SCIENCE OF THE EUROPA JUPITER SYSTEM MISSION

A white paper submitted to the NRC Planetary Science Decadal Survey

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1 OVERVIEW

Jupiter is the archetype for the giant planets of the Solar System and for the numerous planets now known to orbit other stars. Jupiter's diverse Galilean satellites—three of which are believed to harbor internal oceans—are the key to understanding the habitability of icy worlds. Each of the Galilean satellites is distinct with respect to its geology, internal structure, evolution, and degree of past and present activity. To place Europa (**Figure 1**) and its potential habitability in the right context, as well as to understand the Galilean satellites as a system, the two internally active ocean-bearing bodies — Europa and Ganymede — must be fully understood. Overall, the Europa Jupiter System Mission (EJSM) is guided by the overarching theme: *The emergence of habitable worlds around gas giants.*

The baseline EJSM architecture consists of two primary elements operating in the Jovian system: the NASA-led Jupiter Europa Orbiter (JEO), which concentrates on Europa and Io, and the ESA-led Jupiter Ganymede Orbiter (JGO), which concentrates on Ganymede and Callisto (**Figure 2**). JEO and JGO would execute a choreographed exploration of the Jupiter System before settling into orbit around Europa and Ganymede, respectively. The Joint Science Definition Team has recommended that JEO and JGO each carry eleven complementary instruments, to be competitively selected. These investigations would characterize water oceans and the ice shells of Europa and Ganymede, map 3-D morphology of the Galilean satellites, determine surface and atmospheric compositions, monitor dynamic phenomena in the Jovian system (notably Io's volcanoes and Jupiter's atmosphere), and monitor the Jovian magnetosphere and its interactions with the satellites.

EJSM fully addresses the high priority science objectives for outer solar system exploration as identified by the National Research Council's (NRC's) 2002 Decadal Survey and ESA's 2005 Cosmic Vision Programme. The 2002 Decadal Survey recommended a Europa Orbiter as the next Solar System flagship mission and identified Ganymede as a highly desirable future mission target. EJSM uniquely responds to several of the central themes of ESA's Cosmic Vision Programme, through its in-depth exploration of the Jupiter system and its evolution from origin to habitability.

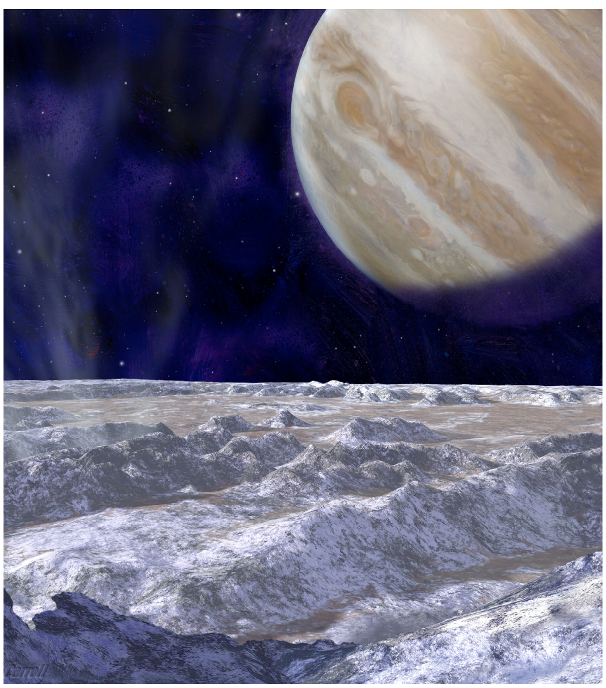

Figure 1: *Artist's conception of the surface of Europa, which is poorly known at fine scales. Visualization by Michael Carroll.*

