty advisors and collaborators from diverse but interconnected research backgrounds.

2.4.1 Management Approach

Since interaction between scientists working in different areas is the key to the success of our astrobiology institute, we will employ a management style that heavily promotes interaction. The PI will take overall responsibility for ensuring the vigor and success of the effort. She will hold bi-weekly meetings with the co-investigators to discuss research direction and progress, financial/management issues and to ensure an active E/PO effort with broad participation.

The co-Is are widely scattered over the University of Hawaii campus and beyond, meaning that face-to-face contacts must be engineered in order to provide a microcosm of the distributed researchers' network which is intrinsic to NASA's astrobiology institutes. We will use 2000 sq. ft. of office space provided to this project by the University President to provide a focal point and venue for regular meetings. These will include weekly meetings at which current research results of the Oo-I's and astrobiology postdocs will be presented and discussed. In addition, the UH-NAI will offer an astrobiology seminar series in which broad university and community involvement will be sought. A sophisticated software tool will be implemented to facilitate scientific interaction between members of the group, building on the capabilities of the NAI Science Organizer. The outside collaborators will be involved in this through the Visiting Scholars Program and frequent communications.

2.4.2 Timelines & Deliverables

With a collaborative framework of this magnitude, there will undoubtedly be a wealth of new ideas, and research directions initiated. However, we do have a set of well-defined deliverables which involve our collaborative efforts.

1. *The Origin of Water and the Formation of Stars and Planetary Systems –*

§	Time	Investigators	Task
2.1.1	5.0 yr	Reipurth, Williams	IR spectra of ∼230 background stars, 20 young stars
2.1.1	5.0 yr	Reipurth, Williams	Water maser maps toward 10 stars
2.1.1	1.0 yr	Williams	Submm interferometry, 20 disks (chemistry), 2 mapped in detail

2. *Obs. and experimental investigation of interstellar and cometary water ice chemistry –*

§	Time	Investigators	Task
2.3.2	5.0 yr	Kaiser	120 ice irradiation experiments
2.1.2	0.5 yr	Kaiser, Bar-Nun, Ehren.	Ne/Ar/Kr/Xe ratios trapped in amorphous ice in the presence of excess CO, N_2
2.1.2	1.0 yr	Kaiser, Bar-Nun, Ehren.	N_2/CO in cometary ices
2.1.2	1.0 yr	Kaiser, Bar-Nun, Ehren.	Gas trapping in CHON particles
2.1.2	4.0 yr	Kaiser, Bar-Nun, Ehren.	Mini-enzymes formation in aqueous media

Note: Typically, one experiment takes 2 weeks (ultra high vacuum generation, preparing ice mixtures, carrying out the irradiation). Including maintenance time (1 mo/yr), 24 irradiation experiments can be conducted per year. Each mixture has to be investigated at different temperatures, irradiation sources, and particle/photon energies. Realistically, we investigate then 10 distinct ice mixtures each at 10 different parameter sets (T, energy, flux).

3. *Origin and Distribution of Planetary Water –*

§	Time	Investigators	Task
2.1.4	1.0 mo	Keil, Krot, Scott	X-ray mapping of 2-5 thin sections of 6 chondrites, backscattered electron studies and electron microprobe studies

4. *Water and Aqueous Alteration on Mars –*

§	Time	Investigators	Task
2.1.5	1.0 yr	Taylor, Gaidos	Develop model of melting ice fields and hydrothermal systems on Mars

5. *Water-rock Chemistry and Habitats for Life –*

§	Time	Investigators	Task
2.1.6	3.0 yr	Cowen, Mottl, Gaidos	Assay biological activity carry out survey of microbial community in lava-seawater plumes
2.1.6	5.0 yr	Cowen, Mottl	Microbial diversity & physiology in low water/rock oceanic crusts
2.1.6	2.0 yr	Mottl	Geochem char of unusual low T, high pH/alkalinity fluids emanating from mud volcanoes at Maiana forearc
2.1.6	3.0 yr	Mottl, Cowen	Char microbial communities of low T high pH/alkalinity fluids at Maiana forearc

6. *Extreme Aquatic Environments & Their Analogy to Potential Habitats in the Solar System –*

§	Time	Investigators	Task
2.1.7	5 yr	Thorsteinsson, Gaidos	Survey biological activity and community composition in Iceland subglacial environments
2.1.7	5 yr	Gaidos	Survey biological activity and community composition in high-altitude fumaroles

7. *An Integrated Model of the Planetary Water Cycle –*

§	Time	Investigators	Task
2.1.8	2 yr	Hammer, Keil, Gaidos	Develop an integrated model of the geologic water cycle and explore the parameter space based on plausible models of planet formation and composition

8. *Signatures of Water-Bearing Exoplanets –*

§	Time	Investigators	Task
2.1.9	5 yr	Meech, Gaidos	Conduct long-term monitoring of earthshine spectrum with particular attention to signatures of water and model its diurnal, season, and interannual variations. Develop model of water loss from planets and giant comets around young stars and assess its detectability

2.4.3 Role of Co-Investigators and Collaborators

All of the project Co-Investigators are taking an enthusiastic and active role in the proposed UH-NAI, regardless of financial support. The core team of Co-Is are those who have been involved in the discussion and planning of the UH-NAI, some since the last Cooperative Agreement Notice. The core team represents 1-2 lead scientists in each of the major water-related disciplines of our research theme. Collaborators , in general, are providing invaluable (non-funded) contributions in more specialized areas of science. This group also includes our international colleagues. All of the Co-Is will be involved in the weekly meetings discussed above, and the local collaborators will be encouraged to join. In addition, we plan an active visiting program with our international collaborators (3.2.2)

- **Meech –** As PI of the program, Meech will be responsible for the overall management of the group. In addition, she will actively conduct research in the areas of cometary studies outlined above. In addition, because of her experiences with running large outreach programs, she will contribute to the E/PO component of the NAI.

- **Anderson –** Anderson will supervise a series of lab based life detection experiments in laboratory ice using technologies like the unique ice penetrating probe, the cryobot, and instruments such as the rotating field mass spectrometer. In addition, these experiments will be extended to ice cores at the National Ice Core Laboratory, which houses cores from around the world. The instruments will also be tested in the glacial lake on the summit of Mauna Kea.

