Jupiter Science with the Jupiter Icy Moons Explorer (JUICE)

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Introduction and Recommendations

The Jupiter Icy Moons Explorer (JUICE) is a European-led single-spacecraft mission concept to explore the Jupiter system (its gas giant planet, satellites and planetary environment). It is an evolution of the European Laplace mission concept (Blanc et al., 2008) and the joint NASA-ESA Europa-Jupiter System Mission (EJSM) concept. Although the core Jupiter science goals of EJSM were developed under a dual-spacecraft framework, JUICE is still capable of achieving the majority of the scientific objectives without significant sacrifices. As Jupiter science was principally accomplished during the orbital tour phases of both JEO and JGO (i.e., between JOI and orbital insertion around the respective satellite targets), a sufficiently well-designed tour of a single spacecraft lasting 2 years or more can still achieve our objectives, irrespective of the satellites visited during this tour.

This report discusses the Jupiter science capabilities of JUICE as compared to the original EJSM-Laplace mission concept and the ESA Cosmic Vision. The recommendations of the Jupiter working group are as follows:

1. **Retain capabilities for multi-wavelength remote sensing** from the UV to the radio spectrum (i.e., UV spectrometer, multi-filtered high resolution imaging, near-IR mapping spectrometer, sub-mm sounding and radio occultation studies), and investigate the inclusion of the thermal infrared (5-100 μm, which was only previously present on JEO) and spectro-polarimetry.
2. **Support a well-designed orbital tour** exceeding two years before Ganymede Orbital Insertion consisting of
    a. Extended periods if time for regular Jupiter atmospheric monitoring across multiple wavelengths;
    b. A well-balanced mix of dayside (for reflected sunlight) and nightside (lightning, thermal emission) observations, with both dayside and nightside apoapses for global 'video';
    c. Access to high jovian latitudes for remote sensing and occultations (retaining the latitude coverage that would have been provided by a dual spacecraft mission).
3. Ensure that the **spatial and spectra resolutions** offered by the model payload provide an improvement over previous works. E.g., increasing spectral resolutions of UVIS and VIRHIS to study Jupiter's upper atmosphere and aurorae.

This report is broken down as follows: we start by reviewing the Cosmic Vision document, both for the mission as a whole and then specifically for Jupiter science. We also explain the need for JUICE in the context of previous studies (especially Juno). The specific scientific objectives of JUICE are then described in detail, before we assess the single-spacecraft mission scenarios. Finally we review the payload instruments relevant to Jupiter science and propose observational strategies to form a part of the mission.

Cosmic Vision 2015-2025: A General Review

Jupiter and Europa featured highly in the original document in the context of **the Jupiter Exploration Program (JEP)**, a coherent and systematic exploration of the habitability and processes at work within a giant planet system, which was seen as a high priority for the Cosmic Vision. The JUICE concept is designed to directly address two of the Cosmic Vision themes:

1. What are the conditions for planet formation and the emergence of life?
2. How does the solar system work?

Although theme one called for exploration of Europa specifically, theme 2 suggested a more general exploration of the Jupiter system and its various components. Thus a Ganymede mission that studies the wider Jupiter system would embody the spirit of theme 2, whilst also addressing some elements of the science in theme 1.

In the following text we paraphrase the Cosmic Vision document (essentially chapters 1, 2 and 4) into a series of questions to be addressed by JUICE. Specifically, JUICE addresses subsection 1.3: *Life and habitability in the Solar System* and subsection 2.2: *The giant planets and their environments via in situ studies of Jupiter, its atmosphere, internal structure and satellites*. The questions are grouped into four themes: **Characteristics, Habitability, Formation and Evolution, Coupling Processes.** Within each theme, we organise the questions raised by the Cosmic Vision document into sub-categories against which the JUICE mission options can be compared. The words used remain true to the original Cosmic Vision text.

1. Characteristics of Giant Planet Systems

- Main Question: What are the main characteristics of giant planet systems in our Solar System? Why are the planets so different from one another, with such a variety of atmospheres and surfaces? What are the implications for extrasolar planetary systems?
- **SATELLITES:** What are the chemical, geological, topographical and morphological characteristics of the surfaces of icy moons? *What is their internal and subsurface structure, especially the icy ones; what is the geological history, and how does this reflect their formation?* Gravity, magnetic fields, surface morphology, topology, mineralogy and composition.
- **ATMOSPHERE:** What is the composition, structure and dynamics of a giant planet planetary atmosphere? Study via atmospheric remote sensing.
- **INTERIOR:** Do the giant planets have a solid core, how large is it and what is its composition? Study via gravitational and magnetic field mapping plus deep remote sensing.
- **ENVIRONMENT:** What are the processes at work in the gas, dust and plasma environment of a giant planet, and how does this affect the habitability and coupling?

2. Habitable Environments

- Main Question: Can forms of life exist elsewhere in our Solar System, could they have a second independent origin and how unique are the habitable conditions of our home planet? What environmental conditions make a planet habitable and enable life to appear, evolve and survive, either today or in the past?
- **SURFACES AND ICY CRUSTS**: What conditions on planetary surfaces (composition, stability, source of nutrients, etc.) are required to support life?

- **SUBSURFACES AND OCEANS:** What are the requirements (energy sources, internal structure, source of nutrients) for a planetary subsurface to accommodate life?
- **ENVIRONMENT:** What are the environmental conditions (geological; hydrological; atmospheric and climatic; magnetic, plasma and radiation environment) that make life possible, and how do those conditions improve or degrade with time?
- **EUROPA:** [This final bullet raised points specific to Europa]. Determine Europa's internal structure and heat sources; composition of the ocean and icy crust; availability of nutrients; plasma and radiation environment around Jupiter. Assess the survivability of any life throughout Europa's history.

3. Planetary Formation and Evolution

- Main Question: Jupiter as a miniature analogue of the solar system: what processes were involved in the formation of our Solar System out of the protosolar nebula; what was the role of the giant planets in the evolution of the solar system and the emergence of habitable environments; and how have planetary systems evolved with time?
- **PROCESSES:** What are the processes in the solar nebula and planetary sub-nebulae that govern the formation of giant planets, their interior structure, atmosphere and magnetosphere and their extended systems of satellites, dust and plasma? What was the timeline and duration of major formation events? I.e., testing the accretion scenario, studying recent impact events on planet and satellites.
- **MATERIALS:** Habitability depends on the materials from which a planet accreted, so what was the composition of those materials (e.g., from Jupiter's atmosphere to satellite composition), and what are the conditions required for planets to form around stars? What determines the presence of water on a planet, now and in the past? What can primitive bodies tell us about this primordial material?
- **MARS:** [Specific Mars question, but could also apply to icy moons]. *How did continued evolution of the planet affect the habitable environment and what happened to the planet to make its surface uninhabitable today?*
- **PRIMITIVE BODIES:** [Specific question but could also apply to icy moons]. *What was the timeline and duration of major events, such as agglomeration, heating and degassing, and aqueous alteration*

4. Coupling Processes

- Main Question: What processes couple the central star to the environment of a planetary system, and what processes couple the central giant planet to its complex gas, plasma and dust environments, as exemplified by the hard radiation environment at Europa's surface?
- **PLANET AND SOLAR WIND:** How is a giant planet system coupled to the radiative and plasma output from the central star, and how are the components of the system shielded? How do planetary atmospheres and magnetospheres respond to the solar wind? Understand the solar magnetic system, its variability and its interactions with planetary environments. [Habitability depends on behaviour of the space environments surrounding the planets.]
- **PLANETARY ENVIRONMENT:** Jupiter magnetosphere is described as "*a wonderful laboratory for studying how plasmas behave in space*" and the "*most accessible environment for studying some further fundamental processes such as the plasma's interactions with neutral gas and with the planet's moons,*

magnetodisc stability, the relaxation of rotational energy and associated energetic processes, and the loss of angular momentum by magneto-plasma interactions."

- **INTERNAL PROCESSES:** [Although not specifically mentioned, coupling processes within sub-components could also fall under this category: e.g., coupling of surface and oceans of icy satellites; coupling of magnetosphere to giant planet upper atmospheres; coupling of giant planets interiors and atmospheres, etc.]

Jupiter Science within the Cosmic Vision

In this section we review the Cosmic Vision goals that are specific to the giant planet itself, which were used to develop the original EJSM-Laplace scientific requirements in Section D. Note that we have omitted subsection 2 (habitability), which will be addressed by the satellite investigations.

1. **Characteristics of Giant Planet Systems:**
   - Main Question: What are the main characteristics of giant planet systems in our Solar System? Why are the planets so different from one another, with such a variety of atmospheres and surfaces? What are the implications for extrasolar planetary systems?
   - **ATMOSPHERE:** What is the composition, structure and dynamics of a giant planet planetary atmosphere? Study via atmospheric remote sensing.
   - **INTERIOR:** Do the giant planets have a solid core, how large is it and what is its composition? Study via gravitational and magnetic field mapping plus deep remote sensing.

3. **Planetary Formation and Evolution:**
   - Main Question: Jupiter as a miniature analogue of the solar system: what processes were involved in the formation of our Solar System out of the protosolar nebula; what was the role of the giant planets in the evolution of the solar system and the emergence of habitable environments; and how have planetary systems evolved with time?
   - **PROCESSES:** What are the processes in the solar nebula and planetary sub-nebulae that govern the formation of giant planets, their interior structure, atmosphere and magnetosphere and their extended systems of satellites, dust and plasma? What was the timeline and duration of major formation events? I.e., testing the accretion scenario, studying recent impact events on planet and satellites.
   - **MATERIALS:** Habitability depends on the materials from which a planet accreted, so what was the composition of those materials (e.g., from Jupiter's atmosphere), and what are the conditions required for planets to form around stars? What determines the presence of water on a planet, now and in the past?

4. **Coupling Processes**
   - Main Question: What processes couple the central star to the environment of a planetary system, and what processes couple the central giant planet to its complex gas, plasma and dust environments?
   - **PLANET AND SOLAR WIND:** How do planetary atmospheres and magnetospheres respond to the solar wind (e.g., aurora)?
   - **INTERNAL PROCESSES:** How is the atmosphere of a giant planet coupled to the deep interior and to the local planetary environment (e.g., magnetosphere, plasma, solar energy deposition, etc.)?

