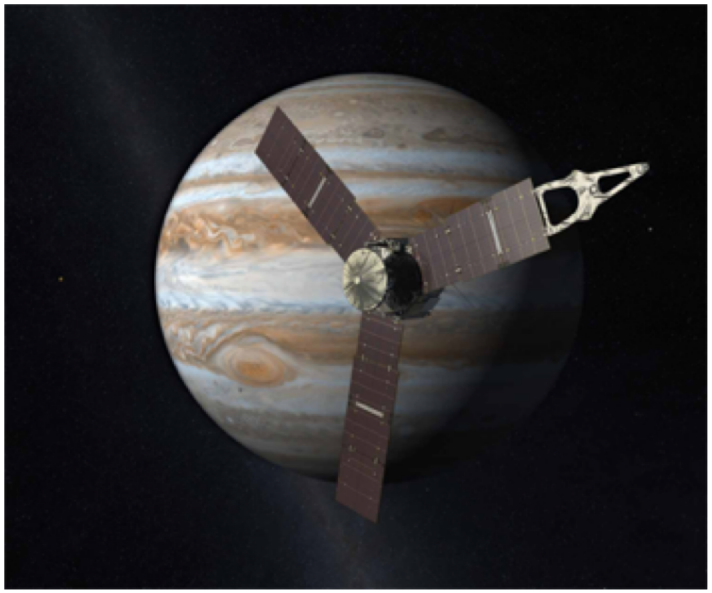

Electromagnetic Compatibility Challenges In The Development Of Jupiter-Bound Interplanetary Spacecraft

Pablo S. Narvaez

Jet Propulsion Laboratory, California Institute of Technology

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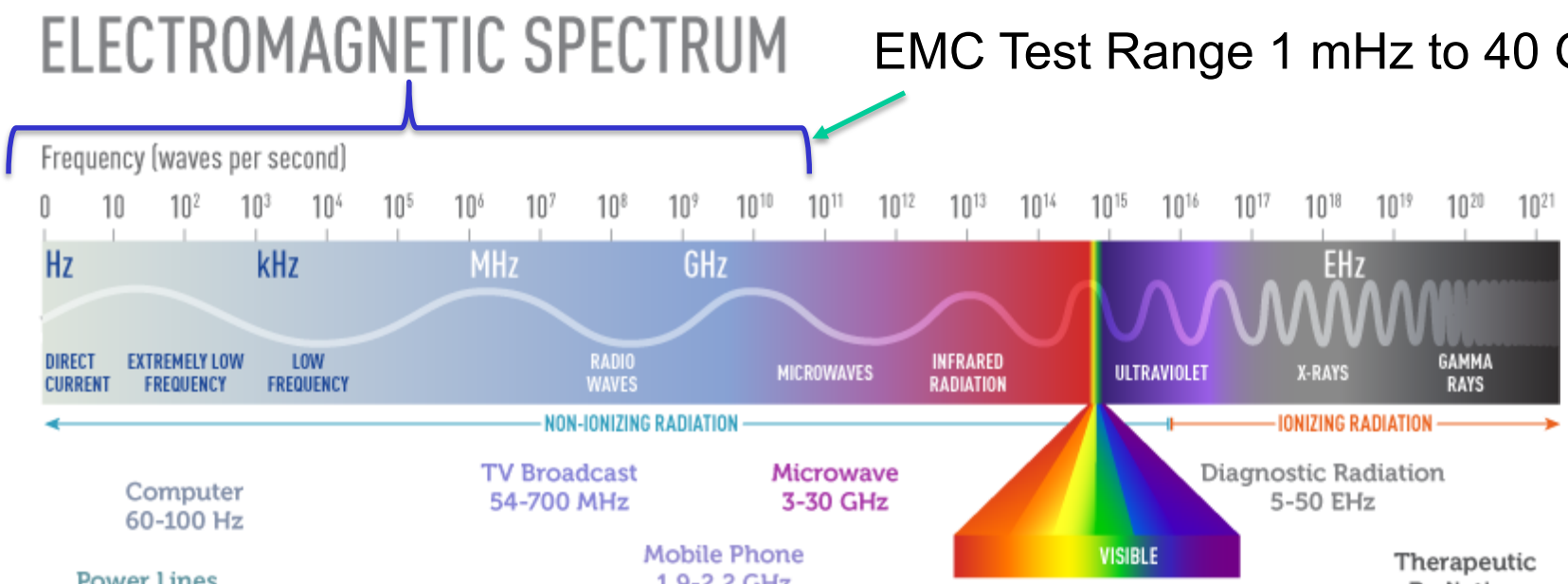
July 22, 2019

Electromagnetic Spectrum

EMC Test Range 1 mHz to 40 GHz



Computer
60-100 Hz

Power Lines
50-60 Hz

Fluxgate Magnetometers
Vector Helium Magnetometer
Scalar Magnetometers

Search Coils, Plasma
Instruments, Low Frequency
Electric Field Sensors

TV Broadcast
54-700 MHz

Radio
AM 520-1610 kHz
FM 87.5-108 MHz

UHF Radio, Microwave
Radiometers, GPS, S/C
S-Band Receivers, X-Band
Focal Plane Arrays/Detectors

Mobile Phone
1.9-2.2 GHz

Smart Meters
0.9-2.45 GHz

Wi-Fi
2.4-2.5 GHz
5-5.8 GHz

Remote Control
5.8 GHz

Microwave
3-30 GHz

CloudSat
SWOT
MLS
Aquarius

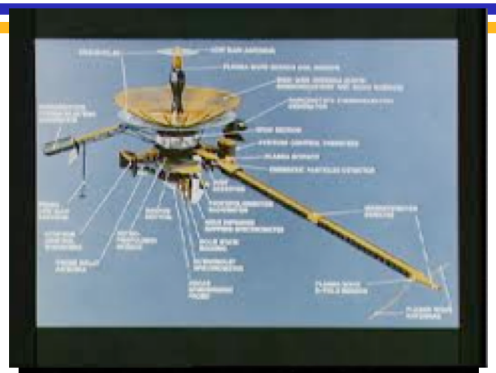
Diagnostic Radiation
5-50 EHz

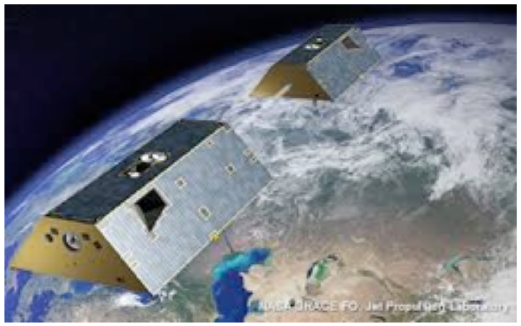
Therapeutic
Radiation
500-5,000 EHz

Electromagnetic Compatibility/Interference

- ElectroMagnetic Compatibility (EMC) is the branch of electrical sciences which studies the intentional and unintentional generation, propagation and reception of electromagnetic energy and its unwanted effects. EMC ensures that electronic components/subsystems function together in the resulting electromagnetic environment and ensures the ability of a system that contains multiple electronic boxes (ie typical science instruments with electronics and sensor elements) to function as intended without degradation or malfunction in their intended operational electromagnetic environment.
  - Emissions are related to the unwanted generation of electromagnetic energy by a source (a component/subsystem that is an emitter of electromagnetic energy).
  - Susceptibility or immunity, in contrast, refers to the correct operation of electrical equipment, referred to as the victim, in the presence of unplanned electromagnetic disturbances. A victim is a component/subsystem that is susceptible to interference).
- ElectroMagnetic Interference (EMI) is a phenomenon in which one component/subsystem interferes with the proper operation of another subsystem due to the propagation of electromagnetic energy.
- Interference, or noise, mitigation and hence electromagnetic compatibility is achieved primarily by addressing both emission and susceptibility issues, i.e., quieting the sources of interference and hardening the potential victims.

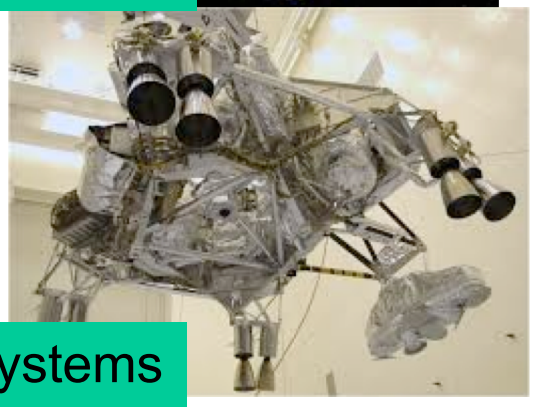
Which Typical Projects Requires EMC?





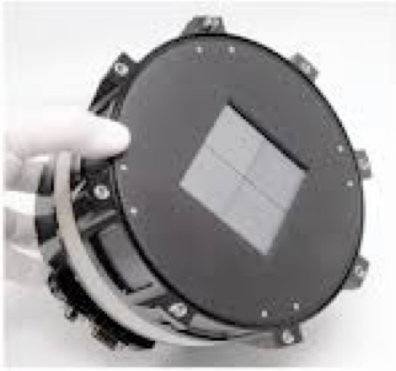
Interplanetary

Earth Orbiters

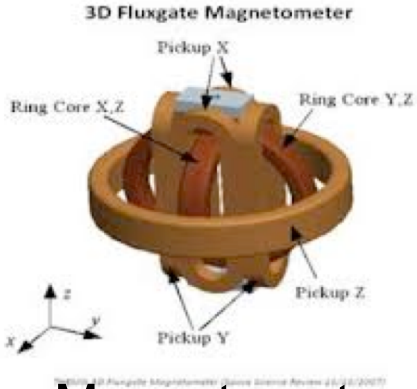


Landed Systems

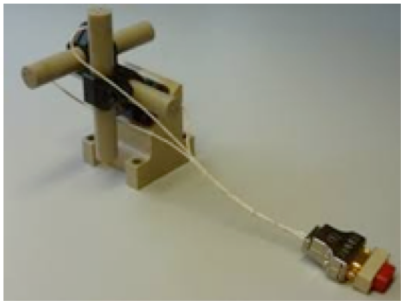
Typical Sensitive Instruments To EMI



Detectors



Magnetometers



Plasma Waves
Search Coils

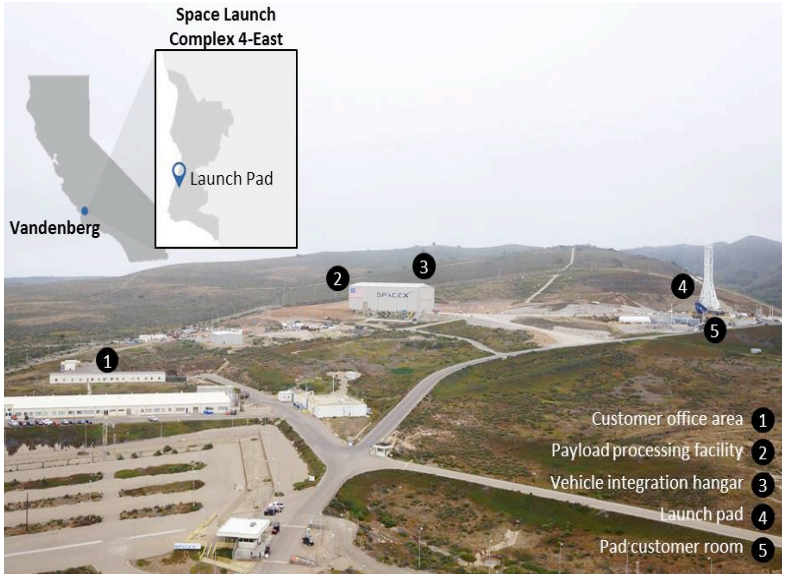
Focal Plane Arrays

Radiometers

UHF/GPS
S/X/Ka Band
Telecom/Receivers

KSC or VAFB Launch Site

On Site Base Transmitters For Weather, Airplane (FAA) Tracking, Launch Tracking, etc.



Low Earth Orbit

Research, Military, Commercial Radars and Tracking Stations Based Throughout The Globe

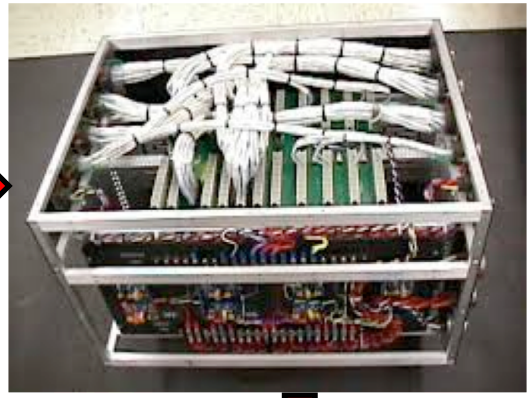
High Powered Tx
Russia
China
US
UK etc…

EMI At Every Level

Part Level

PC Board Level

Box Level

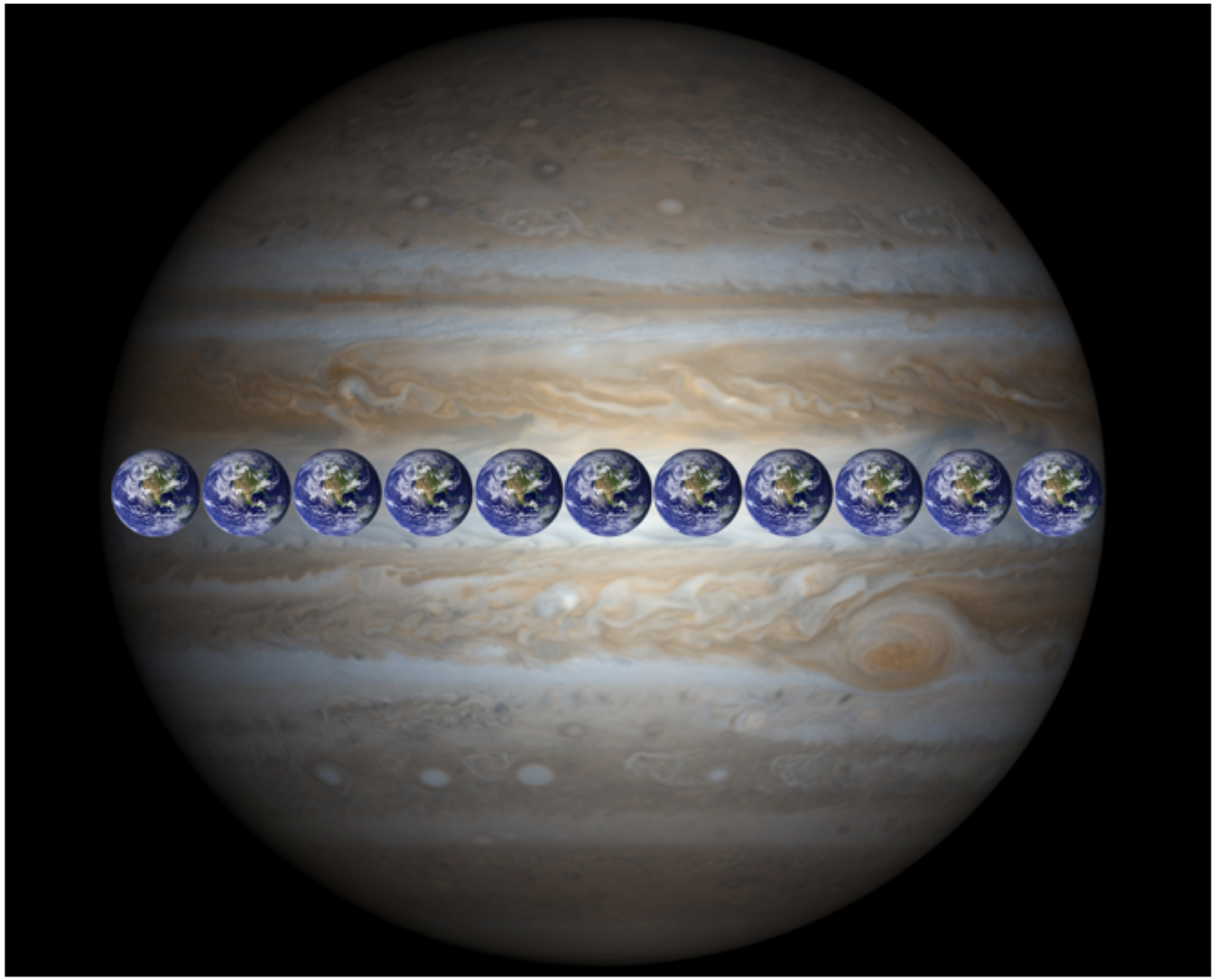


Subsystem Level

Instrument Level

System Level

Jupiter



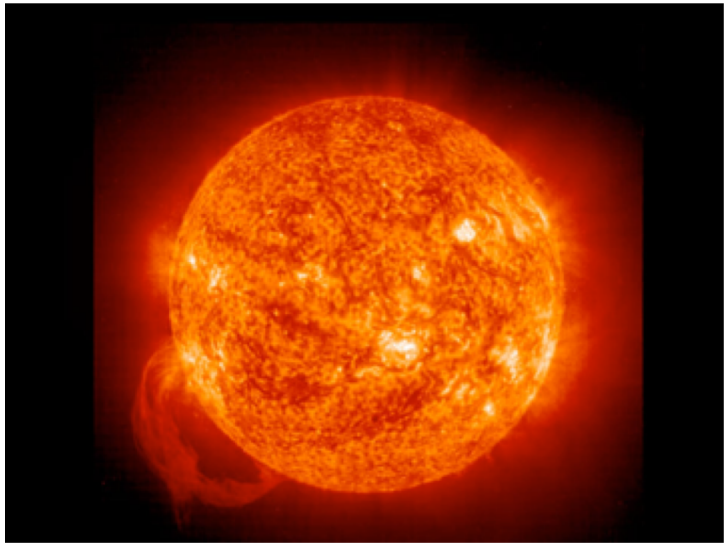
Why Jupiter?

