The Europa Clipper Mission: Understanding Icy World Habitability and Blazing a Path for Future Exploration

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This paper discusses the science expected to be achieved by the Europa Clipper mission, in order to provide context for the future exploration of Europa and other icy worlds. In addition, we discuss how the science will be achieved as we strive to operate as “One Team.”

1. Introduction: Science Goal and Objectives of the Europa Clipper Mission

Europa is a complex geophysical and geochemical system with great astrobiological potential, and host to a wide range of processes relevant to understanding the Solar System’s ocean worlds. These processes include: ice tectonics, cryomagmatism, impact cratering, mass wasting, ice convection, tidal deformation and heating, surface-plasma chemical and physical interactions, exospheric and ionospheric processes, magnetospheric interactions, and possibly plume dynamics. It is also a key target for astrobiological exploration because it may contain the “ingredients” for life: liquid water, bioessential elements, and the chemical energy to power metabolism; moreover, these ingredients may have persisted since early Solar System history, providing opportunity for life to emerge. This astrobiological potential has made Europa exploration a top priority of the first two planetary science decadal surveys, ultimately giving rise to the Europa Clipper mission in 2015. Expected to arrive at Jupiter near the end of the coming decade, this mission will result in discoveries and knowledge that will feed forward and inform future ocean world missions, so its potential should factor into the present planetary decadal planning.

As shaped by prior decadal surveys, the science goal of the Europa Clipper mission is to explore Europa to investigate its habitability. Addressing this goal are three science objectives:

- (1) Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface-ice-ocean exchange;
- (2) Understand the habitability of Europa’s ocean through composition and chemistry;
- (3) Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities.

The search for and characterization of recent activity is cross-cutting and may manifest as plumes, thermal anomalies, or surface geological and/or compositional changes.

To address the science of the Europa Clipper mission, a highly capable suite of instruments that comprise the mission’s scientific payload is now under development. This payload includes five remote sensing instruments¹ that will observe the wavelength range from the ultraviolet through radio (radar) and four *in situ* instruments that will measure neutral gases, magnetic fields, dust particles, and plasma. In addition, gravity and radio science will be conducted through tracking of the spacecraft’s telecommunication signal during Europa flybys, and valuable scientific data can come from the spacecraft’s radiation monitor engineering subsystem. To achieve the goal and objectives of the mission, combining multiple data sets will provide insights into the geophysical processes that affect this icy world. Toward this end, Europa Clipper adopts a “One-Team” philosophy, which may serve as a model for future flagship missions.

¹ In this paper, “instrument” refers to the hardware, while “investigation” refers to the collection of science that an instrument is intended to achieve. The Europa Clipper has 9 science instruments (if the EIS camera suite is counted as one), while science investigations can also be achieved via the telecommunications and radiation monitor engineering subsystems.

2. Science Investigations of the Europa Clipper Mission

2.1 Remote Sensing Investigations of Europa

Europa Clipper's remote sensing instruments provide the capability for in-depth study of Europa's interrelated processes. They will be employed to understand the detailed processes associated with ocean-ice shell interactions, transport within the ice shell, tectonism, cryomagmatism, cratering, and recent activity. Below we summarize the key characteristics of each remote sensing instrument and associated investigations, in wavelength sequence.

Europa Ultraviolet Spectrograph (Europa-UVS). Europa-UVS is the mission's primary plume finder. The instrument will search for plumes by spatial and spectral imaging of UV emissions (airglow) and transmission (stellar occultations) in the wavelength range of 55–210 nm and a spectral resolution of 0.6 nm. Data to be collected by Europa-UVS will be used to interrogate the composition and chemistry, sources and sinks, and structure and variability of the tenuous Europa atmosphere. In addition, it will be possible to constrain surface composition and microphysics, and relationships to endogenic and exogenic processes. Europa-UVS data will also permit a better understanding of Europa's plasma environment, notably the energy and mass flow into Europa's atmosphere, neutral cloud, and plasma torus.