To summarise, the Jupiter science goals of the Cosmic Vision are: **Atmospheric Characteristics**; **Probing the Interior**; **Formation and Evolution**; and **Coupling Processes.**

Relation to Previous Jupiter Exploration and Juno

The core goals of Jupiter exploration have evolved in the decades since Jupiter was first explored by Pioneer 10 and 11 (1973-1974) and Voyager 1 and 2 (1979). In particular, JUICE seeks to answer questions raised by previous spacecraft exploration (Galileo, 1994-2003; Cassini, 2000; New Horizons, 2007; and Juno, 2016). Fly-by spacecraft provided 'snapshots' of the dynamics, composition and clouds that have been supplemented by ground-based campaigns to study Jupiter's long-term evolution. Galileo studied the jovian atmosphere at high spatial resolution but with limited coverage; discovering evidence for moist convection (e.g., lightning) and coupling between different atmospheric layers. The Galileo probe (1995) measured the composition and clouds within a near-equatorial hotspot (a site of atmospheric subsidence). JUICE will greatly extend the scientific discoveries and objectives of Galileo (which remain largely incomplete due to the loss of Galileo's HGA) by providing global high-resolution multi-wavelength monitoring of the atmosphere over an extended period of time.

The NASA Juno mission, due to arrive in 2016, will focus on understanding the deep interior of Jupiter (e.g., microwave studies of the volatiles H2O and NH3 below the clouds; gravity mapping of the internal mass distribution and existence of a core), the magnetosphere, aurorae and sources of near-IR opacity in the polar atmosphere.

The Juno spacecraft's suite of seven science instruments will study:

- **Origins:** Determine the ratio of oxygen to hydrogen, giving an idea of the abundance of water on Jupiter; obtain a better estimate of Jupiter's core mass, which will help distinguish among prevailing theories linking the gas giant's formation to the solar system.
- **Interior:** Precisely map Jupiter's gravitational and magnetic fields to assess the distribution of mass in Jupiter's interior, including properties of the planet's structure and dynamics.
- **Atmosphere:** Map the variation in atmospheric composition, temperature structure, cloud opacity and dynamics to depths far greater than 100 bars at all latitudes (In 1995, the Galileo probe reached only ~ 22 bars at a single location).
- **Magnetosphere:** Characterize and explore the three dimensional structure of Jupiter's polar magnetosphere and its auroras.

JUICE will complement Juno by focusing on a complete three-dimensional understanding of atmosphere from the tropospheric clouds (the weather layer) up into the upper atmosphere. Juno will address the Jupiter science themes **Probing the Interior** and **Formation and Evolution** (described above) by investigating the internal mass distribution and constraining Jupiter's bulk oxygen content. JUICE will supplement Juno's studies, but the main emphasis of the science objectives is on **Atmospheric Characteristics** and **Coupling Processes**, as described in the next section.

JUICE Jupiter Science Objectives

The science objectives for the original EJSM-Laplace mission concept are relatively unchanged within JUICE. These were developed to address the themes of the Cosmic Vision and to build on the discoveries of previous spacecraft exploration.

The value of Jupiter exploration can be summarized in four points:

- Jupiter as the archetype for gas giants in the solar system
- Jupiter as a window on solar system origins.
- Jupiter as a template planetary system for exoplanets.
- Jupiter as a fundamental geophysical fluid dynamics laboratory.

The exploration of Jupiter's dynamic atmosphere has played a pivotal role in the development of our understanding of the Solar System, serving as the paradigm for the interpretation of planetary systems around other stars and as a fundamental laboratory for the investigation of large-scale geophysical fluid dynamics and the many physiochemical phenomena evident on the gas giants. However, despite decades of intense investigation, our characterization of this archetypal giant planet remains incomplete, with many fundamental questions about its nature unanswered. The thin atmospheric 'weather-layer', the only region accessible to direct investigation by remote sensing, is only a tiny fraction of Jupiter's total mass, yet it provides vital insights to the interior structure, bulk composition and formation history of most of our Solar System. JUICE offers an unprecedented opportunity for study of Jupiter's atmosphere, with a long temporal baseline of 2 years or more, and complementary spectral and imaging coverage from the far-UV to the sub-millimetre.

Jupiter's atmospheric structure and composition is the end product of energetic accretion processes, thermochemistry, photochemistry, condensation processes, planetary-scale turbulence and gravitational differentiation. Its atmosphere is characterized by multiple latitudinal bands of differing cloud colours, temperatures, vertical mixing strengths and molecular composition; separated by strong zonal winds and perturbed by long-lived vortices, storms, polar circulations, convective outbreaks, wave activity and global changes to the large-scale circulation patterns (Rogers, 1995; Ingersoll et al, 2004; West et al., 2004). Although primarily composed of hydrogen and helium, Jupiter also contains significant amounts of heavier elements found in their fully reduced forms (CH_4, PH_3, NH_3, H_2S, H_2O), providing the source material for rich and complex photochemical pathways powered by UV irradiation (Taylor et al, 2004; Moses et al., 2004). The abundances of most of these heavy elements are enriched over the solar composition, providing a window into the past and a reflection of the primordial nebula material incorporated into the gas giants during their formation (Lunine et al., 2004). Jupiter's vertical atmospheric structure is governed by the complex balance between solar, chemical and internal energy sources, and its layers are coupled by poorly understood dynamical processes which transport energy, momentum and material between the layers (e.g. Vasavada and Showman, 2005). Most importantly, Jupiter's atmosphere is intricately connected to the charged-particle environments of the ionosphere and magnetosphere (e.g. Yelle and Miller, 2004), and the local Jovian environment of the rings and icy satellites. JUICE will study Jupiter's plethora of atmospheric phenomena in the context of this coupled planetary system.

The proposed Jupiter science objectives for JUICE fall into three main categories (a) **Atmospheric Dynamics and Circulation**, (b) **Composition and Chemistry**, and (c) **Vertical Structure**. While each objective and sub-investigation is individually valuable, these objectives are cross-disciplinary in nature, and are meant to be combined to address fundamental 'big picture' science questions, outlined below.

A. Atmospheric Dynamics and Circulation

The plethora of dynamical and chemical phenomena of Jupiter's "visible" upper atmosphere (the "weather-layer") are thought to be governed by a balance between radiative-forcing due to the deposition of solar energy and forcing from deeper internal processes. Remote sensing over the past several decades has provided a wealth of information about atmospheric processes at discrete altitudes in localised regions, but the crucial challenge for experiment and modelling is to develop a fully three-dimensional model of the observable atmosphere and its connection to the deep interior. Moist convection, eddy momentum fluxes, turbulence, vertical wave propagation and frictional damping are all believed to play a role in shaping and maintaining atmospheric circulation, transporting and mixing energy, momentum and material tracers both horizontally and vertically (e.g. Vasavada and Showman, 2005; Salyk et al., 2006). JUICE will measure (a) atmospheric motions in the cloud tops over a range of timescales; (b) the temperature and compositional gradients associated with dynamical phenomena; (c) the role of wave propagation in coupling between the different layers (e.g. Leovy et al., 1991); (d) the structure, morphology and energy transport mechanisms of Jupiter's aurora (e.g. Vincent et al, 2000); (e) the interrelationship between the ionospheric and thermospheric heating and the propagation of waves and (f) the origin of the H Lyman alpha bulge (Yelle and Miller, 2004).

Measurements of lightning (as a proxy for thundercloud activity) in individual convective cells will also constrain the energetics of the atmosphere at depth (Little et al., 1999; Gierasch et al., 2000), helping to distinguish between 'shallow' and 'deep' models for the origins of eddies, vortices and belt/zone contrasts. In order to understand the physical conditions of the lightning storms, JUICE would measure the spectral energy distribution of the lightning flashes, the global discharge rate, the spatial distribution and temperature of the lightning. Furthermore, if the depth of the discharges is confirmed to be within the water cloud or below (Little et al., 1999), then tracking the motion and lifetimes of the lightning storms will provide an additional method of determining zonal windspeeds at depth.

Furthermore, Jupiter exhibits a wealth of time-variable phenomena, ranging from short-lived thunder-storms, lightning, and atmospheric waves to multi-year-long, quasiperiodic variations in the banded cloud patterns (e.g. Rogers, 1995). Global upheavals of the banded structure occurred throughout 2007 [Sanchez-Lavega et al. 2008], as well as the formation and reddening of new anticyclonic ovals in 2006 and 2008 [Simon-Miller et al. 2006, Cheng et al. 2008]. Meteorological investigations will benefit from the long temporal baseline offered by JUICE and by studying these changes over a wide range of wavelengths, JUICE will connect dynamical changes with thermodynamic (temperature, pressure, potential vorticity) and chemical (aerosols, chemical gradients, cloud colours) variability *[NB. This will only be accomplished if a thermal instrument is retained.]*

Asteroidal/cometary impacts influence the atmosphere in a dramatic fashion over timescales from minutes to months and may be quite common. From JUICE, wave activity would be studied over a range of spatial scales, from (a) sporadic equatorial mesoscale waves; to (b) planetary-scale Rossby waves and the forcing of the Quasi-Quadrennial Oscillation [Leovy et al., 1991]; and (c) gravity waves in the middle and upper atmosphere, which are thought to play an important role in energy transfer between different layers, particularly as a dominant source of heating in the thermosphere. JUICE would provide a comprehensive four-dimensional climate database of Jupiter to reveal the underlying physical processes at work in outer planet atmospheres.

Top Level Questions:

1. *How is the deposited solar energy redistributed in the Jovian atmosphere and what dynamical processes are involved in the energy transfer between atmospheric layers?*
2. *How are localized processes (lightning, discrete vortices) on Jupiter related to the dynamics of the atmosphere?*
3. *What is the time-variable three-dimensional flow field and how important is wave activity in the global circulation of Jupiter?*

JA. Characterize the atmospheric dynamics and circulation.
JA.1 Investigate the dynamics of Jupiter's weather layer.
JA.2 Determine the thermodynamics of atmospheric phenomena.
JA.3 Quantify the roles of wave propagation and atmospheric coupling.
JA.4 Investigate auroral structure and energy transport.
JA.5 Understand the interrelationships of the ionosphere and thermosphere.