- Understanding the origin of Jupiter helps us understand how solar systems formed.
- Want to understand how Jupiter formed so that we can learn how Earth formed.
- Sun consists of 99.5% mass of solar system, and it formed first, and remaining 0.5%, 2/3 is from Jupiter, which formed next, and the rest 1/3 is from the other planets, asteroids, comets etc.

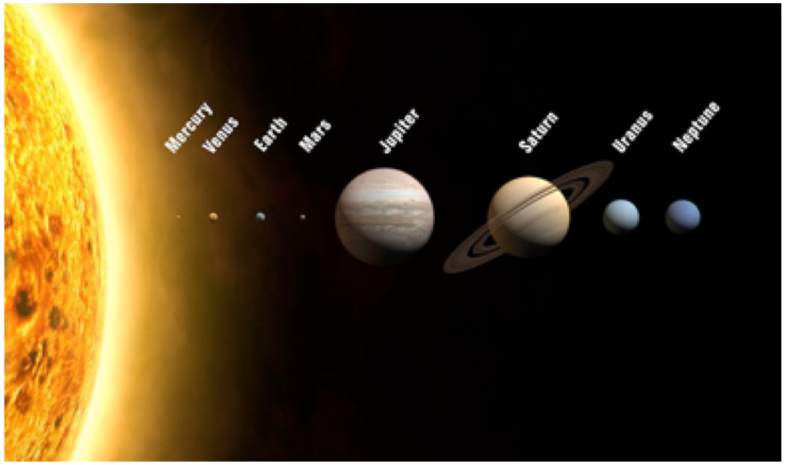
Solar System Mass

99.5%

0.5%



2/3



Mostly Hydrogen, Helium

1/3 rest of planets, asteroids comets…

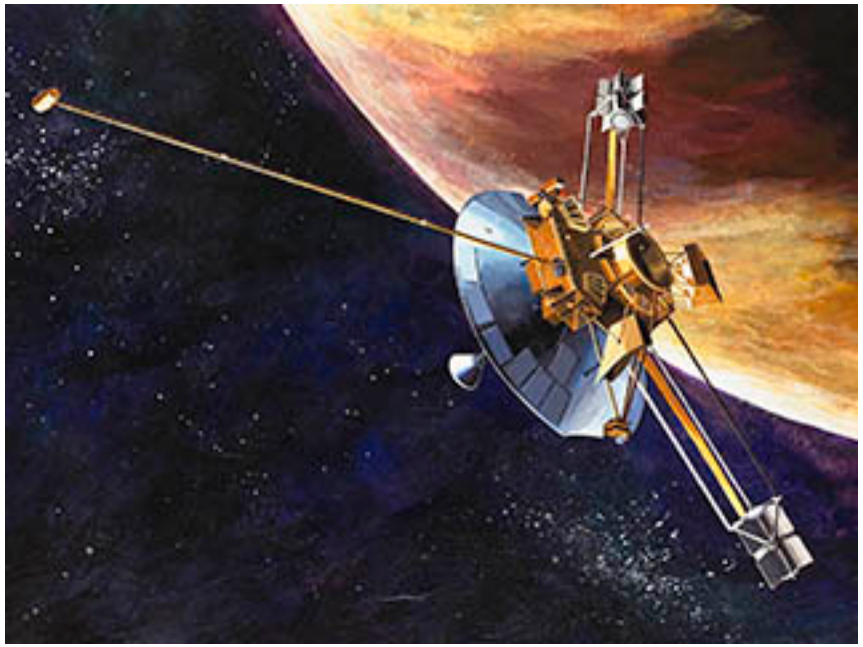
Why Jupiter?

- Solar system most abundant elements: first hydrogen, then helium and followed by oxygen. The first solid is water (H_2O).
- Finding water therefore provides answers to how Jupiter formed
- Jupiter is mostly made of hydrogen and helium, just like the Sun.
- Determining the extent of water in Jupiter will shed some light on how the planet formed. Asteroids collided? Far from Sun (where it is cold) or close to Sun?
  - Want to find the core and determine the water content
  - Want to see beneath the clouds and understand the interior to the planet.
- Want to understand the big red spot, storms, jet streams and understand the weather in general.
- Want to understand the interior, how everything moves within the planet.

The Pioneer Spacecraft

Pioneer 10 & 11

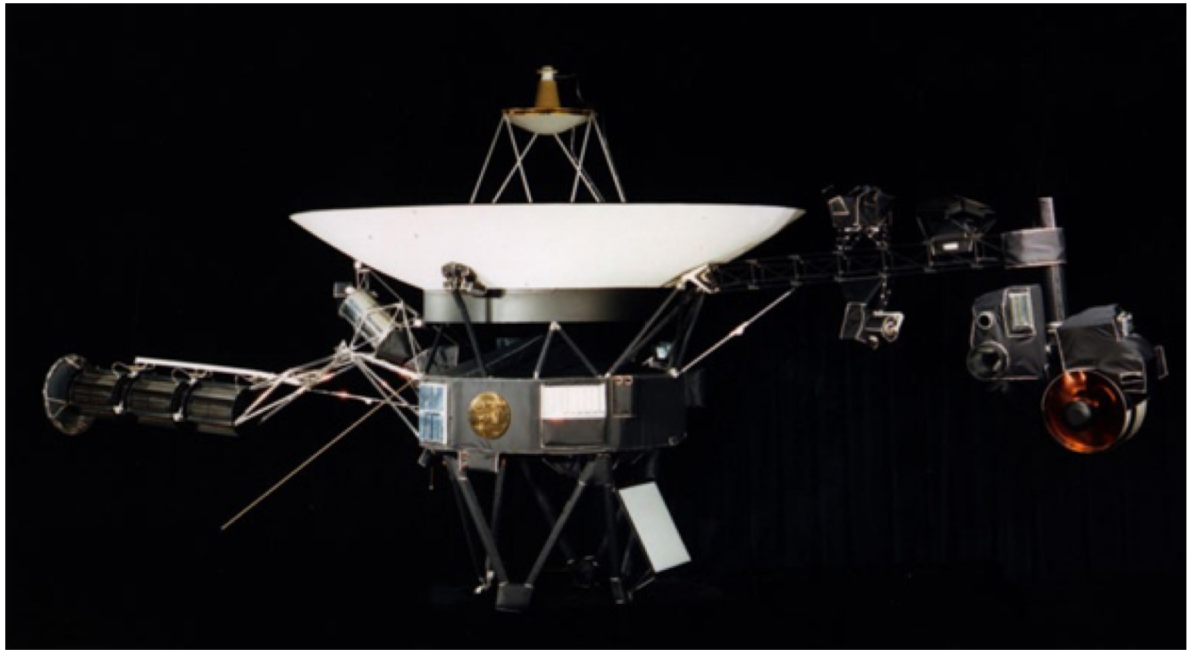
Pioneer 10 and Pioneer 11 were the first spacecraft to travel to a planet beyond Mars. They were launched one year apart, in 1972 and 1973. They both flew by Jupiter (Pioneer 10 arriving first), and Pioneer 11 went on to Saturn.



The Voyager Spacecraft

Voyagers 1 and 2

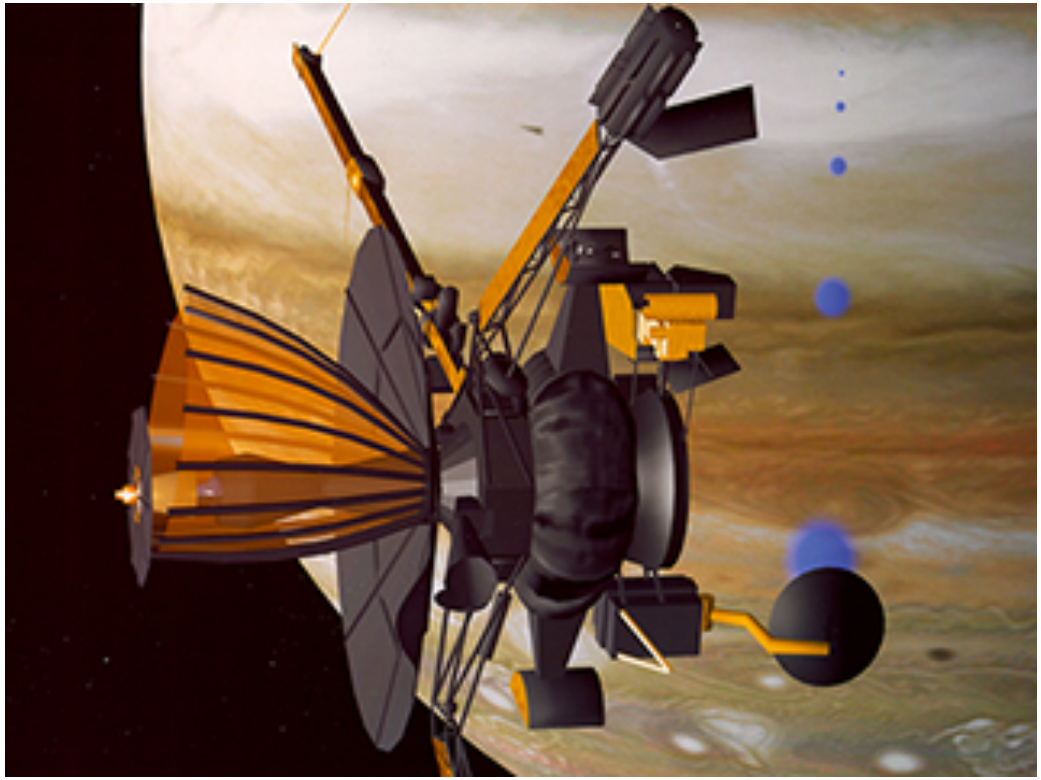
The Voyagers made many important discoveries at Jupiter. Launched in 1977, they sent back detailed pictures of Jupiter's incredible cloud system, including the Great Red Spot, a giant storm that rotates endlessly like an enormous hurricane. The Voyagers also took pictures of Jupiter's major moons.



The Galileo Spacecraft

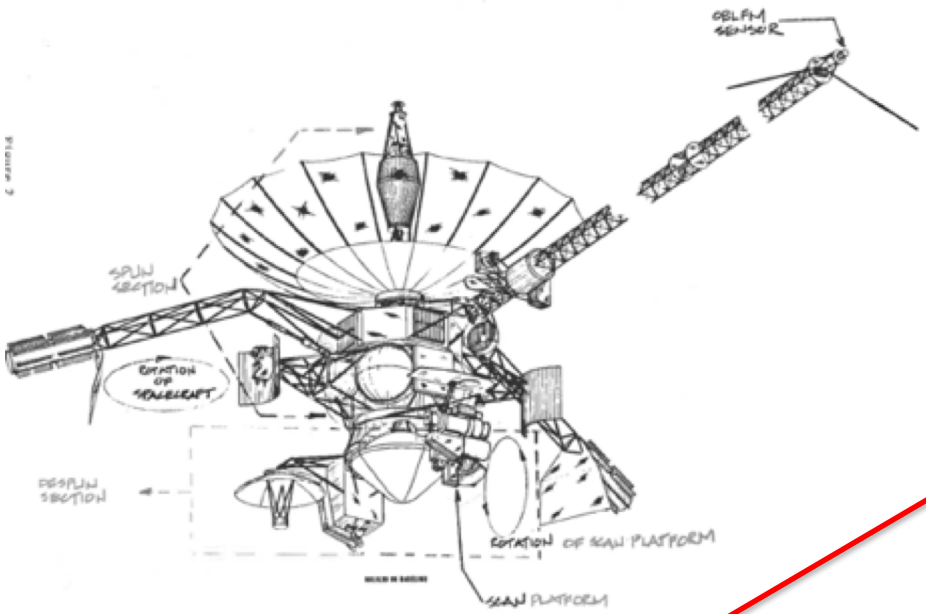
Galileo

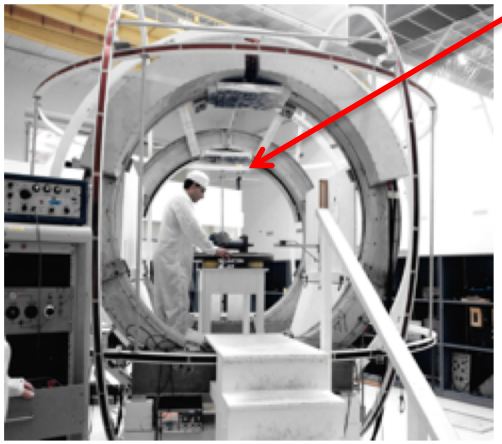
No spacecraft revealed more about Jupiter and its moons than the Galileo orbiter. Galileo, launched in 1989, spotted the first of evidence of an ocean on Europa, and also found signs a few other large moons may have liquid water under an icy crust.



