Jupiter System Observatory at Sun-Jupiter Lagrangian Point One

A Mission Concept White Paper for the Decadal Survey on Planetary Science and Astrobiology 2023-2032

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Summary

We present a New Frontiers class mission concept of a Jupiter system observatory, located at the Sun-Jupiter Lagrangian point L1 focused on time-domain sciences, including the weather systems and deep interior structure of Jupiter, ionosphere-magnetosphere-solar wind coupling, activities of Galilean moons, and impact flashes on Jupiter. This concept also brings unique advantages to study jovian irregular satellites, upstream solar wind, interplanetary/interstellar dust populations, and other minor bodies that are critical to understand the current and past interactions between the jovian system and the solar system that cannot be achieved otherwise. The conceptual observatory will provide high synergistic values to current and future missions with broad scientific implications regarding solar system evolution, exoplanets, and astrophysics studies, and could serve as a strategic facility for the planetary science and exploration in the coming decade.

1. Introduction

If solar system exploration is the grand voyage of humankind, the jovian system is the compass that guides the way. The jovian system is rich in cross-disciplinary science and exploration opportunities. Jupiter's weather layer is a manifestation of its intrinsic energy emission through chemical and physical processes in the top fluid envelope (Vasavada and Showman, 2005), which provides the ground truth for investigation of distant exoplanets and brown dwarfs (Showman and Guillot, 2002; Showman et al., 2019). From its turbulent atmosphere to the activities of the Galilean moons connecting through electric currents flowing along Jupiter's magnetic field lines, a variety of phenomena including energetic aurora emission to radio waves highlight processes operating at scales orders of magnitude different in time, space, and energy. The volcanic activities of Io (de Kleer et al., 2019, de Pater et al., 2020a,b), and tentatively Europa (e.g., Roth et al., 2014; Sparks et al., 2016; Jia et al., 2018), are fundamental in addressing tidal heating mechanisms and habitability of ocean worlds. In addition, as the system with the most significant gravity around the Sun, early solar system information that has been lost elsewhere may be preserved within the jovian system. Characterization of the ancient traces, including Jupiter's core structure (Wahl et al., 2017; Liu et al., 2019) and its irregular satellites (Jewitt and Haghighipour, 2007), is essential to constrain how our solar system reached its current configuration as well as the diversity of planetary systems around other stars. Essentially, **the Jupiter-system science is a bridge connecting planetary sciences to exoplanet and astrophysics studies.**

Because of the highly dynamic nature of the jovian system, various research disciplines have recognized that **the overall science return can be significantly and uniquely enhanced by improving the observation continuity, longevity, and simultaneity** (e.g., Fletcher et al., 2009; Crary et al., 2020). Such requirements are difficult to achieve by orbiter missions or most Earth-based observatories (including astrophysical assets). Constant changing observational configurations complicates the interpretation of orbiter data, whereas Earth-based observatories are limited by their multi-purposed nature and celestial mechanics. Lack of measurement cadence and duty cycle leave a significant gap in connecting short-term (minutes to hours) and long-term (months to years) processes that hinders our ability to address the nature of time-variant phenomena, e.g., the connections between weather systems at various scales, and the system's response to exogenous (e.g., solar wind) and endogenous (Io volcanism) processes. The success of SOHO on heliophysics and JAXA's recent ultraviolet astronomy satellite, SPRINT-A (Hisaki), on Io-magnetosphere interactions (e.g., Yoshikawa et al., 2017) are clear demonstrations about the rich science potential and growing demand of solar system observations focusing on time-domain science.