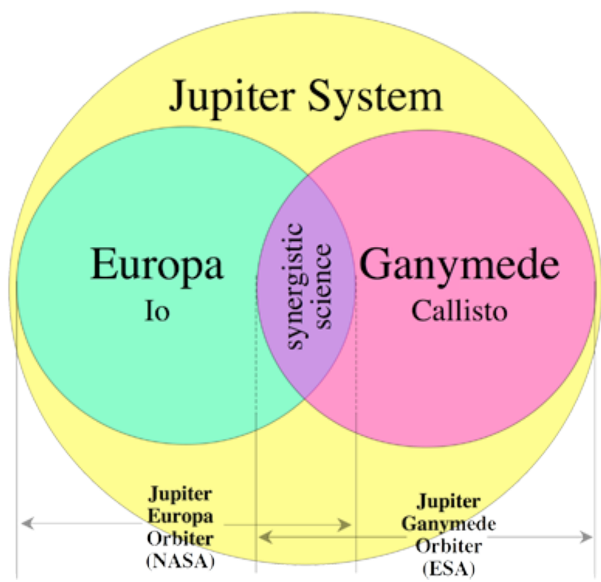

Figure 2: *EJSM is carried out by two flight elements, each with specific scientific targets as well as synergistic science objectives. The satellite-specific objectives of each are encompassed by Jupiter system science, as addressed in significant part by both.*

EJSM is designed to reveal the potential habitability of the active ocean-bearing moons Europa and Ganymede, detailing the geophysical, compositional, geological, and external processes that affect these icy worlds. EJSM would also explore Io and Callisto, Jupiter's atmosphere, and the Jovian magnetosphere. By understanding the Jupiter system and unraveling its history, the formation and evolution of gas giant planets and their satellites can be better known. Most important, EJSM can shed new light on the potential for the emergence of life in the celestial neighborhood and beyond.

The EJSM architecture is fundamentally based on critical stand-alone measurements of Europa and Ganymede by each spacecraft. It also provides rich opportunities for "synergistic" observations by both JEO and JGO (§4), including of Jupiter's atmosphere, the Jupiter and Ganymede magnetospheres, the volcanoes and torus of Io, and fundamental comparative planetology of icy satellites.

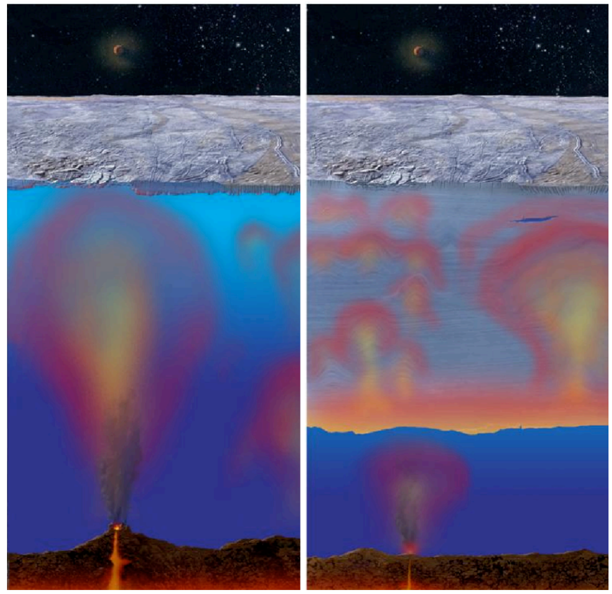

Figure 3: *JEO would address the fundamental issue of whether Europa's ice shell is ~ a few km (left) or ≥20 km (right), with different implications for processes and habitability. In either case, the ocean is in direct contact with the rocky mantle below, which may infuse chemical nutrients necessary for life.*

2 SCIENCE GOALS AND OBJECTIVES

Derived from the overarching theme described above are specific science goals and associated objectives for EJSM. These are of two categories: icy world habitability and Jupiter system processes.

Goal: Determine whether the Jupiter System harbors habitable worlds.

Europa is believed to have a saltwater ocean beneath a relatively thin and geodynamically active icy shell (**Figure 3**). Europa is unique among the large icy satellites because its ocean is in direct contact with its rocky mantle beneath, where the conditions could be similar to those on Earth's biologically rich sea floor. Analogous to hydrothermal fields on Earth's sea floor, such areas on Europa could be excellent habitats, powered by energy and nutrients that result from reactions between sea water and hot rock. Chemical nutrients might also enter the ocean from above, as oxidants are generated through at Europa's surface from radiolysis. Potentially containing the necessary "ingredients" for life, Europa is the prime candidate in the search for habitable zones and life in the solar system. However, the details of the processes that shape Europa's ice shell, the fundamental question of its thickness, and methods for transport of materials between the ocean and surface, are not well understood.

