A Look Inside the Juno Mission to Jupiter[1,2]

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Abstract—Juno, the second mission within the New Frontiers Program, is a Jupiter polar orbiter mission designed to return high-priority science data that spans across multiple divisions within NASA's Science Mission Directorate. Juno's science objectives, coupled with the natural constraints of a cost-capped, PI-led mission and the harsh environment of Jupiter, have led to a very unique mission and spacecraft design.

The mission and spacecraft design accommodates the required payload suite of instruments in a way that maximizes science data collection and return, maintains a simplified orbital operations approach, and meets the many challenges associated with operating a spin-stabilized, solar-powered spacecraft in Jupiter's high radiation and magnetic environment. The project's efforts during the preliminary design phase have resulted in an integrated design and operations approach that meets all science objectives, retains significant technical, schedule and cost margins, and has retired key risks and challenges. As a result, Juno has been authorized to proceed with the detailed design phase and work toward an August 2011 launch.

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1. INTRODUCTION

The Juno mission to Jupiter is expected to significantly advance current theories of the Solar System's origin and evolution. Juno will launch in August 2011, perform two deep-space maneuvers approximately one year after launch, perform an Earth-gravity assist approximately 26 months after launch, and achieve Jupiter orbit insertion in 2016 after a five-year journey. Juno will investigate the gas giant for one year, operating a suite of eight instruments to meet its scientific objectives. After completing one year of orbital science, the spacecraft will de-orbit into Jupiter for the purpose of planetary protection.

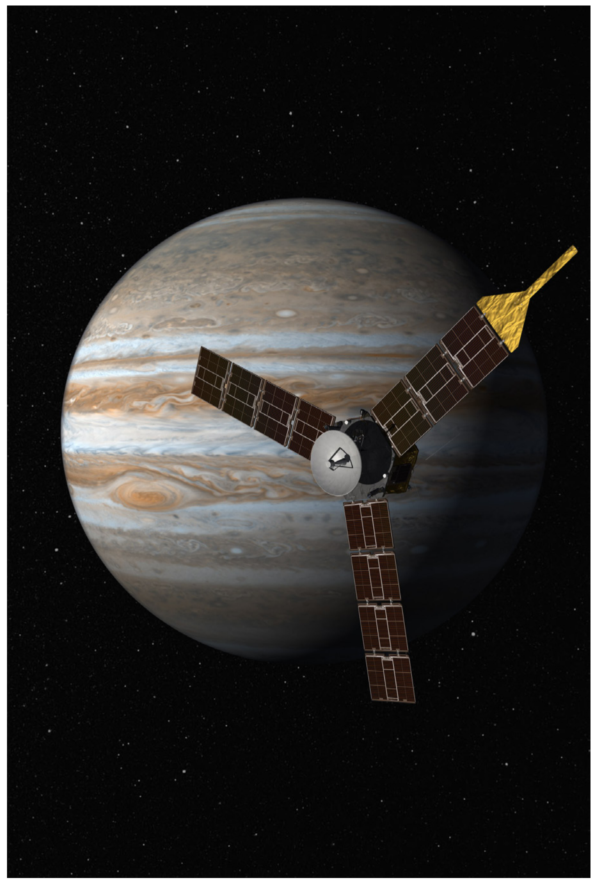

Figure 1 – The Juno Spacecraft in Orbit about Jupiter

This paper will describe the primary science objectives of the Juno mission and how these objectives have been translated into the instrument suite and mission and spacecraft designs. This will include a discussion of key requirements and how these requirements have been realized in the current design, as well as an examination of the associated technical challenges and design solutions.

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A brief history on the mission will be provided, followed by a description of Juno's primary science objectives. Next, the scientific payload will be introduced with a brief description of each instrument and associated science objectives/requirements. A brief overview of the spacecraft will then be followed by a more detailed treatment of the mission design that primarily focuses upon the orbital operations and how the design has evolved to satisfy key science and operational requirements. Finally, a more in-depth look at the spacecraft will be conducted to describe how its design has been influenced by the science and mission requirements, as well as the associated technical challenges.

2. HISTORY

Juno was selected in May 2005 as the second mission in the New Frontiers Program within NASA's Science Mission Directorate (SMD). Juno was originally scheduled for a 2009 launch opportunity, but was subsequently slipped to a 2010 launch and, ultimately, a 2011 launch (within the first year following selection) due to factors not specifically related to Juno itself. This resulted in an extended Phase B period (almost three years). The extended Phase B allowed the project to dedicate much more effort to requirements and preliminary design maturation, as well as to focus on key risk-reduction activities. As a result, Juno had a very successful Preliminary Design Review (PDR) and obtained authorization from NASA Headquarters to proceed into Phase C effective September 1, 2008.

3. PRIMARY SCIENCE OBJECTIVES

The overall goal of the Juno Mission is to improve our understanding of the solar system by understanding the origin and evolution of Jupiter. The science objectives for the Juno investigation are:

(1) Atmospheric Composition — Juno investigates the formation and origin of Jupiter's atmosphere and the potential migration of planets through the measurement of Jupiter's global abundance of oxygen (water) and nitrogen (ammonia).

   a. Measure the global O/H ratio (water abundance) in Jupiter's atmosphere.

   b. Measure the global N/H ratio (ammonia) in Jupiter's atmosphere.

(2) Atmospheric Structure — Juno investigates variations in Jupiter's deep atmosphere related to meteorology, composition, temperature profiles, cloud opacity, and atmospheric dynamics.

   a. Determine microwave opacity as a function of latitude and altitude (pressure).

   b. Determine depths of cloud and atmospheric features such as zones, belts, spots, and map dynamical variations in ammonia and water.

   c. Characterize microwave opacity of the polar atmosphere region.