In this white paper we present a mission concept of a long-term observatory located at the Sun-Jupiter Lagrangian point one (L1) as the most advantageous, both scientifically and technically, in addressing the observational needs of the jovian system in the coming decade. The primary phase of the mission starts when the observatory spacecraft enters a libration orbit around Jupiter-Sun L1 (see Sect. 3.1), which is about 0.35 AU (i.e., the Jupiter's Hill radius) from Jupiter upstream towards the Sun. The L1 position (i) provides an advantage in distance, comparing to Earth-bound observatories, so that the desired remote sensing observations can be achieved with a moderate-size telescope (see Sect. 3.2.1), (ii) enables simultaneous field-and-particle measurements (see Sect. 3.2.2) to constrain the exogenous inputs (e.g., solar wind, interplanetary and interstellar dust) and endogenous outputs (e.g., radio emission, energetic neutral atoms, and Iogenic nanodust particles) associated with the processes occurring at the jovian system, and (iii) offers a wide range of observation opportunities for jovian irregular satellites and Hilda/Trojan asteroids . In addition, before arriving at the L1 libration orbit, close-encounter opportunities can be planned to study irregular satellites with unprecedented resolution. The ideal mission duration is 12 years in order to cover the variability of the course of a solar cycle (e.g., changing solar UltraViolet radiation level) and Jupiter's orbit around the Sun. This extended temporal coverage is essential in addressing long-term cyclic processes in the jovian atmosphere (Simon-Miller and Gierasch, 2010; Fletcher 2017) as well as monitoring sporadic events, such as Europa's outgassing activity (Roth et al., 2014; Sparks et al., 2016) and meteorite impacts on Jupiter (Hueso et al., 2018).

2. Science Themes and Science Traceability Matrix

This mission concept will address the following three science themes by focusing on objects within or interacting with the jovian system, with further implications regarding exoplanet and solar system evolution studies. A preliminary science traceability matrix (STM) is presented in Table 1.

2.1 Jupiter, the exoplanet at the front door

Jupiter serves a paradigm for studying gas giants around other stars. Continuous and high-cadence observation is the key to address the dynamic nature of a gas giant system, including its atmosphere, ionosphere, magnetosphere, and the hierarchy of various processes involved. Many open questions remain regarding our own gas giant planet, including: what are the driving forces associated with the stability and variability of zonal jets? How is the zonal wind ejected by convective storms? How do the predominantly zonal bands transition to the more chaotic regions polewards of 65°? What are the correlations between the long-term cyclic activities, such as quasi-quadrennial oscillation (QQO), and other weather phenomena (Simon-Miller and Gierasch, 2010; Fletcher 2017)? How and to what extent does the solar wind control Jupiter's magnetosphere? How does Jupiter's magnetosphere respond to the variable volcanic output from Io? (Crary et al., 2020).

A long-term L1 observatory provides an ideal platform for time-domain sciences to address these fundamental questions. Targets of observation include the weather systems and the energy budget of Jupiter (Li et al., 2018), auroral activities covering UV to radio wavelength range, variability in Io plasma torus extreme-UV (EUV) emission (Yoshikawa et al., 2017), and upstream solar wind monitoring. Moreover, Doppler imaging seismology (Gaulme et al., 2011), a novel method to probe its deep interior complementing the Juno gravity and magnetic field measurements (Guillot et al., 2018; Iess et al., 2018; Kaspi et al., 2018), is also applicable to examine the core structure and evolution scenarios (e.g., Liu et al., 2019). These observations will not only address the jovian system science, but will also help to refine the atmosphere and interior models of gas giants and brown dwarfs and inform the electromagnetic interactions between exoplanets and their satellites and stellar wind. Fundamental improvement of our observation capabilities for the jovian system is a timely, synergistic goal to complement the fast-growing exoplanet research.