- **Binsted –** Binsted will be responsible for designing, implementing, testing and evaluating a software tool to aid interdisciplinary scientific collaboration. She will also conduct research in scientific visualization and collaborative systems. Because the resulting network of astrobiological concepts, hypotheses and results may well be useful in introducing non-experts to the field, Binsted will also participate in the E/PO component of the NAI.

- **Cowen –** Cowen will actively conduct field research in microbial geochemistry of hydrothermal systems at mid-ocean ridges and in ridge flank crusts. He will also lead response expeditions to study seafloor eruptions for geochemical and microbial indicators of subsurface communities. He will participate in outreach activities, especially in science teacher enhancement projects (*e.g.* teacher at sea).

- **Gaidos –** Gaidos will lead expeditions to subglacial volcanoes in Iceland and high-altitude fumarolic environments in South America to assess the presence and adaptation of microbial communities in these environments and to explore the possibility that life could exist outside the range of stable liquid water. He will also participate in research on extreme aquatic lake environments in Hawaii. He will develop models of liquid water production and transport on the surface of Mars and will be responsible for developing models of the planetary water cycle and the detectability of extrasolar cometary and planetary comae. He will lead a program of observations of the earthshine spectrum from Mauna Kea.

- **Jewitt –** Jewitt will be in charge of studying Kuiper Belt objects and comets and determining their physical properties, and icy compositions. Jewitt is also involved in the Pan Starrs telescope project, and is chair of its Science Working Group. His role will be to help determine the mass spectrum of all NEAs, and to enable further compositional study.

- **Kaiser –** Kaiser will perform all of the ultra-vacuum lab experiments in his capacity as the lead of the Reaction Dynamics group. In addition Kaiser will take an active lead in the development of a graduate program of astrobiology courses.

- **Karl –** Karl will supervise and participate in field and laboratory studies related to comparative aquatic ecosystem analysis and in the evaluation of life detection systems, especially ATP analysis. He will also supervise a postdoc who will conduct laboratory studies of Antarctic ice cores and experimental studies using ice mesocosms.

- **Keil –** Keil collaborates with NAI colleagues Sasha Krot and Ed Scott to conduct research into the aqueous and weathering history of asteroidal meteorites. Keil will synthesize the information to derive an understanding of the aqueous evolution and activities on small, asteroidal-sized planetesimals.

- **Kudritzki –** Kudritzki will help provide the astronomical infrastructure for the proposal by ensuring the future development of Mauna Kea and Haleakala. In addition, he will assist with the management of the NAI. He is keen to take an active role in all of the science of the NAI, including regular science meetings, infusing astrophysical perspectives.

- **Mottl –** Mottl will conduct field research in the geochemistry of microbial habitats, including cold springs on serpentinite mud volcanoes in the Mariana forearc and hot springs in the Lau (back-arc) Basin, where he has NSF-funded programs. He will participate in the studies of Hawaiian lakes and coastal areas where lava is flowing into the sea, as described in the proposal. He will provide chemical analyses and will collaborate with microbiologists in characterizing unusual microbial habitats. He will participate in outreach activites, especially in science teacher enhancement projects, including taking teachers to sea.

- **Owen –** Owen will investigate the D/H composition of comets in order to establish how much isotopic equilibration took place in the solar nebula between H_2O and H_2. In addition he will investigate the ability of water ice to trap noble gases to determine how much cometary water was contributed to Earth.

- **Reipurth –** Reipurth will carry out the research on water observations in the interstellar medium. In addition, he will develop and run the Astrobiology winter school, and will be significantly involved in the outreach component of the UH-NAI.

- **Taylor –** Taylor will have overall responsibility for studies relating to aqueous processes on Mars. In addition, Taylor is the lead on the E/PO program discussed herein. †Jeff Taylor will spend at least one month of his time on this his Hawaii Space Grant activities. His participation University of Hawaii as part of the state's matching Grant.

Table 1: UH NAI Proposal Collaborators

Personnel	**Location & Role**	**Expertise**
Akiva Bar-Nun	Tel-Aviv University	• Comet Impacts; Chem of Emergence of Life
Cecilia Ceccarelli	Obs. Grenoble	• Astrochemistry, Water in Circumstellar Disks
Pascale Ehrenfreund	Leiden Observatory	• Astrochemistry; Interstellar Ices & Organics
Julia Hammer	University of Hawaii	• Volatile/Mineral Interactions at Mod. Pressures
James Heasley	University of Hawaii	• Faulkes Telescope Outreach
Mary Kadooka	University of Hawaii	• Educational Outreach; Physics Resource Agent
Alexander Krot	University of Hawaii	• Meteoritics
Gary McMurtry	University of Hawaii	• Methods for in-situ Biomolecule Identification
Dina Prialnik	Tel Aviv University	• Comet Thermal models; Ice Physics
Ed Scott	University of Hawaii	• Meteoritics & Cosmochemistry; Petrology
Thor. Thorsteinsson	Nat. Energy Auth.	• Glaciology
Jonathan Williams	University of Hawaii	• ISM; Submm Interferometry

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3 Plan for Strengthening the Astrobiology Community

3.1 Education and Public Outreach

3.1.1 Introduction

Our group has a strong record of education and public outreach, and we intend to capitalize on that experience by providing innovative laboratory-based learning opportunities for teachers and by engaging the public in our research. We will leverage our efforts funded under this proposal with other programs in our state, particularly with the Hawaii Space Grant Consortium, Space Science Network Northwest (OSS Broker/Facilitator), and the Pacific Regional Planetary Imaging Facility. We will also use our extensive network of teachers throughout the state and our active involvement in the Hawaii Science Teachers Association, the American Association of Physics Teachers and other professional organizations to help disseminate the products we create. For the first time, due to the Hawaii Teachers Standards Board, teachers need to be re-certified by 2005 and this requires professional development. This provides the perfect opportunity for our proposed programs to assist in Hawaii teacher re-certification. Our outreach programs will be funded by several sources.