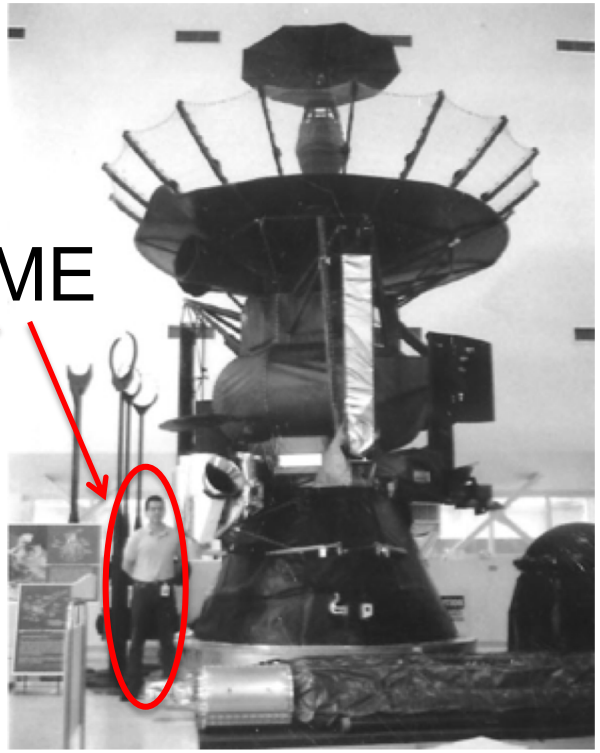
The Galileo Spacecraft

Galileo





ME



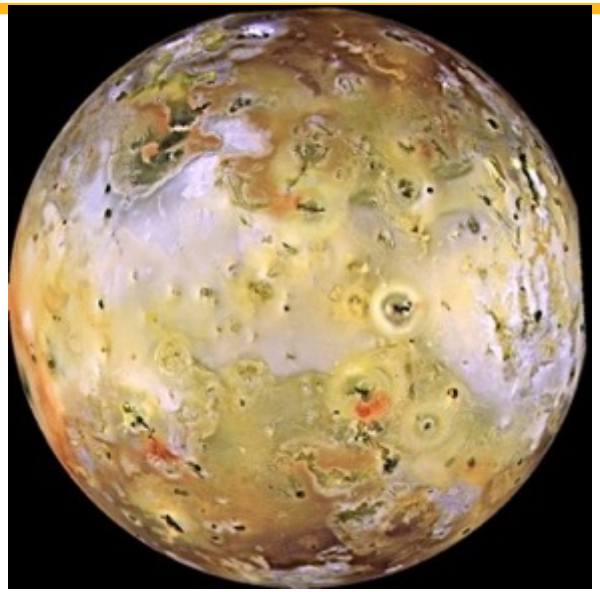
The Galileo Spacecraft

Galileo

Galilean Moons

Four Moons
Discovered
By Galileo Galilei

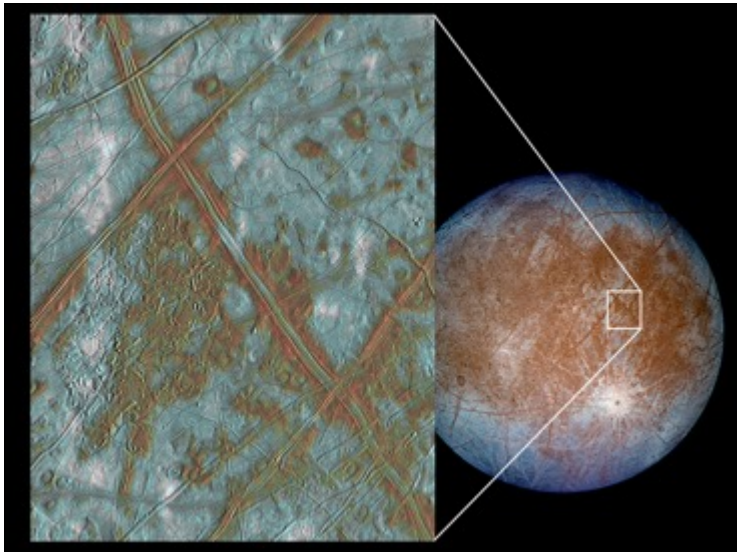
Jupiter Has At
Least 67 Moons



Callisto

Io

Ganymede

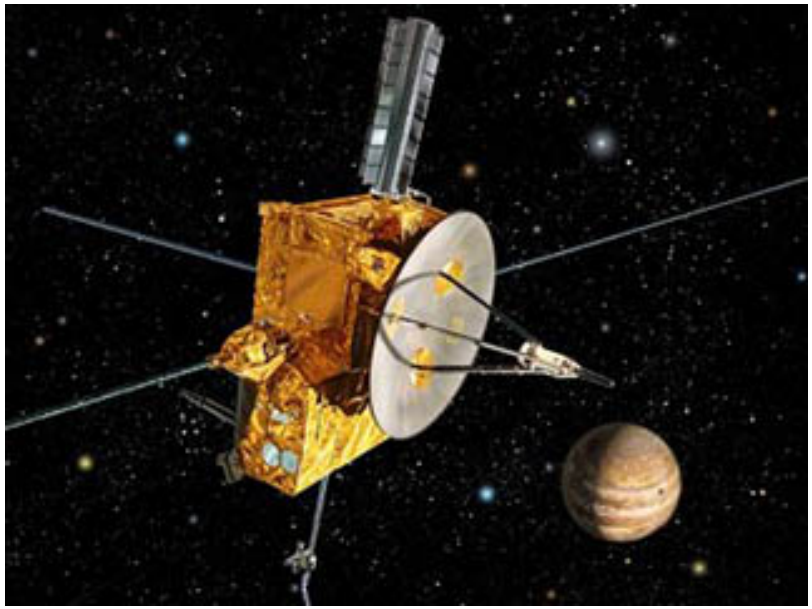


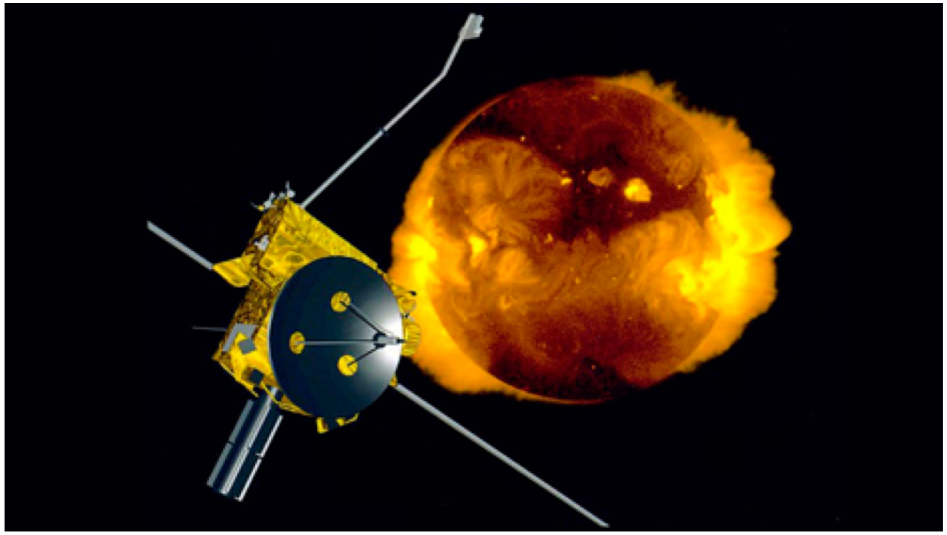
Europa

The Ulysses Spacecraft

Ulysses

On February 8, 1992 the Ulysses spacecraft used Jupiter's gravity to swing "up" so it could explore the poles of our sun. Ulysses found that Jupiter's gravity had changed, and there were fewer volcanoes erupting on Io.

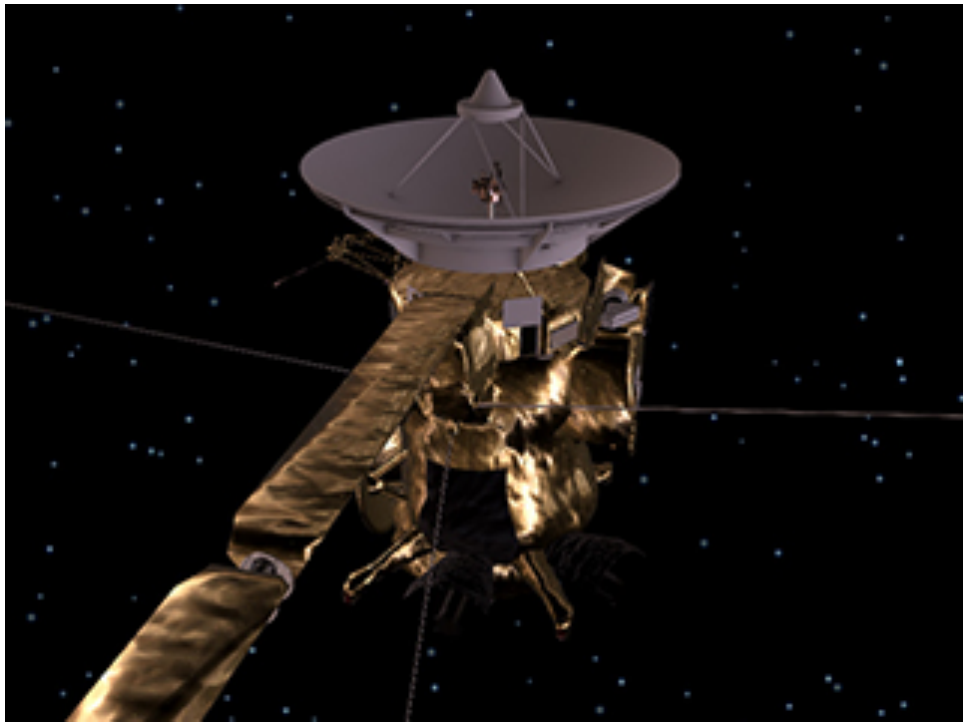




The Cassini Spacecraft

Cassini

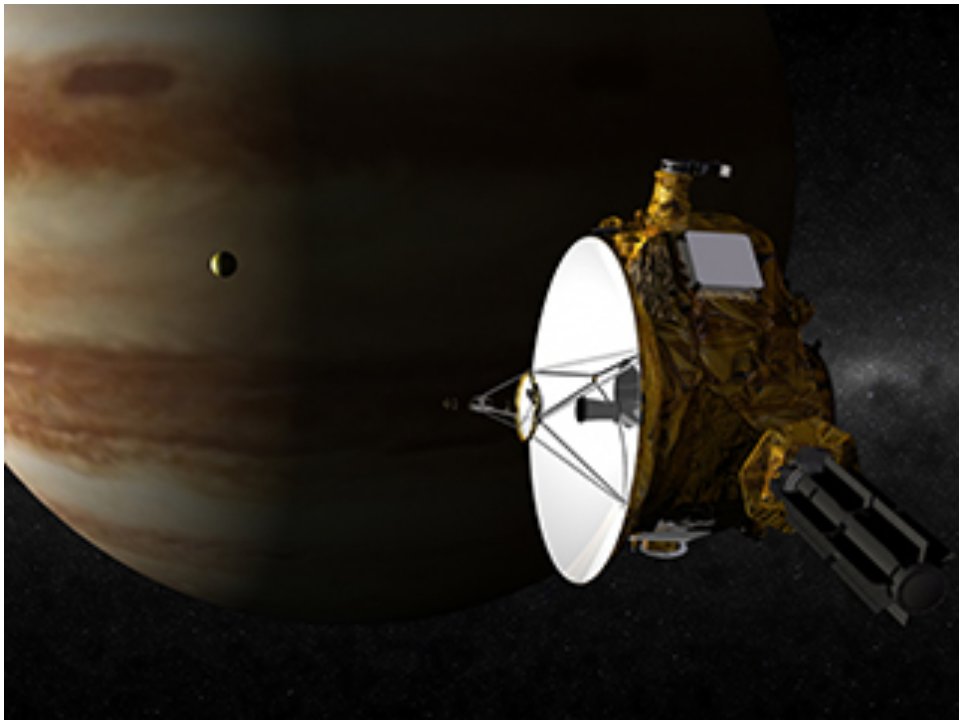
Cassini used Jupiter's gravity to boost it on to Saturn. Launched in 1997 on its way to Saturn, Cassini flew past Jupiter to get a gravity boost. The spacecraft also teamed up with the Galileo spacecraft, already in orbit at Jupiter at the time of Cassini's gravity boost, to study the Jovian system from two unique vantage points at the same time.



The New Horizons Spacecraft

New Horizons

Pluto-bound New Horizons used a 2007 Jupiter gravity assist to study the giant world and test out its science instruments before its historic Pluto flyby in 2015. The spacecraft captured new images of Europa and other key moons.

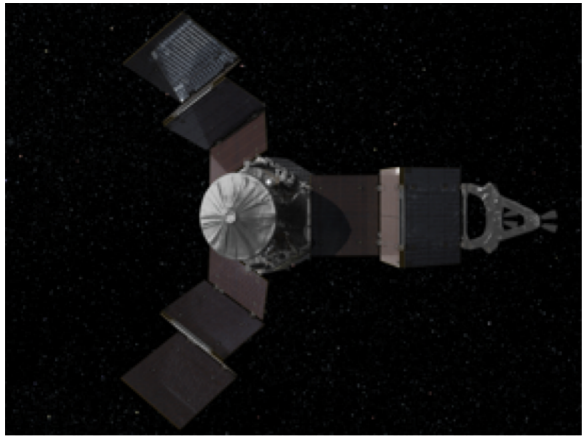


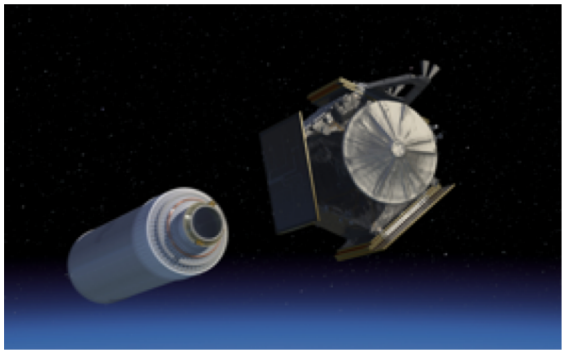
The JUNO Spacecraft

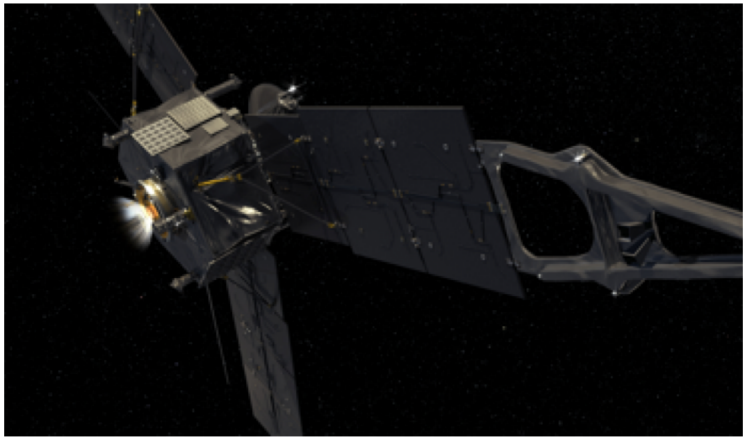
Juno

Juno is currently contributing to our knowledge of how Europa and Jupiter's other moons contribute to the planet's magnetosphere and auroras. Juno is also observing tides raised within Jupiter by the gravity of Europa and the other large moons.

JUNO





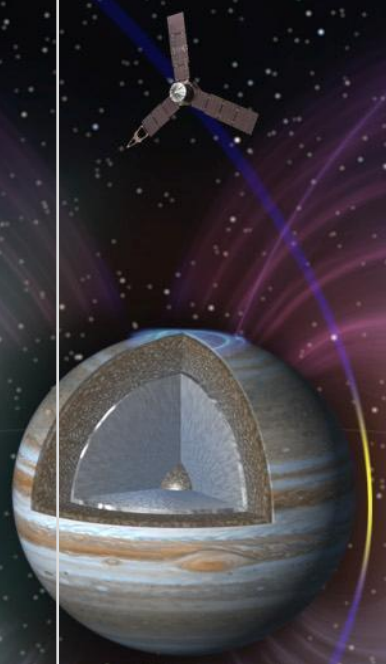


Salient Features:

- First solar-powered mission to Jupiter
- Eight science instruments to conduct gravity, magnetic and atmospheric investigations, plus a camera for education and public outreach
- Spinning, polar orbiter launched on 8/5/2011
  - 5-year cruise to Jupiter, arrived July 4, 2016
  - 53-day polar orbit
  - Perijove science Aug 27, Dec 11, Feb 2, Mar 27, May 19, July 11, Sept 1, Oct 24, Dec 16, Feb 7, Apr 1, ...

Principal Investigator:

Scott Bolton, Southwest Research Institute



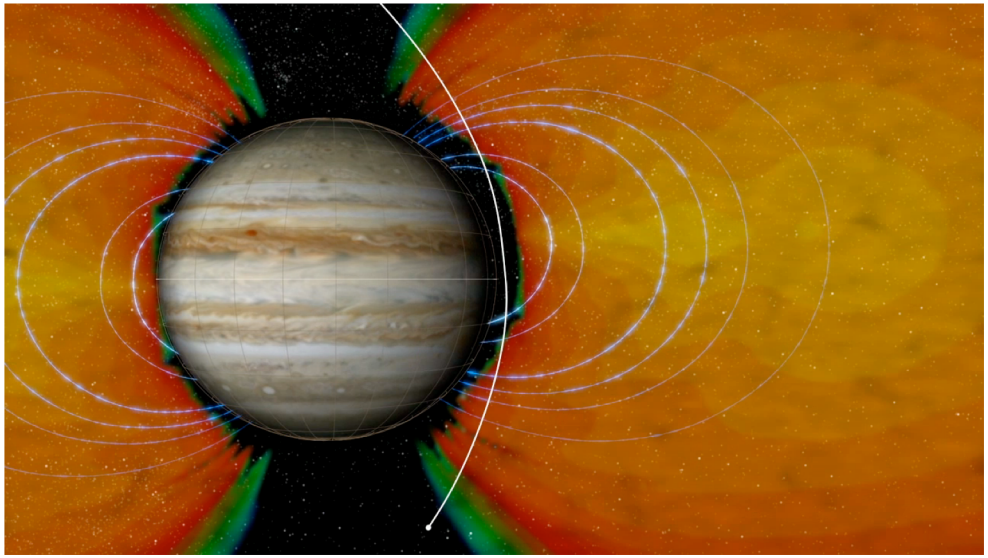
The spacecraft is healthy, we're getting great science data, and there is a lot more to come!

Origin
Determine the abundance of water and constrain the mass of Jupiter's dense core to distinguish among theories of planet formation.

Interior
Understand Jupiter's interior structure and how material moves deep within the planet by mapping its gravitational and magnetic fields

Atmosphere
Map variations in atmospheric composition, temperature, cloud opacity and dynamics to depths greater than 100 bars at all latitudes

Magnetosphere
Characterize and explore the three-dimensional structure of Jupiter's polar magnetosphere and auroras.



**** Gravity Science (JPL, ASI)
**** Magnetometer— MAG (GSFC)
**** Microwave Radiometer— MWR (JPL)
**** Jupiter Energetic Particle Detector— JEDI (APL)
**** Jovian Auroral Distributions Exp.— JADE (SwRI)
**** Plasma Waves Instrument— Waves (U of Iowa)
**** UV Spectrograph— UVS (SwRI)
**** Infrared Camera— JIRAM (ASI)
**** Visible Camera— JunoCam (Malin)

Why Jupiter?

