Galileo's Medicean Moons: their impact on 400 years of discovery
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The Juno Mission

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Abstract. Juno is the next NASA New Frontiers mission which will launch in August 2011. The mission is a solar powered spacecraft scheduled to arrive at Jupiter in 2016 and be placed into polar orbit around Jupiter. The goal of the Juno mission is to explore the origin and evolution of the planet Jupiter. Juno's science themes include (1) origin, (2) interior structure, (3) atmospheric composition and dynamics, and (4) polar magnetosphere and aurora. A total of nine instruments on-board provide specific measurements designed to investigate Juno's science themes. The primary objective of investigating the origin of Jupiter includes 1) determine Jupiter's internal mass distribution by measuring gravity with Doppler tracking, 2) determine the nature of its internal dynamo by measuring its magnetic fields with a magnetometer, and 3) determine the deep composition (in particular the global water abundance) and dynamics of the sub-cloud atmosphere around Jupiter, by measuring its thermal microwave emission.

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1. Juno Investigation of Jupiter: Goals and Objectives

Solar system formation models all begin with the collapse of a proto-solar nebula. Because Jupiter is mostly hydrogen and helium, it must have formed early, while the proto-solar nebula was still present. How this happened, however, is unclear. Models range from a proto-planetary core forming first all the way to a gravitational instability in the nebula triggering its collapse. Differences between these scenarios are profound. Even more importantly, the composition and role of icy planetesimals inplanetary formation hangs in the balance and with them, the origin of Earth and other terrestrial planets. The role of icy planetesimals, likely carriers of volatiles including the water and organics that are the fundamental building blocks of life and produced bio-molecules on early Earth, remains particularly crucial.

Juno measures water abundance and determines if Jupiter has a core, a crucial step in discovering the origin of this giant planet and our solar system. Juno will uncover vital chemical and physical clues to the nature of the nebula out of which the solar system formed and the manner and timing of giant planet formation. Next to the Sun, Jupiter is the largest object in the solar system. As such, it is both a record and a driver of the formation of the planets. By mapping the gravitation and magnetic fields, Juno investigates Jupiter's interior structure and measures the mass of its core. How deep Jupiter's zones, belts, and other features penetrate is one of the most outstanding fundamental questions in Jovian atmospheric dynamics. The mapping of variations in atmospheric composition, temperature, cloud opacity and dynamics at depth can help determine the global structure and dynamics of Jupiter's atmosphere below the cloud tops. Juno also investigates Jupiter's powerful magnetospheric dynamics create the brightest aurora in our solar system. How are the electrons and ions precipitated down into Jupiter's atmosphere to create the aurora? Juno directly measures the distributions of these charged particles, their associated fields, and the concurrent UV and IR emissions of Jupiter's polar magnetosphere. Jupiter's massive gravitational field shaped the dynamical environment in the terrestrial planet region, affecting the timing of the growth of Earth and its rocky neighbors as well as the delivery of water and organics to the surface of our planet. Jupiter is the archetype for extrasolar giant planets, now known to exist around a few percent or more of sunlike stars. An understanding of the formation of Jupiter from gas and icy planetesimals in the solar nebula therefore illuminates processes of planet formation throughout the universe.

Jupiter's core. The mass of Jupiter's core helps distinguish among competing scenarios for the planet's origin. We know that young stars lose their gaseous accretion disks rapidly, in 1-10 Myr (Strom *et al.* 1993). Because it is made mostly of hydrogen and helium, Jupiter had to form early, and hence prior to terrestrial planet formation. Being much more massive than the other planets, it probably grew more rapidly than any other planet. One set of models propose that a protoplanetary core (∼10 or more Earth masses) was formed first by accretion in the cold outer part of the protosolar nebula in ∼2 to 5 million years (Mizuno 1980, Lissauer 1993, Pollack *et al.* 1996, Wuchterl *et al.* 2000, Hersant *et al.* 2003). The collapse of the surrounding hydrogen and helium followed (Lissauer 1993; Pollack *et al.* 1996; Wuchterl *et al.* 2000), yielding a planet with a central dense core of at least 10 Earth masses (ME) and a hydrogen-helium envelope. An alternate model proposes an even faster process: a gravitational instability in the nebula triggers a collapse that forms the giant planets in about 0.1 Myr (Boss 1997, 2000). The simplest version of this model suggests a core mass of only zero to six ME. The early evolution of the solar system would have been very different, as would the number and nature of planetesimals captured by the giant planets, depending upon which formation mechanism is correct (Guillot & Gladman 2000). Analysis of the Juno gravity and microwave investigations constrains the core mass and the total mass of heavy elements sufficiently to resolve this planetary formation question.