1. We will be supporting outreach at a level of ∼$50K / year (5% of the total) from the UH-NAI budget ($10K for workshops, and $40K for staffing (1 summer month of graduate student, 2 months for a web programmer, and 2 months of an Education specialist);

2. The University of Hawaii is committing $50K/year to UH-NAI outreach (see 3.4.1);

3. The Pacific Resources for Education and Learning group is commiting ∼4K per year for teacher travel from Micronesia (2 trips per year).

3.1.2 Astrobiology Laboratory Institute for Instructors (Alii)

The multidisciplinary nature of astrobiology lends itself to broad scientific training of teachers. It can revitalize a teacher's approach to whatever science subjects they teach, including biology, chemistry, physics, earth science, and astronomy. Because the typical secondary science teacher reaches about 150 students a year, a focus on teacher training leverages our resources effectively. We will develop a one week summer program to have grade 7-12 teachers learn about astrobiology and how to incorporate activities into their courses. activities into their courses. Exemplary activities such as those in SETI's Voyages Through Time modules will be used. Pacific Island teachers will be recruited with support from the Pacific Resources for Education and Learning (see 3.4.2). (PREL is one of 10 educational laboratories that serve geographic regions across the nation to improve education, and is supported by the U.S. Dept. of Ed.)

This program, Astrobiology Laboratory Institute for Instructors, or acronym, Alii, means royalty in Hawaiian (actually spelled Ali'i and pronounced "ah-lee-ee"), a fitting name for important people like teachers. Experience in doing teacher workshops (TOPS-Towards Other Planetary Systems; and Exploring Planets in the Classroom) has taught us the most effective teaching strategies. Begun in 1993 with NASA funding, with a student component funded by a private donor, the TOPS program has trained over 120 secondary science and mathematics teachers from

Hawaii, Micronesia, and other Pacific Islands. The TOPS team and the Hawaii Space Grant Consortium (sponsor of Exploring Planets in the Classroom) are committed to helping implement our teacher-training program. Our plans focus on integrating laboratory experiences with delivery of content materials in alignment with state and national science standards.

3.1.3 Summer Workshop and Research Experience

The focal point of our teacher-training program will be a semester-long professional development program to do cutting-edge research in astrobiology,. We will collaborate with the school district to support this program by allowing teachers to take a semester sabbatical leave to minimize our cost. Teachers from the Alii summer workshops with their basic astrobiology background will be recruited for a rich research experience. Each semester several teachers will conduct research in a focus area of this proposal (protostar formation, comets and the interstellar medium, use of spacecraft data for Mars, meteorite studies, extreme aquatic habitats,

This research component will be patterned after the Research Experiences for Undergraduates and Research Experiences for Teachers program that has been run at the Institute for Astronomy (NSF). Besides doing research, the teachers will explore hands-on astrobiology activities, attend talks by our Astrobiology Institute, and develop skills mentoring students for astrobiology science projects. These teachers will make presentations on their research at local and national science teachers conferences. (For those who have only lived in Hawaii, this could be their first experience since the school district does not subsidize teachers.

For six hours each day, teachers will work on well-defined projects aligned with the NAI Roadmap objectives and under the supervision of NAI-affiliated scientists. For example, teachers could experience the 13,000 ft altitude of Mauna Kea while participating in observing. This corresponds to the Roadmap Goal 3, "Understanding how life emerges from cosmic and planetary precursors". Or teachers could utilize the educational Faulkes Telescope Facility (see 3.1.5). Co-I Cowen will continue his "Teacher-at-Sea" program, where a teacher is involved in a research project by being assimilated into the planning and staging of the research cruise, participates in the cruise as a scientist in training, and writes a report or paper on his/her experiences. The teacher helps his/her class or school set up an active web page and arrange for ship-to-shore email communications to integrate others into the research project. Also, the teacher will carry out experiments at sea based on questions posed by the students prior to or during the cruise. For the UH-NAI program, Cowen plans to mentor the teacher during studies of geochemical and microbial indicators of subsurface communities. This project aligns with NAI Roadmap Goal 5, objective 5.3, "Biochemical adaptation to extreme environments". The real challenge is getting the teacher/school to build on their opportunity; the goal is to have a sustained program by which the school reaches out to their new contacts and instill in the school personnel sufficient boldness to ask familiar and potential educational partners for help. With the contributed funding from the University of Hawaii (see 3.4.1) we will have a person to help coordinate the followup.

With each year, the number of astrobiology teachers will multiply and promote astrobiology education in Hawaii's schools. This model replicates our existing cadre of TOPS teachers who conduct workshops, give presentations at national conventions and continue to implement astronomy activities in their classrooms.

3.1.4 Astrobiology in a Course for Pre-Service Teachers

Using the summer workshop and research experience as a base, we will also enhance an existing course for pre-service teachers. Geology & Geophysics 168 is designed both to fulfill a science requirement for elementary teachers and to introduce planetary science to future science teachers. It is a combined lecture/laboratory course, with emphasis on learning from hands-on, inquiry-based classroom activities. We will greatly increase the astrobiology content in the course through collaboration with others in our branch of the NAI. The course content may include some of the following topics: the processes operating on the surface of Mars, extremophiles, searching for and recognizing fossilized microorganisms, Mars site selection for sample return, debate about life in Martian meteorite ALH8400. The class will also include some exposure to research, such as mini-internships in which students help in research laboratories for a few hours a week for part of the semester. This course will also be offered to experienced science teachers to introduced them to astrobiology. We hope to establish a a wide network of teachers who will promote astrobiology topics in their course curriculum.

3.1.5 The Faulkes Telescope Facility

The Faulkes Telescope is a joint project between the Faulkes Telscope Corporation and the University of Hawaii Institute for Astronomy. The telescope, located on Haleakala, Maui, to be completed in late 2003, will be the largest professional grade telescope in the world dedicated to education and public outreach. The 2.2 m diameter telescope will be used for astronomy education with students in Hawaii and the U.K. being mentored by teachers and professional astronomers. Research projects with astronomers searching for extra-solar planets and Kuiper Belt Objects will give our students first-hand experience on cutting-edge research relating to the water theme of our NAI proposal.