(3) Magnetic Field — Juno investigates the fine structure of Jupiter's magnetic field, providing information on its internal structure and the nature of the dynamo.

   a. Map the magnetic field of Jupiter, globally, by direct measurement of the field at close-in radial distances.

   b. Determine the magnetic spectrum of the field, providing information on the dynamo core radius.

   c. Investigate secular variations (long-term time variability) of the magnetic field.

(4) Gravity Field — Gravity sounding by Juno explores the distribution of mass inside the planet.

   a. Determine the gravity field to provide constraints on the mass of the core.

   b. Determine the gravity field to detect the centrifugal response of the planet to its own differential rotation (winds) at depths of kilo-bars and greater.

   c. Investigate the response to tides raised by the Jovian satellites.

(5) Polar Magnetosphere — Juno explores Jupiter's three-dimensional polar magnetosphere and aurorae.

   a. Investigate the primary auroral processes responsible for particle acceleration.

   b. Characterize the field-aligned currents that transfer angular momentum from Jupiter to its magnetosphere.

   c. Identify and characterize auroral radio and plasma wave emissions associated with particle acceleration.

   d. Characterize the nature, location and spatial scale of auroral features.

Table 1 – Instrument Mapping to Science Objectives

Instrument	Description	Science Investigation	Associated Objective
Gravity Science	X- & Ka-band uplink and downlink	Interior Structure	4
Magnetometer (MAG)	Vector fluxgates (FGM)	Interior Structure & Magnetic Dynamo	3
Microwave Radiometer (MWR)	6 wavelengths (1.3-50 cm)	Deep atm. sounding & composition	1, 2
Juno Energetic particle Detector Instrument (JEDI)	TOF vs. energy, ion & electron sensors	Auroral distributions, ion composition	5
Jovian Auroral Distributions Experiment (JADE)	Ion mass spec. & electron analyzers	Auroral distributions, ion composition	5
Waves	4-m. elec. dipole and search coil	Radio & Plasma waves	5
Ultraviolet Spectrometer (UVS)	FUV spectral imager	Spatial & temporal auroral structure	5
Juno Infra-Red Auroral Mapper (JIRAM)	IR imager and IR spectrometer	Auroral structure, troposphere structure, atmospheric sounding	2, 5

4. INSTRUMENT PAYLOAD

To satisfy the science objectives described previously, Juno carries a complement of eight scientific instruments. Refer to Table 1 for a mapping of the scientific objectives to each instrument.

The Microwave Radiometer (MWR) is a Jet Propulsion Laboratory (JPL) delivered instrument that consists of six peripherally mounted antennas, radiometers, and control/calibration electronics for six frequencies between 600 MHz and 22 GHz. The MWR is used for deep atmospheric sounding and composition.

The magnetometer (MAG) is a Goddard Space Flight Center (GSFC) delivered instrument consisting of dual flux-gate magnetometers as well as co-located star cameras (for precise attitude reference measurement) located on a boom structure. The MAG is used to investigate the interior structure and magnetic dynamo of Jupiter.

The Gravity Science experiment uses both X-band and Ka-band telecommunications elements on the spacecraft as well as on the ground to provide simultaneous X/Ka up/down signals to observe the Doppler shift while close to Jupiter. This experiment is used to determine the even-normalized gravity coefficients J4 to J14. The spacecraft X-band system is provided by JPL. The Ka translator on board the spacecraft is contributed by the Italian Space Agency (ASI). The ground elements are provided by the Deep Space Network (DSN) at the Goldstone, CA station (DSS-25).

5. FIELDS AND PARTICLES INSTRUMENTS

Juno carries a suite of five field and particles instruments to study and characterize the three-dimensional structure of Jupiter’s polar magnetosphere and aurora. This suite of instruments measures the fields (magnetic field, plasma waves, and radio emissions) and charged particles (ions and electrons) and obtains ultraviolet images of the auroral emissions to provide context for the in-situ observations.

The Jovian Auroral Distribution Experiment (JADE) instrument provided by the Southwest Research Institute (SwRI) measures the pitch angle and energy distributions of electrons as well as the time variable, pitch angle, energy, and composition distribution of ions over both polar regions. JADE consists of three electron analyzers and one ion mass spectrometer.

The Jupiter Energetic-particle Detector Instrument (JEDI) also measures electrons and ions in the Jovian polar region. However, JEDI, which utilizes three sensors measures different energy ranges than the JADE instrument. Johns Hopkins University Applied Physics Laboratory (JHU/APL) provides the JEDI instrument.

The Waves instrument, provided by the University of Iowa, measures the radio and plasma wave emissions associated with the auroral phenomena in Jupiter’s polar magnetosphere to reveal the processes responsible for particle acceleration. The experiment consists of an electric dipole antenna and a magnetic search coil, along with associated receivers.

An Ultraviolet Spectrometer (UVS), also provided by SwRI, is used to characterize the ultraviolet auroral emissions and consists of a telescope/spectrometer with associated electronics.

The Juno Infra-Red Auroral Mapper (JIRAM) instrument acquires infrared (IR) images and spectra of Jupiter to investigate auroral structure and troposphere structure, and to perform atmospheric sounding. JIRAM consists of both an infrared imager and an IR spectrometer. This investigation is provided by the Italian Space Agency (ASI).

Though not a scientific instrument, there is a visible camera (JunoCam) carried as part of the payload. JunoCam is intended to capture color images of Jupiter (and its poles), and is being provided by Malin Space Science Systems for education and public outreach/engagement.