B. Composition and Chemistry

Jupiter as we see it today is the product of the myriad of thermochemical and photochemical pathways resulting from its bulk composition (Atreya et al., 2003). The composition determines the altitudes and structures of the cloud decks and hazes; radiative energy balance in the troposphere and middle atmosphere; and condensation processes can provide the energy required for convective dynamics described in Section 3.1. Furthermore, Jupiter's bulk composition provides a window on the formation and evolution of the gas giant, and connects is directly to the nature of the extensive satellite system. High-resolution spectroscopy would (a) determine bulk elemental abundances (He, C, N, S, P, As and Ge) and isotopic ratios (D/H, C, N, O) for comparison with Galileo probe (e,g, Niemann et al, 1998) and Juno results; (b) measure the three-dimensional distribution and variability of stratospheric hydrocarbons and exogenic material (Moses et al., 2004) ; (c) study localised and non-equilibrium composition associated with discrete atmospheric features like storms and instabilities; (d) use the spatial distribution of volatiles to understand the importance of moist convection in cloud formation, lightning and chemistry (e.g. Roos-Serote et al., 2004; Baines et al., 2002); and (e) assess the composition, especially hydrocarbons, in the mesosphere and thermosphere.

Top Level Questions

1. *How is the spatial variation of composition of condensables related to the meteorology?*
2. *How do non-equilibrium species vary spatially and relate to the global circulation?*
3. *What is the composition of the stratosphere and how is it related to dynamical processes and photochemistry?*

JB. Characterize the atmospheric composition and chemistry.
JB.1 Determine Jupiter's bulk elemental abundances.
JB.2 Measure the composition from the stratosphere to low thermosphere in three dimensions.
JB.3 Study localized and non-equilibrium composition.
JB.4 Determine the importance of moist convection in meteorology, cloud formation, and chemistry.

C. Vertical Structure of the Atmosphere and Interior

The third objective is to characterise Jupiter's atmospheric structure from the deep interior up to the magnetosphere, and the coupling mechanisms between each of these layers. Fundamental questions surrounding the existence and size of Jupiter's core, the workings of the internal dynamo and the exotic conditions of metallic hydrogen (e.g. Guillot et al., 2005) will be partially addressed by Juno, but would be significantly enhanced by observations of acoustic mode oscillations of the atmosphere, which probe the density gradients within the interior (Jovian seismology). Compositional mapping of volatiles and disequilibrium species would provide constraints on the importance of deep internal convection in determining the meteorology visible at the cloud tops. Near-IR studies of clouds and hazes at a range of phase angles and observational geometries would constrain the global vertical structure and composition of the clouds in Jupiter's atmosphere (e.g. West et al, 2004). Thermal-IR, ultraviolet, sub-millimetre and radio science occultations would determine the vertical temperature, density, pressure and zonal wind structure from the troposphere to the thermosphere, and the charged particle distribution in the ionosphere and magnetosphere. The presence of vertically propagating waves (and their temporal variability) inferred from these measurements will be vital to our understanding of material and energy transport between these different layers.

JUICE aims to globally map the vertical structure and optical properties of clouds and hazes from the millibar level to approximately 5 bar [e.g., West et al., 2004] to reveal the mechanisms responsible for aerosol production – photochemical production and sedimentation, condensation and uplift of NH3 and NH4SH ices, shock chemistry in lightning. In particular, we hope to discover the chromophores responsible for the differences in cloud coloration on Jupiter. Finally, JUICE would study the unique physiochemical processes occurring at high latitudes (e.g., auroral energy deposition and associated haze production, circumpolar waves, north/south asymmetry and high-latitude vortices) as a vital counterpoint to the seasonal asymmetries observed on Saturn by Cassini.

Top Level Questions

1. *What is the nature of the coupling processes between Jupiter's deep interior and upper layers ?*
2. *What is the altitude, thickness and composition of the clouds and coloured chromophores in the atmosphere of Jupiter?*
3. *What are the processes responsible for the formation of upper atmospheric haze at high latitudes?*

JC. Characterize the atmospheric vertical structure.
JC.1 Determine the three-dimensional structure from Jupiter's upper troposphere to lower thermosphere.
JC.2 Explore Jupiter's interior density structure and dynamics below the upper troposphere.
JC.3 Study coupling across atmospheric layers.

Open Questions and cross-disciplinary connections

The three Jupiter science objectives are designed to address several recent discoveries and unanswered questions, including but not limited to:

- Dynamics: What is the importance of moist convection in maintaining the zonal winds, belt/zone contrasts in temperatures and composition, and how can the 'classical view' of upwelling, cloudy, moist "zones" adjacent to subsiding, clear and dry "belts" be reconciled with observations of convective updrafts within the belts and horizontal convergence of momentum into the jets due to eddy momentum flux (Salyk et al, 2006)? What is the role of ion drag for redistributing energy from the high latitude thermosphere towards low latitudes?

- Waves: What is the relationship between gravity waves and the Quasi-Quadrennial Oscillation (QQO, Leovy et al., 1991); which type of wave is its main driver? Why are equatorial mesoscale inertia–gravity waves only observed sporadically? Do atmospheric conditions change sufficiently to influence wave production or vice versa? How do planetary scale thermal and Rossby waves influence coupling between atmospheric layers? Can acoustic waves be used to probe the interior? What role does wave forcing from below play in the energy crisis problem of Jupiter's thermosphere?
- Interior: Does Jupiter have a rocky core, and what is its size? What is the nature of density gradients in the deep atmosphere associated with the exotic conditions of metallic hydrogen?
- Polar Processes: What is the connection between aerosols within polar vortices and chemistry associated with the aurora? Does Jupiter exhibit small cyclonic polar vortices like Saturn (Fletcher et al., 2008)? Why do the polar hazes appear asymmetric between the hemispheres? What is the nature of the persistent UV dark spot seen at high northern latitudes? How do polar wind jets, meridional circulation, and circumpolar waves influence the distribution of auroral and photochemical products?
- Cloud Structure and Temporal Evolution: What is the composition of the visible cloud deck (NH3 or NH4SH ice)? Why does it vary with location and with time during episodic outbursts and quasi-periodic 'upheavals' in the climate?

The three Jupiter science objectives of JUICE will provide insights into these fundamental questions, and many more, through its unique combination of advanced instrumentation, multiple spacecraft platforms and long-term baseline of Jupiter observations.

Goals in the JEO Report (2009)

In this section we review the original goals of the NASA Jupiter Europa Orbiter, as described in the 2008 and 2009 reports. The goals were modified into the dual-spacecraft framework for the final 2010 report of the Joint Jupiter Science Definition Team.

1. Jet Stream Meteorology.

High resolution long-term cloud tracking at visible and near-IR wavelengths at 30 km resolution allows the zonal (east–west) and meridional (north–south) velocities to be obtained, and could allow measurement of the mean-meridional velocity at the cloud level for the first time. High spectral-resolution sub-mm investigations of the 1-500 mbar region may allow direct measurements of wind velocities without the need for cloud-tracking. Observations of any correlation between zonal and meridional velocities will determine whether small eddies are pumping the jets at cloud level [Salyk et al. 2006] and how this process varies with latitude and time. Observations at different wavelengths from the visible to the sub-mm permit studies of the vertical wind shear in the tropospheric jets, which could then be related to the deep structures observed by Juno to determine the vertical coupling between the upper and lower atmospheres. Spectroscopic studies will constrain the thermal and chemical environments in the vicinity of these cloud tracers.

2. Tropospheric Hazes and Clouds.

The characterization of the altitude and global distribution of photochemical hazes and condensation clouds will provide fundamental clues to their origin and the meridional transport in the troposphere. The haze distribution is vital to understanding the details of solar energy deposition in the atmosphere and its role in hemispherical asymmetries. Correlation between temporal variations of cloud properties (size, optical properties, vertical distribution, color and albedo) with changes of environmental temperatures and composition will be used to determine what is responsible for major changes in Jupiter's cloud properties. These may provide a fundamental clue for the origin of their various colors. The detection of condensed ammonia, ammonium hydrosulfate and water ice will provide significant clues to the size and strength of updraft regions in the atmosphere [e.g., Baines et al. 2002].

3. Evolution of discrete cloud features.

Weather-layer phenomena such as thermal hotspots, large anticyclonic vortices, turbulent regions, convective plumes, and thunderclouds can be monitored using visible and IR imaging over a long temporal baseline. Spatial resolutions as high as 30 km provide the capability to examine the cloud properties, energetics, and angular momentum of individual storm systems [cf. Porco et al. 2003] and their relation to the global atmospheric circulation. Measurements of thunderstorms on the dayside and lightning on the night side will constrain the energetics of the atmosphere at depth.

4. Atmospheric Waves and the Thermosphere and Ionosphere.

Radio science investigations will characterize the detailed vertical temperature structure in the stratosphere and upper troposphere, thus providing a window into stratospheric dynamics. This will allow a characterization of the vertical propagation of a variety of atmospheric waves, including small-scale gravity, larger-scale Rossby waves, and the altitude dependence of slowly moving thermal waves that are uncorrelated with cloud structures. A characterization of such waves would also prove invaluable in understanding the dynamics of the quasi-periodic stratospheric oscillation (QQO), which is a time-evolving stratospheric phenomenon, much like the Earth's quasi-biennial oscillation (QBO), and thought to be driven by atmospheric wave absorption. Radio and stellar occultations can also be used to characterize the thermosphere and determine the extent to which wave absorption can cause the high thermospheric temperatures.

5. Tropospheric Dynamical Tracers.

To complement the Juno investigation of the lower troposphere, near-IR spectroscopy will measure H2O and NH3 in the upper troposphere, in addition to disequilibrium species such as PH3, GeH4 and CO as diagnostics of the dynamics associated with the jet stream meteorology and discrete cloud features. In particular, high-inclination orbits will be able to map these species and tropospheric aerosols at polar latitudes to determine the relative roles of dynamics and seasonally-forced radiation in maintaining Jupiter's cold and hazy polar vortices [cf. Vincent et al. 2000, Porco et al. 2003]. High spectral resolution long-wavelength observations could also provide 3-D information on the vertical distribution of trace gaseous species, as well as providing vertical temperature structure and wind velocities in regions of the atmosphere inaccessible to nadir-sounding thermal-IR spectroscopy.