Europa Imaging System (EIS). EIS is composed of a narrow-angle camera (NAC) and a wide-angle camera (WAC), each with both framing and pushbroom capability, along with stereo and color imaging capability. Together, the EIS camera suite will be used to map Europa near-globally at better than 100 m resolution and capable of imaging almost any point on the surface at better than 20 m resolution. EIS images and topography data will build a foundation for geologic mapping and for testing geophysical models to understand the formation of surface features and their implications for subsurface water. The WAC provides topographic data to characterize surface clutter in REASON shallow subsurface profiles. NAC very high-resolution imaging (≤ 1 -m pixel scale) will characterize the surface at the meter scale, addressing local-scale regolith processes. Distant imaging by EIS will search for active plumes, and color imaging will search for surface changes from previous Voyager and Galileo imaging and during Europa operations. NAC science measurements are prioritized in the mission's formal requirements over those from the WAC. Also, while not part of Europa Clipper's formal objectives, EIS and other Europa Clipper data can be used to characterize the science value and engineering safety of sites for a possible future landed mission.

Mapping Imaging Spectrometer for Europa (MISE). Operating in the 0.8–5.0 μm wavelength range, MISE data will be used to assess the habitability of Europa's ocean through the examination of the inventory and distribution of surface compounds, including materials relevant to astrobiology. MISE data will be used to identify and map the distributions of organics, salts, acid hydrates, water ice phases, altered silicates, and radiolytic compounds. It also has the potential to detect sufficiently warm thermal anomalies.

Europa Thermal Imaging System (E-THEMIS). The E-THEMIS instrument data can be used to detect and characterize thermal anomalies that may indicate recent or current activity. Thermal inertia information derived from E-THEMIS temperature measurements can be used to characterize regolith particle size, block abundance, and subsurface layering.

Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON). Data from the REASON instrument will permit mapping of the vertical structure of Europa's icy shell and the

associated search for subsurface water and brine. REASON will also be used to search for the deeper ice-ocean interface, while characterizing the ice shell's global thermophysical structure. This will provide insights into material exchange among the ocean, ice shell, surface, and atmosphere. Derived physical properties of surface permittivity and roughness will support characterization of sites at local scales, including for a potential future lander.

2.2 In situ Investigations of Europa

The influence of the Jovian space environment on Europa is multifaceted, and observations of moon-magnetosphere interaction by Europa Clipper's instruments will provide an understanding of the satellite's interior structure and compositional makeup, among the many advances. The variability of Jupiter's magnetic field at Europa induces electric currents within the moon's conducting ocean layer, the magnitude of which depends on the ocean's location, extent, and conductivity. Europa is also embedded in a flow of co-rotating plasma, which continuously impacts and sputters the surface to produce the moon's tenuous atmosphere. In addition, micrometeorite impacts eject particles off the surface to wrap Europa in a cloud of dust. The neutral atmosphere is readily ionized by energetic particles to produce an ionosphere, which gives rise to current systems electromagnetically connecting Europa to Jupiter; neutral and ionized volatiles and particles define Europa's exosphere. Summarized below are some highlights of the moon-magnetosphere interaction science that we seek to unravel with the Europa Clipper mission and the primary instruments involved in these investigations. We also briefly summarize gravity / radio science and radiation science.

Europa Clipper Magnetometer (ECM). The facility-managed Europa Clipper Magnetometer (ECM) will measure magnetic fields generated by currents induced in Europa's subsurface ocean and the electromagnetic coupling of the moon to Jupiter. Jupiter's tilted dipole magnetic field and Europa's eccentric orbit expose the moon to time-varying magnetic fields inducing eddy currents in the ocean. By inferring the induced field response at multiple frequencies, the ice shell thickness and the ocean layer thickness and conductivity can be uniquely determined for a range of likely parameters. The ECM consists of three fluxgate sensors mounted on an 8.5-m-long boom, with its control electronics hosted in a vault shielding it from radiation damage. The use of three sensors allows for dynamic removal of higher-order spacecraft-generated magnetic fields on a boom that is short compared with the spacecraft dimensions.