Jupiter's water abundance. Given that oxygen is the third most abundant element in the universe and recognizing that icy planetesimals were the dominant carriers of heavy elements in the solar nebula, a measurement of Jupiter's global water abundance is pivotal in understanding giant planet formation and the delivery of volatiles throughout the solar system. Jupiter contains key evidence about the nature of the protoplanetary disk, or solar nebula, out of which the solar system formed. For example, if water is found to be enriched in similar proportion to nitrogen, carbon, sulfur, and the noble gases (∼3 times solar)(Figure 1), a model producingplanetesimals from ice that condensed at less than

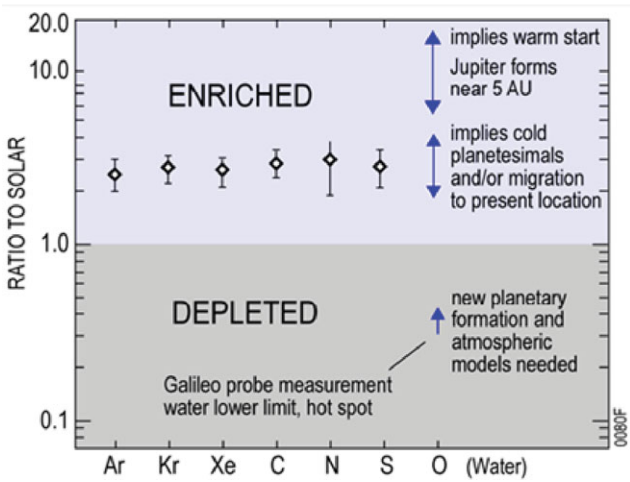

Figure 1. Juno's measurement of O discriminates among Jupiter's formation scenarios as shown in this figure. Abundances of Ar, Kr, Xe, C, and S are well determined on Jupiter at 3× Solar. O is not yet determined. Juno determines both the N and O abundances.

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∼30 K (cold) is favored (Owen *et al.* 1999, Mahaffy *et al.* 2000, Owen 2004). This could require inward migration of core-forming planetesimals (or Jupiter itself) from much larger distances or a model of the formation of the solar nebula, that includes the direct transfer of interstellar material in large agglomerations. If water is much more enriched than the noble gases, i.e., by 9 or more relative to solar, then the trapping of noble gases would be more characteristic of that expected through formation of planetesimals from ice grains that condensed at ∼150 K near Jupiter's present location with subsequent cooling to 35 K (Gautier *et al.* 2001, Hersant *et al.* 2003). Determination of the mixing ratio of water to hydrogen and hence (through Galileo measurements) to the noble gases provides a direct test for the mode of origin of the icy planetesimals that enriched Jupiter. These planetesimals may have been the most abundant solid material in the early solar nebula and therefore may also be important to the delivery of volatiles to the inner planets (Owen and Encrenaz 2003). The Juno microwave radiometry investigation determines the water abundance in Jupiter with sufficient precision to resolve this question of planetary formation, and because it maps the water over all latitudes, it is not prone to the sampling bias by measurements at one or a few probe locations as Galileo was.

Juno produces five pole-to-pole latitudinal maps of microwave opacity as a function of altitude to depths greater than 100 bars (Figure 2). The independent swaths at different longitudes provide the ability to understand large scale features such as the Great Red Spot. The 0.1% precision of the radiometer allows us to measure small variations in radiance with respect to horizontal position and emission angle. With these measurements, we determine the global O/H and N/H ratios; we correlate the patterns of ammonia and water abundance below the clouds with the principal dynamical features at cloud-top level; we examine the deep roots of features like the Great Red Spot, the belts and zones, and potentially the 5- ?m hot spots. Context for these features is provided through coordinated Earth-based images and comparison with data from the E/PO imager, JunoCam.