- Want to understand the atmosphere by using radio waves because radio waves see through the clouds.
  - Can see into the planet and learn about the atmosphere.
  - The more water the more absorption and the less water the deeper we can see.
- *Ocean of liquid metallic hydrogen* swirling inside below the atmosphere generates the magnetic fields.
  - The pressure inside Jupiter is millions of times that of Earth
  - The pressure is so high that the hydrogen is squeezed that it releases electrons and the movement of these electrons creates magnetic fields.
- By measuring the speed of the spacecraft we measure the gravity and we can learn about the interior.
  - Jupiter rotates at 10 hours, gravity pulls spacecraft as it orbits.
  - Measuring gravity we can learn about the core.

Origin
Determine the abundance of water and constrain the mass of Jupiter's dense core to distinguish among theories of planet formation.

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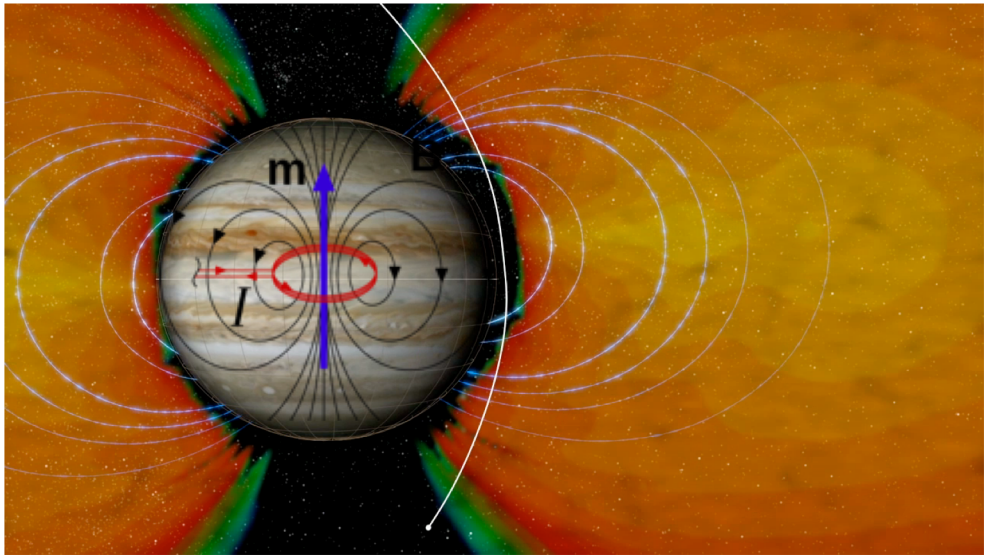

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**** Infrared Camera— JIRAM (ASI)
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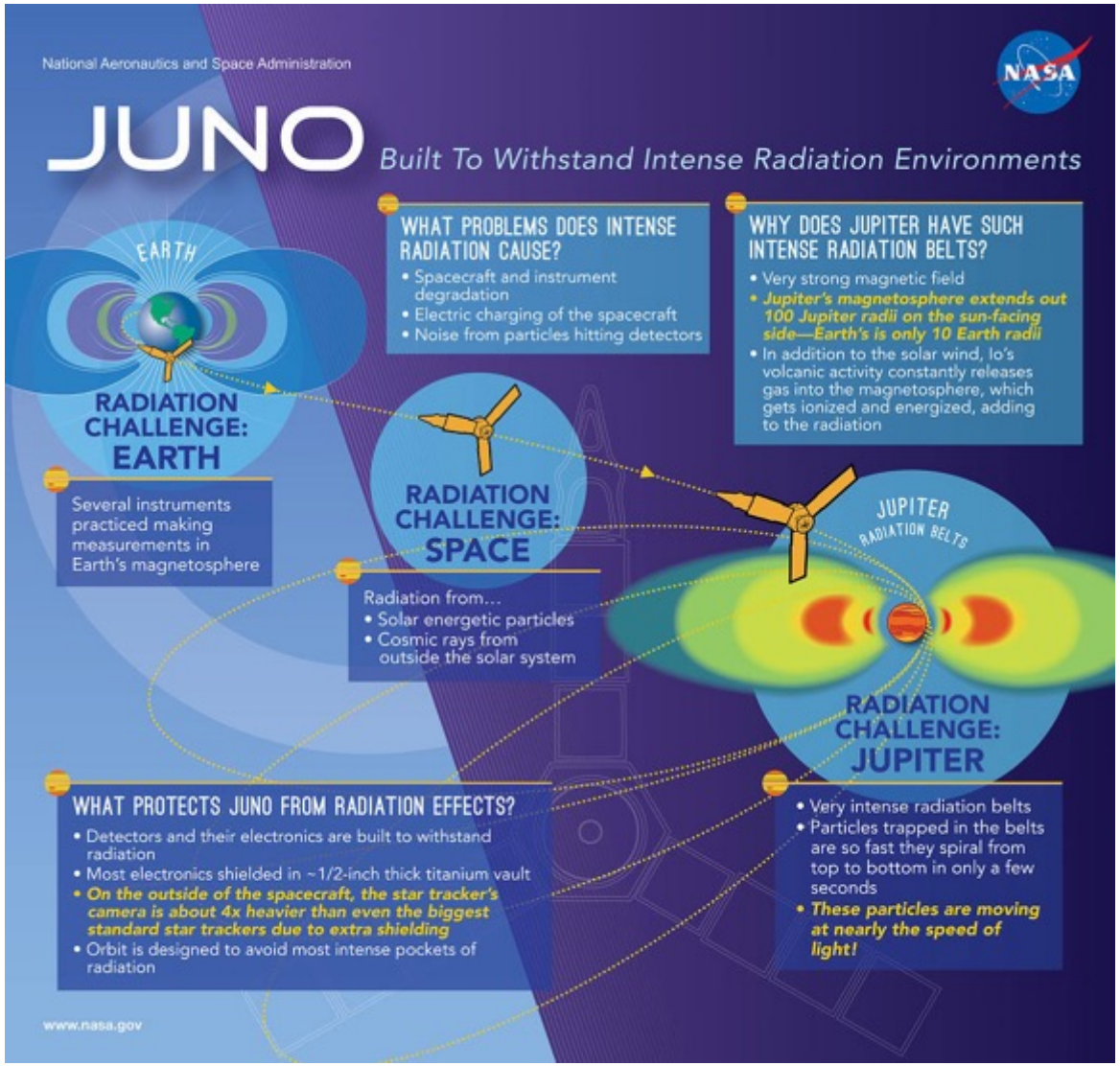
The JUNO Spacecraft- Instruments

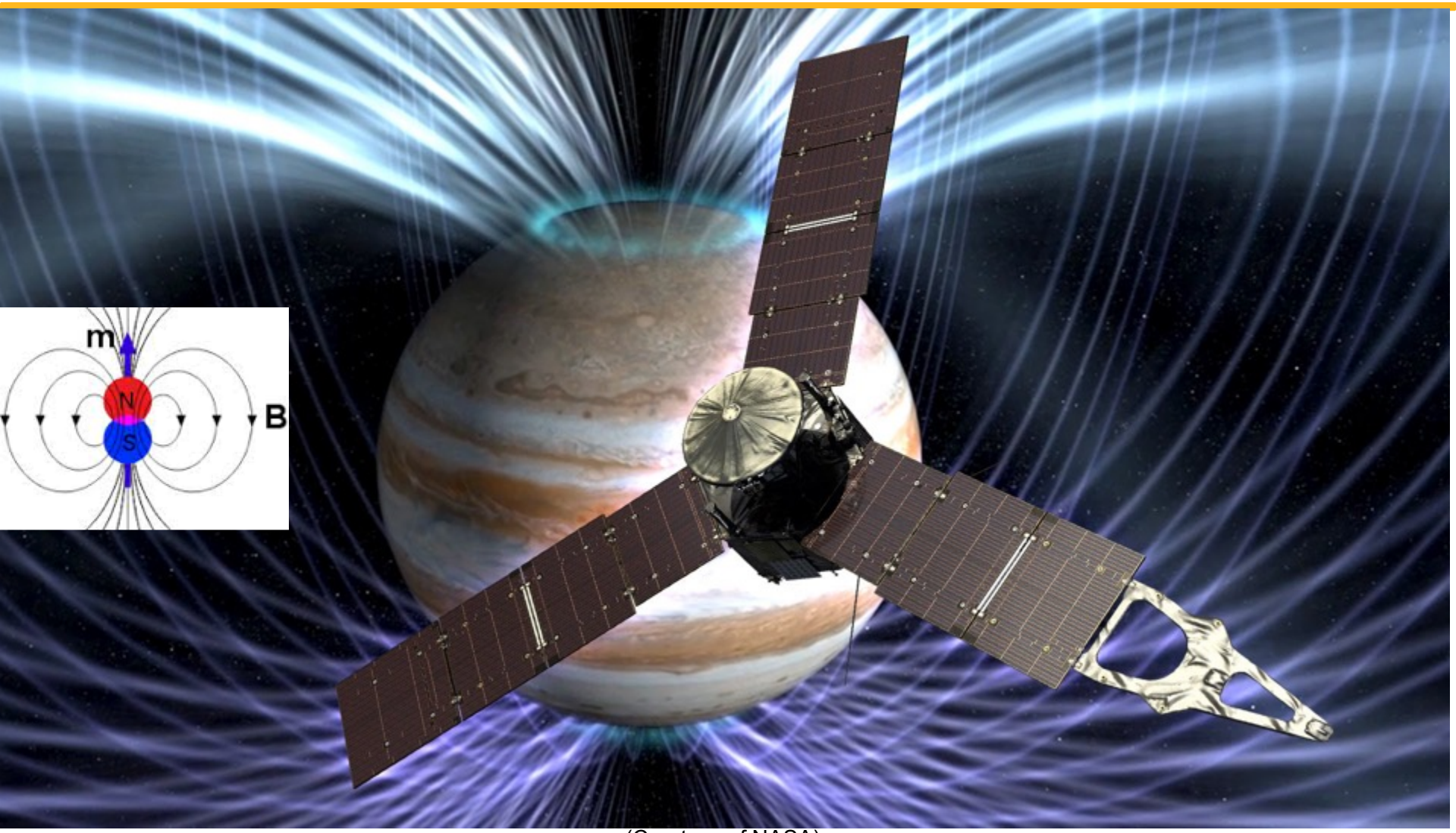
- JUNO Mission
  - Juno mission carries nine instruments (some with multiple sensors)
    - Two Magnetometers, Gravity Science experiment, Jupiter Energetic Particle Detector Instrument (JEDI), Jovian Auroral Distributions Experiment (JADE), **Microwave Radiometer (MWR),** plasma instrument WAVES measures radio and plasma waves, The Ultra Violet Spectrogram (UVS), (JIRAM) Jovian Infrared Auroral Mapper, JUNOCAM is to photograph Jupiter's clouds.

JUNO Spacecraft (Courtesy of NASA)

The JUNO Spacecraft



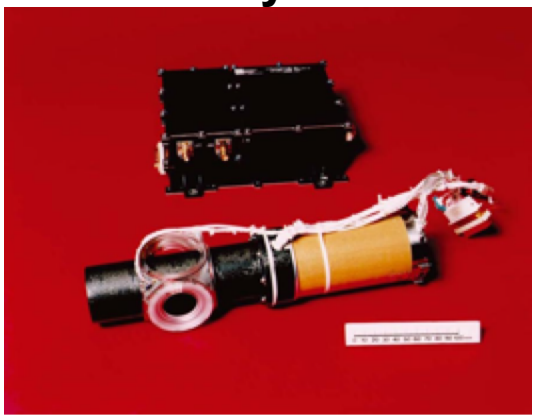
Jupiter's High Magnetic Fields

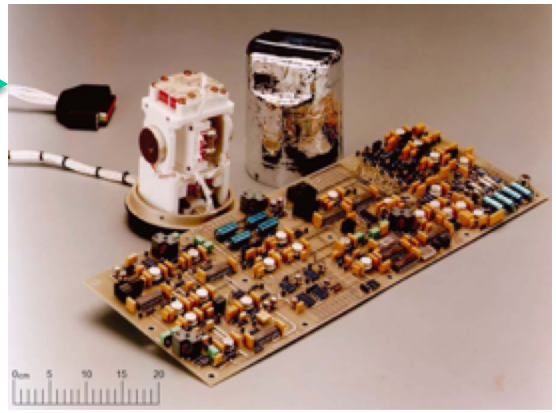


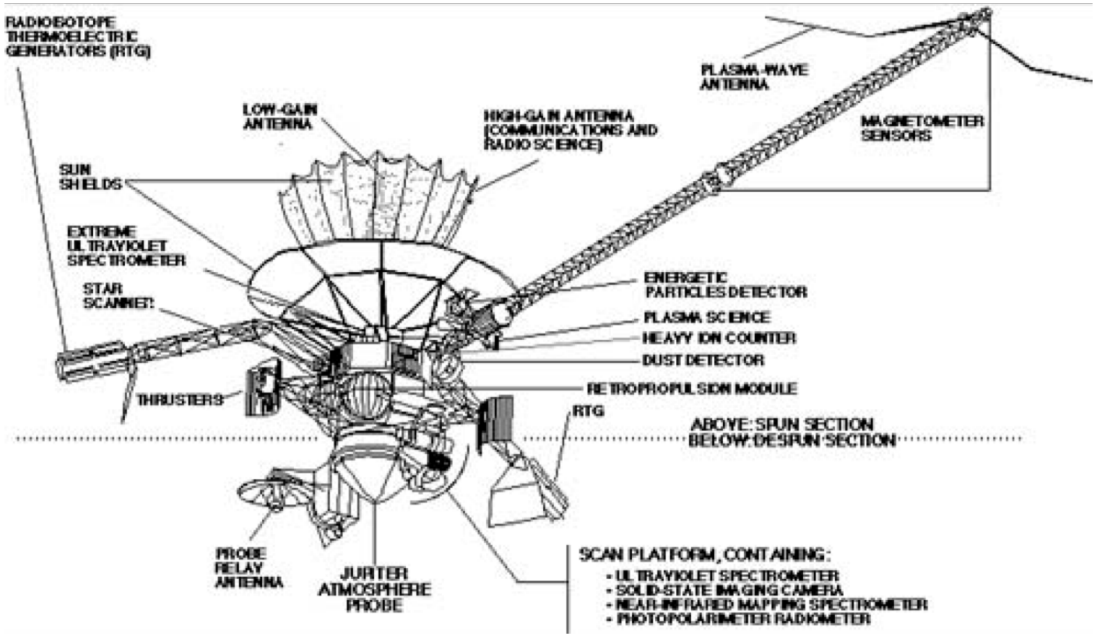
(Courtesy of NASA)

Galileo's Measurements of Magnetic Fields at Jupiter

- **Instruments measure mag fields to a high degree of accuracy and precision**
  - **Vector helium magnetometers (DC)**
  - **Fluxgate magnetometers (DC)**
  - **Plasma wave search coils (AC)**