Ganymede is believed to have a liquid ocean sandwiched between a thick ice shell above and high-density ice polymorphs below, more typical of volatile-rich large icy satellites. It is the only satellite known to have an intrinsic magnetic field, generated by an internal dynamo, which makes the Ganymede-Jupiter magnetospheric interaction unique in the Solar System (**Figure 4**).

EJSM would undertake in-depth comparisons of Europa and Ganymede to establish their geophysical characteristics and potential habitability. To this end NASA's JEO spacecraft would investigate Europa in detail while ESA's JGO spacecraft would focus on Ganymede. For Europa and Ganymede, both mission elements have objectives to:

- Characterize and determine the extent of sub-surface oceans and their relations to the deeper interior.
- Characterize the ice shells and any subsurface water, including the heterogeneity of the ice, and the nature of surface-ice-ocean exchange.

- Characterize the deep internal structure, differentiation history, and (for Ganymede) the intrinsic magnetic field.
- Compare the exospheres, plasma environments, and magnetospheric interactions.
- Determine global surface compositions and chemistry, especially as related to habitability. Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.

Accomplishing these objectives would fulfill the goal of determining whether the Jupiter system harbors habitable worlds, while detailing the geophysical, compositional, geological, and external processes that affect these icy and active planet-sized worlds.

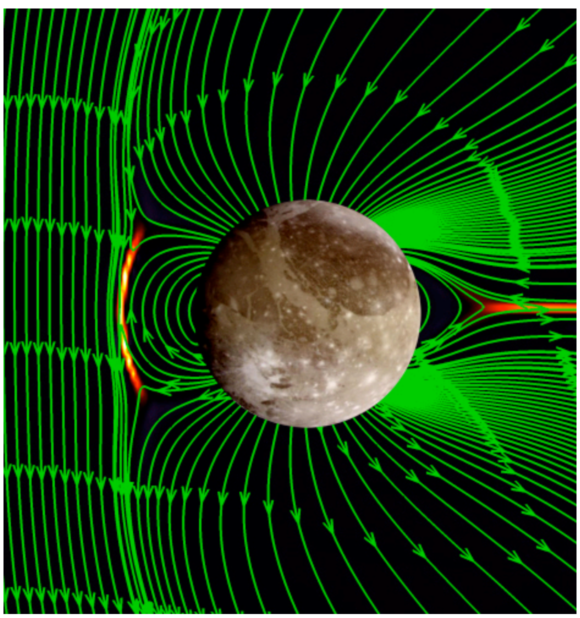

Figure 4: *JGO would determine how Ganymede's unique magnetic field interacts with Jupiter's, how the interactions vary with time, and the role of a convecting core and internal ocean.*

Goal: Characterize the processes within the Jupiter System.

The Jupiter system includes a broad diversity of objects, including Jupiter itself, more than 50 currently known outer irregular satellites, the Jovian ring system, four small inner satellites, and the four large Galilean Satellites: Io, Europa, Ganymede, and Callisto.

The Galilean satellites comprise a fascinating and diverse array of planetary bodies (**Figure 5**). Io is the solar system's most volcanically active world. The "ocean world" Europa is believed to have a relatively thin ice shell above a saltwater ocean in direct contact with its rocky interior. The ice-rich moons Ganymede and Callisto have similar bulk properties and both are believed to have internal oceans; however, these moons have divergent evolutionary histories. Ganymede is strongly differentiated with a hot convecting core and a history of active tectonics and icy volcanism. Callisto is weakly differentiated with no signs of internal geological activity. EJSM's strategy for understanding the Galilean satellites as a system is to conduct an in-depth comparative study of the two pairs of rockier inner Galilean satellites (Europa-Io) primarily with JEO, and the icier outer satellite pair (Ganymede-Callisto) primarily with JGO, with the most in-depth focus on Europa and Ganymede and their probable subsurface oceans. The results can then be interconnected and placed in the broader context of the whole Jupiter system.