Atmospheric Dynamics and the Galileo Probe. The depth of the major flow features is the most basic question of Jovian meteorology. The objectives of the Galileo probe mission were to measure composition, temperatures, winds, clouds, lightning, and radiative heating from the top of the ammonia cloud at 0.5 bars to below the base of the water cloud which was expected to lie at 5 bars. There it was supposed to sample the well-mixed interior of Jupiter. These measurement objectives were derived from an atmospheric model that neglects large-scale motion below the clouds. The three condensable gases H_2O, H_2S, and NH_3 were expected to form clouds above the 6, 2, and 0.8 bar levels, respectively. The probe survived to 22 bars, but did not reach the well-mixed interior. Based on remote sensing data, the probe entered a dry spot, a so-called 5μm hot spot. The surprise was that the roots of the hot spot extended down at least to the 22-bar level, about 150 km below the tops of the visible clouds. These deep roots are apparently part of a large-scale dynamical structure. One theory is that the hot spot is a giant downdraft extending 150 km below the ammonia cloud (Atreya *et al.* 1997, Owen *et al.* 1997); another theory is that it is the trough of a giant wave with vertical displacements of 150 km (Showman and Dowling, 2000). There are other possibilities. For instance, 99.9% of the planet might look like a hot spot, with the saturated updrafts concentrated in a few violent thunderstorms occupying 0.1% of the area. Jupiter has no solid or liquid surface, so the dynamical structures could extend to 100 bars or deeper. The dozen or more pairs of dark and light bands that circle the planet on lines of constant latitude are called belts and zones. The highspeed jets are on the boundaries. The prevailing view, based on clouds and chemical tracers, is that the belts are sites of downwelling, but the concentration of lightning in the belts (Gierasch *et al.* 2000) seems to contradict this view. Individual belts, zones, and ovals have persisted for over 100 years. This longevity is remarkable given that Jupiter is a fluid planet with no solid surface to provide stability. Deep roots and their large inertia may be the key to this longevity (Busse 1976, Ingersoll and Pollard, 1982).

The Polar Magnetosphere. A set of instruments measures the polar magnetosphere by determining:

- the electric currents along magnetic field lines;
- the electromagnetic emissions associated with aurora and electrostatic waves;
- the distribution of energetic particles and distribution of auroral and magnetospheric plasma;
- the ultraviolet auroral emissions.

Juno's polar orbit is ideal to answer the fundamental questions of how auroras are generated. Juno's instruments are designed to determine the physical processes occurring in the high latitude magnetosphere and allow us to relate them to auroral activity and to our understanding of the equatorial magnetosphere. At Earth, auroras are primarily driven by the energy of the solar wind. At Jupiter, the primary energy source is the rotation of the planet, but a second source is the motion of the galilean satellites across rotating jovian magnetic field lines. The solar wind also plays a role. These three sources are apparently reflected in the three types of auroras observed at Jupiter (Figure 3): the main ovals of emissions encircling the north and south magnetic poles; emissions emanating from the base of magnetic flux tubes connected to the Galilean satellites; erratic emissions poleward of the main ovals which will be observed by Juno on the two polar caps, also revealing interhemispheric symmetries and asymmetries. Despite their differences, the Jovian and terrestrial auroral displays are thought to be caused by similar processes: strong electric currents flowing along the magnetic field and electromagnetic fields accelerating the charged particles that bombard the upper atmosphere. The closure of these currents across the ionosphere and in the magnetosphere or solar wind transfers