Under the auspices of a broad Hawaii NAI outreach program, we will have a teacher training program for use of this telescope. TOPS 2003 summer workshop is piloting an experimental program in preparation for this proposed Faulkes Telescope NAI workshop. TOPS teachers will learn how to conduct telescope observations, *e.g.*, target selection, filters to be used, exposure time dependent upon magnitude, and how images are used for analysis of data. At the end of three weeks, they will be expected to write a research report. With proper training the teachers will be able to mentor students for science fair projects. This will serve as a model to be used for the NAI workshop. Teachers will also be mentored by project scientists, their post-docs and graduate students. A survey completed, whereby IFA astronomers and HIGP scientists indicated interest in mentoring teachers, will be used. Hawaii's team, NASA OSS Space Science Network Northwest, conducted this survey. This exemplifies how Hawaii's NAI education and public outreach effort will be integrated with other entities to play a a major role in promoting science and mathematics education.

3.1.6 Engaging the Public

Discoveries in Astrobiology: a Science Magazine on the Internet

We will manage and edit a web magazine modeled after PSRD, whose central theme is "planetary scientists sharing ideas and discoveries". (PSRD can be found at www.psrd.hawaii.edu, and is managed by G. Jeffrey Taylor and Linda M. V. Martel.) The audience for PSRD is the public, teachers, high school and college students, and government decision makers. Discoveries in Astrobiology (DNA) would be similar: "astrobiologists sharing ideas and discoveries." We do not intend this online magazine to duplicate the excellent Astrobiology Magazine produced by the Astrobiology Institute. Instead, our site would focus on reporting recently published peer-reviewed articles by the scientists associated with our branch to be responsible for translating articles for the public. The magazine would also contain summary articles about various central topics in astrobiology, profiles of scientists involved, and virtual tours of our laboratories. We envision having a board of editors composed of scientists involved in NAI to review articles for content and clarity, including ease of navigation and quality of graphics. We would be responsible for html coding and production of graphics not supplied by our scientific colleagues.

Taylor and Martel began PSRD because they feel strongly that scientific research is not finished until the results are communicated to the general public, which pays for it. The articles in DNA will tell the public what their dollars discovered, and do so in understandable English. In addition, it is an excellent format for keeping policy makers at NASA Headquarters and in the Congress informed about the accomplishments of the Institute.

Other Public Engagement Activities

It is crucial to share our discoveries with the public, in order to help raise the level of science literacy both in Hawaii and in the nation. We plan to do this in three major ways. First, we will host a regular series of public lectures about astrobiology. These will be advertised widely to attract a large audience. Second, we will organize a speaker's bureau, allowing local organizations (*e.g.*, Rotary Club, Downtown Club of Honolulu, etc.) to request a researcher to talk about the wonders of some aspect of astrobiology. Initial contacts with these organizations are already in place. Third, we will make effective use of our local press to publicize our most interesting research findings. The press is a vital partner in public engagement and we have an experienced and talented group of local science reporters.

3.1.7 Evaluation

Our plans for evaluation is that we will use the effective partnerships we have already developed with teachers. They will help us in the development and testing of classroom activities. Testing will be done partly during teacher workshops, via an evaluation form for each activity. Testing will also be done in the classrooms of cooperating teachers. We will rely on their expert opinion as to the effectiveness of each new activity. Teacher workshops themselves will also be evaluated through questionnaires filled out by the participants and through follow-on surveys designed to determine if teachers are using the materials and, if not, why not. We will also adapt the rigorous evaluation techniques developed for the TOPS program, which involved a continuous, action-oriented, decision-making evaluation model. This involved planning, formative and summative assessment phases. We will work with PREL to develop and execute a formal evaluation of our outreach programs.

3.2 Professional Community

3.2.1 Winter Astrobiology school

A fundamental aspect of astrobiology is its cross-disciplinary nature. The network of Astrobiology Institutes is successfully creating an environment in which researchers from widely different backgrounds can interact and break down the barriers between subjects erected during their different paths of training. However, if astrobiology is going to be an increasingly vibrant discipline, we must prepare the young researchers who, a generation from now, will be leading the future efforts. We should foster a cross disciplinary attitude in young people *before* they develop the myopic science view that arises from traditional specialization. This is possible if we reach out to students well before they finish their PhD. Young people have a remarkable ability to connect easily to each other, and the strong personal connections that are established in youth tend to last the longest. By bringing young students together across the astrobiology spectrum, we are helping to build the network of cross disciplinary contacts that will be part of the foundation of astrobiology for the next generations.

We propose to establish the Hawaii Astrobiology Winter School to be held yearly in the Hawaiian islands. It will be open to all graduate students in the course of doing a PhD in astronomy, biology, biochemistry, chemistry, or geology, and with an interest in astrobiology. We envisage a school with about 20 students lasting two, or ideally three, weeks, with 4 to 6 courses taught by experts in various fields. The students will, in small teams, write the lecture notes themselves under supervision of the lecturers, and the lectures will be made available at a dedicated web site. It will be easier to engage busy senior scientists if they do not have to do a time consuming write-up afterwards. The idea is not that each years school should be covering all of astrobiology, rather each years school will have its distinct character, determined by the subjects offered by the lecturers.

Young people move around a lot after their PhD until they eventually get tenure somewhere, so there is reason to be concerned that the contacts established during the school will die out merely for practical reasons. To help counter this we will establish the Astrobiology Quarterly (AQ), an internet - bazed forum for dialogy and interaction amongst past participants in the Winter School. The AQ will contain abstracts of papers written by past and present school participants, summaries of PhD theses by school participants, and address changes so contacts can be maintained.

3.2.2 Visiting Faculty Scholars Program

The UH-NAI is proposing a Visiting Faculty Scholars program which will bring external collaborators to work with local researchers, to participate in the Astrobiology Winter School (3.2.1), and help with the E/PO (3.1). Having a strong visitor program will inject a breadth of innovative ideas to the UH-NAI, and maintain and strengthen our interdisciplinary research. Because the University of Hawaii has made a concession to the usual Faculty Housing policy (3.4.1) we will be able to house our visitors for longer-term visits to engage in meaningful research that is fully integrated into all aspects of our proposed NAI.