Table 1. Preliminary Science Traceability Matrix of the Jupiter L1 Observatory concept

Science Theme	Objectives	Investigations
1. Jupiter, the exoplanet at the front door	**(a)** Characterize meteorological processes and their connections in Jupiter's weather layer; **(b)** Study atmosphere-ionosphere-magnetosphere-Io-solar wind coupling; **(c)** Probe Jupiter’s deep interior; **(d)** Determine Jupiter’s energy budget	Tropospheric dynamics through cloud tracking and Doppler imaging; monitor stratospheric haze, storms and convective plume activities; correlations between waves, vortices, eddies, and cyclic activities; polar region atmosphere; aurora activity; Doppler imaging seismology; monitor albedo and spectral variation; solar wind and radio wave monitoring.
2. A Song of Ice and Fire - Geological Activities of Io and Europa	**(a)** Monitor Io’s volcanic activity; **(b)** Constrain atmospheric, magnetospheric, and surface activities of Galilean satellites	Simultaneous Io and tours monitoring (including Iogenic ENA and nanodust); monitor atmosphere variability, auroral activity, and surface changes of Galilean moons; Ganymede’s magnetosphere
3. Time Capsules of the Solar System - Irregular Satellites and Minor bodies	**(a)** Understand the origin and shaping processes of irregular satellites; **(b)** Characterize m- to sub-km-sized population near Jupiter; **(c)** Characterize interplanetary and interstellar dust populations; **(d)** Target-of-Opportunity observations	Constrain the orbital elements, size, rotation period, surface properties of irregular satellites; monitor impact flash and debris on Jupiter; survey unknown minor bodies; characterize composition and dynamics of interstellar and interplanetary dust populations; ToO observation of asteroids and comets.

2.2 A Song of Ice and Fire – Geological Activities of Io and Europa

The Galilean moons demonstrate the diversity of a mini-solar system, which have been and will be the focus of the upcoming orbiter missions to the jovian system, e.g., NASA’s Europa Clipper, ESA’s JUICE, and potentially NASA’s Io Volcano Observer (McEwen et al., 2014). Io’s vibrant volcanism and Europa’s potential habitability make them high-priority exploration targets.

Io’s volcanic emission is the major plasma source in the gigantic jovian magnetosphere. Understanding of the eruption and emplacement of volcanic activity and time variability have profound impacts in magnetospheric sciences as well as Io’s geology. For example, measuring the global heat flow pattern of Io helps to probe its lithosphere and mantle structure as a result of tidal heating (e.g., McEwen et al., 2014; de Kleer and de Pater, 2016). On the other hand, direct evidence of cryovolcanism or outgassing activity on Europa remains elusive. Its outgassing activity seems to be of a sporadic nature without clear correlation to its orbital phase and has therefore been difficult to detect with attempted observation cadences. Yet such activity, once confirmed and characterized, could address critical questions about the processes of Europa’s complex icy crust and interactions with its subsurface ocean, including: what is the driving force and cadence of Europa’s plume activity? Do the plume eruptions lead to detectable regional or global surface changes (Schenk 2020)? What does the plume activity inform Europa’s ice crust structure and subsurface water composition, and the present-day energy budget? All these are key information to investigate the subsurface ocean habitability.

Long-term monitoring of surface changes and atmospheric and auroral activities of Galilean moons with multi-wavelength observations is another major science objective. The L1 libration orbit provides observation opportunities at various phases, including in eclipse, which is useful to address the interactions between the surface deposits, volcanic plumes, and the global atmosphere of Io. Nanodust and energetic neutral atom (ENA) measurements will provide constraints on the composition and processes of Io's volcanic plumes, as well as the correlation to magnetospheric and auroral variabilities (Krüger et al., 2003; Bonfond et al., 2012; Smith et al., 2019). The L1 observatory will serve as the ultimate "Europa plume hunter" with unmatchable temporal and multi-wavelength coverage. The continuous "bird-eye" view on the Galilean moons will provide synergistic information for scientific analysis as well as strategic planning that complements and enhances the science return of future orbiter/lander missions to the jovian system.

2.3 Time Capsules of the solar system – irregular satellites and minor bodies

Irregular satellites are objects with eccentric orbits with sizes up to 0.5 Hill radius of the host planet. Their capture is believed to occur during the early stage of the solar system as processes leading to dissipation of energy from heliocentric orbits do not exist in the modern-day solar system (Jewitt and Haghighipour, 2007). These objects therefore offer a unique window to examine the path of Jupiter's migration and conditions in the early solar system. Outstanding questions include: What was the dominant process for irregular satellite capture? Where did they initially form and when were they captured (Nesvorny et al., 2014)? What is their composition and what does that inform about their origin? Does their lower size limit inform the condition of the dissipated gas envelop around protoplanetary disc (Guillot and Hueso, 2006) or reflect their collisional history?