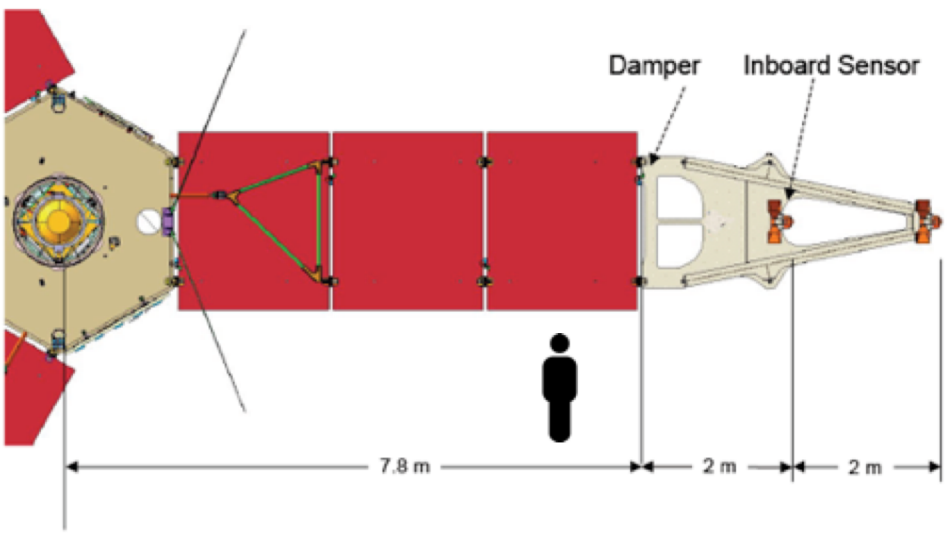


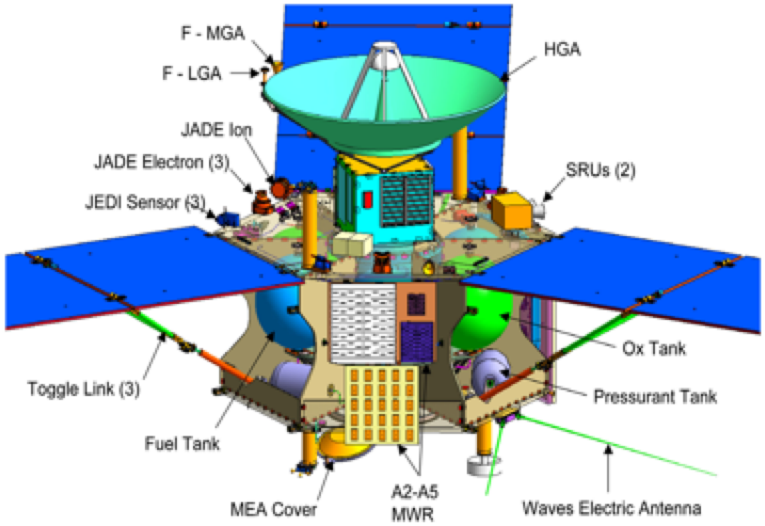




The JUNO Spacecraft

- **JUNO includes a magnetometer instrument that is presently performing measurements of Jupiter's magnetic field.**
  - **The instrument consists of two magnetic sensors; an Inboard Fluxgate Magnetometer sensor (IFGM) and an Outboard Fluxgate Magnetometer Sensor (OFGM).**
    - **Both sensors are mounted on a magnetometer boom platform whose closest edge is approximately 10 meters from the center of the spacecraft X-direction, with the IFGM located at about 10 meters, and the OFGM located at about 12 meters from the center of the spacecraft.**

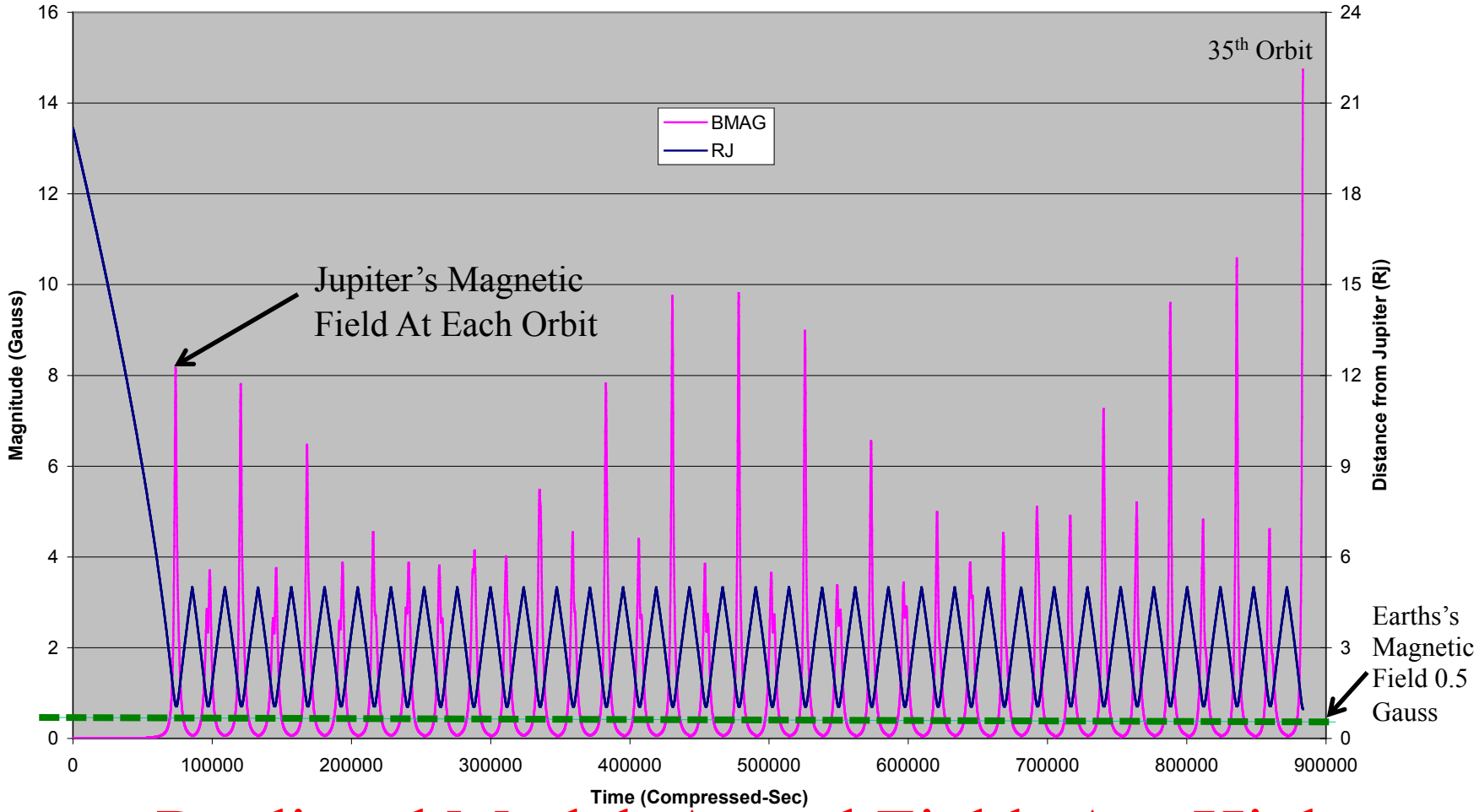




Jupiter's Strong Magnetic Fields

JUNO magnetic field magnitudes in Jupiter's Orbit

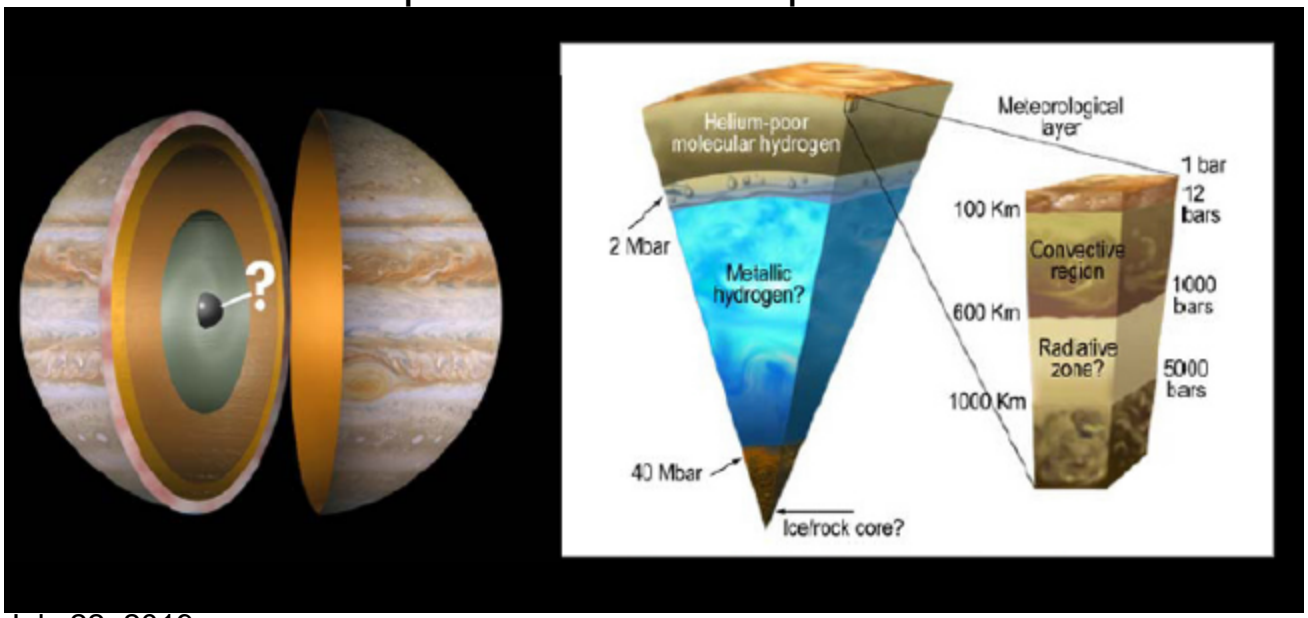
Jupiter's magnetic field is on average 14 times larger than of earth!

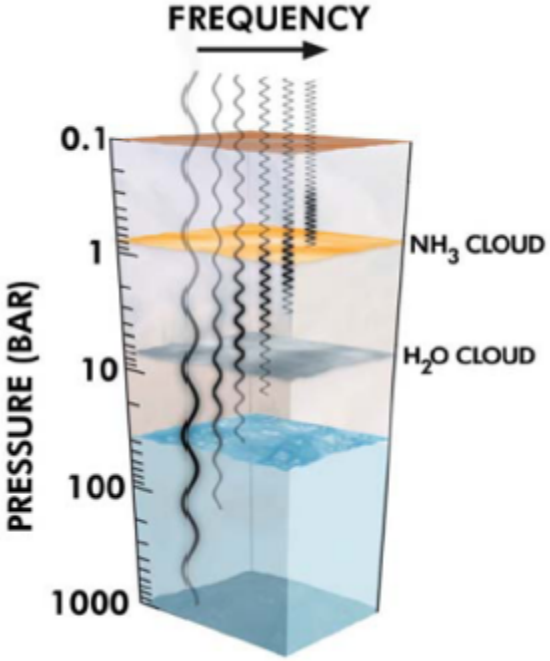


Predicted Model, Actual Fields Are Higher

The JUNO Spacecraft - MWR

- JUNO Microwave Radiometer (MWR) Is Key Instrument In Mission:
  - JUNO's MWR has been looking below the dense cover of clouds to answer questions about the gas giant and the origins of our solar system.
  - MWR measures thermal radiation from the atmosphere to as deep as 1000 atmospheres pressure (~500–600 km below Jupiter's visible cloud tops).
  - Determines water (H_2O) and ammonia (NH_3) abundances in the atmosphere all over the planet.





Magnetic Susceptibility
The Problem Statement

The isolators, made of ferrite material, are used in the front end of the microwave radiometer (MWR) science instrument. It is influenced by external magnetic fields. Jupiter's field, when seen from the rotation frame of the spacecraft, was predicted to cause cyclic variations in the gain and offset of the system. If uncorrected there would be a direct impact on the antenna temperature retrieval and limb darkening error.

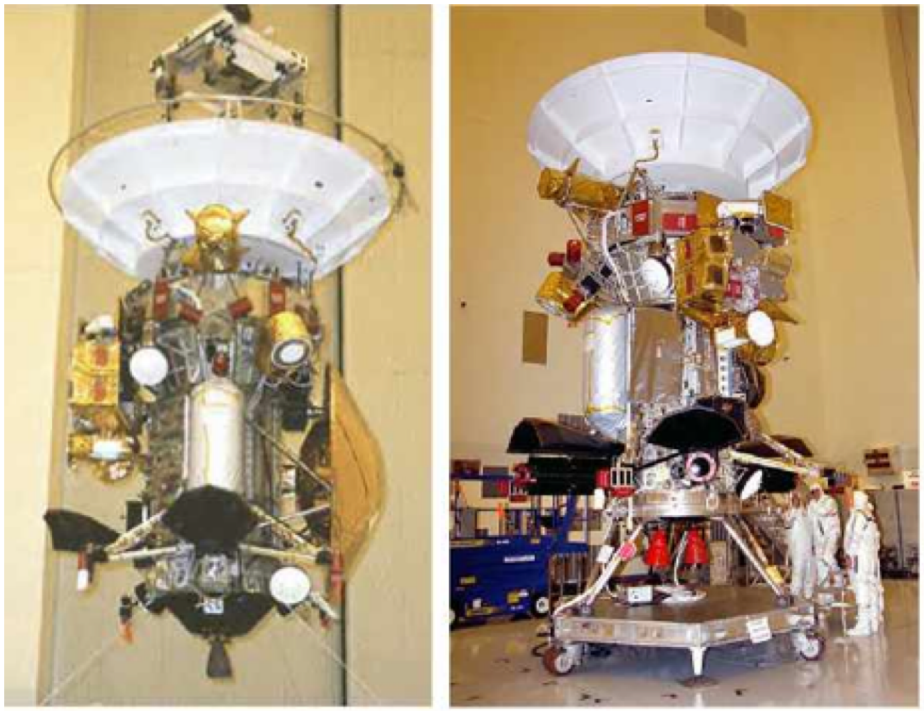
ISOLATORS ARE SUSCEPTIBLE TO MAGNETIC FIELDS AND COULD SATURATE

MWR Has Six Radiometers Each With An Isolator, Thus Producing Six Magnetic Interference Concerns

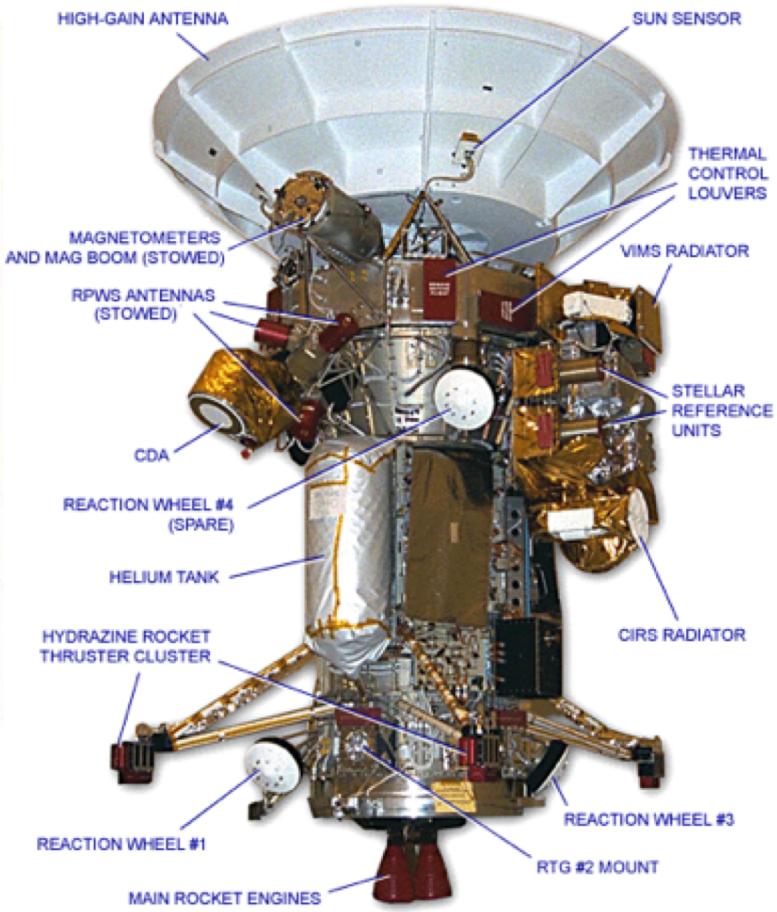
(Isolators Identified As R1 R2, R3, R4, R5, R6)

Magnetic Susceptibility
The Problem Statement

Cassini's Biggest Magnetic Interference From:
Reaction Wheel Assemblies

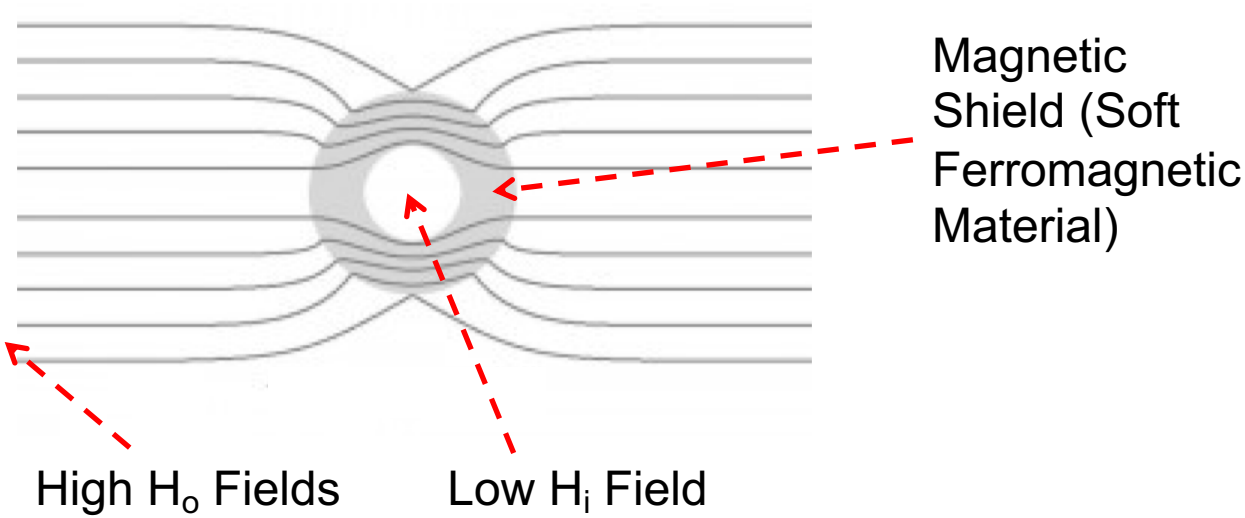


Cassini Spacecraft (Courtesy of NASA)