3.3 Teaming with Minority Institutions

The University of Hawaii is a Minority Institution, with only 19% of the student body Caucasian, 14% Hawaiian or part Hawaiian, and another 12% of mixed ethnicity, the remainder being Asian. In addition, our unique geographical location places us in an ideal position to interact with communities in Micronesia (90% minority groups). Through our previous E/PO programs, we have considerable experience and have developed contacts with the Micronesian educational community in the US-Affiliated pacific entities: (American Samoa, Chuuk, CNMI, Guam, Kosrae, Pohnpei, Palu, Marshall Islands and Yap), and we will actively integrate teachers from these regions into our E/PO program (3.1.2).

3.4 Institutional Commitment

3.4.1 University of Hawaii

The University of Hawaii fully supports this project and, to this end, is contributing a substantial matching component to the program.

- **Staff Salaries –** First, we will be utilizing the bulk of the funds to recruit high-caliber postdoctoral fellows to work with the team and foster the collaborative interactions, only a small component of salary support is requested by the team. The in-kind value of the state-funded salary for the team amounts to $1,545K.

- **Tenure Track Positions –** The Institute for Astronomy will committ a senior tenure-track professorship in the area of Star and Planet Formation to the NAI, at an anticipated level of $140K/year (plus fringe and overheads), and in addition will contribute a junior tenure-track position at a level of $77K/year. This will be continued beyond the 5 year NAI program. The Institute sees the NAI goals as being an area of science where Hawaii is especially well-qualified to become a world leader in research because of our unique astronomical facilities and is therefore making this substantial commitment.

- **Center for Star and Planet Formation –** The Institute for Astronomy will provide $20,000 in funds per year to establish the Center for Star and Planet Formation. The goal of the Center is to develop closer ties between researchers studying star and planet formation, primitive planetary bodies (including the Kuiper belt objects and comets) and meteorites and the early solar system. The funding will be used to bring visiting scientists to the Center.

- **EPO Staffing –** The University of Hawaii will fund outreach staffing at a level of $50,000 (loaded) per year to help orchestrate our outreach program.

- **Office Space –** The University of Hawaii will give the program 2000 sq. feet of space for our postdoctoral community, and an additional $20,000 of funds to renovate the space, purchase furniture and set up wireless networking.

- **Faculty Housing –** In order to support our strong visitor program (see 3.2.2), President Dobelle of the University of Hawaii has agreed to place us on a high priority list for rented faculty housing. Hawaii is expensive, and even at the state per diem level of $80 / day (which cannot begin to cover hotel costs in Honolulu), a visitor program would be costly.

Short-term apartments are difficult, if not impossible to find. The UH faculty housing has a long waiting list (1-2 years) for space. Eligibility for priority for faculty housing is determined by the Board of Regents Policy, which only the President can override. Visiting Faculty Scholars, as a group, are at number 12 on the list, which means, in effect, that an apartment would be impossible to acquire. In response to our request, the President will place the UH-NAI at a high priority on this list, and extend the term of lease to the duration of the UH-NAI, if funded (normally it is 1-3 years maximum). Our project proposes a 3 month period per year, and the Institute for Astronomy Director will pick up the remaining 9 months of the year. Apartment rents range from $600-$1800 per month.

3.4.2 Outside Contributions

The director of the Pacific Eisenhower Mathematics and Science Regional Consortium at Pacific Resources for Education and Learning (PREL) will support the cost of airfare for 2 Pacific Island teachers each year to attend our summer Astrobiology programs. (Est. value: $4K/year).

Table 2: Summary of Cost-Sharing and In-Kind Contributions Amounts Correspond to Fully Loaded Salaries

Contribution	**Amount [$K]**
Faculty Salaries	1,545
1 Tenure track senior position ($140K/yr)	1,639
1 Tenure track junior position ($70K/yr)	934
Center for Star & Planet Formation	100
Outreach Staffing	250
2000 s.f. office space	N/V
Office rennovation	20
PREL Teacher Contribution	20
Access to R/V Kilo Moana	
Total Matching	**$4,508**

3.5 Flight Missions

Karen Meech

- Meech is a co-Investigator on NASA's 8^{th} Discovery mission, *Deep Impact*, which will explore the interior of a comet. One of her roles in the mission is to be in charge of all the ground-based observing support both for pre-mission target characterization, and during the encounter. She is also heavily involved in the mission outreach.

Scott Anderson

- Anderson helped to run the Mars Orbiting Laser Altimeter (MOLA) on the Mars Global Surveyor and the Gamma Ray Spectrometer (GRS/NS/HEND) on 2001 Mars Odyssey.

- Member of the 2003 MER rover landing site working group.

Tobias Owen

- Interdisciplinary Scientist & member of Galileo Mission Probe Mass Spectrometer Team ('97-'03).
- Interdisciplinary Scientist & member of the Spectrometer and Aerosol Collector Cassini-Huygens Teams.
- Associate investigator on Rosetta, which will be the first good chance to get noble gas abundances for a comet.
- Member of the Neutral Mass Spectrometer Team on the Japanese Mission NOZOMI.
- Owen will also be joining Discovery Proposal teams for two comet missions, one mission to search for water on Jupiter (the greatest unknown for that planet right now), and a Venus mission designed to study atmospheric abundances and isotopes, again to investigate the origin of the Earth's volatiles and the possible comet (=ice) connection.

Jeffrey Taylor

- Member of the 2001 Mars Odyssey Gamma Ray Spectrometer Team.

3.6 Information Technology

We plan to design, implement and evaluate a software tool to aid interdisciplinary scientific collaboration, tentatively called HypMaT (Hypothesis Management Tool). It would be aimed at groups of researchers working in different fields, possibly remotely, but towards a common goal or theme.