Because of their small sizes (<100km, mostly a few km), light curves, color and spectral information, and ephemeris are the major data products to investigate the compositional and physical properties of irregular satellites. Stationing at Jupiter L1 provides advantageous observation conditions compared to Earth-based observatories, including larger angular separation from the bright Jupiter and more-than ten-fold reduction in distance. As mentioned, close flyby opportunities are feasible to aim for resolving surface features and studying the surface composition with high resolution spectroscopy and in situ characterization, in order to understand their origin, evolution, and relationships to other minor bodies, such as Trojan asteroids.

Observing small impacts in Jupiter will tell us about the populations of small bodies that cannot be observed directly and will have consequences for our knowledge of the chemical composition of the upper stratospheres of the gas giants (Hueso et al., 2018). It will also have an important value to understand atmospheric airbursts in a non-terrestrial atmosphere with potential to guide planetary defense analyses of terrestrial airbursts. Determining the current impact rate of small object in Jupiter will also provide a direct measurement of the current impact rate in its Galilean satellites, providing synergistic information to understand their geologic history with future missions, e.g., JUICE and Europa Clipper.

Other topics that can be studied with a "planning for serendipity" approach are (i) surveying the surroundings for unknown objects (permanent / temporary satellite, impactor), which can be executed with low impacts on primary investigations, (ii) the rings of Jupiter, and (iii) interstellar and interplanetary dust characterization (Altobelli et al., 2016), which would also benefit from an extended operation period given the low flux. Photometric and spectroscopic characterization of Trojan, Hilda asteroids, and comets can be implemented with a Target-of-Opportunity program.

3. Preliminary Mission Architecture

The L1 observatory requires no special radiation protection typically required for a jovian orbiter and can be achieved with existing technology used in missions sent to similar heliocentric locations (e.g., Juno and Lucy). On-board data processing will be essential to reduce the overall data volume. The proposed science scope can be best realized with a New Frontiers class mission. The operation of the conceptual mission can be divided into three phases: interplanetary cruise, Jupiter Orbit Insertion (JOI), and L1 main mission.

The L1 main mission science phase starts few months after JOI, i.e., once the spacecraft enters the L1 libration orbit. Given the nature of the observation requirements (long-term and high-cadence), a repetitive schedule is sufficient to cover most measurements and reduces the complexity and cost for mission operation. Additionally, a Target-of-Opportunity (ToO) program will be implemented for occasional, high-science-value observations (e.g., comets, asteroids, and impact events).

The JOI phase includes the period several months before and after JOI, i.e., when the spacecraft remains closer to the inner jovian system, allowing opportunities for high-spatial-resolution imaging and spectroscopy of Jupiter and its Galilean moons and field-and-particle measurements of the inner magnetosphere, similar to a flyby mission with valuable close flyby opportunities of Galilean moons and irregular satellites. The interplanetary cruise phase also offers diverse science opportunities for other Solar system bodies, including minor bodies (asteroids and comets) and Venus (if a gravitational assist is selected). The on-board field-and-particle suite could also perform heliosphere observations during the cruise phase.

3.1 Mission Design

Many trajectories may be used to transfer a spacecraft to an orbit about the Sun-Jupiter L1 point. A direct transfer is the quickest, which may arrive in under three years. The direct transfer requires a very high launch C3 (characteristic energy) and hence a large launch vehicle with smaller payloads. On the other side, complex transfers such as those used by Galileo and Cassini may be designed which minimize the launch energy, but which require approximately six years to reach Jupiter – and also have multiple gravity assists and very low perihelion ranges. The concept described here balances the strengths of each of these extremes, transferring the spacecraft to Jupiter in under four years and requiring a reasonably low C3.