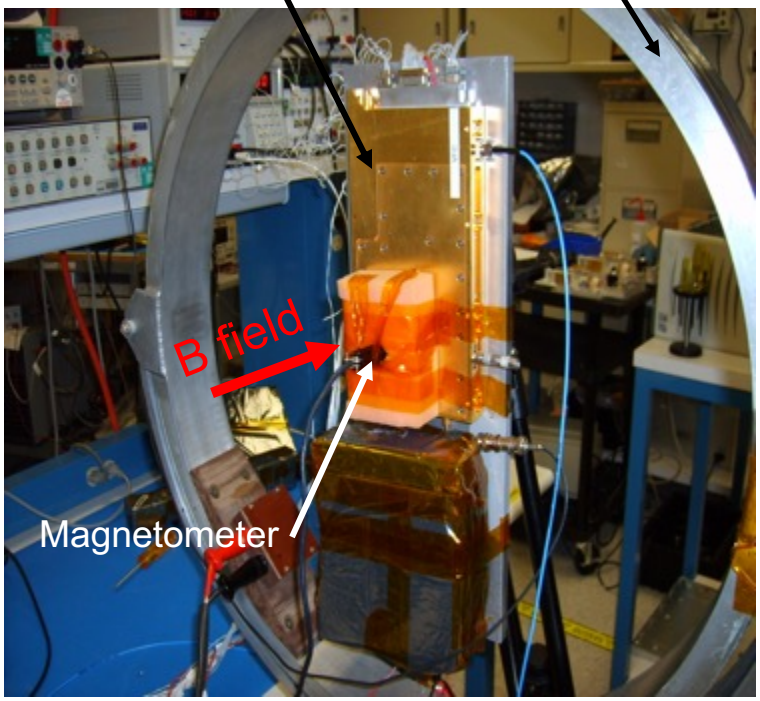


How Magnetic Shields Perform

- Magnetic shields re-direct magnetic flux around it so that it reduces the magnetic field inside the shield, thus protecting the victim inside the shield
- Magnetic shields do not reflect, destroy or permanently absorb magnetic fields, but rather provides a low reluctance path for the magnetic fields to follow.
- The type of material that can provide the lowest reluctance path for magnetic fields should be able to attract these flux lines, such as ferromagnetic material
- Ferromagnetic materials are necessary because shields work by pulling the magnetic fields towards them and away from what is being shielded
  - The magnetic field will be concentrated within the shield itself

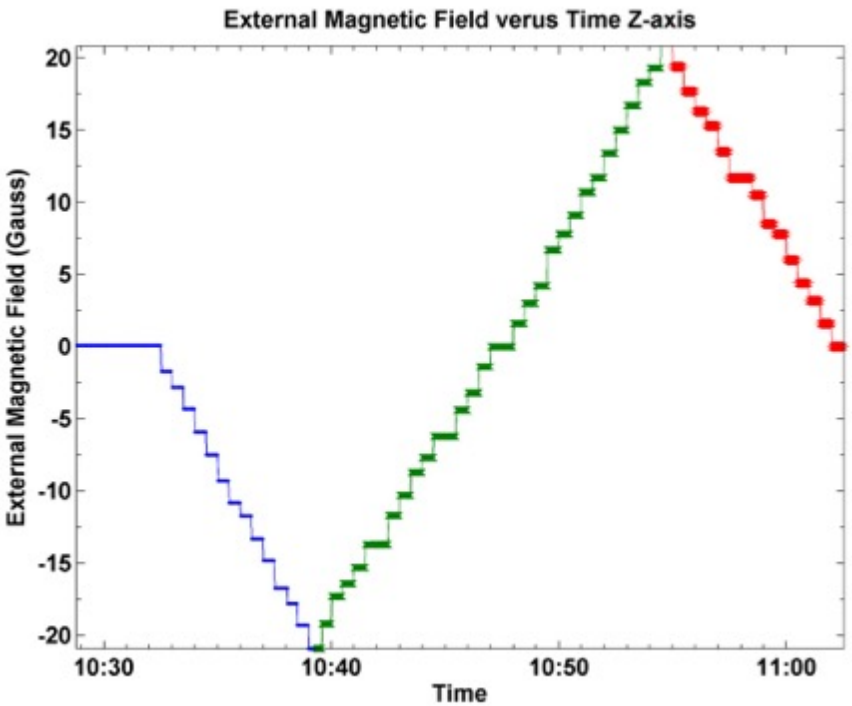


MWR Magnetic Susceptibility Tests



Magnetic field in z-axis
Test setup

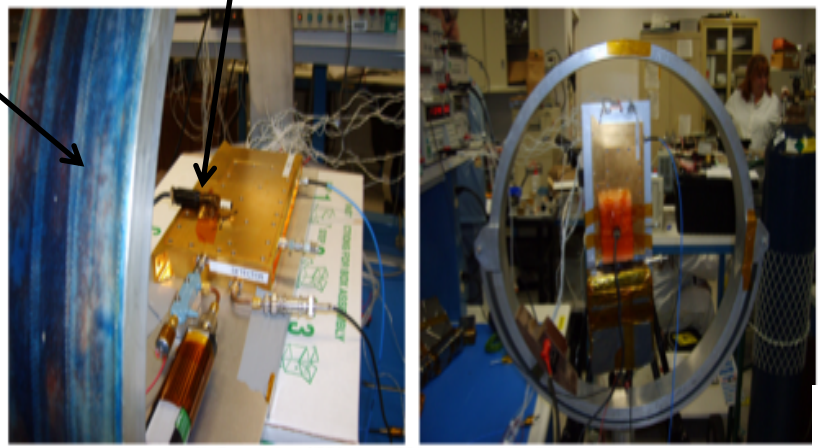
- Radiometer and directional Gauss meter mounted inside a coil.
- Current in coil stepped to vary magnetic field at center of coil (isolator location) from 0 Gauss to -20 Gauss to +20 Gauss then back to 0 Gauss



MWR Magnetic Susceptibility Tests

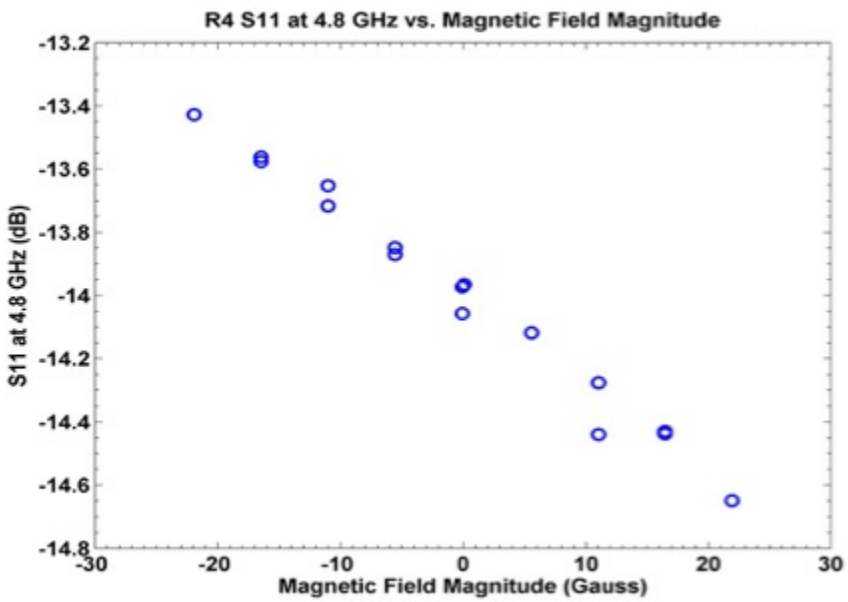
R2 breadboard Radiometer

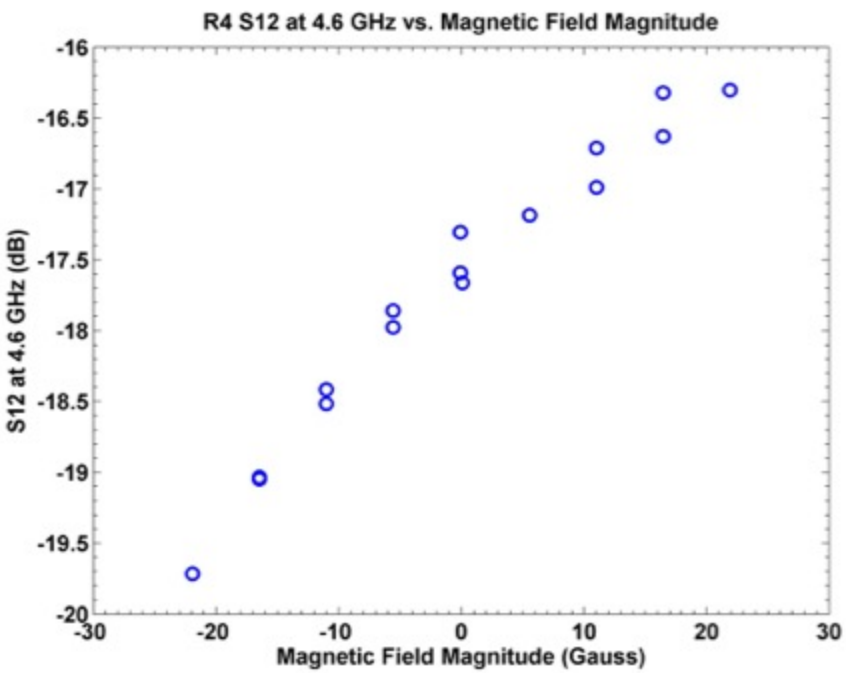
Coil



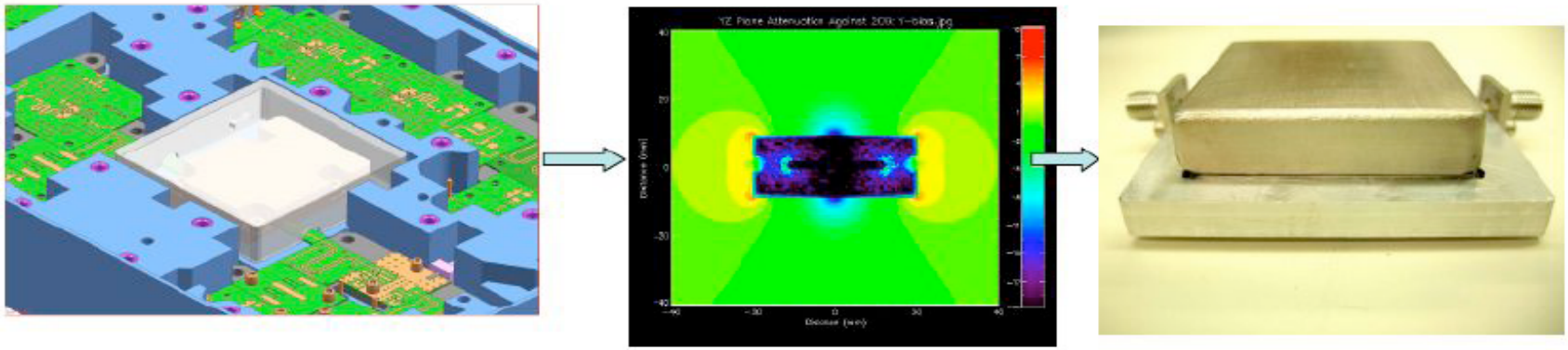
MWR Tested In Three Axes

- S11 changes by as much as 1.4 dB
- S12 changes by as much as 4 dB
- Change in system gain mainly due to change in S11 (85%) and less from S21 (15%)
- R4 isolator would see a 0.03%/gauss gain modulation, similar to R2 result