NAI already uses ScienceOrganizer[109], a knowledge management tool that allows distributed NASA teams to organize and navigate through project information. Like ScienceOrganizer, HypMaT would be a combination of a semantic network and a relational database. However, it would represent the knowledge at a higher level, and provide an intuitive graphical interface, allowing users to visualize relations between hypotheses, concepts, experimental results, and speculations across scientific fields. We plan to make HypMaT compatible with ScienceOrganizer, so that users can move easily between the two tools.

One of the problems of interdisciplinary scientific collaboration is how to allow a non-expert in some particular field to successfully interpret and use the high-level expertise of an expert in that field. For this reason, HypMaT would allow users to assign Confidence Factors (CFs), ranging from -1 to 1, to both the nodes in the network and to the relationships between them. A CF value captures the expert user's confidence in the information represented by the node. These CF values would percolate through the network, allowing a non-expert to access, at a high level, an expert's deep understanding of how concepts in his or her field of expertise interrelate.

For example, a biologist might want to know which of two theories of planetary formation are favored by the astronomers in the collaborating community. Using HypMaT, the biologist could see at a glance that Theory A (CF=3D0.8) is strongly preferred over the Theory B (CF=3D-0.1).

If she were to explore the network further, she could see that, although most observations support both theories equally, one recent observation would seem to disconfirm Theory B. That is, there is a relationship between the observation (CF=3D0.8) and Theory B, and this relationship contributes negatively to the CF of Theory B. Finally, the biologist could choose to access (perhaps via ScienceDesk) detailed information regarding that observation, including published papers, web pages, and data archives.

HypMaT is intended to be used by distributed teams of scientists. HypMaT users in a collaborative group would be able to synchronize their versions of the knowledge network over the internet. HypMaT would also maintain a record of past and alternate versions of the knowledge network, so that users can revert to earlier versions, or maintain different versions in cases of disagreement.

As an aid to collaborative composition, HypMaT would be able to transform a knowledge network (or sub-network) into a text outline, which could serve as a starting point for a scientific paper. The text outline would include any bibliographic data that were included in the network, saving time and reducing cross-referencing errors.

Although we envisage HypMaT as primarily for collaboration, it could also be used as a pedagogical tool. Students could explore the networks that result from various NAI projects, and thus learn more about the various disciplines involved in astrobiology and how they interrelate.

Kim Binsted, the co-investigator in charge of HypMaT, is a specialist in artificial intelligence and human-computer interaction. She is currently designing and building a prototype of a collaborative system similar to that described above. Because such systems are best developed in the context in which they will be used, Co-I Binsted is eager to use the distributed, interdisciplinary team associated with this proposal as a prototypical set of users for the system. Likewise, the team is eager to explore a tool that will allow them to collaborate more effectively.

3.7 Other Astrobiology Commitments

Karen Meech

- **Towards Other Planetary Systems Outreach Program –** Meech has run a major NSF- and NASA-funded teacher enhancement program in Hawaii since 1993. The program is designed to help high school math and science teachers integrate math and science standards into their classes by teaching astronomy. The Astrobiology content of this summer program also teaches about cutting edge astronomical research that is ongoing in Hawaii. A privately funded student component also exists for this 3-week summer program. This program was funded as a pilot by NASA from 1993-1995, and then by the NSF for 1999-2003.

- **Bioastronomy 1999 Meeting, Hawaii –** Meech was the Local Organizing chair for this meeting held on the Kona Coast in Hawaii, and in addition she facilitated a large educational outreach component at the meeting.

- **Bioastronomy 2004 Meeting, Iceland –** The local organizing chair of the meeting is Thorstein Thorsteinnson, one of our NAI collaborators. PI Meech is also a member of the local organizing committee, and the scientific organizing committee (SOC), and Gaidos and collaborator Ehrenfreund are members of the SOC. Many of the UH-NAI members will take an active role in this meeting (and 4 of the 15 SOC members are UH-NAI affiliates).

- **IAU Commission 51 on Bioastronomy –** Meech is a member of the Organizing committee, and the incoming President of Commission 51 of the International Astronomical Union as of the summer of 2003, and is currently the Vice President of the Division.
- **WGESP –** Meech is a member of the IAU Working Group on Extra-Solar Planets. The working group is charged with acting as a focal point for research on extra solar planets and organizing IAU activities in the field, including reviewing techniques and possibly maintaining a list of identified planets.
- **PSRD –** Meech is a member of the Board of Editors of the University of Hawaii on-line magazine, Planetary Science Research Discoveries.
- **COMPLEX –** Meech is a member of the National REsearch Council's Committee on Planetary and Lunar Exploration and has taken an active role in the development of several studies, including: *The Quarantine and Certification of Martian Samples*, *Organic Environments in the Solar System* and the *Assessment of Mars Science and Mission Priorities*.

James Cowen

- **Ridge2000 Program –** Cowen is a Steering and Executive Committee member of NSF's Ridge2000 program. The program is focused on the complex linkages between life and planetary processes at mid-ocean ridges. There are strong linkages between Ridge2000 and NASA's Astrobiology programs.
- **LExEn –** Cowen has been an invited participant to numerous planning workshops including those for LExEn (Life in Extreme environments) and NEPTUNE (ambitious plan for seafloor observatory based on fiber optic cable/instrument node/AUV system).
- **Teacher at Sea –** Cowen has developed and actively supports a Teacher at Sea program (see 3.1.3).

Eric Gaidos

- **Terrestrial Planet Finder –** Gaidos is a member of the Terrestrial Planet Finder Working Group (2002-2006)
- **Planetary Ecosystems and Biosystems Lab –** Gaidos has set up this laboratory and curriculum at the University of Hawaii.
  http://www.soest.hawaii.edu/GG/FACULTY/GAIDOS/pebl.html

Ralf Kaiser

- **UK Astrobiology Network –** The Co-I is member of the UK Astrobiology Network and also an advisor to the UK Astrobiology Forum highlighting future research initiatives in astrobiology.

- **Centre for Astrobiology, The Open University (UK) –** The Co-I holds an adjunct professorship at the Department of Physics and Astronomy, Centre for Astrobiology, at The Open University, Milton Keynes (UK). In collaboration with Prof. Nigel J. Mason, one experiment is currently being setup at the synchrotron to investigate the synthetic routes and destruction rates of aminoacids and carbon hydrates in astrobiologically important ices.