Io, Europa, and Ganymede are coupled in a stable resonance that maintains their orbital periods in a ratio of 1:2:4 and forces their orbital eccentricities; Callisto is not included in this resonance. Tidal interaction heats the interior of Io and is responsible for its unparalleled volcanic activity. At Europa, tidal heating maintains a liquid ocean and causes faulting of its surface and convection within its ice shell. Ganymede may be cooling from a past more intensive tidal event, currently driving convection within the metallic core to produce the satellite's intrinsic magnetic field. Callisto may owe its relative lack of endogenic activity to being left out of the resonance. EJSM results would enable detailed comparative studies of how different conditions with respect to tidal heating have led to such different histories and internal structures, surfaces, and dynamic activities among the four Galilean satellites.

Jupiter's internal and atmospheric structures are intimately coupled to the Jovian system environment. EJSM would complement the Juno investigation of Jupiter's internal structure and composition by characterizing the evolution of fundamental meteorological phenomena in the dynamic "weather-layer" to create the first global database for the Jovian atmosphere. EJSM's multi-wavelength instrumentation would be used to study the coupling (via energy and momentum transport) of weather-layer dynamics and composition to the deep convective flow within the interior; the stratosphere and higher-altitude neutral regions; and the charged-particle environment of the ionosphere, magnetosphere, and extended interplanetary environment.

Jupiter's magnetosphere is closely coupled to the upper atmosphere and interior by electrodynamic interactions. The high latitude auroral zones map to a vast region of the magnetosphere. This giant magnetized environment, driven by the fast rotation of its central spinning zone and populated by ions coming from its moons, is the most accessible and intense environment for direct investigations of general astrophysical processes. EJSM would measure the dynamics of the Jovian magnetodisk (with angular momentum exchange and dissipation of rotational energy), determine the electro-dynamic coupling between the planet and the satellites, and assess the global and continuous acceleration of particles.

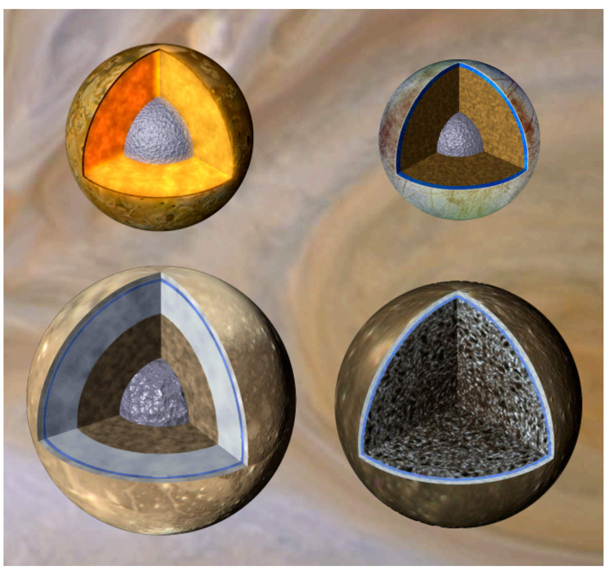

Figure 5: EJSM would greatly improve upon simple models of the interior structures of the Galilean satellites based on Galileo data. The smaller, rockier pair — Io and Europa (top) — is the focus of JEO. The larger, icier pair — Ganymede and Callisto (bottom) — is the focus of JGO. The satellites are shown to scale, along with the western edge of Jupiter's Great Red Spot (background).

One of the most important aspects of solar system studies is the identification of the processes leading to the formation of gas giant planets. EJSM would provide new insight into this issue through understanding of the interior structure and properties of the Galilean satellites (especially Europa and Ganymede), derivation of the bombardment and geological history of the Galilean satellites, and comparative compositional study of the satellites. Along with better understanding of Jupiter's composition, this would improve knowledge of the thermodynamics of the Jovian circum-planetary disk.

For the Jupiter system, both mission elements have objectives to:

- Understand the Jovian satellite system, especially as a context for Europa and Ganymede.
- Evaluate the structure and dynamics of the Jovian atmosphere.
- Characterize processes in the Jovian magnetodisk/magnetosphere.
- Determine the interactions occurring in the Jovian system.
- Constrain the origin of the Jovian system.