6. Stratospheric temperature and Composition:

Spectroscopic studies of Jupiter's stratosphere (in the near-IR, visible, UV and sub-millimeter) will shed light on the photochemistry and atmospheric motion responsible for the distribution of hydro-carbons and hazes. Thermal monitoring could allow the first detection of tides raised by the Galilean satellites. Detection of material from exogenic sources (HCN, CO, CO2, H2O) will permit studies of the changing environment surrounding the satellites and rings.

7. Electrodynamic Phenomena

The diverse Jovian tour phase of the JEO mission offers the prospect of measuring the time variability of the Jovian ionosphere for the first time. The temporal evolution of the distribution of ions within the ionosphere will be probed at a range of latitudes through radio occultations at multiple frequencies, accomplished using precisely time-referenced Ka- and X-band transmissions. The coupling between Jupiter's 3D auroral spatial structure and source regions within the magnetosphere will be studied using imaging of H-3+ emission in the near-IR, as well as in the visible and UV.

Descope: From EJSM-Laplace to JUICE

In this section we evaluate the impact on Jupiter science of the loss of the NASA-led Jupiter Europa Orbiter, and the reformulation of JGO as a single spacecraft mission. As we describe in subsequent sections, the core scientific goals defined above are still accomplished. The main losses are (i) full coverage from the UV to the sub-mm; (ii) the synergistic opportunities that existed within a dual spacecraft mission; and (iii) a reduction in the time available for atmospheric monitoring. We propose that these objectives could be recovered by:

- Developing a well-designed tour with multiple occultation opportunities, extended periods for Jupiter monitoring, high orbital inclinations to access a range of latitudes, and a good balance of dayside and nightside global and regional imaging.
- Plugging the 5-250 μm gap by adding capabilities in the thermal infrared.
- Encouraging a campaign of amateur and professional ground-based imaging to provide contextual information for close-in studies.

Spacecraft-Spacecraft Occultations

Occultations constrain neutral atmosphere T(p), density, composition, wave propagation, energy transport; ionospheric electron density and ion distribution in the upper atmosphere. S/C-Earth occultations sample **limited dawn/dusk local times and limited latitude ranges** (only southern hemisphere for the JUICE mission period). By comparisons, the S/C-S/C occultations included in the EJSM-Laplace mission probed a much wider range of latitudes, longitudes and local times.

However, the neutral atmosphere varies little with local time due to the long radiative times (multiple years) in the stratosphere and troposphere, so the main loss for the neutral atmosphere is (i) the frequency of occultation studies and (ii) the latitude coverage (i.e., reduced spatio-temporal sampling). **JUICE could retain some of these with a well-designed tour (multiple S/C-Earth occultations) and with higher orbital inclinations (providing a wider range of latitudes).**

Unfortunately the lack of S/C-S/C occultations prevents us from studying local time variability of electron density and ion distributions in the charged upper atmosphere. ***Is there any way to recover this within JUICE?***

Spectral Coverage (Loss of Thermal-IR)

The presence of two spacecraft would have permitted multi-frequency remote sensing observations from the UV to the radio spectrum using UV spectrometers, multi-wavelength visible imaging, near-IR mapping spectrometers, thermal imagers, sub-mm sounders and radio occultations. The majority of these instruments (or variants thereof) were included in the strawman payloads for both JEO and JGO, providing (i) coverage from multiple vantage points (e.g., better coverage of the whole range of scattering phase angles from jovian aerosols to break the degeneracy in cloud structure retrievals); and (ii) additional spectral coverage if instruments were unable to operate together (e.g., due to different pointings or data rate constraints). A well-designed jovian tour could still provide good coverage of lighting conditions for cloud and haze studies.

However, the most important loss from the Jupiter mission is the thermal infrared (between the upper limit of VIRHIS at 5 μm and the lower limit of the SWI at 250 μm). Only JEO featured a thermal instrument to study thermodynamics of atmospheric phenomena (plus emission, energy balance and thermal interia of satellite surfaces). Without the thermal-IR instrument **we cannot map tropospheric and stratospheric temperatures globally, nor couple cloud dynamics and composition to thermodynamic variability.** This has serious consequences for our ability to constrain atmospheric dynamics, and **we propose that the JUICE science requirements relevant to the thermal-IR be retained in the instrument AO,** even if it is not in the strawman payload.

Synergistic Science

The presence of multiple S/C would have meant multiple vantage points for studying atmospheric events. For example, we would have obtained multiple wavelengths and viewing angles for a better determination of the vertical structure of storms, plumes, vortices, e.g., 'stereo imaging' of atmospheric phenomena. However, if we assume that the atmosphere is static over short time intervals we may still be able to do this as Jupiter rotates beneath the spacecraft over a 3-5 hour period. The two spacecraft could also have provided **simultaneous narrow-angle an contextual imaging** if one S/C was at apoapse while the other was at periapse. This can also be partially recovered if we **engage ground-based supporting observations from both amateur observers and professional telescopes** (when Jupiter is sufficiently separated from the Sun).

Another example of the synergies between two spacecraft was assessing the connectivity between different parts of the Jupiter system. For example, the interaction of the atmosphere with the immediate planetary environment could have been studied if magnetospheric and plasma instruments on one spacecraft observed phenomena in the magnetodisc that had direct manifestations on the upper atmosphere being studied by the second spacecraft. The loss of this capability does not affect the core science goals.

Temporal Coverage

The greatest return for Jupiter science would be from maximising the length of time spent in the jovian tour. The presence of two S/C effectively doubled the length of time available for Jupiter monitoring, and added flexibility for dynamics and composition monitoring to generate the 4D Jupiter climate database. In a single spacecraft mission this could still be provided by **an extended jovian tour of 2+ years**. The original baseline JGO tour provided better dayside opportunities for long-range apoapse monitoring than JEO, and was better optimised for Jupiter studies.

Evaluation of JUICE Mission Scenarios

During the re-formulation study of the mission three options are being investigated, namely: (1) keeping the original JGO scenario unchanged; (2) expanding the science goals by a few Europa flybys; (3) changing the JGO primary objective focusing on ocean research at Europa and Ganymede. In this section we evaluate the three scenarios with regards to Jupiter science.

JUICE#1: Original Ganymede Orbiter

The first two options are very similar from the perspective of Jupiter science because (i) the full instrument complement is retained (unlike JUICE#3); and (ii) the maximum amount of time is available for Jupiter science. In order to recover Jupiter science goals originally covered by the dual-spacecraft mission, we recommend the following:

- Inclusion of thermal-IR capabilities (5-250 μm) to bridge the gap between VIRHIS and SWI and allow us to determine the thermodynamic properties of atmospheric phenomena in the troposphere and stratosphere.
- Designing a jovian tour with a variety of orbital inclinations, ranges and phases over 2+ years to provide:
    a. Access to high jovian latitudes (covering those lost due to the absence of S/C-S/C occultations), providing us with polar views and a range of orbital inclinations over the course of the mission.
    b. A balance between dayside and nightside apoapse viewing for cloud tracking studies (global monitoring and the production of movies) and lightning/thermal emission studies, respectively.
    c. A balance between lighting conditions at close-in periapses to provide high resolution views to each instrument over the course of the mission (e.g., close-range orbits for the SWI to observe the limb, for the NAC and VIRHIS to see detailed cloud morphologies).
    d. Good coverage of Jupiter phases for investigations of jovian aerosols and clouds.

In summary, the model trajectory should be formed from a trade off between having long periods of good lighting with low resolution (apojove on dayside) and short periods of good lighting with high resolution (perijove on dayside). The trajectory should also provide multiple opportunities for high phase angles with good resolution for nightside IR imaging and lightning studies.

[From the EJSM yellow book, February 2011:] After the 5.9 year transfer to Jupiter, JUICE would arrive at Jupiter orbit insertion (JOI) in February 2026. After the first 13x243 R_J orbit (179 days), JUICE will continue on an evolving elliptic orbit around Jupiter outside the Ganymede orbit and thus radiation belts. The final apojove and perijove are 50 RJ and 12.2 RJ, respectively (duration 120 days). This **phase will be focused on monitoring of the Jupiter atmosphere and coupling processes**, and will allow detailed investigations of the inner magnetosphere of the giant planet. Seven flybys of Ganymede would allow an initial investigation of the moon. The second year (388 days) is a Callisto pseudo-orbital phase that would last for ~13 months during which JUICE will perform 10 flybys of Callisto to investigate internal structure, surface and exosphere or this moon. The **time between Callisto flybys will be devoted to continuous monitoring of Jupiter's atmosphere** and magnetosphere, rings and dust environment, and remote observations of the other moons. The following 240 days of transfer to Ganymede will again be favourable for the studies of interaction of the Jovian magnetosphere with the intrinsic magnetic field of the moon, together with remote observation of the giant planet and the icy moons. Thus, **using the original JGO orbital tour as a baseline for JUICE gives 2.7 years of Jupiter monitoring opportunities**.

JUICE#2: Ganymede Orbiter + Europa Flyby(s)

The second option is for a mission with the same core payload as JGO, but optimised to include a number of Europa flybys during the tour phase. This would reduce the amount of time spent devoted to Jupiter monitoring, but may affect the tour design in favourable ways (e.g., higher orbital inclinations) in addition to providing valuable new science at Europa. This option can be assessed when the mission scenario is better understood.

JUICE#3: Ganymede/Europa Ocean Mission

This mission option includes a smaller core payload with detection and characterisation of the oceans as its highest priority, and is therefore the least favourable for Jupiter science. The payload currently under investigation would consist of radio science, laser altimeter, magnetometer, VIR spectrometer, WAC and NAC, radar, plasma instrument. Furthermore, it is likely that the visible and near-IR remote sensing instruments would not be optimised for atmospheric sounding. The removal of the UV spectrometer, thermal instrument and sub-mm sounder would have **detrimental effects on the quality of Jupiter science.** In particular, the following losses from the core payload will cause issues for Jupiter science:

- SWI: Loss of stratospheric temperature, wind and trace species sampling on Jupiter; loss of the ability to measure the thermal emission from satellite surfaces. From an atmospheres perspective, SWI was going to provide **new science** that has never been done on any giant planet.
- UV: Loss of upper atmosphere mapping/aeronomy, limiting our prospects for solving the 'energy crisis' (whereby the upper atmosphere and thermosphere are much hotter than expected from solar irradiation alone). We'd also lose the ability to map some stratospheric hydrocarbons, the homopause height from stellar occultations, etc.