- **Course Development –** Kaiser developed a graduate course at the University of Hawaii in Astrochemistry and Astrobiology.

- **Textbook –** Cambridge University Press commissioned Kaiser to write a textbook for graduate students entitled "The Chemical Evolution of the Interstellar Medium: From Astrochemistry to Astrobiology".

- **Graduate Program –** In collaboration with faculty members from Department of Chemistry, Department of Physics & Astronomy, the Institute for Astronomy (IfA), and the Hawaii Institute of Geophysics and Planetology (HIGP), Kaiser organized a new graduate program at the University of Hawaii. Astrobiology is a key component of this endeavor.

David Karl

- **1998 Lake Vostok Workshop –** Washington DC, Karl was co-chair of this international workshop that led to a series of recommendations on future research in Antarctic subglacial lakes.

- **Polar Research Board, National Research Council –** Karl is currently a member of this polar sciences advisory board.

- **Meeting Planning Committee –** Karl is currently co-chair of an American Academy of Microbiology planning committee for a future international colloquium with the tentative title, "Marine Microbial Diversity: The Key to Earth's Habitability"

Klaus Keil

- **SScAC –** Keil served on the Space Science Advisory Committee (SScAC), NASA Headquarters, Washington, D.C. from 1993-2000, during which time discussions took place regarding the creation of the Astrobiology Program.

- **Planetary Protection –** Keil served on the Planetary Protection Task Force, NASA Headquarters, in 1999.

- **Chondrule and CAI Formation –** Krot, Reipurth, Scott and Keil are organizing this interdisciplinary workshop in October 2004, in Kauai which aims at bringing meteoriticists and astronomers together to explore formation mechanisms for chondrules and CAI's.

Tobias Owen

- **Astrobiology Text –** Owen has written a well-used Astrobiology textbook with D. Goldmith: *The Search for Life in the Universe*, (University Science Books, Sausalito) 573 pp. (2002).

- **Astrobiology Conference –** Co-Director, 7^{th} Trieste Conference on Chemical Evolution and the Origin of Life 15-19 Sep. 2003.

Bo Reipurth

- **IAU Division IV – Interstellar Medium –** President: B. Reipurth.

- **Protostars and Planets V Meeting, 2005 –** Reipurth has spearheaded getting this meeting to come to Hawaii during Oct 24-29, 2005. Team members Reipurth, Keil and Jewitt constitute the Scientific Organizing Committee of the meeting and Meech is the Local Organizing Chair. This will be a highly visible meeting with Proceedings published through the University of Arizona series.

- **Outreach –** Reipurth is very active in outreach, having conducted over 150 radio broadcasts, participated in various TV programs, and has written over 30 newspaper articles on popular astronomy, some related to Astrobiology.

- **NAI Affiliation –** Reipurth was an affiliate of the Colorado Astrobiology group (1998-2001).

Jeffrey Taylor

- **Planetary Science Research Discoveries –** Manager and editor of a web magazine called Planetary Science Research Discoveries (www.psrd.hawaii.edu) which translates recently published articles to the level appropriate for teachers, high school students and the public.

- **Hawaii Space Grant Consortium –** Taylor is the Associate Director for Space Science for the Hawaii Space Grant Consortium. He has been instrumental in helping to develop on-line classroom activities which are related to exobiology.
  http://www.spacegrant.hawaii.edu/class_acts/index.html

4 Facilities & Equipment

- **The Mauna Kea Observatories –** The 4,200 meter high summit of Mauna Kea in Hawaii houses the world's largest observatory for optical, infrared, and submillimeter astronomy. The University of Hawaii staff have priviledged access on a competitive basis to all of the facilities on Mauna Kea which are shown in the Table below, thus all of our UH NAI team members will have the opportunity to use these facilities. Through collaborations with our local NAI team, members of the national NAI will also have access. The UH gets 10-15% of the time on all of the facilities listed, and 100% of the time on the University of Hawaii 2.2m telescope.

Table 3: Facilities on Mauna Kea, Hawaii

Telescope	**Diam [m]**	**Partners**	λ **Regime**
Keck	2×10	Caltech, USC, NASA	optical, IR
Subaru	8	Japan	optical, IR
Gemini	8	Internat. consortium	optical, IR
UKIRT	3.8	United Kingdom	IR
CFHT	3.6	Canada, France, Hawaii	optical, IR
IRTF	3.0	NASA	IR
UH	2.2	University of Hawaii	optical, IR
JCMT	15.0	UK, Netherlands, Canada	submillimeter
CSO	10.0	Caltech	submillimeter
SMA	8×6	Smithsonian, Taiwan	submm interferometer

The Submillimeter Array (SMA), is nearing completion on Mauna Kea, and will be optimized for high angular aresolution observations at λ = 1.3-0.3mm, ideal for looking at thermal continuum emission, rotational lines of light molecules, and atomic fine structure lines, which arise in compact regions such as the vicintiy of young stars, protoplanetary disks and solar system bodies. This will be a unique tool for astrobiology.

- **The Haleakala Observatories –** The Faulkes Telescope is a joint project between the Faulkes Telescope Corporation and the University of Hawaii's Institute for Astronomy. The 2-meter facility is under construction and scheduled for completion this year. When complete, this will be the largest professional grade telescope in the world dedicated to education and public outreach.

- **Ultra-High Vacuum Surface Scattering Machine –** All experiments will be carried out in an extreme ultrahigh vacuum (10^{-11} mbar) surface scattering machine in which frozen, astrobiologically relevant ice samples (10K-293K) are irradiated with charged particles (electrons, protons, helium nuclei) and photons. The analysis will be carried out quantitatively on line and in situ via Fourier transform spectroscopy in absorption-reflection (solid state) and through a calibrated quadrupole mass spectrometer (gas phase) to determine temperature dependent production rates of astrobiologically relevant molecules such as sugars, aminoacids, and phosphates. This machine presents the only setup world wide in which an extreme ultra high vacua and low temperatures can be reached and the solid state as well as the gas phase can be monitored simultaneously. This setup can be operated as a user facility for qualified NAI members.