Achieving these objectives would fulfill the goal of characterizing processes in the Jupiter system, and would provide for rich comparisons to Cassini results in the Saturn system.

3 SCIENCE APPROACH

Together, JEO and JGO address the science goals and objectives of EJSM. Each spacecraft would carry instruments to intensely characterize one internally active icy satellite and provides significant science for the others, and each addresses significant aspects of Jupiter system science. The overlap provides important synergistic and complementary observations (§4). Nonetheless, each has the potential to be a "stand-alone" mission, providing compelling Decadal Survey (§6) and Cosmic Vision science. The following discussion of science approach is based on the model payloads recommended by the Joint Science Definition Team; the final competitively selected payloads may address the objectives in somewhat different ways.

JEO has as its sub-goal***: Explore Europa and investigate its habitability***. During its Europa orbital phase, JEO would address the objectives of characterizing Europa's ocean and its deeper interior through geophysical methods: using gravity, altimetry, and magnetometry measurements conducted from low-altitude orbit (100 – 200 km). To characterize Europa's ice shell and any subsurface water, JEO can employ ice-penetrating radar to map subsurface structure and the distribution of water within and potentially beneath the ice shell. The tenuous atmosphere of Europa and its magnetospheric interactions would be investigated through magnetometry, energetic particle and plasma measurements, ion and neutral spectroscopy, and UV spectroscopy including stellar occultations. Surface composition and chemistry would be characterized remotely through IR spectroscopy and *in situ* through ion and neutral mass spectroscopy. Surface geology and potential future landing sites can be characterized through imaging at a variety of scales (100 m/pixel, 10 m/pixel, and 1 m/pixel from 100 km orbital altitude) and through thermal imaging that could locate any active "hot spots." The JEO model payload (**Table 1**) ensures excellent remote sensing and *in situ* observations of the Jupiter system, both from a distance and during close satellite flybys.

Europa's very tenuous atmosphere (2 picobar) is a boon to orbital investigations of the surface and interior. Orbital operations can be conducted from low altitudes (~100-200 km), and atmospheric absorption and scattering are absent, allowing for optimal spatial resolution of remote sensing instruments. The low altitude greatly increases the sensitivity of radar sounding and magnetometry. The absence of atmospheric drag improves orbit and pointing knowledge, enabling measurements of higher order and time-dependent gravity field components accurately and quickly. Europa is unique among icy worlds in that intensive sputtering brings surface material to the spacecraft where it can be measured *in situ* through ion and neutral mass spectroscopy and plasma measurements. The benefits of exploring bodies with very tenuous atmospheres are applicable to flybys of the other Galilean satellites.

While the primary focus of JEO is to orbit Europa, the science return encompasses the entire Jovian system, especially as relevant to Europa's potential habitability. JEO's Jovian Tour includes several flybys of each of the four Galilean satellites, plus ~2.5 years of monitoring Io's volcanism and observing Jupiter's atmosphere, magnetosphere, and rings.

JGO has three sub-goals, expressed as: ***Determine whether the Jupiter System harbors habitable worlds; Characterize the processes within the Jupiter System; Gain new insight into the origin of the Jupiter System***. JGO addresses its sub-goal of determining whether the Jupiter System harbors habitable worlds by focusing on Ganymede. From Ganymede orbit, JGO would characterize Ganymede's ocean, deeper interior, magnetosphere, and surface using techniques analogous to those of JEO. Specifically, JGO would exploit low-orbital altitudes to characterize the satellite's ice shell and putative ocean, understand its deeper interior and intrinsic magnetic field, and map its geological features and composition.

To address the JGO sub-goals pertinent to the Jupiter system, JGO would intensely investigate Callisto from a resonant orbit, and would make extensive observations of the Jupiter system to complement those of JEO. Differences in techniques reflected in the model payloads (**Table 1**) are that JGO would employ sub-millimeter wave sounding among its compositional measurements, JGO would include a plasma wave instrument, and JGO would forego thermal imaging.