This option would also limit us in time - so less time for cloud tracking with the NAC, for aerosols and compositional mapping with the VIR spectrometer, and for radio science occultation studies. That would reduce our chances of producing a 'leap' in understanding of jovian weather layer dynamics (also hampered by the absence of thermal-infrared capabilities).

In the event that JUICE#3 is the most favourable, then the caveats on a well-designed orbital tour in JUICE#1 also apply here – an extended tour with access to a balance of lightning conditions, ranges and orbital inclinations will allow recovery of some atmospheric science (notably cloud-tracking and aerosol observations).

Accessing High Jovian Latitudes in JUICE

Arno Wielders prepared a memo (2011-05-09) summarising the prospects for JUICE reaching high latitudes on Jupiter. The following text is paraphrased from his report. After JOI the inclination w.r.t. Jupiter is ~7-8 deg. Resonant swing-bys can be used to increase the inclination. The maximum inclination is a function of:

- The infinite velocity: the higher the vinf, the higher the maximum inclination, BUT the higher the vinf, the larger the number of swing-bys needed to reach the maximum inclination.
- The moon that is used to increase the inclination: Ganymede or Callisto. Callisto allows to reach a larger maximum inclination and accumulates less radiation BUT Ganymede orbit period is smaller, thus influencing the total duration of this phase
- The resonance used during this phase: the lower the resonance, the higher the maximum inclination, BUT the lower the resonance the higher the radiation

The 2011 report concluded that a duration of about 144 to 200 days would be needed for a transfer to high inclination and back into the equatorial plane, along with a moderate increase of radiation dose.

- Ganymede, vinf=4 km/s, 2:1, 5 flybys. The maximum inclination is ~17 deg, i.e. 2 deg more than with the 3:1. The time to transfer is 72 days and the accumulated radiation dose is 3 krad. For a relatively small increase in radiation, the duration is drastically reduced and the maximum inclination slightly increased.
- Callisto, vinf=4 km/s, 1:1 A total of 6 swing-bys are necessary to transfer from equatorial to maximum inclination. The maximum inclination is ~28 deg. The time to transfer is 100 days and the radiation dose is 1 krad. It is recommended to use Callisto with an infinite velocity of 4 km/s and a 1:1 resonant orbit.

The Jupiter science team **strongly supports the use of the Callisto 1:1 orbit to raise the orbital inclination** to 28 degrees, thereby providing access to higher latitudes to recover some of the science lost by the absence of JEO.

Problem: At the moment, the high inclination phase must be seen as separate from the other mission phases, it cannot be done in combination. It requires specific Callisto flybys,in order to reach the required inclination and come back. Due to the inclination, it cannot replace anything in the baseline mission profile. If the same mission envelope is retained, then **something else would have to give**. There is an advantage, though, in that the rate of increase of radiation dose will be less than for Europa. In first approximation the total dose would be half the dose of the Callisto phase in the baseline mission, which is almost 400 d, i.e. yielding 3 krad at 10 mm Al. *Could the Callisto objectives still be met with the increasing inclination?*

Reassessing Traceability Matrices for JUICE

Based on the three mission options for JUICE, we now compare the original EJSM science requirements (e.g., the traceability matrices) to the updated mission. This section is organised following the traceability matrices, with comments on the capabilities of JUICE given **in bold type.** Where significant science is lost, the measurement is highlighted in red. In many cases we simply have less time available (and hence less frequent) Jupiter observations from a single spacecraft mission, but this has been omitted from the discussion below.

Characterize the atmospheric dynamics and circulation

Top Level Questions:

1. How is the deposited solar energy redistributed in the Jovian atmosphere and what dynamical processes are involved in the energy transfer between atmospheric layers?
2. How are localized processes (lightning, discrete vortices) on Jupiter related to the dynamics of the atmosphere?
3. What is the time-variable three-dimensional flow field and how important is wave activity in the global circulation of Jupiter?

Summary: Radio science will provide the same studies as before, albeit without the local time coverage and possibly with less frequency. The loss of the thermal instrument prevents spatial mapping of tropospheric and stratospheric temperatures. UVIS, NAC, WAC and VIRHIS will operate in the same way as before, but still will *not achieve the high spectral resolutions required for some of the Doppler studies. The sub-mm instrument will still provide new science in Saturn's stratosphere and upper troposphere.*

JA.1 Investigate the dynamics of Jupiter's weather layer.

- **JA.1a. Cloud Tracking:** Image the dayside with ~15-km/pixel resolution to determine cloud-top windspeeds (zonal and meridional) and eddy momentum fluxes. Imaging should include repeated coverage of the same regions at ~2 hour intervals for cloud tracking (necessary to obtain winds, divergence and vorticity) with 2-m/s accuracy. Wavelengths should include visible and/or near-IR continuum (e.g. 3.7 micron) as well as one or more methane absorption band (e.g., 889 nm and another near-IR e.g. 2.3 micron). Characterize behavior over a range of timescales, including short (1- to 3-days), medium (~1 month), and long (~1 year) variability. Global or near-global daily coverage for periods of weeks-to-months is desired. **A well-designed orbital tour will allow JUICE to monitor cloud features over the duration of the jovian tour.**
- **JA.1b. Sub-mm Sounding:** Measure Doppler broadening of molecular lines at a wide range of latitudes and times to derive 5- to 300-mbar temperatures and stratospheric wind speeds with high vertical resolution (10- to 20-km/pixel, R>1E6 for line shape, 2- to 10-m/s accuracy). **Still possible if JUICE retains a sub-mm sounder.**
- **JA.1c. Doppler Imaging:** Global view of velocity fields at the cloud level through Doppler shift of reflected visible solar lines, with a precision of about 2 m/s and a resolution of 100 km/pixel. **This was not possible in the original EJSM mission due to the absence of a Doppler spectro-imager from the payload.**
- **JA.1d. Material Tracers:** Generate global maps of material tracers of tropospheric dynamics (NH_3, H_2O, PH_3, AsH_3, GeH_4) in the 1- to 5-bar region at wavelengths from 1.0- to 5.2-microns, R> 400 with 100-km/pixel spatial resolution. **The VIRHIS instrument will allow JUICE to achieve this goal.**
- **JA.1e. Lightning Studies:** Image (15- to 100-km/pixel) lightning flashes at visible wavelengths on the nightside of Jupiter and combine with imaging of discrete thunderstorms on the dayside at the same resolution. Obtain multiple views of all latitudes on the nightside with clear filter imaging combined with imaging of discrete thunderstorms on the dayside. Acquire repeated imaging while tracking a feature (usually near 90° phase). Combine with complementary plasma and fields measurements to understand global distribution. **JUICE can still provide lightning studies using the NAC and RPWS instruments.**

JA.2 Determine the thermodynamics of atmospheric phenomena.

- **JA.2a. Thermal IR Mapping**: Repeated thermal observations in the 7- to 250-micron spectral range to globally map the three-dimensional temperature structure, horizontal gradients (thermal windshear) and potential vorticity. Perform nadir mapping in the 80- to 700-mbar region (troposphere) and 0.5- to 20-mbar region (stratosphere) to an absolute accuracy of 1.0 K, relative accuracy of 0.4 K with spatial resolution of 100-km/pixel. Requires limb viewing geometry to achieve 10- to 20-km altitude resolution at a wide range of latitudes. Track discrete features (e.g. storms, waves) over a range of timescales (days to months). **This will not be possible with JUICE, preventing us from constraining the global tropospheric and stratospheric temperatures.**
- **JA.2b. Radio Occultations** Perform repeated radio occultations closely spaced in latitude and time (e.g., at the same latitude +/-10 degrees, once every 2 weeks and at a similar longitude where possible), retrieving pressure as a function of

altitude to relate to zonal winds. **Although JUICE offers fewer occultation opportunities than EJSM, the sparser dataset can still achieve the aim of studying vertical waves.**

- **JA.2c. Stellar/Solar Occultations:** Perform stellar and solar occultations in the near-IR and UV (down to 90 nm for H2 band absorptions and provide information on the upper thermosphere) for high vertical resolution temperature (and methane profile) to sub-scale height resolution sounding over a wide range of latitudes and local times in the upper stratosphere. **Should still be possible from JUICE with the same instruments.**
- **JA.2d. Sub-mm Sounding:** Determine the three-dimensional temperatures of selected atmospheric species (HCN, H2O and CH4) between 400 mbars and 1 microbar. **Still possible if JUICE retains the sub-mm instrument.**

JA.3 Quantify the roles of wave propagation and atmospheric coupling.

- **JA.3a. Cloud-Tracking Windshears:** Multispectral imaging in the 0.4- to 1.0 micron and 4.0- to 5.0-micron spectral range to determine the depth and shears on the zonal wind fields and the vertical structure of vortices and plumes between 2- to 3-bar and the 0.5- to 1.0-bar levels (50- to 200-km/pixel). Acquire multiple high-resolution images of mesoscale waves and cloud structure on a timescale of hours, days, months, and years. **Still possible with NAC and VIRHIS on JUICE provided we have sufficient spatial resolution.**
- **JA.3b. Radio Occultations:** Perform radio occultations repeated closely in space and time (e.g. at the same latitude +/-10 degrees, once every 2 weeks) to determine pressure, density and temperature profiles perturbed by vertically-propagating waves which couple the troposphere and middle-atmosphere. **Still possible, even though the frequency of occultations will be less with a single spacecraft.**
- **JA.3c. Sub-mm Sounding:** Determine the vertical temperature structure and thermal wave activity at high spatial resolution between 1-microbar and 400-mbars from molecular lineshapes (R>1E6, 20- to 40-km vertical resolution depending upon altitude). In addition, perform limb observations in the thermal-IR (e.g. methane/hydrocarbon emission at 7.7 and 12- to 13-µm) to determine stratospheric temperature oscillations (20-km vertical resolution), with particular focus on the equatorial QQO. **Thermal-IR limb observations could be omitted provided that plenty of opportunities exist for stratospheric sounding in the sub-mm.**
- **JA.3d. Near-IR and UV stellar occultations** to obtain high-resolution stratospheric temperatures and study wave forcing from below the thermosphere. Near-IR imaging of multiple altitude levels to determine vertical structure of horizontally propagating waves. Observations of dayside (0.4- to 5.2-micron range) or nightside (2.5- to 5.2-micron range), including coverage of equatorial regions and polar vortices. UV occultations down to 90 nm to provide access to upper thermosphere by H2 band absorptions to study thermospheric heating. **Still possible with UVIS and VIRHIS on JUICE.**
- **JA.3e. Thermal Mapping**: Image from 7- to 250-microns for tropospheric and stratospheric temperatures and wind shears at regular (2 week) intervals, with 200- to 400-km/pixel spatial resolution to determine the latitudes, amplitudes and periodicities of zonal thermal wave activity, and to track oscillations of equatorial temperature field associated with the Quasi-Quadrennial Oscillation (QQO). **No longer possible with the absence of a thermal instrument from JUICE.**

JA.4 Investigate auroral structure and energy transport.