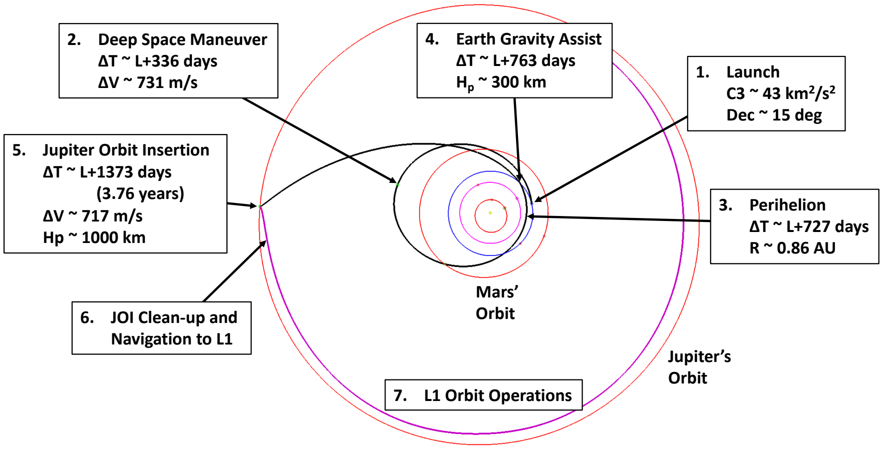

Figure 1. The interplanetary cruise to Sun-Jupiter L1 orbit.

The mission design developed for this mission concept is illustrated in Figures 1 and 2. The geometry repeats every 13 months; thus, nearly every year has a launch opportunity. It involves a launch with a characteristic energy, C3, of only 43 km^2/s^2, plus additional to produce a 21-day launch period. The interplanetary trajectory supports launches from Florida, Virginia, and anywhere with a latitude near or above 15 degrees. The transfer involves a deep space maneuver conducted about 11 months after launch, an Earth Gravity Assist (EGA) about 25 months after launch, and then a rapid transfer to Jupiter. The key to the success of this mission design is the fast interplanetary leg from the EGA to the Jovian arrival. This leg sets the spacecraft up for a relatively small Jupiter Orbit Insertion (JOI) and an immediate insertion into the stable manifold of the target Sun-Jupiter L1 libration orbits.

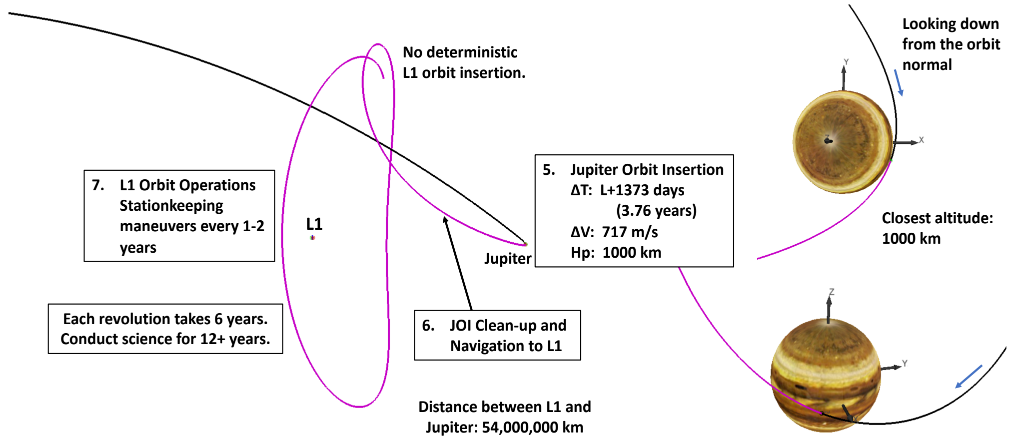

Figure 2. The Jupiter arrival, orbit insertion, and arrival at the Sun-Jupiter L1 orbit.