JGO results would enable detailed comparisons with the results for Europa obtained by JEO. These results would be coupled with the data returned from Io, Callisto, and the Jupiter system as a whole, to provide unparalleled insight into the archetypical gas giant planetary system. In this way, JEO and JGO combine to address the overall EJSM theme of the emergence of habitable worlds around gas giants.

4 SCIENCE SYNERGIES

The EJSM architecture offers unique opportunities for dual-spacecraft synergistic observations that significantly enhance the overall science return of the mission, while providing unprecedented opportunity for comparative planetology of icy satellites. An example timeline of the JEO and JGO elements for

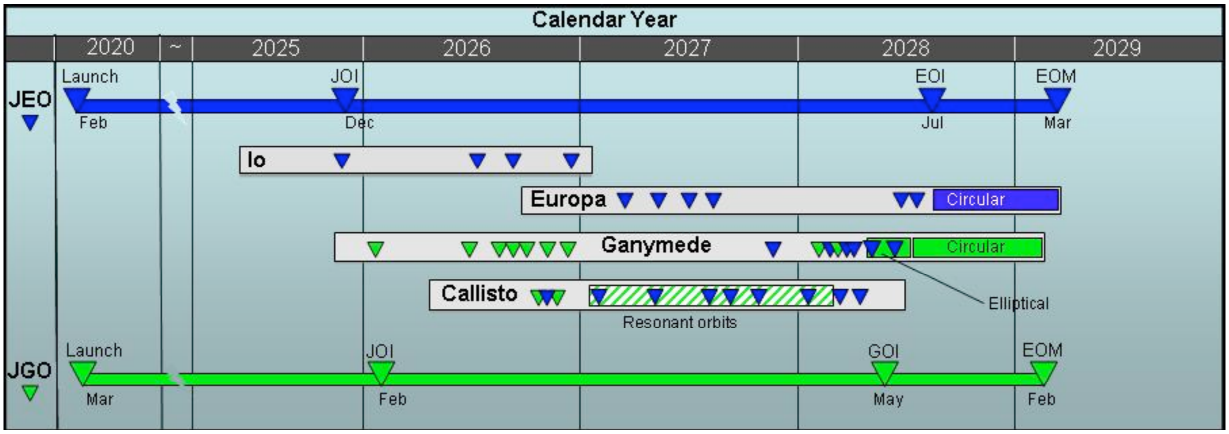

Figure 6: *Notional timeline for the EJSM, assuming launches one month apart in 2020. The blue bar represents the JEO timeline, and icy moon encounters are shown with blue triangles. Similarly, green bars and triangles represent the JGO timeline. The resulting synergistic observations of magnetospheric and other dynamic phenomena are unprecedented in planetary exploration, and would be completed by 2029. The relative phasing of the two spacecraft elements can be adjusted to optimize synergistic science opportunities.*

current planning dates (**Figure 6**) shows that both would be in the Jupiter system simultaneously, yet with staggered arrival times at Jupiter and with different Jovian tours. Trajectory design flexibility permits a variety of phasing options for science as the actual mission timelines are developed. Examples of synergistic science opportunities include:

- *Jupiter magnetosphere:* In the notional example where JEO enters Jupiter orbit a few months prior to JGO, then JGO monitors solar wind, while JEO observes the Jovian magnetosphere from within, to untangle the solar-wind versus internally driven processes in magnetospheric dynamics.
- *Io volcanism and torus dynamics:* JEO would observe Io's volcanic activity through remote sensing and *in situ* observations during close flybys, while JGO would observe the context and effects on the Io torus via remote sensing from afar.
- *Satellite and Jupiter monitoring:* Both spacecraft would observe dynamic phenomena, such as the meteorology of Jupiter and Io's volcanic plumes, by simultaneous observations with different viewing geometries, wavelengths, and resolutions. It is possible that communication between the spacecraft would permit radio occultations of Jupiter and the satellites with unprecedented radio geometries and signal-to-noise.
- *Ganymede magnetosphere studies:* JGO could observe the Ganymede magnetosphere *in situ*, while JEO monitors the external Jovian magnetosphere from Jupiter orbit and makes flybys through Ganymede's magnetosphere. Such observations allow for a better understanding of effects of Jupiter's field on the Ganymede magnetosphere and for plasma measurements by JEO that aid in interpreting JGO's measurements of the induced component of Ganymede's field.
- *Comparative planetological study of icy satellites:* The ultimate synergy of EJSM is that of comparative planetology that comes from the detailed understanding of the sibling icy satellites Europa and Ganymede. The scientific benefit that is greater than the sum of the parts comes from study of both Europa, with its thin ice shell above an ocean in direct contact with its rocky mantle, and Ganymede, with its thick ice shell and ocean that is "sandwiched" between ice layers along with a hot core that generates an intrinsic magnetic field. In this way, EJSM's detailed investigations would span the variety of potentially habitable icy worlds.