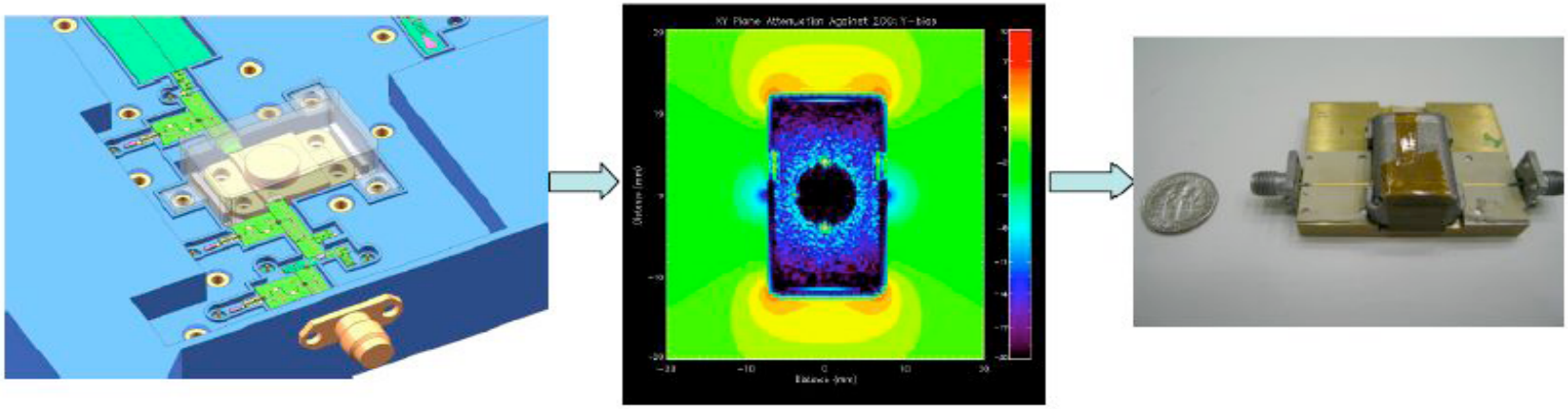




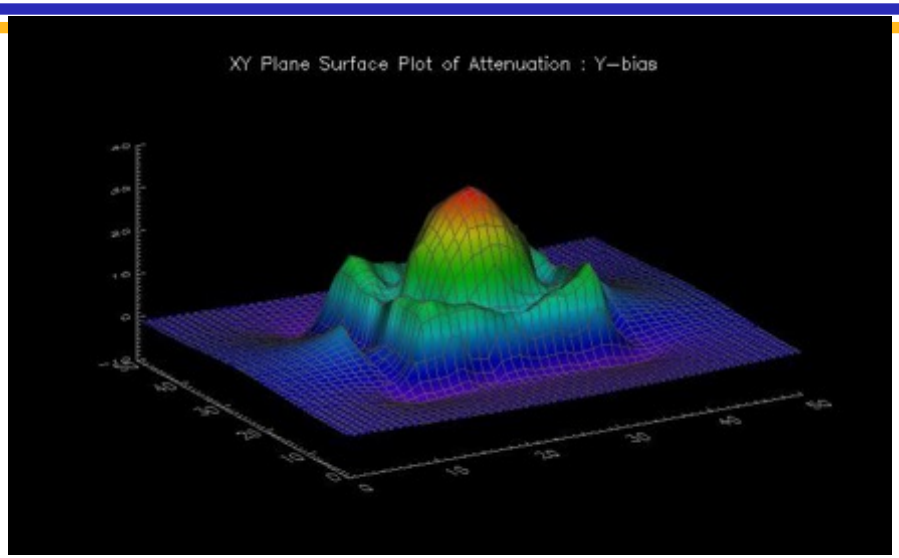
Shielding Experience

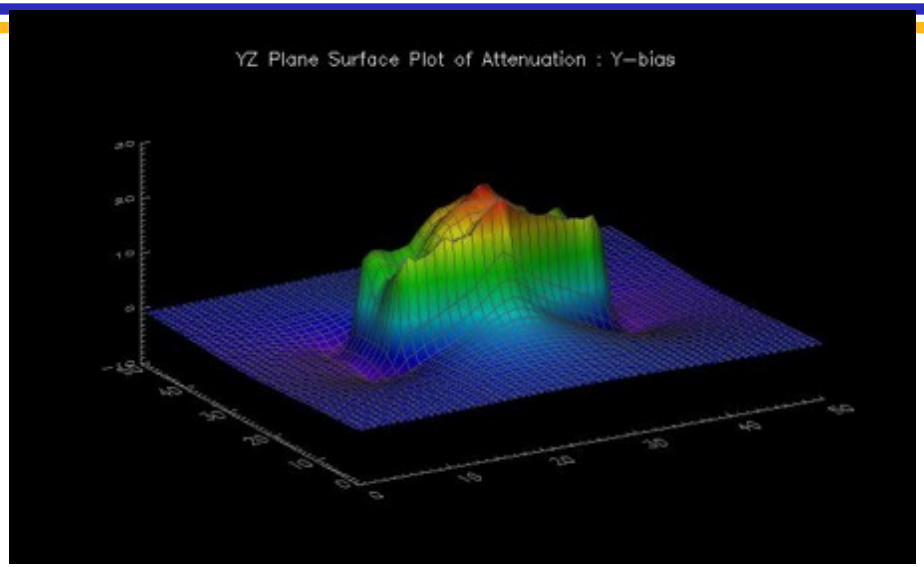


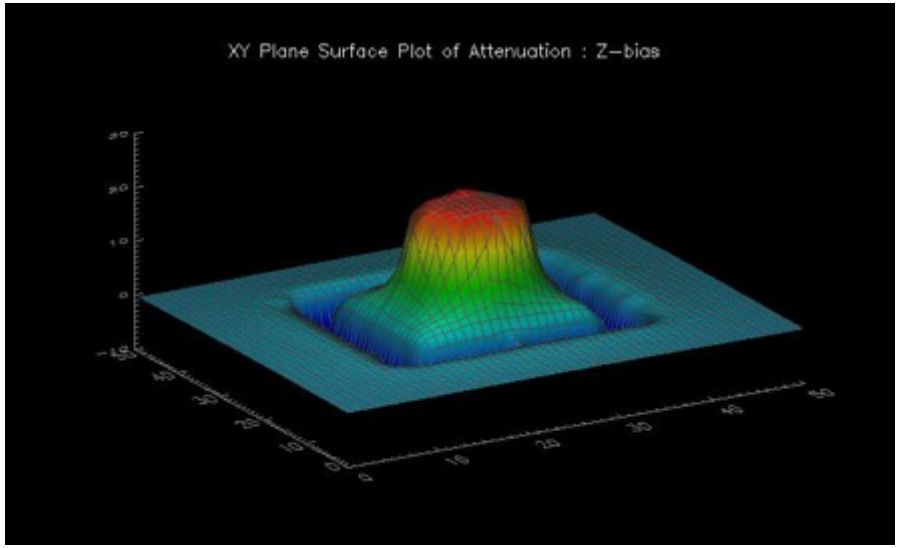
R1 - R3 (above) R4 - R6 (below)

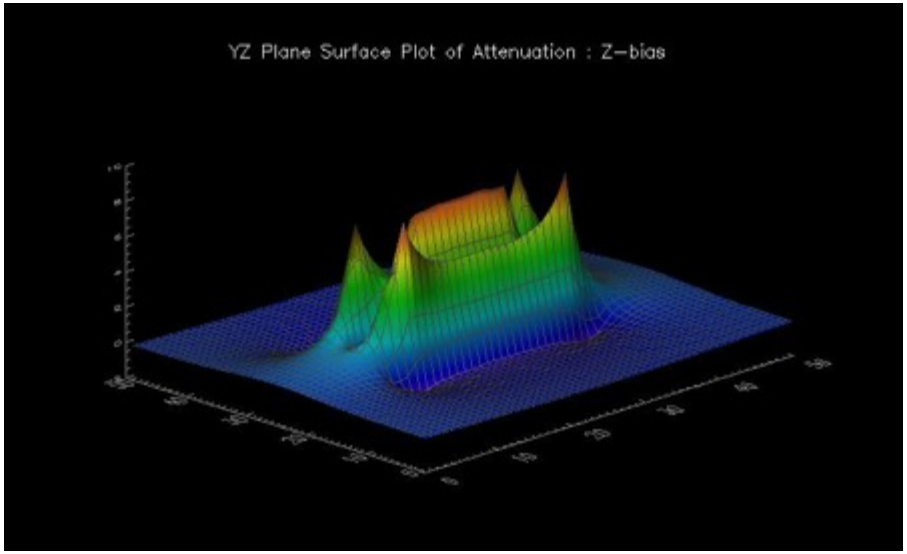


Concept Magnetic Field Attenuation Surface Plots

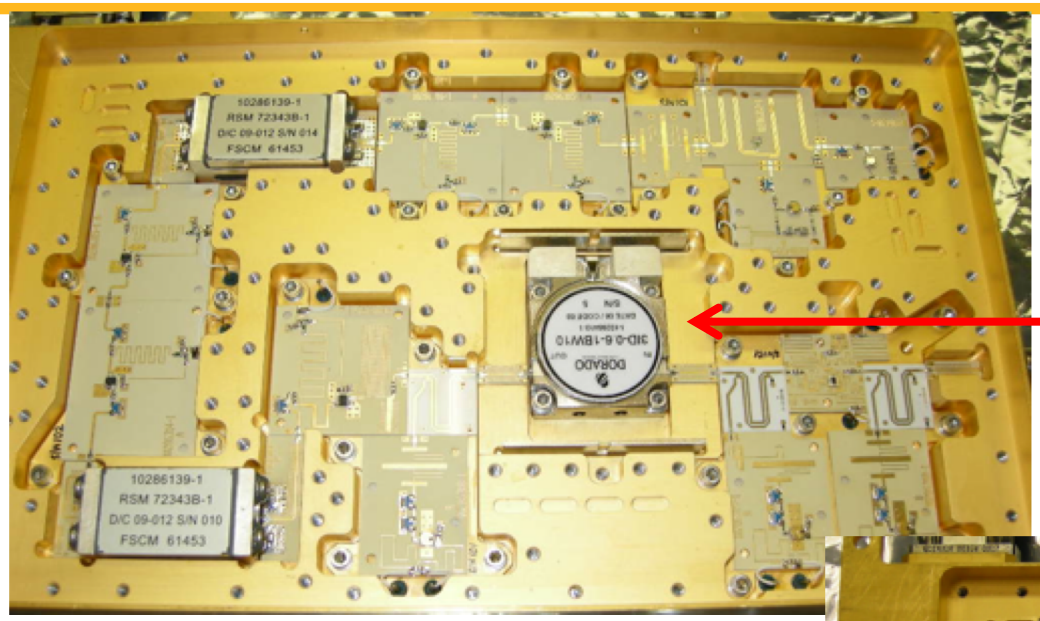




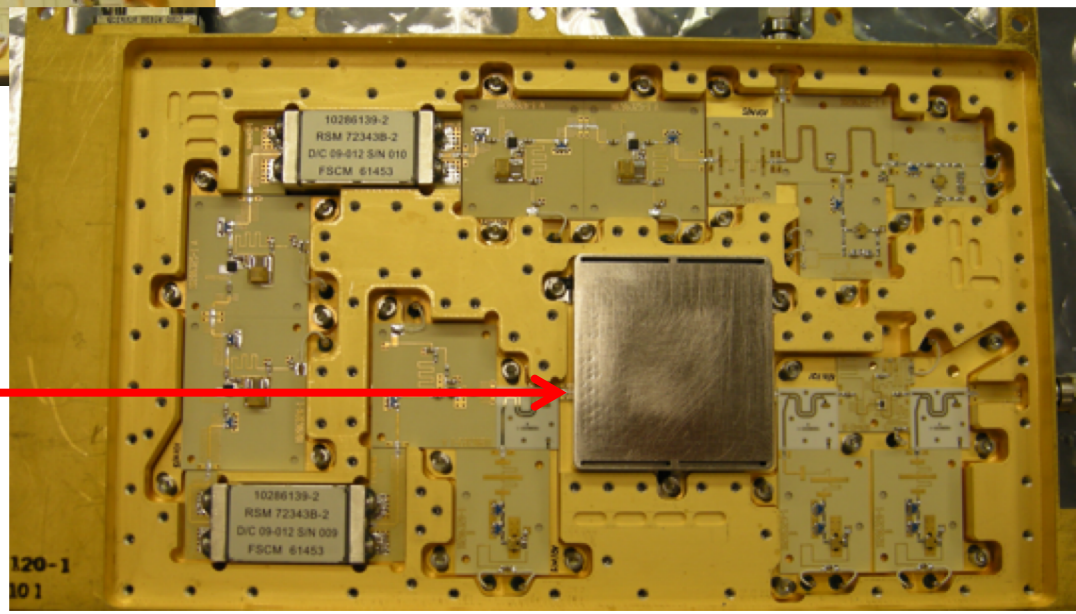




MWR Flight Mag Shield Design



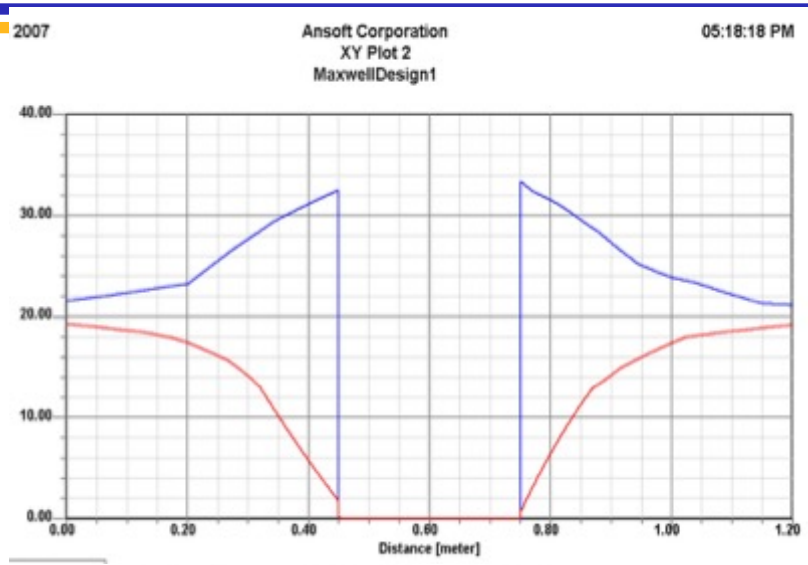
Isolator Unshielded

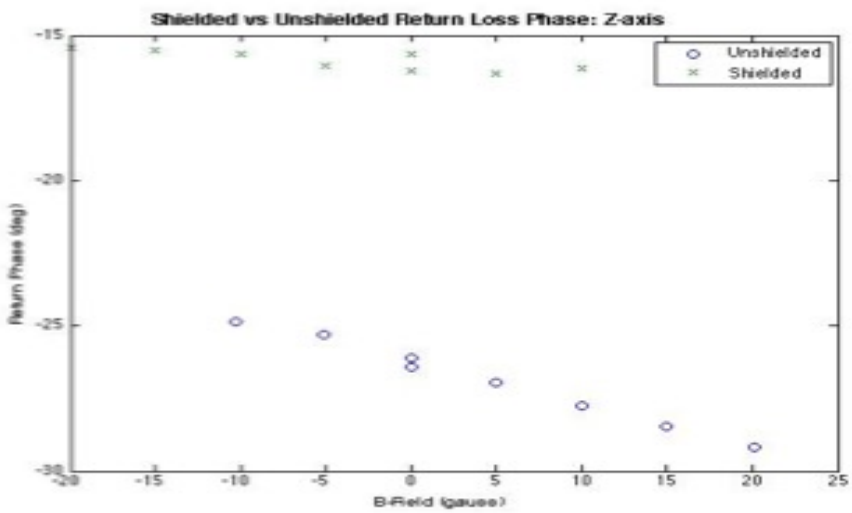


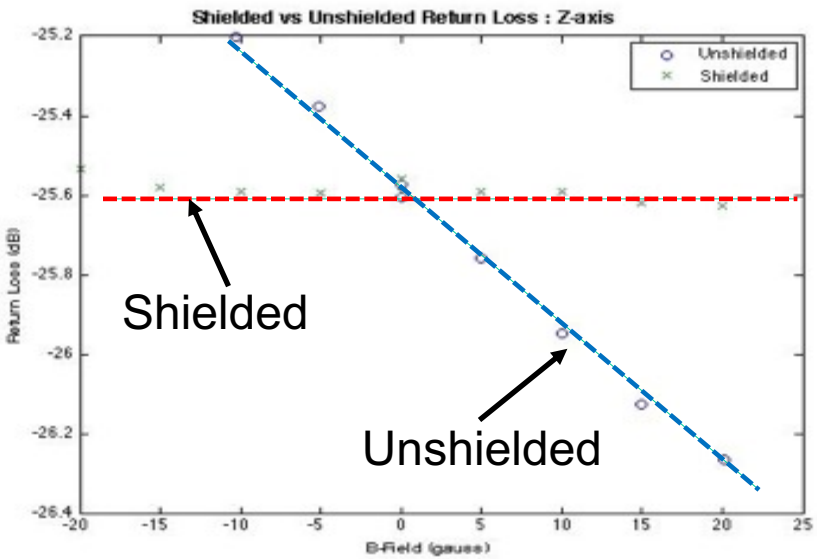
Isolator Shielded

Modeling Approach and Solutions

- Model consists of a 30 cm 1 cm thick cube surrounded by 40 mils of mu-metal in a 20 gauss uniform field
  - Used vendor "stock" mu-metal B/H curve
  - Shielding may actually be more effective than indicated due to the fidelity of the simulation
- Experience with using Mu-metal shield from past NASA missions in general: Voyager, Galileo, Cassini
- R4 shielding results are presented



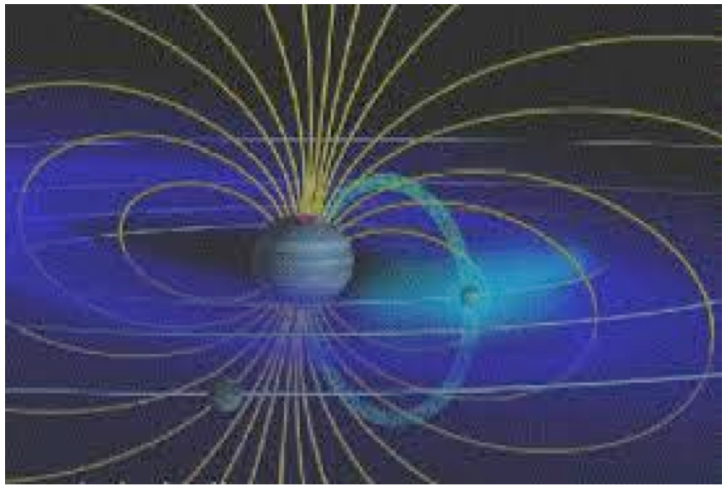


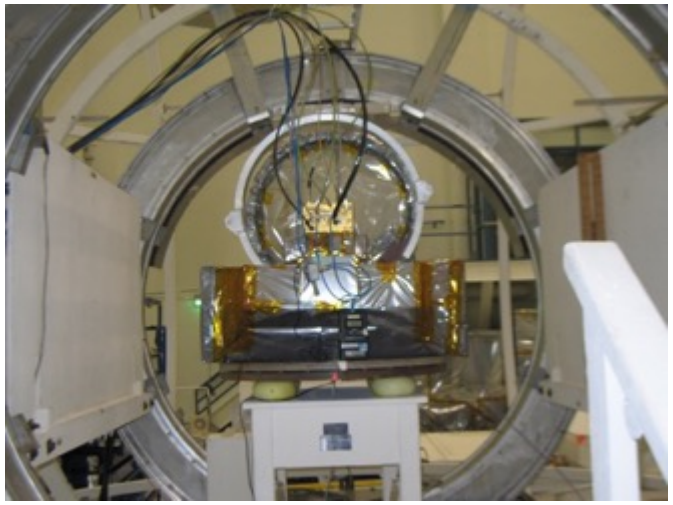


Final Verification Of MWR

- MWR Flight Unit Placed Inside Helmholtz Coil
- External coils generated uniform fields with a magnitude of 16 Gauss with the field parallel to the coil axis and encompassing all of MWR
- The magnetic field was modulated at 2 rpm (simulates a rotating spacecraft)