- **JA.4a. Polar Near-IR Scans**: Imaging and polar spectral scans (70- to 90-degrees latitude, both hemispheres) and measure H3+ emission in the 2- to 5-micron range at regular intervals with 100 km/pixel spatial resolution. Sample from less than an hour (for solar flares) to days to study the internal structure of the aurora and identify satellite footprints. **VIRHIS would be able to provide better polar coverage with high inclination orbits, otherwise polar views will be difficult to obtain.**
- **JA.4b. UV Studies of Aurora:** Acquire images and scans of the polar H2 glow, morphology and the composition of the polar vortices (aerosols, exotic chemicals) in the 90- to 170-nm range (115-170 nm possible). Obtain H Lyman alpha spectral line profiles for Doppler-shifted proton aurora and superthermal upper atmosphere measurements with R=20000 resolution. Spectral analysis of H2 Lyman and Werner bands and H Ly alpha for inferrring information on the auroral precipitating electrons. Perform stellar and solar occultations over the poles in the upper atmosphere (90- to 200-nm). **Polar views require high-inclination orbits. High resolution spectroscopy was not feasible in the original EJSM, nor JUICE.**
- **JA.4c. Limb Observations**: Perform high spatial resolution (30-km vertical resolution) limb observations to determine the three-dimensional morphology of the Jovian aurora (200- to 500-km/pixel spatial resolution, target 100 km/px), and the nature of energy deposition and transport processes. Perform imaging in the wavelength ranges of 50- to 320-nm and 0.4- to 1.0-µm with a resolution of 150 km/pixel of the polar regions, dayside and nightside. **Very similar to 4a and 4b because most views will be along a slant path. It is unlikely that the vertical resolution will be achievable.**

JA.5 Understand the interrelationships of the ionosphere and thermosphere.

- **JA.5a. Radio Science:** Perform repeated radio occultations to study the relation between vertically propagating waves and the heating mechanisms for the thermosphere. Derive both neutral density and electron/ion density profiles in the ionosphere. Monitor variability with local time at multiple different latitudes/longitudes. **A single S/C cannot measure local time variability, but will provide snapshots of wave activity in the upper atmosphere.**
- **JA.5b. Stellar Occultations**: Perform stellar occultations in the wavelength ranges of 200- to 320-nm to sample the stratosphere, 90- to 160-nm to sample H2 above the homopause, and near 2 microns to measure the vertical structure of the thermosphere with 10- to 15-km vertical resolution. **A single spacecraft will provide fewer stellar occultations, but will it still provide the high vertical resolutions required?**
- **JA.5c. High-res Near-IR**: Perform limb observations of H3+ ionic species and tracers, intensity modulation by gravity waves in the upper atmosphere (3.3- to 3.6-microns, Resolution > 10,000). Requires vertical resolution of half a scale height, coverage of mid and low latitudes with 300 km/pixel spatial resolution. Short and continuous time coverage (1 rotation or more) is required. **VIRHIS will still be able to detect H3+, but the high resolution goal was not realistic for EJSM.**
- **JA.5d. UV Imaging**: Acquire two-dimensional spectral-spatial images in the wavelength range of 90- to 230-nm for H2 and Lyman alpha (121.6 nm) and from 100- to 200-nm for O and S ions/neutrals to study the latitudinal morphology of the thermosphere; the H Ly alpha bulge and H2 emissions (from nadir viewing). Determine the origin of the H bulge and the possible connection to auroral activity and thermospheric circulation. **UVIS will still achieve this goal.**

- **JA.5e. Doppler Shifted Thermospheric Lines:** Measure the thermospheric circulation and winds, both zonally and meridionally, and determine the importance of wave acceleration and ion drag at these altitudes from high spectral resolution near-IR observations and UV line Doppler shifts (e.g., H3+at 3.4 µm, 2.1 µm; Lyman alpha at 121.6 nm with high SNR and 1 km/s accuracy). Perform measurements in the wavelength range of 90- to 160-nm to determine the latitudinal morphology of H2 band brightnesses for thermospheric winds. **UVIS and VIRHIS are unlikely to have the high spectral resolutions required to measure these Doppler shifts, so this was not possible within the EJSM framework.**
- **JA.5f. Sub-mm:** Measure molecular lines to determine atmospheric temperatures, neutral density profiles and three-dimensional distribution of atmospheric species between 1-microbar and 400-mbars. **Still possible on JUICE with the sub-mm instrument, but 1 µbar is not thermospheric, the goal of this section.**

Characterize the atmospheric composition and chemistry.

Top Level Questions

1. How is the spatial variation of composition of condensables related to the meteorology?
2. How do non-equilibrium species vary spatially and relate to the global circulation?
3. What is the composition of the stratosphere and how is it related to dynamical processes and photochemistry?

JB.1 Determine Jupiter's bulk elemental abundances.
JB.2 Measure the composition from the stratosphere to low thermosphere in three dimensions.
JB.3 Study localized and non-equilibrium composition.
JB.4 Determine the importance of moist convection in meteorology, cloud formation, and chemistry.

Characterize the atmospheric vertical structure.

Top Level Questions

1. What is the nature of the coupling processes between Jupiter's deep interior and upper layers ?
2. What is the altitude, thickness and composition of the clouds and coloured chromophores in the atmosphere of Jupiter?
3. What are the processes responsible for the formation of upper atmospheric haze at high latitudes?

JC.1 Determine the three-dimensional structure from Jupiter's upper troposphere to lower thermosphere.
JC.2 Explore Jupiter's interior density structure and dynamics below the upper troposphere.
JC.3 Study coupling across atmospheric layers.

Jupiter Tour Evaluation

Once the Jupiter tour scenario is better established, the atmospheres working group will be looking for a range of products with which to assess the observing opportunities and science return. As part of the EJSM-Laplace study, we used figures generated by Erick Sturm at JPL.

Specifically, here is a list of the sort of figures that will be valuable for the proposed tours.

- Jupiter range and phase angle versus time.
- Chart showing the time allocation for Jupiter observation (i.e., no close or distant flybys).
- Sub-spacecraft latitude and visibility of poles versus time.
- Spatial resolution of each instrument (km/px) versus time.
- Cumulative time (days) spent at different Jupiter-S/C ranges (i.e., how often do we get the best spatial resolution?)
- Cumulative time (days) spent at different Jupiter phase angles (i.e., how long on the dayside, how long on the nightside?)
- Cumulative time (days) spent at varying resolutions for each of the instruments.
- Jupiter radio occultation entry and exit latitudes.
- Number of radio occultations versus time (to assess repeat coverage of different latitudes).
- Distance to Jupiter versus phase angle.
- Spatial resolution of each instrument (km/px) when the pole is in view.
- Filling factor of each instrument FOV versus time.
- Available data volume/rate versus time, particularly for obtaining cloud-tracking 'movies.' E.g., the yellow book currently specifies 1 Gbit/day, but how much is this in terms of images/spectra?
- Sub-spacecraft longitude (System III) versus time (this is a very low priority now, but will become important later as we try to target certain features, which all drift in longitude).

Many of these could be produced from a table of range, phase angle and sub-spacecraft latitude versus time. Others (such as radio occultations and the time allocated to Jupiter observations) will need more comprehensive data. It is hoped that the MAPPS tool can be used to provide this information.

Instrumentation for Jupiter Science

Core Payload

Radio Science Experiment

- Ka-band transponder with USO so the orbiter has a fully-fledged radio occultation capability.
- Sounds the vertical structure of the neutral atmosphere and the electron density and ion distribution in the ionosphere. Additional outcomes include the microwave absorption profiles due to gaseous absorptions and characterization of the small-scale structure of the atmosphere due to turbulence and gravity waves.
- Precision measurements of the perturbations to frequency, phase and amplitude of downlink sinusoidal signal.
- The addition of the USO enables us to achieve precise frequency and phase

measurements, and hence precision measurements of the refractivity profiles, as well as permitting RSS studies during both ingress and egress.

- By having a dual X and Ka band capability we should be able to separate ionized and neutral media along the radio path.
- The good S/C pointing required for the NAC will also enable precise signal amplitude measurement for the radio science.
- The resolution achieved during ionospheric and atmospheric occultations is determined by the Fresnel scale F=sqrt(lambda*D/2), where D is the distance from the probed limb. For D=0.4-1.0 Mkm and lambda=3.6cm (X-band downlink), we'll achieve 2.6-4.2 km. For lambda=0.94 cm (Ka band) we'll achieve 1.3-2.1 km, so the additional band improves our spatial resolution. These are smaller than the atmospheric scale height, making RSS surveys particularly useful.
- Need to ensure that the signal strength, as characterized by the available free-space signal-to-noise ratio SNR_0, mostly limits how deep in the atmosphere the signal can probe before it is extinguished by the ammonia cloud. Need to make sure that the available SNR_0 is sufficient to probe down to this pressure level. ***Will the signal strength from JUICE be sufficient to probe down to the ammonia cloud?***
- The ionospheric measurements rely primarily on the frequency measurement, hence are primarily limited by the USO performance and are not sensitive to the exact SNR_0 provided it is not too small. The strong radiation environment should not affect the measurements as long as the spacecraft is not embedded in the radiation belt (which may adversely affect the USO performance).
- Hopefully, the USO frequency stability is sufficiently good (order 10E-13 in one second integration) to enable this potential capability.