5 MODEL PAYLOADS

The EJSM model payload instruments (**Table 1)** were identified to respond directly to the science objectives, along with traceability to the science measurement requirements. They

Table 1: *The Complementary Model Payloads of JEO and JGO*

JEO model payload	JGO model payload
Narrow Angle Camera	Narrow Angle Camera
Wide Angle and Medium Angle Camera	Wide Angle and Medium Resolution Camera
Vis-IR Imaging Spectrometer	Vis-IR Hyperspectral Imaging Spectrometer
UV Spectrometer	UV Imaging Spectrometer
Radio Science	Radio Science
Magnetometer	Magnetometer
Ice Penetrating Radar	Sub-Surface Radar
Laser Altimeter	Laser Altimeter
Thermal Instrument	Sub-Millimeter Wave Instrument
Ion and Neutral Mass Spectrometer	Plasma Package & Ion and Neutral Mass Spectrometer
Particle and Plasma Instrument	Radio and Plasma Wave Instrument

were also evaluated on the basis of their ability to perform in the radiation environment, and meet planetary protection requirements. The model payloads, while notional, are used to bound the engineering aspects of the mission design, spacecraft, and operational scenarios associated with obtaining the data to meet the science objectives. The model payload instruments are used to show proof of concept only, and are not to be taken to be final selections nor final implementations. The mass of the model payloads, without shielding, are 106 kg for JEO and 104 kg for JGO.

Synergistic and complementary instruments carried by the separate mission elements would enhance the science while maintaining a strong science return value for each independent element. With the aim of exploring the Jupiter system as a whole in addition to focused investigations of individual satellites, the model payloads provide instrumentation for remote sensing (during flybys as a distant observer, and while in orbit around the satellites), and to characterize the Jovian environment.

Remote sensing instruments would provide overlapping spectral coverage to readily facilitate data cross-correlation and analysis. Comparable field and particle payloads would provide new information on the 3-D and temporal variability of the Jupiter radiation environment, as well as the local external environments surrounding Europa and Ganymede. The combined capability of the two mission elements would provide science return that exceeds that of each standing alone.

6 RESPONSES TO DECADAL SURVEY

EJSM fully addresses the high-priority science objectives identified by the 2002 NRC Decadal Survey. That Decadal Survey's Steering Group recommended a Europa Orbiter as the highest priority Solar System flagship mission: its science objectives would all be met by JEO as a stand-alone mission. The 2002 Decadal Survey also identified a Ganymede orbiting mission, similar to JGO, as a highly desirable future mission. Moreover, some 20 specific questions were posed by the Large Satellites Panel for the exploration of large satellites in the outer solar system. Through the combined operation of JEO and JGO, EJSM would investigate 19 of them (the sole exception being the Titan-specific objective of how organic chemistry evolves in a hydrocarbon solvent).

Operation of two spacecraft at Jupiter provides the unparalleled opportunity to address high-priority questions for exploration of the outer solar system. Determining the habitability of Europa and comparing the results with Ganymede can provide critical clues to habitability and the potential for the emergence of life in the outer solar system. The EJSM concept represents an approach to successfully answering these questions and making a major step forward in understanding the emergence of habitable worlds around gas giants.

Additional detailed information on EJSM can be obtained from the 2008 NASA and ESA study reports, which are posted at: https://opfm.jpl.nasa.gov/library .