The design described here avoids a Venus Gravity Assist (VGA) in order to keep the perihelion as high as possible (currently at 0.86 AU), but a VGA would reduce the launch energy and/or reduce the deep space ΔV, at the expense of a lower perihelion (0.72 AU) and a more sensitive planetary alignment constraint. The mission concept without the VGA is very flexible to launch date with a total ΔV budget of ~1800 m/s.

The JOI is conducted as close to Jupiter as possible – the design illustrated here has an altitude of 1000 km, though that may be adjusted as needed. For reference, Juno's orbit insertion had an altitude of 5000 km, though Juno also needed a higher periapse than this mission concept. The JOI requires approximately 717 m/s, plus finite burn losses, and is conducted 3.76 years after launch. A JOI clean-up maneuver will be needed soon after JOI, but no deterministic maneuvers are required to enter the L1 orbit.

Once in orbit about L1, the mission will conduct small stationkeeping maneuvers every 1-2 years, which should require very little fuel. Each revolution about the L1 orbit takes approximately six years; the mission is aiming for two revolutions to cover an entire Jovian year. One can see in Figure 2 that the distance to Jupiter oscillates about 54 million kilometers (~755 Jupiter radii) as the spacecraft traverses the orbit. The spacecraft remains at the leeward edge of the Jovian system and has a pristine view of the solar wind as it arrives at the system.

3.2 Science Payload

3.2.1 Optical Remote Sensing

Remote sensing observations can be carried out by a main telescope with additional small telescope(s) for specific needs. In a preliminary consideration, a derivative of the HiRISE telescope imager (McEwen et al., 2007) on Mars Reconnaissance Orbiter (MRO) mission is a feasible option for the main telescope. It provides about 100 km telescope resolution performance for jovian system bodies from the Sun-Jupiter L1. The corresponding resolution and collecting power roughly equal to an 8-meter class telescope on Earth, sufficient for most studies focusing on Jupiter.

Imaging sensors with color information and focal plane sharing for multiple small back-end instruments using pick-off mirrors can be adapted to accommodate observation needs based on the final STM. For example, in addition to a Wide Field Camera focusing on Jupiter, a Narrow Field Camera with an optical design to provide ~25 km resolution focusing on Galilean moon sciences, and a baseline spectrometer similar to CRISM of MRO (covering 362 to 3920 nm wavelength range, Murchie et al., 2007).

Additional small telescopes may be considered to cover specific observation requirements that cannot be accommodated technically or operationally by the main telescope. For example, EUV observations of Io Plasma Torus may be carried out by a standalone instrument similar to ALICE on the New Horizons (Stern et al., 2005). To enhance the observation duty cycle, a gimbaled small telescope could be shared between Doppler imaging and impact flash monitoring tasks. Note that a ten cm aperture telescope at L1 could deliver comparable results of a 1.4 m telescope on Earth.

3.2.2 Field-and-Particle Instruments

We considered four field-and-particle instruments based on the preliminary STM: (a) Solar Wind Ion and Magnetic Field Monitor to provide upstream solar wind condition with a propagation time uncertainty less than one hour; (b) Dust Analyser capable of mass spectrometry to monitor Iogenic nanodust, interplanetary and interstellar dust populations and characterize surface ejecta composition during close encounter(s) of small body (Kempf et al., 2012) (c) Energetic Neutral Atom Instrument to monitor the Io torus (Smith et al., 2019); (d) Radio Wave Instrument to study jovian auroral and magnetospheric radio emission and plasma waves in the solar wind.

4. Conclusion

This conceptual hybrid observatory at the Jupiter-Sun L1 focuses on time-domain sciences to address key issues across planetary science disciplinaries, including gas giant evolution, solar system dynamics, planetary volcanism, and geoactivities of Ocean Worlds, with broad implications and synergy to ongoing and future planetary missions and astrophysics studies. We advocate the concept and opportunities for it to be further developed for the New Frontiers program.

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