Visible InfraRed Hyperspectral Imaging Spectrometer (VIRHIS)

- Pushbroom imaging spectrometer with two channels and a scan system, 0.4-5.2 μm, 2.8 nm resolution below 2.5 μm and 5.0 nm above 2.5 μm.
- Cube 60x60 mrad/ 0.250 mrad/px, 1Gb/cube.
- Composition, structure and dynamics of Jupiter's atmosphere, plus monitoring of aurora and other non-LTE emissions.
- MCT detectors, 640x480, IFOV 0.125-0.250 mrad, with a FOV of 3.4 degrees.
- IR detector operates at 90-100 K.
- *Size of individual images?*
- The extension from 5.0-5.2 micron in the instrument description was driven by the need to sound tropospheric ammonia and water.

Ultraviolet Imaging Spectrometer (UVIS)

- EUV (50-110 nm, 0.2 nm resolution) and FUV+MUV (110-320 nm, 0.5 nm resolution) grating spectrometers, 50-320 nm
- FOV 35 mrad, ifov 0.07mrad/px, 240 Kb/s uncompressed data volume.
- Microchannel plate detectors, 512x512, IFOV 0.01 mrad, FOV 2 degrees.
- At Jupiter, UVIS will provide information on the interaction between Jupiter and the moons through high resolution observations of the magnetically mapped moon footprints, as well as global monitoring of the main emissions linked to a wide volume of the magnetosphere. Occultation measurements of the Jovian atmosphere will lead to high resolution information on the stratospheric temperatures, and atmospheric composition and chemistry.
- The operational modes for UVIS include: nadir pointing, limb pointing, stellar and solar occultations. All require ~0.1°/s stability with 2 sigma accuracy,

except the solar occultations which need ~0.01°/s stability with 1 sigma accuracy.

- Jovian atmosphere and aurora (H2 bands, H Ly a, CH4, acetylene): 90-170 nm with a 0.5 nm resolution (at least) and a temporal resolution of 1 s for occultations; solar occultations (if possible) in the EUV for H2 density; in the auroral regions: 110-170 nm required for estimating the hard electron component and 90-110 nm, for the soft electron component).
- FUV Spectral range: 110-230 nm [jovian atmosphere and aurora (e.g., H2 Lyman and Werner emission bands and H Ly α emissions; acetylene in absorption.
- H Ly a at 121.6 nm needs a very high spectral resolution of 0.001 nm. Most intense auroral line. Line profile richer than unresolved emission lines, provide density, temperature and wind velocity if the emitting H atoms.
- Note that for including the possibility of solar occultations which would primarily provide H2 density over the whole thermosphere, one needs an angular size for a pixel, of the order of an atmospheric scale height or less. This is a very strong constraint. We keep solar occultation as a secondary, non-critical requirement, even though of great interest.
- UV nadir mode to measure total column abundances; limb mode for vertical profiles of atmospheric emission; stellar occultation for vertical density profiles from absorbed stellar light.
- Solar occultations are much harder, and involve a bright, extended source.

Narrow Angle Camera

- Pushbroom imager for Ganymede, framing imager for distant targets.
- Colour and multispectral imaging with filter wheels (12 colours, 0.35-1.05 μm)
- CMOS 1024x1024 sensor, FOV 0.3 degrees, IFOV 0.005 mrad
- FOV 20 mrad
- IFOV 10 microrad
- The uncompressed data volume is 2048x2048x14=59 Mbit/image.
- Expected to get dayside imaging of Jupiter with 15 km.px resolution to study cloud properties and dynamics; monitor lightning flashes on the nightside; and provide limb imaging with 30 km vertical resolution to study aurora and hazes.
- What will be the size of a single image in Gb? Date volume and rate will probably prohibit the use of the NAC throughout the orbit.
- ***Recommendation: Ensure NAC filters are at leas as capable as the Cassini/ISS instrument, which had 23 filters including polarisation.***
- ***Ensure that the NAC features some of the following filters:*** f
    - For atmospheric imaging at multiple pressure levels for detection of winds and vertical shears. Four narrow filters (890, 910, 920 and 934; 15-20 nm widths) sample the core and wings of a CH4 absorption feature.
    - Five broad filters (<450 nm, 510-610 nm, 630-670 nm, 725-775 nm and > 930 nm) provide color discrimination for cloud particles and possible indications of their chemical formation mechanisms.
- ***Require that the camera is stable to within 33% of a pixel over 0.5s of integration.***

Wide Angle Camera

- Framing imager for contextual imaging of Jupiter to study clouds and dynamics.
- Multispectral imaging with filter wheels (12 filters, 0.35-1.05 μm)
- SMOS detector 1024x1024, IFOV 2mrad, 117 deg FOV.
- FOV 2 rad.
- Uncompressed data volume 140 Mb/image

Sub-Millimetre Wave Instrument (SWI)

- The sub-mm spectrum of Jupiter from 100-1000 μm (0.1-1.0 mm, or 300-3000 Ghz) is dominated by the absorption features of NH3, PH3 and CH4.
- Vertical wind (from Doppler shifts of spectra lines) and temperature profiles for the general circulation and strength of vertical mixing in Jupiter's stratosphere will be determined from H2O and CH4 lines.
- The sub-mm allows determination of the distribution and origin of stratospheric water (and its role in chemistry), and the dispersion of impact related material (CO, HCN and CS).
- Organic species and isotopic species (such as HD and HDO) can also be detected in this spectral range.Heterodyne microwave spectrometer with 2 bands, 230-550 μm.
- Sub-harmonically pumped Schottky mixers and tunable solid-state LO system. Two spectrometer backends (Chirp Transform Spectrometers, CTS) with 1 GHz bandwidth and 100 kHz spectra resolution.
- FOV 0.15-0.065 degrees. 60-cm antenna with along and cross track scanning mirror (2D). 2.6 mrad, 10 Kb/s uncompressed.
- Telescope diameters between 30-60 cm. The telescope size determined the SNR. From large distances, in limb viewing geometry, the beam becomes diluted because it samples both cold deep space and the tropospheric CIA. FOV of 0.065-0.15 deg, with a goal of 0.03-0.07. IFOV of each pixel 1.3-3.0 mrad, goal of 0.6-1.5 mrad.
- Hot load and cold deep-space calibration references.
- Local Oscillator: tunable, based on solid-state design for Herschel/HIFI. Being tunable means that a large number of molecular lines can be detected. Need a larger power than HIFI because they are not cooled.
- Radiator needed to cool detectors to 150 K if Schottky mixers are used.
- Structure, composition and dynamics of Jupiter's middle atmosphere. Direct measurements of wind speeds in the stratosphere, and high-sensitivity compositional measurements.
- SWI will perform point observations in two bands: 530-600 GHz and 1075-1275 GHz with very high resolving power
- Spectral line profiles in the sub-mm range containing information between 400 mbar and 1 μbar.
- 1200 Ghz suited to CO, HCN, NH3, H2O, CH4. A strong CH4 line here may be useful for temperatures, with a H2O line within 2 GHz for simultaneous water sounding.
- 557 GHz best for water (1(1,0)-1(0,1) transition of water at 556.936 GHz).
- 300 Ghz best for heavier species (organics).

Radio and Plasma Wave Instrument (RPWI)

- Set of sensors to measure electric field, plasma waves, electromagnetic waves, radio emissions and the characteristics of thermal plasma.
- Contribute to the characterisation of the Jovian radiation environment and its time variability; study Jupiter radio emissions and their time variability; and contribute to the study of the auroral foot print of the moons.

Additional Instrumentation

Although not presently included as a part of the model payload, European instrument providers have expressed interest in a number of additional instruments which would complement and extend Jupiter science. The dual spacecraft EJSM-Laplace featured a thermal instrument, the only instrument capable of determining tropospheric temperatures. In addition, the EJSM Open Science workshop at ESTEC described a range of additional instrument options that are not presently included:

- Advanced spectroscopic capabilities in the thermal-infrared (e.g., CIRS-lite or TIRS, Brasunas et al.)
- Spectro-polarimetric observations to study jovian aerosols (e.g., Stam et al, Shalygina et al.)
- Enhanced UV instruments with high spectral resolution + polarization to characterise the detailed line shapes (Barthelemy et al., Nichols et al., Galand et al., Bunce et al., Quemerais et al.).
- Doppler Spectro Imager (Schmider et al.)

Thermal Infrared Instrumentation

EJSM-Laplace featured a simple thermal imager as part of the JEO model payload. Four narrow wavelength bands were devoted to measuring the temperature of the Jovian atmosphere. The four filters (centred at 17.2, 21.0, 28.2 and 40 um) sounded the collision-induced absorption for temperatures (and possibly para-hydrogen) in the 100-400 mbar range. The instrument was baselined with a 2.5 mrad IFOV, 9 linear arrays of 21 pixels providing a 3 degree cross-track FOV. The unshielded JEO/TI mass 3.7 kg, with a 5 W operating power.

A thermal instrument was also part of the JGO model payload until late changes removed it from the strawman. The JGO/Thermal Mapper had a 0.5 mrad IFOV (smaller than JEO), 6 degree FOV, and an uncooled imaging microbolometer array. It had a mass of 5 kg and power of 5 W. The instrument originally had filters sensitive to the stratosphere and upper troposphere to study thermal wave activity (7.66, 7.79, 7.61 and 16.7 um). Late changes altered the priority and gave JGO very similar filters to JEO (i.e., sensitive to the upper troposphere), and then removed the instrument altogether.

With the loss of both thermal instruments from the JUICE concept, the new mission limits the capabilities for studies of fundamental meteorology and Jovian climatology from JUICE. The upper tropospheric temperatures, vertical windshears, infrared aerosol opacity and para-H2 distribution (all necessary for determining the potential vorticity distribution, a tracer of atmospheric motion) can no longer be obtained by this mission. The thermodynamic environmental conditions associated with discrete features (storms, plumes, vortices, belt/zones) will not be assessed. Furthermore, there are no mapping capabilities for studying atmospheric wave activity and stratospheric phenomena. The only previous thermal-IR studies of Jupiter used spectroscopy from flyby spacecraft (Voyager/IRIS covered 4.0-55.0 μm, Cassini/CIRS (~35 kg, 34 W, 4 kbps) covered 7.1-1000 μm with a dual FTS system), leaving fundamental questions about the thermodynamics of atmospheric phenomena unanswered.