6. SPACECRAFT OVERVIEW

To provide context for the more detailed treatment of the mission design and orbital science operations, a brief introduction to the Juno spacecraft is provided herein. (Refer to Figure 2 for an overall view of the spacecraft.)

Due to the cost and uncertain availability of a radioactive power source (as well as the associated complexity), the spacecraft is solar powered. Since the solar incidence at Jupiter is only 2% to 3% of that of Earth, the spacecraft had to be designed in such a way as to be able to provide sufficient power for the instrument suite while minimizing overall power requirements at Jupiter. This led to a decision to select a spin-stabilized spacecraft to avoid power-hungry reaction wheels. Selection of a spin-stabilized spacecraft was also influenced by the nature of the science payload data-acquisition needs and a desire to avoid the complexities of instrument scan platforms and associated complex spacecraft maneuvers and pointing requirements. The placement of instrument sensors and antennas on the edges of the deck and periphery of the structure complemented the use of a spin-stabilized spacecraft and maintained operational simplicity. As the spacecraft slowly spins in its polar orbit over Jupiter, all instrument sensors have the fields of view of Jupiter required to obtain their measurements while avoiding complex pointing maneuvers or scan platforms. Refer to Figure 3 for an illustration of instrument sensor locations as described.

Figure 4 illustrates the spacecraft view of Jupiter and orientation during orbital operations.

7. MISSION AND OPERATIONS DESIGN

A brief overview of the mission was previously provided in the Introduction section of this paper. This section will primarily focus upon the science mission design following Jupiter arrival. Following Jupiter orbit insertion (JOI), the spacecraft is placed into a 78-day polar orbit and, subsequently, performs a main engine burn to achieve the desired 11-day polar orbit required for science operations. The large capture orbit was chosen to reduce the amount of propellant required for JOI while providing a unique opportunity for early science observations. The science orbit is a high-inclination polar orbit characterized by apojove of approximately 39 Jupiter radii (39Rj) and a perijove of approximately 1.06 Rj and an altitude of approximately 4600 km above Jupiter's cloud tops. This 11-day polar orbit was selected for many mission-enabling reasons. First, the high inclination (90 degrees ± 10 degrees) and close perijove allows the spacecraft to dip below Jupiter's very high radiation belt (refer to Figure 5) and significantly minimizes the spacecraft's overall mission radiation dosage. As primary science data collection occurs around ± 3 hours of perijove, the instrument and spacecraft sensor operations occur in the lowest radiation environment possible, thereby minimizing effects on such things as instrument sensor signal-to-noise ratios and possible star tracker outages. Another advantage of this orbit is that the close perijove and high inclination provide greater resolution for key science, such as the MWR and gravity science experiments. This orbit also enables full global coverage of Jupiter during the one year of mission operations, which is key to the magnetometer (MAG) experiment.