Plasma Instrument for Magnetic Sounding (PIMS). The PIMS instrument will measure ions and electrons in Europa's ionosphere and Jupiter's magnetosphere, to quantify magnetic fields associated with electric currents driven by dynamic plasma pressure gradients, which are produced by the interaction of corotating Jovian plasma with Europa and its atmosphere. The PIMS instrument consists of two sensors each hosting two Faraday cups, each with a 90° field of view. The instrument measures electrons and ions with energies of up to 2 keV and 6 keV/q, respectively, with an energy resolution of <15% and a temporal resolution of 1–4 s. From the energy distribution functions, the ion density, temperature, and velocity as well as the electron energy and temperature can be inferred.

Mass Spectrometer for Planetary Exploration (MASPEX). The MASPEX instrument will measure trace neutral species, to determine the composition of Europa's atmosphere. The atmosphere is produced by particles sputtering off the surface and may be augmented by possible contributions from plumes. MASPEX data will be used to determine the distribution of major volatiles (such as H₂O, H₂, O₂, and CO₂) and key organic compounds (CH₄, C₂H₂, C₂H₄,

C₂H₆, HCN, and CH₃OH) with respect to latitude and longitude, altitude, and local solar time. The data will permit us to distinguish endogenic and exogenic sources. MASPEX is a multi-bounce time-of-flight mass spectrometer for species with atomic mass ranging from 2 to 500 u. The instrument's high mass resolution $m/\Delta m$ of greater than 17,000 enables measurement of individual fragmented ions generated by electron impact ionization of parent molecules. It is planned that MASPEX will be equipped with a cryotrap for sample storage of trace species, for subsequent analysis near apoapsis, an operational environment that has a significantly lower background radiation-noise environment than that encountered during the Europa flybys. NASA has deemed MASPEX to have a higher risk classification than the rest of the science payload.

Surface Dust Analyzer (SUDA). The SUDA instrument will permit analysis and mapping of the chemical composition of particles ejected from Europa's surface by hypervelocity impacts of micrometeoroids. The dust particles have a typical size of 0.5–1 μm and exhibit a near-isotropic distribution and only weak temporal variations. SUDA will also measure particles from exogenous sources, such the other Galilean satellites, notably Io. SUDA is a time-of-flight mass spectrometer for atomic and molecular species with mass ranging of up to 500 u ionized during hypervelocity impact of ice/dust particles on SUDA's target, and is capable of detecting up to 100 ejecta particles per second.. Owing to the deterministic nature of the ballistic trajectories of the ejected particles, the composition measurements at spacecraft altitude can be correlated with geologic features on the surface. It has been experimentally demonstrated that trace amounts of complex organic species, such as amino acids, embedded in ice grains with abundances <0.1 ppm can be detected. In addition to micrometeorite ejecta, SUDA could measure the makeup of potential plumes by directly sampling microscopic particles.

Gravity and Radio Science (G/RS). NASA has recently selected a science team to plan, process, and analyze gravity and radio science (G/RS) data through tracking of the spacecraft's telecommunication signal during Europa flybys. The selected geodetic investigations include topics of Europa's gravity anomalies in the ice shell and silicate interior, time-varying gravity field and tides, planetary orientation, and ephemeris and orbital evolution. Moreover, radio occultations will provide information about Europa's ionosphere.

Radiation Monitoring System (RADMON). RADMON is an engineering subsystem system that consists of a charge monitor stack and eight dosimeters distributed around the spacecraft. It will permit monitoring of the radiation environment at Jupiter beneath different thicknesses of shielding, to understand the instantaneous dose rate and accumulated ionizing dose over time. RADMON will permit measurements of energetic particles up to 40 MeV, complementing PIMS measurements.