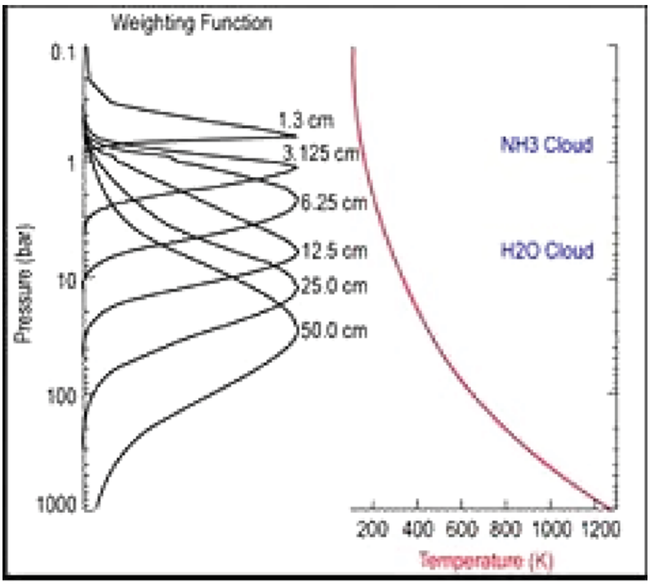

Figure 2. Contribution functions for the emission from Jupiter's atmosphere at nominal MWR frequencies. The ammonia cloud tops lie above the 1-bar pressure altitude. H_2O clouds are expected at higher pressure. The longest wavelength will penetrate Jupiter's atmosphere to depths below 100 bars.

momentum between the two electrically connected regions (Figure 4). Exploring how the auroral circuit provides magnetic coupling of Jupiter to its surrounding nebula, its satellites and the solar wind paves the way for a better understanding of astrophysical systems similarly dominated by rotation of a central magnetic object coupled to a surrounding plasma-such as a young star in a nascent planetary system.

Main Aurora. Jupiter is a rapid rotator with its volcanic moon Io as the main plasma source. Under the effect of centrifugal forces this plasma produces an equatorial disk that rotates with the giant planet, but the "rigidly" corotating plasma begins to slip beyond ∼20 RJ. This breakdown of corotation results in a region of radially outward current in the plasma disk, which continues at either end along magnetic field lines to complete a circuit in the polar regions of Jupiter's ionosphere (e.g., Hill *et al.* 1983; see Figure 4). The ionosphere currents dissipate much energy (Joule heating), and the westward drag of the sub-corotating plasma disk on the ionosphere results in strong (several km/s) winds (cf., Cowley *et al.* 2003) in Jupiter's upper atmosphere. To carry the outward current (away from the ionosphere) magnetospheric electrons are accelerated into Jupiter's atmosphere, where they excite the main oval auroral emissions. The main oval morphology is remarkably stable, but the brightness varies substantially over days. Juno provides an unprecedented look at the poorly understood parts of the main oval circuit -the field-aligned currents, acceleration region, and electrojet winds-along with the auroral emissions.

Satellite footprint auroras. Localized auroral emissions are observed at the feet of the magnetic field lines that connect to the Galilean satellites. In addition, the Io interaction generates a wake extending up to halfway around Jupiter. Characterization of the electrodynamic coupling requires in situ measurement of particles and fields and remote sensing of auroras. Juno observes magnetospheric structures and the ionospheric response (currents, fields, particles): it will determine if Europa, Ganymede and Callisto have wake auroral structures (similar to Io) as well as spots, and ascertain the role played by Alfven waves.

Polar aurora. Bursts of auroral emissions erupt poleward of the main oval. Studying these polar emissions tells us about dynamics of the magnetotail, the dayside magnetopause and coupling to the solar wind. Previous spacecraft found plasma to be flowing

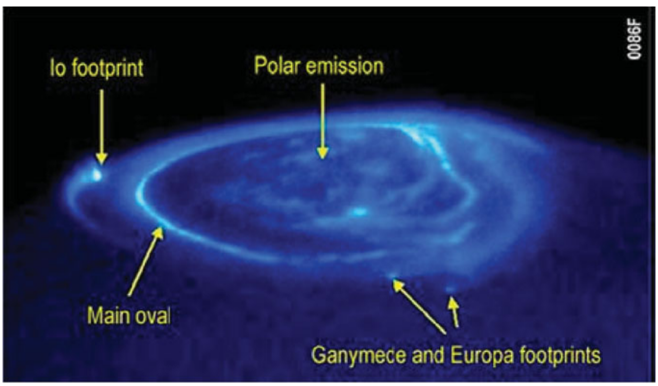

Figure 3. Three types of auroras revealed in this HST image of Jupiter's aurora. Each are signatures of momentum transfer processes.