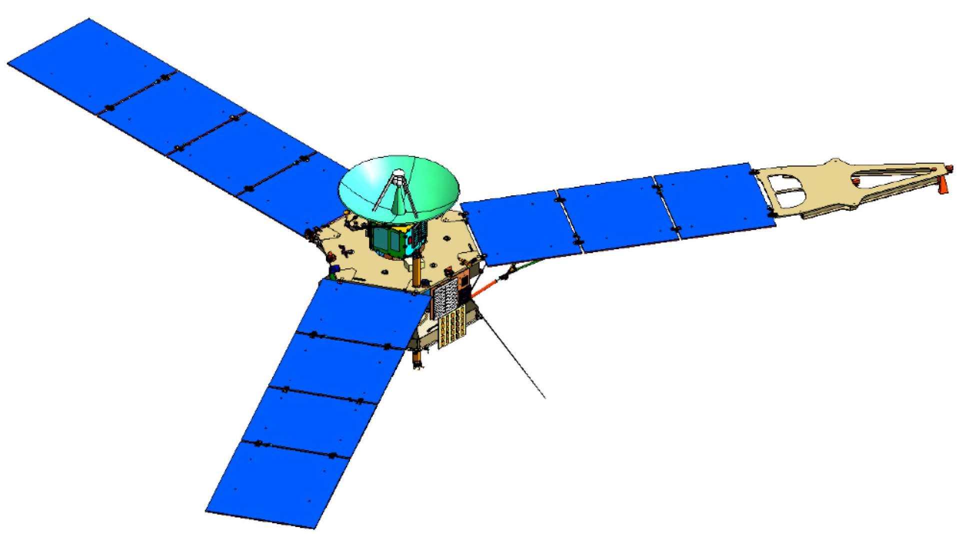

Figure 2 – Overall View of Juno Spacecraft

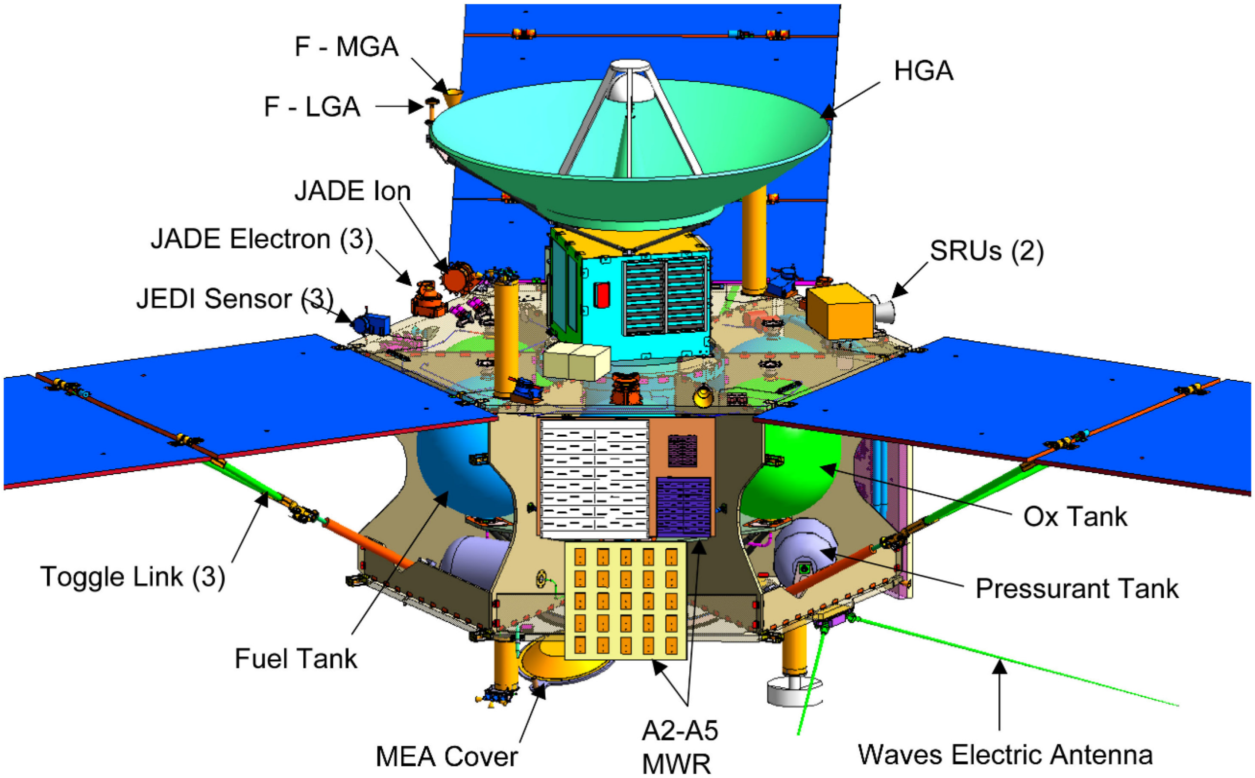

Figure 3 – Spacecraft exploded view with Instrument Highlights

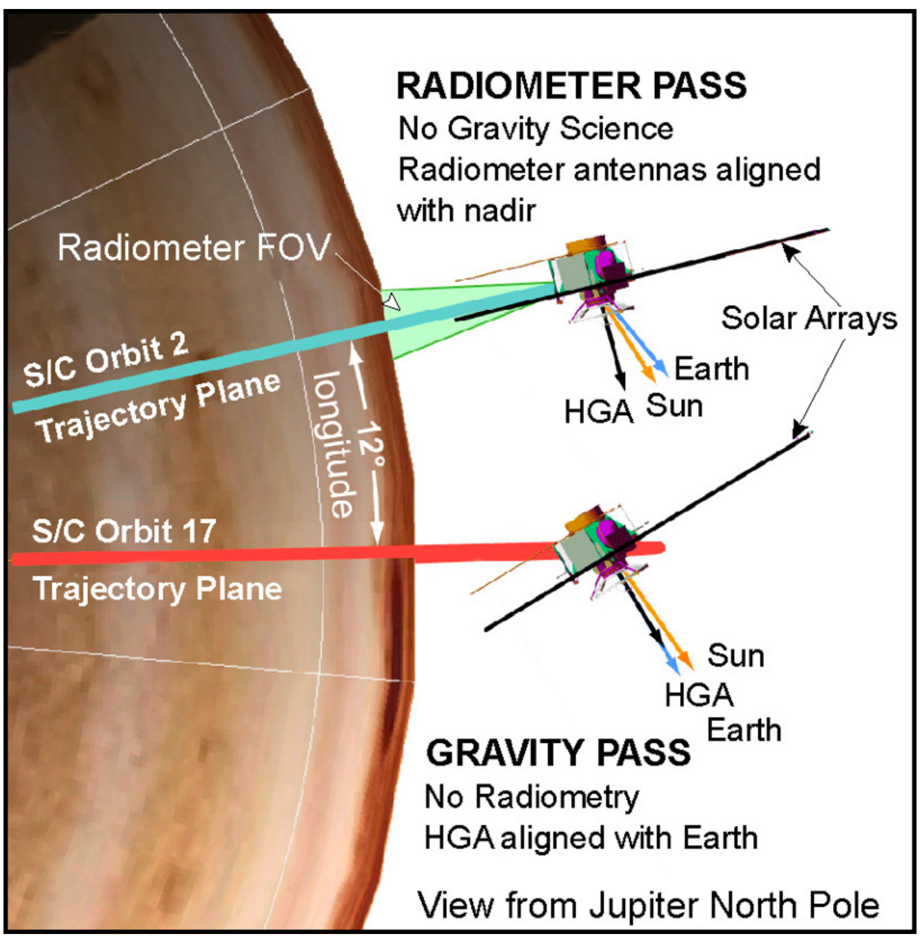

Figure 4 – Spacecraft Orientation for Science Observations at Jupiter

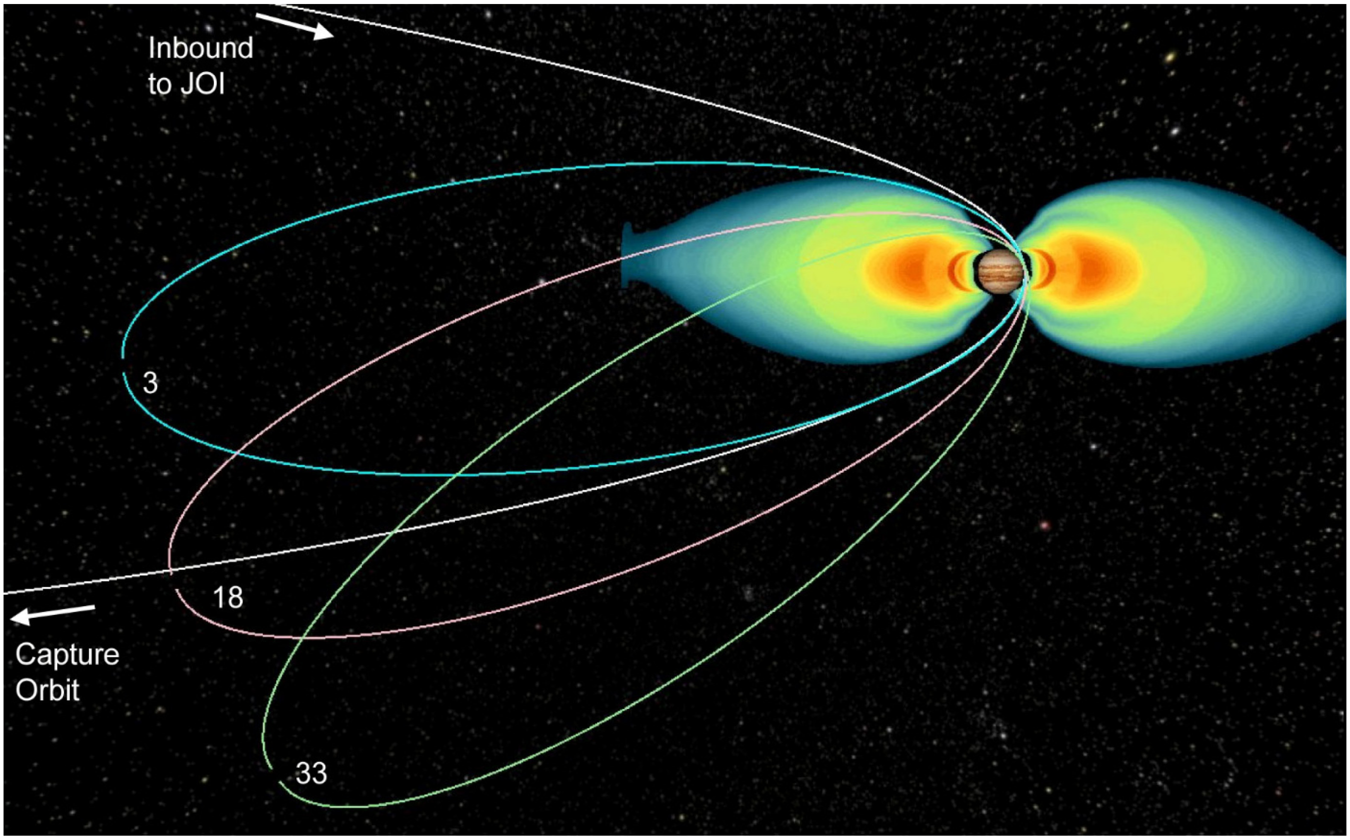

Figure 5 – Juno's orbit dips below Jupiter's radiation belts

For the MAG to achieve its desired science and global coverage, the longitude spacing at the equatorial crossings must be equally spaced. Consequently, the first 15 science orbits provide for 24° longitude spacing for full global coverage. Just after the perijove of the 15^{th} science orbit, a maneuver is performed to adjust the longitude crossing by 12°. After the last 15 science orbits (for a total of 30), the MAG experiment will have completed a global map of Jupiter's magnetic field with 12° longitudinal spacing (refer to Figure 6). Another key characteristic of the science orbit selected for Juno is that the line of apsides of the orbit precesses due to Jupiter's oblateness. This has the affect in the latter half of the science mission of the spacecraft passing through more of Jupiter's radiation belts and increasing its total radiation dose significantly. Thus, through the first half of the mission, the spacecraft and instruments only receive about 20% of the total radiation dose. This is complemented in the science mission design by the fact that the majority of Juno's desired science return can be accomplished within the first 15 science orbits when the radiation dose is lowest (refer to Figures 5 and 7 as illustrations of these orbital characteristics). An additional characteristic of the mission design is that the entire mission occurs between solar conjunctions, thus further enabling a solar-powered mission.

As previously noted in the spacecraft overview, the use of a spin-stabilized spacecraft and placement of the instrument sensors has led to simplified orbital science operations. Essentially, only two operational science templates are necessary. The first template is the MWR pass. This orbit is characterized by the spacecraft spin plane aligned with the center of Jupiter and the MWR antennas aligned with nadir. During MWR science orbits, all other science instrument observations are active, with the exception of gravity science (telecom). The second template is the Gravity Science pass, which is characterized by the high gain antenna (HGA) being aligned with Earth. During the gravity science passes, all science instruments are collecting data except for MWR, JIRAM and JunoCam. Refer to Figure 4 for a depiction of these two science templates. The mission has been designed such that science orbits 1 and 3 through 6 are MWR passes, with the remaining science orbits designated as Gravity Science passes. The mission has designated a 31st science orbit as a spare orbit in the event of the need for replacing one of the previous science orbits or as a special opportunity for observing an unplanned event. Following this spare orbit, the spacecraft will be de-orbited into Jupiter itself to avoid planetary protection concerns associated with the Galilean moons were the spacecraft to remain in orbit.