3. Mission Concept

The current Europa Clipper mission design consists of ~40–50 low-altitude flybys of Europa while the spacecraft is in orbit about Jupiter. The flybys extend over a ~3.8-year period. The altitudes of closest approach typically range from 25 km to 100 km, and up to 2400 km. The tour is divided into two principal campaigns, first making flybys that concentrate on the sunlit anti-Jovian hemisphere, followed by observations primarily of the sunlit sub-Jovian hemisphere. There are also several night-time flybys included in the tour design. The flybys occur over a wide range of latitudes and longitudes, and they are also well-distributed in true anomaly of Europa's orbit, local solar time, and System III Jovian longitude. The tour is thus well-suited for

characterization of Europa's surface, ocean, ice shell, atmosphere, and ionosphere, and interactions with Jupiter's magnetosphere.

4. Europa Clipper One-Team Structure

To understand Europa and its potential habitability, the science must be synergistic, with the suite of instruments and investigations working together, each making contributions toward addressing the science objectives and goal. In this section we discuss the structure of the science team and how it works as a single entity to advance our knowledge of this icy world.

4.1 Flight System Operability

Fundamental to the science team working together as one is the premise that the flight system—which comprises the spacecraft and the instrument payload—enables the instruments to operate simultaneously. Deliberate care was taken to design the Europa Clipper flight system such that all of the Europa Clipper science instruments can be operated simultaneously, for each and every Europa flyby. This approach presents challenges in the areas of energy usage and power storage, data rate into the spacecraft's storage system, and in the mutual placement of the instruments. This commitment is fundamental to the Europa Clipper team operating as one by diminishing the conflict over the mission's most precious resource: time.

The mission lifetime is limited by radiation, so use of only some instruments on a given flyby would be inefficient. Moreover, an operational plan that is relatively simple and repeatable reduces costs by simplifying planning and execution. But just as important, limiting competition for the key resource of close-approach observation time allows the science team to work cooperatively toward common scientific ends, rather than debating the merits of limited instrument usage. One challenge has been achieving gravity and radio science during flybys, successfully addressed by situating 2 low-gain antennas and 3 fan-beam antennas around the spacecraft, in configurations such that at least one has a line-of-sight to Earth during about 2/3 of the Europa flybys. Electromagnetic compatibility of the flight system, including instruments, is a significant challenge ahead.

4.2 Science Team Structure and Composition

The Europa Clipper Science Team is composed of members of its 10 Investigation Teams (consisting of a Principal Investigator (PI) or Team Leader (TL), Co-Investigators [Co-Is], and Affiliate members (including Professional, Postdoctoral, and Graduate Student Affiliates) and the Project Science Team (Project Scientist and Deputies, Project Staff Scientists, and Investigation Scientists). In the future, it is planned that the mission will include Participating Scientists from the scientific community, solicited and selected by NASA. All science team members have the opportunity to participate in Project Science Group (PSG) meetings (i.e., science team meetings) and occasional cross-investigation science meetings (such as plume workshops).

The Europa Clipper mission PIs and Co-Is were competitively selected by NASA in 2015. PIs each proposed a science investigation implemented through a specific instrument, along with a team of Co-Is to complete the science investigation. At the time of selection, the 9 PI-led instrument/investigation teams included 96 unique individuals, with 16 women (17%). Of the 78 scientists from US institutions, 15 are women (19%). Very few members of the competitively selected science team are people of color. The addition of Affiliate and Project Science Team

members on this long-duration mission has increased the ratio of women science team members to approximately 25%. Team members proactively seek out social-science-backed best practices and engage in regular discussions so as to continue to improve inclusivity and diversity within the team. Our One-Team philosophy strives to provide team members with an inclusive environment, empowering them to be an integral part of the Europa Clipper Mission.

4.3 Thematic Working Groups and Focus Groups

Science implementation of the Europa Clipper mission is supported by a set of four Thematic Working Groups (TWGs) that represent the mission's science goal and objectives: Habitability, Interior, Geology, and Composition. The TWGs are designed to provide a high-level, cross-instrument and cross-discipline, objective-driven science perspective. All Europa Clipper Science Team members have the opportunity to participate in the strategic and tactical science planning efforts through the TWGs. This aids in ensuring that the goal and objectives of the mission are met through achieving high-quality integrated science, maximizing scientific impact.