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downtail on the dawn side at distances of ∼40 RJ. One model proposes that this jovian planetary wind was a signature of reconnection, with "plasmoids" being ejected down the tail. Analogous to substorms at Earth, we expect such processes to produce currents, particle acceleration and auroral emissions. Alternatively, these emissions may be related to reconnection at the dayside magnetopause. Juno distinguishes between these theories via simultaneous in situ measurements and remote sensing of the polar aurora.

Juno science objectives. The Juno science objectives are 1) to determine the O/H ratio (water abundance) and constrain core mass to decide among alternative theories of origin; 2) understand Jupiter's interior structure and dynamical properties by mapping its gravitational and magnetic fields; 3) map variations in atmospheric composition, temperature, cloud opacity and dynamics to depths greater than 100 bars; and 4) explore the three-dimensional structure of Jupiter's polar magnetosphere and auroras. Each objective will be addressed with a set of dedicated instruments on the Juno spacecraft.

2. Juno Science and Payload

Juno is a solar powered, spinning spacecraft that will be placed into an elliptical polar orbit around Jupiter. The launch is August of 2011 and, with gravitational assistance of an Earth flyby, the spacecraft will arrive at Jupiter after a 5 year journey. The payload consists of of nine instruments:

Gravity Science (JPL/ASI). The primary objective of the Gravity Science Experiment is to determine the internal structure of Jupiter by making detailed measurements of its complete gravity field from a polar orbit. The investigation is a Doppler radio science experiment that uses the telecommunications system. Mass distribution in the interior of Jupiter causes asymmetric variations in the gravity field of Jupiter, exerting a variable gravitational *pull* on the Juno spacecraft. These variations lead to tiny variations in the motion of the spacecraft around Jupiter, which are detected using the Doppler shift in the X and Ka band transponders used by the radio sub-system. A correction is usually applied for the effects resulting from the Earth's atmosphere during data processing.

Magnetometer (GSFC)-MAG. Investigations with MAG have three goals: mapping of the magnetic field, determining the dynamics of Jupiter's interior, and determination of the three-dimensional structure of the polar magnetosphere. To achieve these goals, the

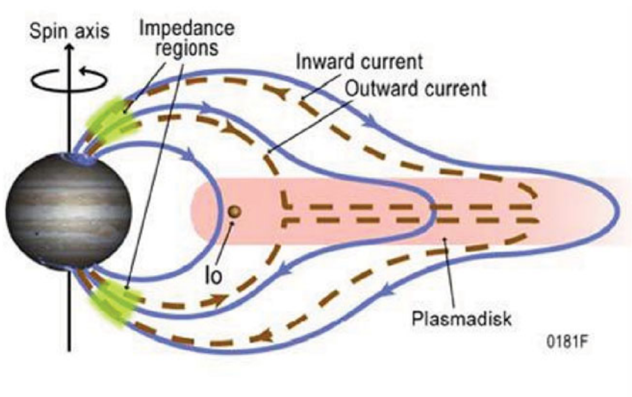

Figure 4. Juno measurements target each critical path in this closed circuit that transfers angular momentum from Jupiter to its nebula.

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mission employs two Flux Gate Magnetometers and two Advanced Stellar Compasses (ASC) to provide accurate location and orientation information of the magnetometers on the Juno spacecraft for precise magnetic field mapping.