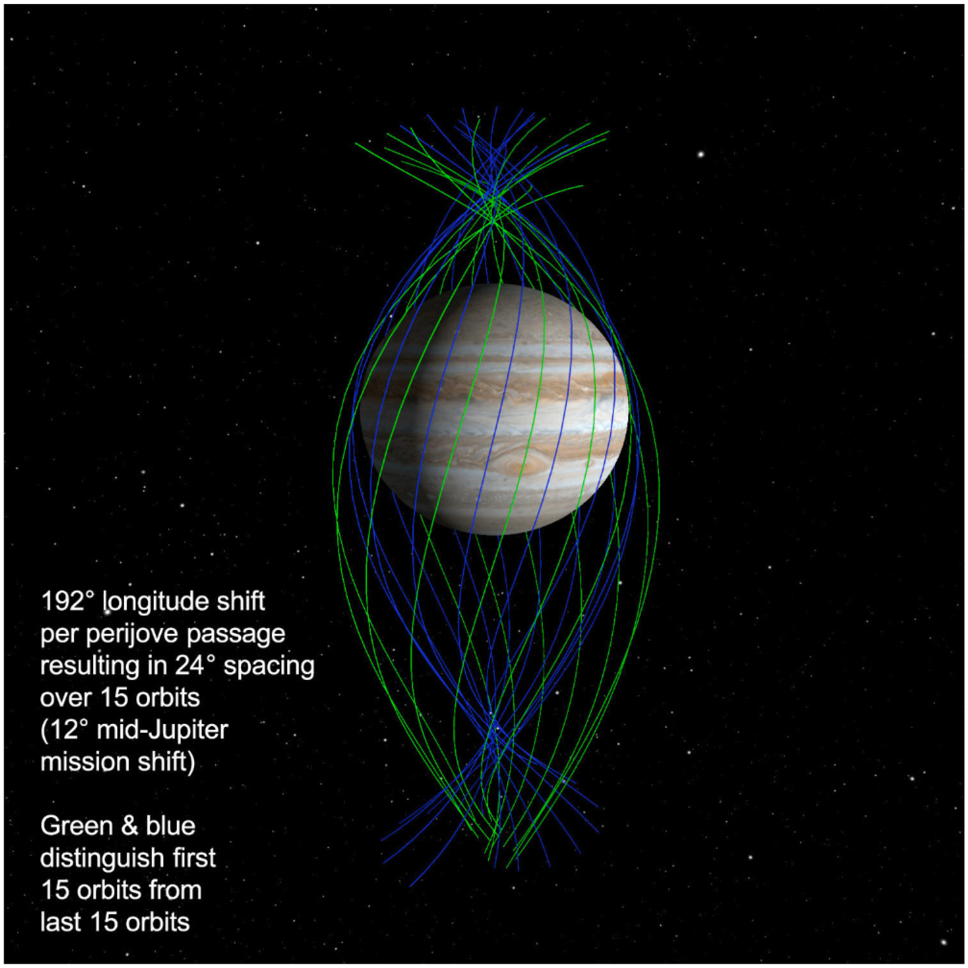

Figure 6 – Juno creates a web about Jupiter

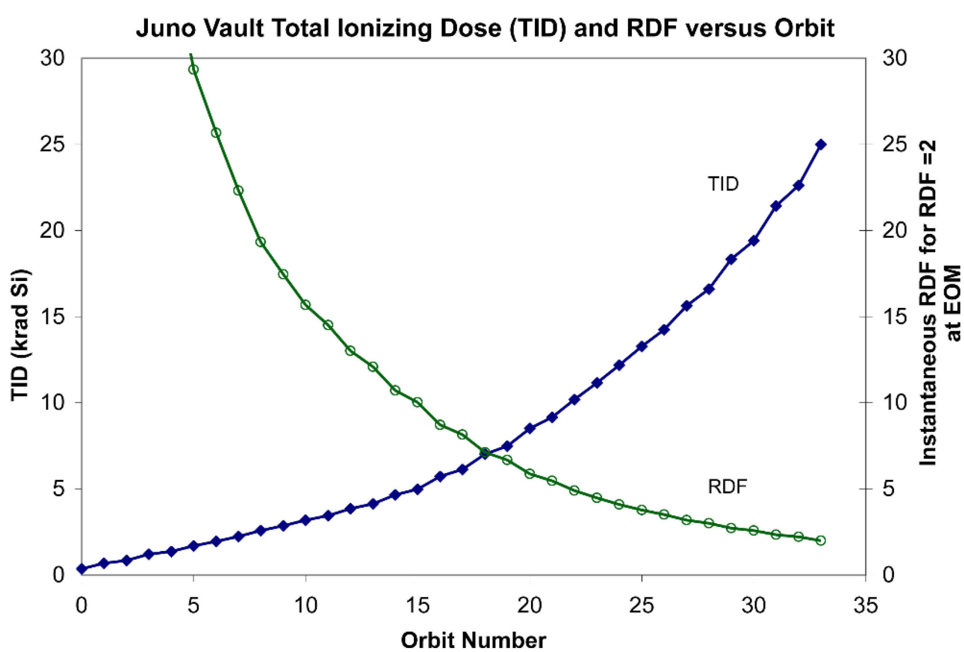

Figure 7 – Illustration of radiation dose within the vault as a function of orbit number

7. Spacecraft Design Solutions

To meet the constraints associated with the overall mission design, operations, and environmental considerations, the spacecraft design has had to address many challenges. Chief among these challenges have been:

(1) Solar arrays that can provide sufficient power at Jupiter.

(2) Protection of heritage electronics from the high radiation environment (to avoid increased costs for new designs).

(3) Accommodations for a large and diversified payload.

(4) Maintenance of required attitude/pointing knowledge during perijove science operations.