Focus Groups address key topical areas that are especially important and relevant to the science team. The Plume Focus Group is charged with studying and discussing science requirements, policies, and trades as they affect the mission's science with regard to potential plumes and related phenomena at Europa. The Radiation Focus Group promotes discussion among the science team of issues related to radiation (>100 keV electrons and ions) and addresses and communicates radiation-related issues that arise from the science team. The Reconnaissance Focus Group considers and advocates for reconnaissance data sets that best enable a potential future landing on the surface of Europa.

Rotation of one of the two co-chairs of the science team's TWGs and Focus Groups every few years aims to broaden participation, foster diversity at the project leadership level, and promote a range of ideas. This system can promote junior team members and members of underrepresented groups to positions that provide valuable leadership experience. These scientists return to the greater science team as demonstrated leaders, bolstering the knowledge and experience base of the whole science team.

4.4 One Team Philosophy

Our "One Team" philosophy prioritizes synergistic science by bridging across the individual instrument-based investigations, while promoting collaborations among members of the Europa Clipper science team. Each of the Europa Clipper individual instruments will be used to investigate Europa and its environs, finding critical clues about how Europa works as a planetary body. In combining and assessing the datasets from each instrument's experiments, we can collectively gain clarity into Europa's mysteries. As is commonly true in science, it is at the overlapping boundaries of our subfields that the greatest insights and discoveries will be made. Integrated science celebrates our individual expertise, challenges our assumptions, breaks through our limitations, and expands our intellectual boundaries. Associated visibility brings trust, promotes partnerships, and enhances personal relationships. These aspirations are the inherent basis for functioning as one science team.

Rules of the Road. The Europa Clipper Science Team "Rules of the Road" document provides team policies on data sharing, publications, professional code of conduct, and science team responsibilities for the team. This document is intended to provide open, transparent, and equitable operating rules for the Europa Clipper Science Team for the duration of the Europa

Clipper project, to enable strong working relationships and to ensure that the highest quality science is delivered from the project. All Europa Clipper Science Team members are required to abide by and uphold the policies and practices described in that document. The Rules of the Road document includes the Europa Clipper Science Team's Code of Conduct, which also describes enforcement and consequences of non-compliance.

Data Sharing. Uninhibited sharing of data among members of the Europa Clipper Science Team is essential if the highest quality interdisciplinary science is to be accomplished. Data sharing enables multiple datasets and multiple perspectives to be considered in concert and can lead to unexpected insights and better understanding of the processes operating at Europa. Therefore, the Europa Clipper Science Team's data sharing policies aim to encourage cross-instrument, cross-investigation, and multi-expert interactions at all levels, to support development of working relationships and partnerships, and engender the trust necessary to enable emerging collaborations across the project. The Europa Clipper project is also committed to ensuring usability and timely sharing and distribution of data to the science community and the public.

Publication Policies. As the end products of our scientific investigations, it is important that science results be shared with the science community, NASA, and the public as soon as feasible. The full Europa Clipper Science Team is presented with the opportunity to contribute to any multiple-investigation scientific publications in ways appropriate and practical, notably during TWG interactions. Outlines or rough-drafts of all manuscripts are posted on a team website when they are sufficiently mature to be written up as a journal paper, to ensure communication and visibility for ongoing projects, and mature drafts of all manuscripts are posted and announced before they are to be submitted to ensure visibility among team members.

5. Conclusion

Taken together, the Europa Clipper mission's robust investigation suite can be used to test hypotheses and enable discoveries relevant to the interior, composition, and geology of Europa, thereby addressing the potential habitability of this intriguing ocean world, in line with recommendations from the previous planetary science decadal surveys.

The one-team philosophy of the mission and associated visibility brings trust, promotes partnerships, and enhances personal relationships. Such an approach should be considered for future strategic missions. For a long-duration mission such as Europa Clipper, one could say that it's all about the journey; therefore, we strive to make this journey a great one, for the good of the science, our mission, and each other.

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