We **strongly recommend the consideration of a simple thermal instrument in the JUICE model payload**, or at the very least to ensure that thermal-IR science objectives are retained in the ultimate AO. Thermal-IR studies of satellite surfaces (thermal inertia, energy output) will also form an important addition to our characterization of the Galilean moons.

JUICE Observational Strategies

In preparation for jovian tour planning, the Jupiter working group assessed a range of different observation types, the desired spatial resolution and frequency of observations. The following descriptions are simple suggestions for the observation types.

Prioritised Observation Templates for Jupiter

1. Dynamics and Winds - GLOB_VIS_MOVIE (dayside apoapse), LIGHTNING_DIST (nightside periapse), SUBMM_WIND
2. Composition and Aerosols - GLOB_NIR_DAYMAP and NIGHTMAP.
3. Vertical Coupling - RADIO_OCC, SUBMM_WIND, UV_STELLAROCC, NIR_STELLAROCC, UV_LIMB, NIR_LIMB
4. Thermal - SUBMM_NADIRMAP, GLOB_THERMAL_MAP*
5. Upper Atmosphere - GLOB_UVMAP
5. Feature Tracking (all instruments): GRS, BA, Equatorial plumes/hotspots, polar vortices, turbulent wake region, small-scale convective activity in belts/zones.
6. Seismology - SEISMO_DSI*

*These observation templates are included in this list, but are presently absent from the JUICE model payload.

Observation Templates

GLOB_VIS_MOVIE:

- Hemispheric map of Jupiter's cloud-top wind velocities, multiple filters.
- Build up global maps via mosaics or north-south strips.
- Repeat mosaics 1 per 60-90 minutes over 1-2 Jovian rotations (20 hours) for a global map.
- Desired spatial resolution 30-100 km/px.
- Dayside imaging at apoapse.
- Repeated monthly to observe changes.

LIGHTNING_DIST:

- Hemispheric map of Jovian nightside at visible wavelengths for lightning detection.
- Require high spatial resolution to see individual strikes - nightside periapse.
- Short integration times with a clear or near-H-alpha filter for good S/N.
- Rapid repeats, 2 short integrations for each region and then move to develop a mosaic.
- Spatial resolution: 10-30 km.
- Nightside imaging.
- Repeat ~ monthly to search for correlations with dayside cloud maps.

VIS_FEATURETRACK:

- Mosaic of a particular feature, multiple viewing geometries (rotate centre to limb).
- Time-step: 20-60 mins (shortest timesteps for mesoscale wave activity), repeated 3-4 time as Jupiter rotates.
- Desired spatial resolution 10 km/px.
- Priority targets: GRS, BA, Equatorial plumes/hotspots, polar vortices, turbulent wake region, small-scale convective activity in belts/zones.
- Repeat ~ weekly for 3 weeks to observe rapid evolution.
- Coordination between JEO and JGO to view the same feature simultaneously.

GLOB_NIR_DAYMAP:

- Near-IR 0.4-5.3 um map of reflected sunlight, global coverage.
- Desired resolution: 200 km/px ?

- Aim to sample a range of phase angles, capture the same features/longitudes under different lighting conditions to constrain scattering properties.
- Repeat mosaics 1 per 60-90 minutes over 1-2 Jovian rotations (20 hours) for a global map.
- Repeat ~monthly for monitoring, plus short campaigns of ~daily hemispherical maps to track feature evolution.

GLOB_NIR_NIGHTMAP:
- Nightside near-IR observation of thermal emission, backlit clouds, disequilibrium species.
- Desired resolution: 200 km/px ?
- Repeat mosaics 1 per 60-90 minutes over 1-2 Jovian rotations (20 hours) for a global map.
- Repeat ~monthly for monitoring, plus short campaigns of ~daily hemispherical maps to track feature evolution.

NIR_FEATURETRACK:
- Simultaneous with VIS_FEATURETRACK.
- Desired resolution 100 km/px.
- Priority targets: GRS, BA, Equatorial plumes/hotspots, polar vortices, turbulent wake region, small-scale convective activity in belts/zones.
- Time-step: 60 mins, repeated 3-4 times as Jupiter rotates.
- Coordination between JEO and JGO to view the same feature simultaneously.
- Repeat ~ weekly for 3 weeks to observe rapid evolution.

NIR_STELLAROCC:
- Stellar occultation for high resolution temperature profile, waves, haze absorption.
- Sample a wide range of latitudes over the course of the mission. High latitude occultations for auroral emission of H3+.
- Desired spatial resolution: 30 km/px vertical.
- Repetition determined by availability of suitable occultation targets.

NIR_LIMB:
- Limb views for atmospheric hazes, atmospheric emission (particularly auroral regions).
- Desired spatial resolution: 30 km/px vertical.
- Repeat ~ 6 months for temporal evolution.

GLOB_UVMAP:
- UV maps in nadir geometry to look for airglow, auroral footprints, UV 'bulge'.
- Desired spatial resolution 200 km/px.
- Repeat ~ monthly to search for changing morphology.

UV_STELLAROCC:
- Stellar occultations over multiple latitudes: hydrocarbons, hazes, etc.
- Priority: high latitude/polar occultations for auroral energy deposition, precipitating electrons, etc.
- Desired spatial resolution: 30 km

UV_SOLAROCC:
- Solar occultation limited by the size of the instrument FOV - sun is a large target.
- Possible with present geometry?

UV_LIMB:

- Limb views for atmospheric hazes, emission (particularly auroral regions).
- Desired spatial resolution: 30 km/px vertical.
- Repeat ~ 6 months for temporal evolution.

SUBMM_NADIRMAP:

- Nadir mapping of thermal emission using sub-mm instrument for temperature, water and trace species.
- Scan the FOV over a range of latitudes, north south as the planet rotates to assemble a global map over a 10 hour period.
- Desired spatial resolution: < 1000 km.
- With scanning capabilities, perform a feature track/raster scan.
- Repeat ~monthly to search for evolution.

SUBMM_WIND:

- Near-limb observations to probe Doppler shift of molecular lines for wind and vertical temperature retrieval.
- Cover a range of latitudes during the mission.
- With a scanning capability, place the FOV on the central meridian and then scan from the centre to the limb.
- Repeat a particular latitude ~6/12 months to search for variability.
- Desired vertical resolution 20-30 km/px (approx. scale height).

RADIO_OCC:

- Multiple radio occultations (S/C->Earth) sampling a wide range of latitudes.
- Repeat a particular latitude ~6/12 months to search for variability, wave propagation.
- Repeat certain latitudes (+/- 5 deg) once every 2 weeks (5 repeats) to identify rapid wave propagation.
- Desired vertical resolution 1-4 km/px for wave activity.

The following templates feature instruments that are not in the strawman payload, but are still highly desirable.

GLOB_THERMAL_MAP:

- Global thermal mapping with multiple filters. Use 10 hour rotation to provide global maps.
- Desired spatial resolution 200 km/px.
- Repeat ~ monthly for slow changes. Short term campaign of ~2day repeats to look for short-term variability.
- Priority targets: GRS, BA, Equatorial plumes/hotspots, polar vortices, turbulent wake region, small-scale convective activity in belts/zones.

SEISMO_DSI:

- Two-week campaign of acoustic observation to search for oscillation modes.
- Dayside imaging, global hemispheric map.
- Duty cycle of 70% during the 2 week interval.
- Desired spatial resolution 700 km/px.

JUICE Implications for Planetary Atmospheric Physics

The diverse range of planetary atmospheres in our Solar System can be understood in terms of the different environmental conditions affecting their meteorology, bulk composition, cloud microphysics, complex chemistry and evolution. Atmospheric science has made significant advances in unravelling the mechanisms responsible for the bewildering range of atmospheric configurations arising from these initial conditions. By studying the plethora of planetary atmospheres - from the giant planets and their moons to rocky planets - we are able to put the complexity of Earth's own atmosphere into a larger context. JUICE's exploration of Jupiter and its collection of icy satellites will provide access to a broad range of atmospheric processes, from large-scale atmospheric organization of jet streams, moist convection, storms, plumes, vortices, and lightning to sputtering and other processes maintaining the tenuous satellite exospheres.

Jupiter's atmosphere serves as a paradigm for atmospheric dynamics and chemistry on giant planets, both in our Solar System and beyond. With its weather layer of alternating zonal jets, long-lived giant anticyclonic vortices and vertical and horizontal wave activity on a variety of scales, Jupiter is often viewed as our best laboratory for fundamental fluid dynamics. Several mysteries remain unresolved: How deep does the zonal motion penetrate – are zonal jets a weather-layer phenomenon, or a manifestation of deeper internal processes? What is the importance of moist convection in determining the transport of energy and material between different levels? What causes vertical and horizontal wave activity, and how do waves govern vertical stratification and energy transfer? What is the balance between solar radiation input and internal energy that governs the existence of belts, zones, eddies and vortices, and what maintains each of these features against dissipation? How does Jupiter's polar atmosphere, the apex of the planet-wide circulation, differ from the rest of the planet? And what cyclic global processes are responsible for 'upheavals' of the belt/zone structure and the variability of Jupiter's appearance?

The advanced instrumentation, broad wavelength coverage and long temporal baseline, JUICE will permit the most extensive study of gas giant dynamics and chemistry ever performed. The product will be a four-dimensional database of Jupiter's climate to inform circulation modeling and permit predictions of variability.

Finally, Jupiter's atmospheric composition (atomic abundances, isotopic ratios) can be compared to those on other planets in our Solar System to reveal how planetary atmospheres evolve. Indeed, the complement of heavy elements in the giant planets is thought to increase with radial distance from the Sun, a signature of the primordial planetary nebula from which the planets formed. As a constraint on the formational history of our Solar System, chemical studies of planetary atmospheres provides a window onto the past and helps us begin to understand the extraordinary range of planetary systems around other stars.

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