Finding acceptable technical solutions to all of these challenges, while remaining within the cost and schedule constraints, were key to passing KDP-C and being authorized to proceed into the Implementation phase.

8. Solar Arrays

The solar arrays on the Juno spacecraft consist of three solar array wings placed symmetrically about the bus (see Figure 2). Each wing consists of four solar array panels (approximately two meters wide by three meters long), except for the one wing containing the MAG experiment. This wing has one less panel, which has been replaced with the MAG boom that hosts the dual fluxgate magnetometers and associated star cameras. This configuration places the MAG experiment as far away from the spacecraft bus (and associated magnetic field) as possible while maintaining the necessary balance of the three-wing configuration. The panel size and number of solar cells on each were determined based upon a significant test and analysis program that was conducted during Phase B. This program consisted of testing multiple samples of triple-junction solar cells in the expected radiation and low-intensity, low-temperature (LILT) environment at Jupiter, characterizing the performance and degradation of various cell-operating parameters that resulted from this exposure, and conducting detailed analysis of the results. The results were used to optimize the design of the panels to ensure sufficient power is available for the conduct of science operations and end of mission disposal. This resulted in a solar array design that has approximately 45 meters^2 of total active cell area and yields an on orbit average power of approximately 460 to 490 watts. Each solar wing has the ability to be articulated by a small amount in flight such that the center of mass about the spin axis can be re-aligned following each main engine burn (which alters the spacecraft's mass properties due to propellant expenditure).

9. Vault Design

Juno is expected to accumulate a total ionizing dose (TID) of greater than 100 Mrads (1×10^8) at the solar cell cover glass to 11 Mrads at the components on the top deck. To protect sensitive electronics and maintain their design heritage as much as possible, the vast majority of the avionics and instrument electronics are placed inside a radiation vault that reduces the TID exposure to a maximum of 25 Krad. The vault is located in the center of the spacecraft on the top deck, is approximately 1 meter square, and has a mass of 180 kg. To account for environment modeling uncertainties, all assemblies within the vault are required to apply a radiation design factor of 2 and be qualified to that level of exposure (or a maximum of 50 Krads). Significant design efforts and risk-reduction tasks were applied to all facets of the vault design during Phase B. Proper sizing of the vault as necessary to accommodate all of the assemblies while optimizing total mass, accommodation and routing of cabling, and consideration of human factors and integration and test requirements, proved to be quite challenging. It took a number of design iterations to achieve a workable baseline. Selection and optimization of the shielding materials (tantalum sandwich material) to provide maximum protection while minimizing mass was a major activity. Once these solutions were initially achieved, a significant thermal analysis activity was conducted. This analysis proved to be quite a bit of work, given the range between the hot case (near earth) and the cold case (5.4 AU from the Sun at Jupiter). Finding acceptable design solutions for these two cases required further vault design modifications (such as louvers) as well as improved definition of necessary thermal power requirements (which, in turn, fed back in to the solar-array power requirements). Of course, electromagnetic interference (EMI) and electromagnetic compatibility (EMC) requirements and issues had to be addressed within the vault as well, resulting in some additional constraints being placed on particular electronics boxes. The vault designers have also begun to address the complicated design considerations associated with cabling penetrations and bulkhead connectors necessary to interface the external sensors and other spacecraft elements with their electronics inside the vault. The design solutions must maintain the vault's integrity as a Faraday cage and minimize any penetrations that increase radiation exposure to the internal components. The experience and work accomplished to date has been tremendous, but it has also indicated that the vault layout and performance characteristics are very sensitive to minor changes associated with the internal electronics boxes, such as small dimensional changes or chassis orientations. Thus, the vault design will continue to change and evolve to optimize the various performance characteristics and constraints that must be met. Refer to Figure 8 for a view of the current vault design.