- **Meteorite Instrumentation –** At the present time at the University of Hawaii, we have the following equipment available to our group in HIGP and SOEST: Three Nikon research optical microscopes (two with automated photography attachments, including a digital camera attached to a computer, and Swift point counter); two Nikon stereomicroscopes (one with automated photography attachments); a state-of-the-art, fully automated 5-spectrometer Cameca SX-50 electron microprobe; a Hitachi H-600 scanning transmission electron microscope (STEM) and sample preparation laboratories including plasma etcher, carbon and gold-palladium coating devices and ultramicrotomes; a JEOL-5900LV scanning electron microscope (SEM); a Princeton Gamma-Tech 4-Plus energy dispersive X-ray spectrometer and digital image analysis systems, both of which are interfaced with the STEM and TEM; atomic absorption and ICP laboratories; a fully automated Siemens SRS303-AS-X-ray fluorescence facility; a fully automated Scintag Pad V X-ray diffractometer; experimental petrology apparatus; extensive computer facilities; laboratory for the preparation of polished thin sections; photography and drafting facilities; and others. In situ isotopic studies of secondary minerals resulted from aqueous activity will be performed in collaboration with Dr. K. D. McKeegan at the University of California, Los Angeles using the UCLA ims 1270 ion microprobe and in collaboration with Dr. I. D. Hutcheon at Lawrence Livermore National Laboratory using the modified Cameca ims-3f and NanoSIMS 50 ion microprobes.

- **Cryobot Access –** In addition to state of the art computational support, Anderson has a 200 square foot laboratory, two rotating field mass spectrometers (RFMS), and access to a Cryobot as part of a shared agreement with JPL (as he is a team member). One of the RFMS systems is housed in a casing rated to 2000m for deep sea deployment, and the other is a benchtop unit suitable for life detection experiments. The Cryobot is a prototype hot water ice drill capable of carrying instruments to hundreds of meters depth in Iceland or Antarctica, as well as deployment in the ocean. The Cryobot can steer, make measurements, process data, and produce realtime video of the subsurface ice. The data is sent through a tether to the surface. Our lab space is suitable for maintenance on the Cryobot and RFMS, as well as experimentation with the RFMS instrument.

- **BioLab – BSL2 –** Gaidos operates an 825 sq. ft. complex that includes a Biosafety Level 2 clean laboratory for manipulation of environmental samples and culturing organisms. This laboratory includes a BSL-2 laminar-flow clean bench, PCR cabinet, compound epifluorescence microscope, stereo field microscope, two (2) water-jacketed controlled atmosphere incubators, an anaerobic chamber with airlock, several refrigerators and freezers, centrifuges, autoclave, dishwasher, ultrapure water system, and miscellaneous equipment to treat samples and extract DNA. The facility also includes a computer lab work area for data analysis and modeling with 3 PC computers equipped with the Linux operating system. In addition, he manages a 1200 sq. ft. shared molecular biology facility that includes a multiple capillary DNA sequencer, laser-scanning blot reader, spectrophotometer, centrifuges, complete denaturing gradient gel electrophoresis (DGGE) system, a laser flow cytometer system, and miscellaneous equipment for molecular biology.

- **Kilo Moana Oceanographic Research Ship –** The R/V *Kilo Moana* is the latest member of the University of Hawaii's research fleet. Owned by the Office of Naval Research and operated by SOEST (School of Ocean and Earth Science and Technology), the twin hull research ship has been called the best in the U.S. academic fleet. The modern vessel is the first Auxiliary General Oceanographic Research ship to be constructed on a Small Waterplane Area Twin Hull design. This provides a comfortable, stable platform for multi-disciplinary marine research. The overall length of 186 feet and 88-foot beam provide ample exterior deck space and 3,000 s.f of dedicated science space. The vessel is equipped with both a deep-water (Simrad EM 120) and a shallow-water (Simrad EM 1002) multi-beam echo sounder capable of accurate sea-floor mapping at any ocean depth, dynamic positioning, and a complement of winches, cranes and other handling gear. The ship has an endurance of 50 days at sea, and a range of 10,000 nautical miles at 11 knots. The ship missions include water sampling, equipment launch, towing, recovery, and shipboard sample analysis and data processing. The *Kilo Moana* can accommodate 31 scientists and 17 crew. Facilities include library and conference rooms and hydrographic, computers, chemistry, wet and meteorology laboratories.

- **Mid-ocean ridge (magmatic/tectonic) Event Detection and Response –** MOR eruptions are unpredictable and short-lived. Scientific exploitation of these fundamental phenomena requires an extensive, well-coordinated infrastructure involving essential equipment, extensive planning and established communication, and dedicated personnel. The Northeast Pacific ED&R team consists of a partnership between researchers at NOAA- PMELs VENTS Program and NSF-RIDGE2000 funded Universities. NOAAs T-Phase Monitoring Program is responsible for event detection: the remote detection of T-Phase seismic waves via the U.S. Navys Sound Surveilance System. The University research team, led by the University of Hawaii (NAI-HI co-PI Cowen), is funded by NSF to develop and maintain readiness to rapidly respond to significant seafloor eruptive events along the Northeast Pacific MOR system; they will be joined by NOAA response colleagues. Communication is facilitated by the RIDGE2000 Program, overseen by the Time-Critical Studies Committee (chaired by Cowen).

- **Hawaii Undersea Research Laboratory –** The Hawaii Undersea Research Laboratory (HURL) was established by the National Oceanic and Atmospheric Administration (NOAA) and the University of Hawaii. HURL's facilities include two deep-diving (2000 m) submersibles Pisces V and Pisces IV, a remotely operated vehicle RCV-150, and the support ship R/V Kaimikai-o-Kanaloa. Its mission is to study deep water marine processes in the Pacific Ocean, including a research focus on submarine volcanology: the geology, geophysics, geochemistry, and biology of volcanic processes. Loihi Volcano, on the flanks of the island of Hawaii, is a prime site for this work, which includes monitoring submarine geophysical, geological and geochemical processes using an Ocean Bottom Observatory.