Microwave Radiometer (JPL)-MWR. The primary goal of the Juno Microwave Radiometer is to probe the deep atmosphere of Jupiter at radio wavelengths ranging from 1.3 cm to 50 cm using six octave-spaced radiometers to measure the planet's thermal emissions (Fig 2). The MWR objective is the determination of the water abundance in Jupiter's deep atmosphere. The MWR will obtain measurements of ammonia and water in the Jupiter atmosphere, which are the principle absorbers in the microwave region, by scanning Jupiter along the orbital track as the spacecraft spins. These observations will allow scientists to determine the global (well mixed) water abundance on Jupiter which represents the oxygen abundance. The Juno MWR avoids the synchrotron emission from Jupiter's magnetosphere observing from above the poles and beneath the Jovian radiation belts. MWR achieves high accuracy to measure water abundance in the deep atmosphere by using *relative limb darkening*, a parameter that depends on the emission angle of the radiation. The vertical profile of water abundance is obtained by using multiple frequencies, much like the retrieval of temperature profiles on earth with multi-spectral infrared measurements from orbiting weather satellites. The MWR uses six antennae mounted on the spacecraft body, which sweep across the planet as the spacecraft spins to measure the radiation at six different wavelengths along the orbital track. Successive orbits will map the planet longitudinally. The six different wavelengths observed by the MWR, combined with the emission angle dependence will provide a good idea of the atmospheric temperature profile (see Figure 2). The latitudinal dependence of the temperature profile and depth will enable inference of the circulation of Jupiter's deep atmosphere to a much greater depth than that obtained by the Galileo probe.

Energetic-particles (APL)-JEDI. JEDI will measure the energy and angular distribution of Hydrogen, Helium, Oxygen, Sulfur and other ions in the polar magnetosphere of Jupiter using the time of light versus energy technique. JEDI consists of three separate sensing heads using time of flight (TOF) versus energy to sort incoming ions into mass species and energy, and uses foiled and un-foiled measurements to discriminate electrons from ions.

Plasma (SwRI)-JADE. The Jovian Auroral Distributions Experiment (JADE) will resolve the plasma structure of the Jovian aurora by measuring the angular, energy and compositional distributions of particles in the polar magnetosphere of Jupiter. JADE will make the first direct measurements of the particles that precipitate into Jupiter's atmosphere and produce its stunning auroral displays. JADE comprises a single head ion mass spectrometer and three identical electron energy per charge analyzers to measure the full auroral electron and ion particle distributions.

Plasma Waves (U of Iowa)-Waves. The Waves instrument will identify the regions of auroral currents that define Jovian radio emissions and acceleration of the auroral particles by measuring the radio and plasma spectra in the auroral region. The Waves instrument uses an electric dipole antenna and a magnetic search coil to measure electromagnetic waves and to discriminate electrostatic and magnetostatic waves.

Ultraviolet (SwRI)-UVS. UVS records the wavelength, position and arrival time of detected ultraviolet photons during the time when the spectrograph slit views Jupiter during each turn of the spacecraft. Using a 1024 256 micro channel plate (MCP) detector, it will provide spectral images of the UV auroral emissions in the polar magnetosphere which allows to relate the these auroral measurements with JADE.

Visible Camera (Malin)-JunoCam. JCM is a camera which will provide the first 3-color images of Jupiter as the Juno spacecraft approaches the poles for context, public engagement and E/PO. It uses four filters mounted directly on the detector to obtain the first close up color images of the poles. The Juno mission plans to invite students to work alongside the science team to capture these images once the Juno spacecraft is in orbit around Jupiter.

Infrared Imager/Spectrometer (ASI)-JIRAM The Jupiter InfraRed Auroral Mapper JIRAM is the first Italian instrument of this kind to be sent to Jupiter. The primary goal of JIRAM is to probe the upper layers of Jupiter's atmosphere down to pressures of 5-7 bars at infrared wavelengths in the 2-5 μ interval using an imager and a spectrometer. By means of its high contrast imaging and spectroscopy, JIRAM will study the dynamics and chemistry of auroral regions and their link to Jupiter's magnetic field and magnetosphere.

3. Summary

Juno's investigation of Jupiter will provide fundamental information on the history of volatiles in early solar system. The distribution and state of these volatiles will shed light on how the planets received their share of volatiles such as water and carbon which eventually led not only to the formation of Earth, but life itself. Understanding the origin of our own solar system by investigating Jupiter's formation may provide information for finding Earth like planets accompanying the recent observed giant planets outside our solar system.

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