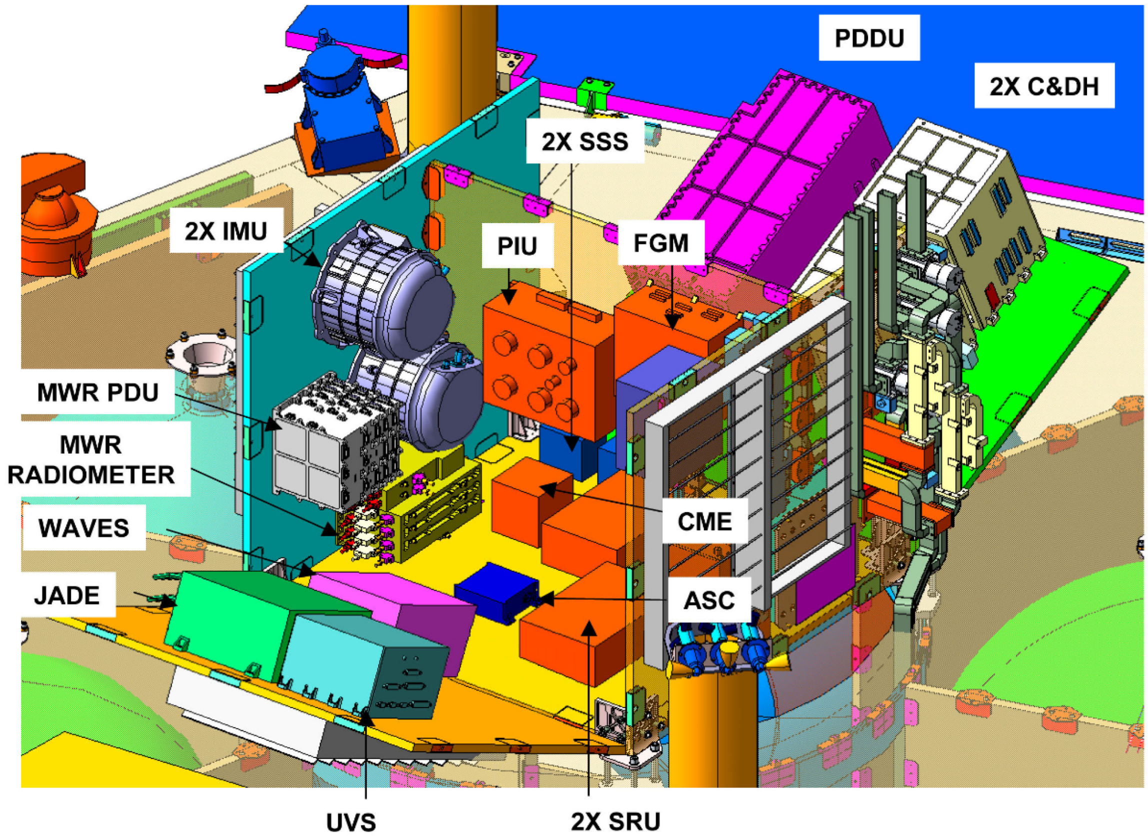

Figure 8 – View Inside the Radiation Vault

10. Stellar Reference Unit (SRU)

The SRUs have presented yet another challenge to the spacecraft design team. It was recognized early in Phase A that there was no viable, off-the-shelf, SRU that could meet the performance requirements necessary to maintain attitude knowledge during the perijove science period of ± three hours of about perijove. This was primarily due to the two primary factors of operating on a spinning spacecraft (spin rate approximately 2 rpm during science operations) and the necessity of identifying sufficient stars (as a result of the high radiation background). The ground attitude reconstruction requirement of the MAG experiment dictated that the SRU not have star outages of more than 30 minutes during the primary science acquisition period. Therefore, during Phase B two SRU vendors were selected for study contracts to explore modifications to their existing designs that would meet the necessary performance requirements. The studies included radiation testing of the proposed SRUs and highly detailed system-level analyses of the resulting SRU performance. Each vendor's study contract culminated in a PDR of the proposed design and an associated cost proposal. As a result of this activity, Galileo Avionica was chosen as the SRU vendor and the proposed modifications to their design are expected to result in few perijove star outages and those outages will be significantly less than 30 minutes.

11. Other Spacecraft Design Characteristics

Due to the number of different view geometries and orientations during the mission, in addition to the high gain antenna (HGA) which will serve as the primary work horse during the science mission, the spacecraft has several different antennas for communications. Specifically, the spacecraft has a fore medium gain antenna (MGA) and a fore low gain antenna (LGA), an aft LGA and, finally, an aft toroid LGA. The toroid LGA is necessary to provide communications during the main engine burns for JOI and the subsequent period reduction maneuver (PRM). Similar to the scheme used by the Mars Exploration Rovers during entry, descent and landing, the spacecraft will transmit various tones via the toroid antenna to convey information regarding the execution of various automated, sequenced events. Though the down link bandwidth during these critical events is quite limited, the use of tones has the ability to convey very important information, as opposed to simply tracking the carrier frequency (as was done on the Cassini spacecraft during its Saturn orbit insertion).

In addition to the single main engine that is used for the two deep space maneuvers, JOI and the PRM; the spacecraft also has four rocket engine module (REM) towers, each consisting of two lateral and one axial thrusters. Two of these towers are located on the fore deck and two on the aft deck. Together, these REM towers are able to accomplish all the remaining maneuvers necessary during the mission, including the de-orbit maneuver at end of mission.

12. CONCLUSION

The Juno mission, payload, and spacecraft designs have been carefully selected and analyzed in a highly synergistic manner such that all science objectives for this difficult mission can be met. Each area has presented unique challenges and requirements on the other two areas, solutions for which have been described and discussed. The resulting system ensures that the required science objectives are met, maintains a simple, orbital operations approach, and meets the many challenges associated with operating a spin-stabilized, solar-powered spacecraft in Jupiter's harsh environments. Further, the mission's ability to meet the majority of its science objectives after only completing half of its planned science orbits represents significant margin and reduces risk for mission accomplishment. Addressing the major challenges during Phase B has allowed the mission to mature its design in such a manner as to retain robust technical, schedule, and cost margins consistent with, or exceeding, NASA requirements and guidelines. As a result, the Juno mission successfully passed all of the required success criteria at PDR and received authorization to proceed into the implementation phase.

Though the preliminary mission, payload, and spacecraft designs have been completed, it is certain that the detailed design phase will present additional challenges that must be addressed. Nonetheless, the Juno team is well positioned to take on the challenges within the framework and architecture that has been developed.

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BIOGRAPHY

Richard Grammier *is the Deputy Director for the Solar System Exploration Directorate at NASA's Jet Propulsion Laboratory (JPL). This Directorate is responsible for all planetary exploration projects (except Mars related projects) managed by JPL.*

Prior to this position, Mr. Grammier served JPL in numerous capacities including: Juno Project Manager, Deep Impact Project Manager, Deputy Director for the Solar System Exploration Directorate, Manager of JPL's Mission Assurance Division, Project System Engineer and Deputy Project Manager of the Stardust Project, and Project Element Manager for the Cassini Command and Data Handling Subsystem.

Mr. Grammier received his B.S. degree from the United States Military Academy and a M.S. in Electrical and Computer Engineering from California State Polytechnic University. He has been awarded the NASA Exceptional Achievement Medal for Cassini, and two NASA Outstanding Leadership medals for his accomplishments on Stardust and Deep Impact.