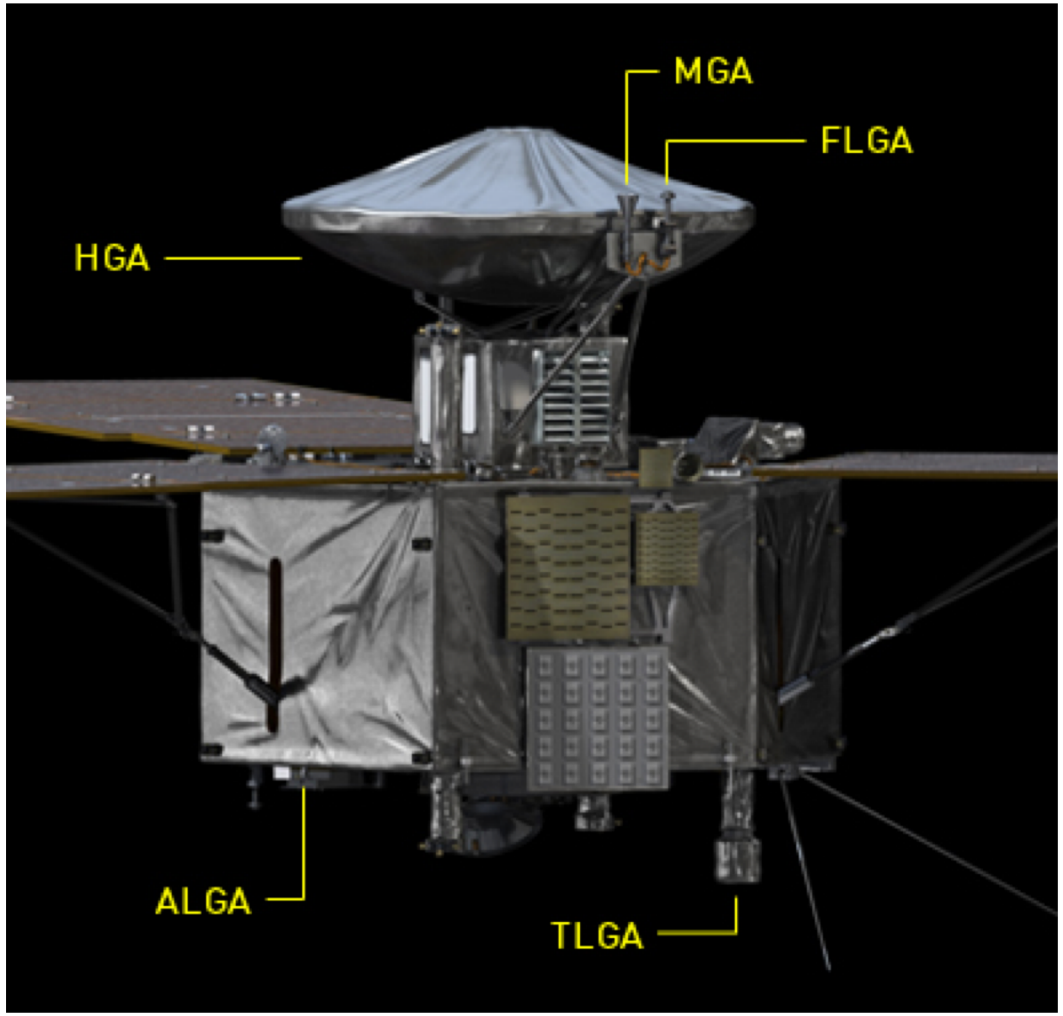
MWR MET ALL ITS PERFORMANCE CRITERIA

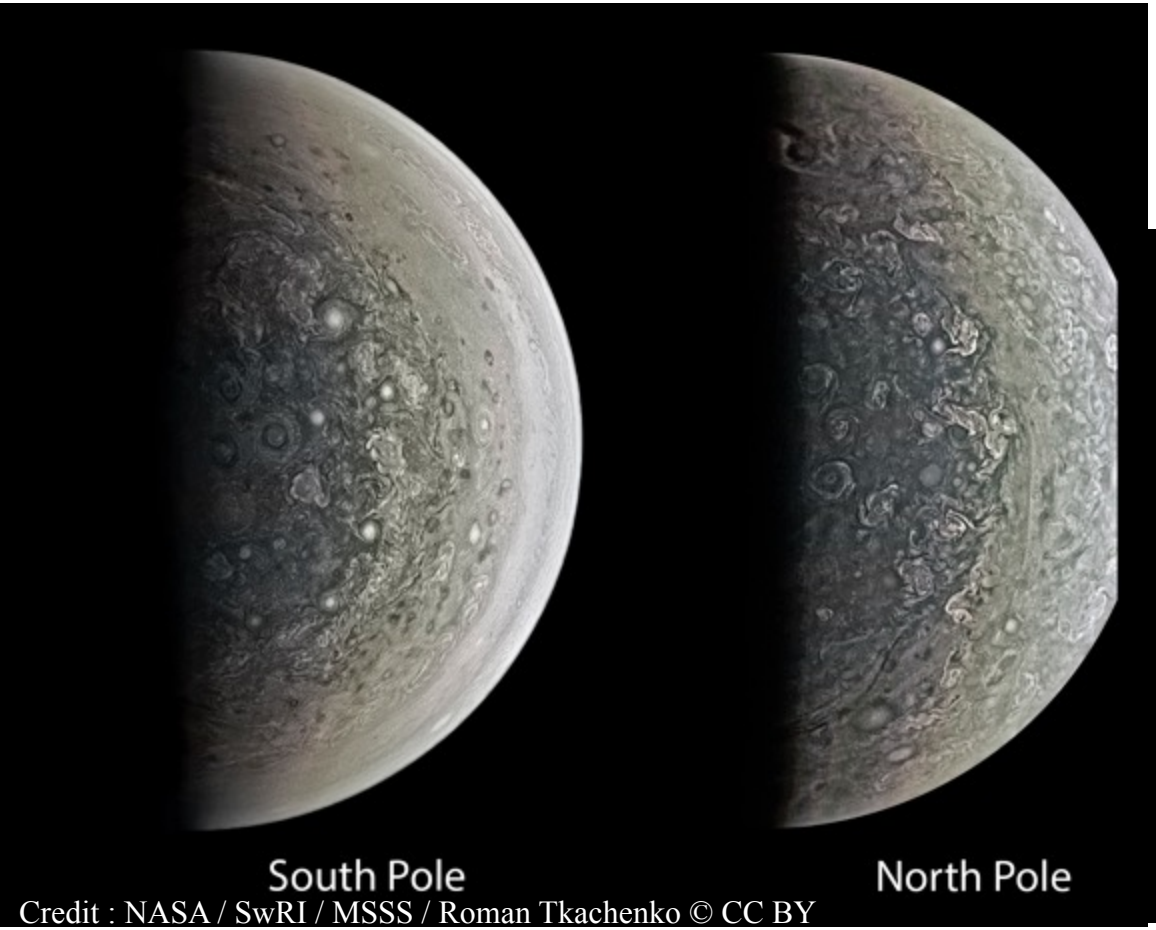




Recreating Jupiter's Field On Earth
Inside Helmholtz Coils

JUNO Telecom System





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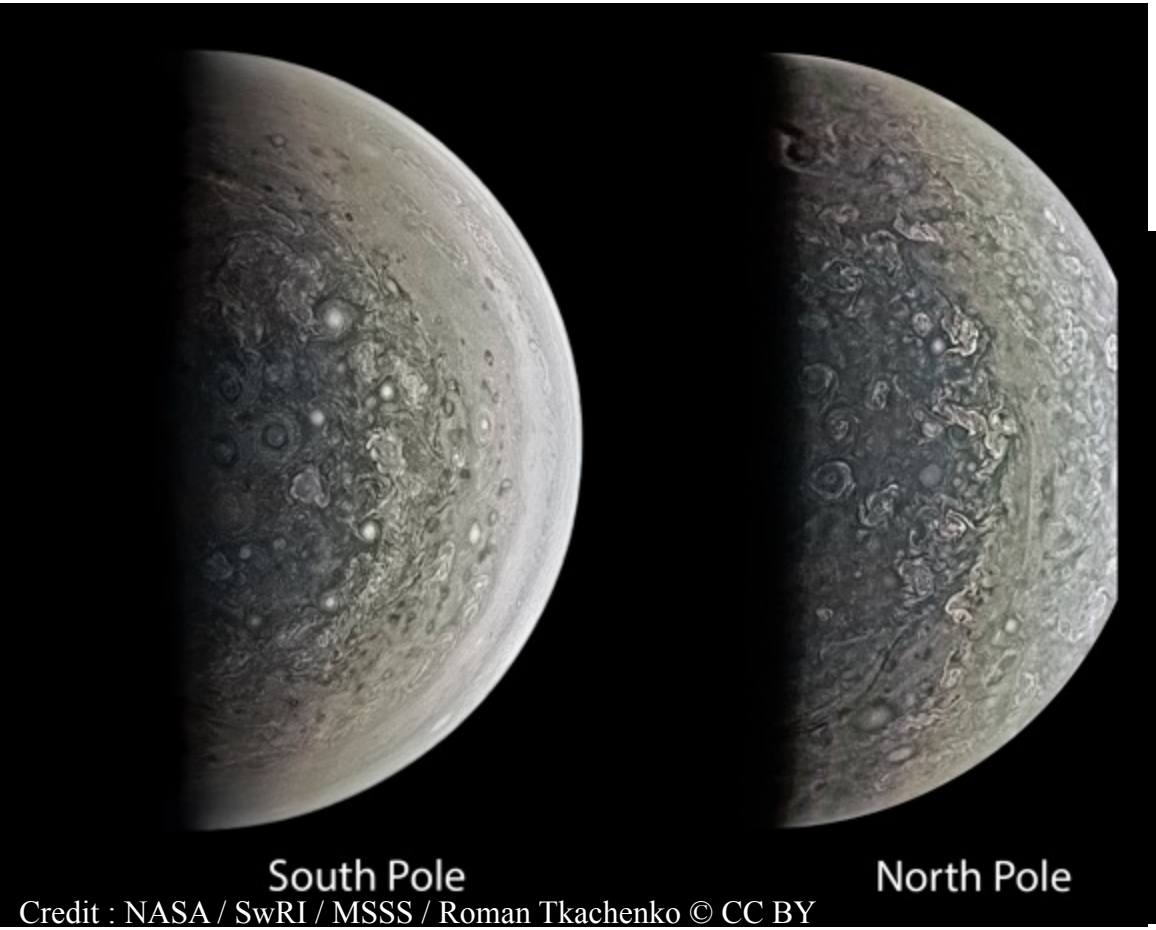
Jupiter’s poles don’t look anything like the equator!



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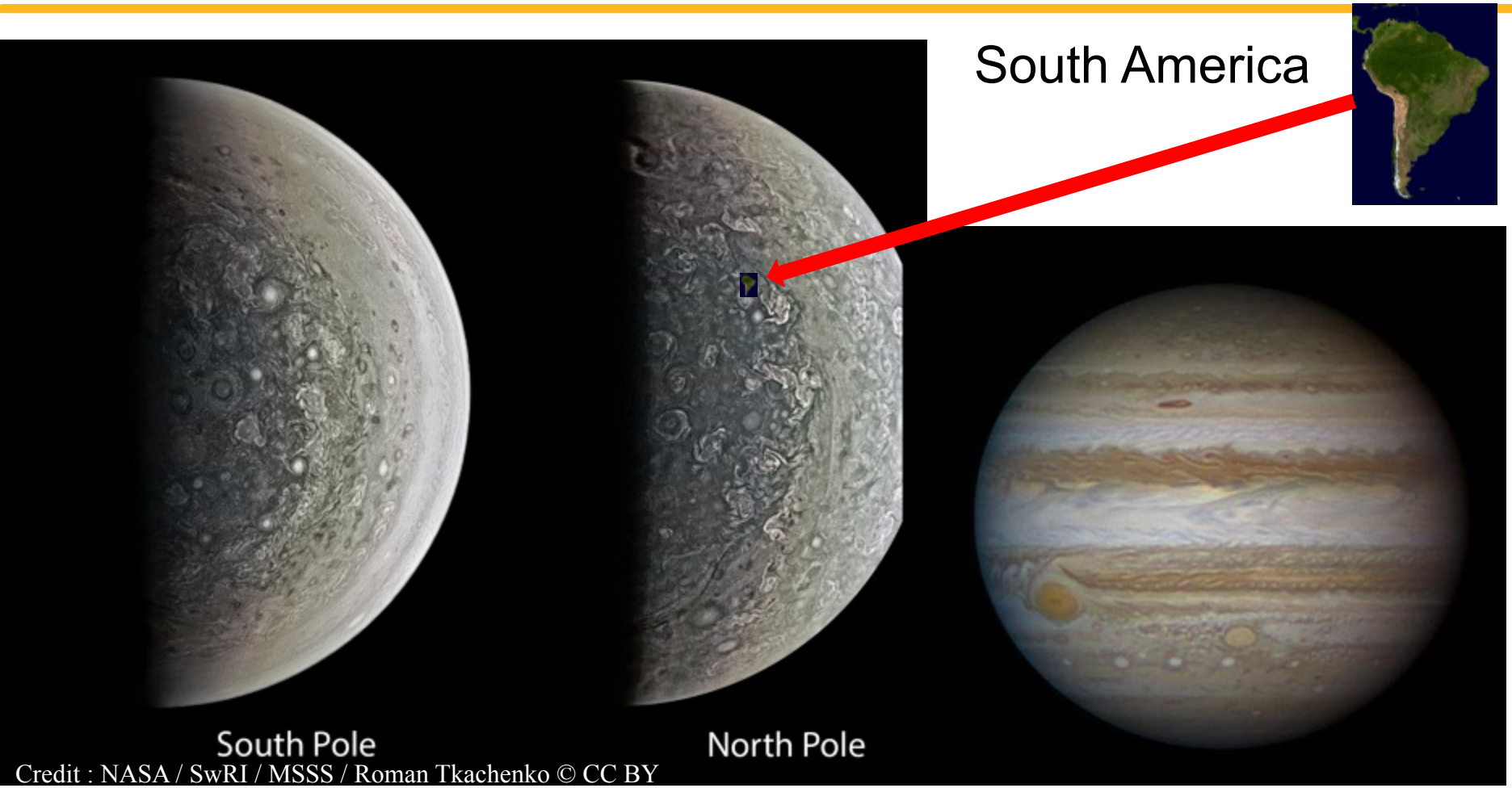
South America

Jupiter’s poles don’t look anything like the equator!



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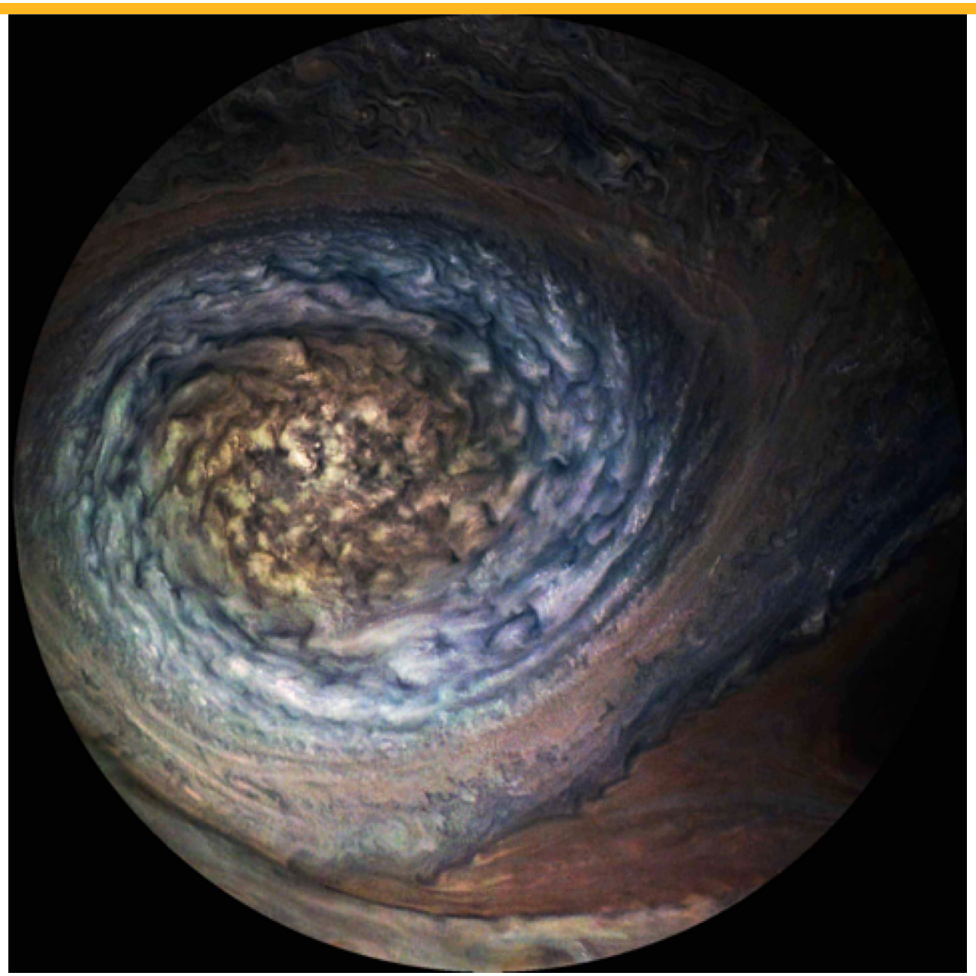
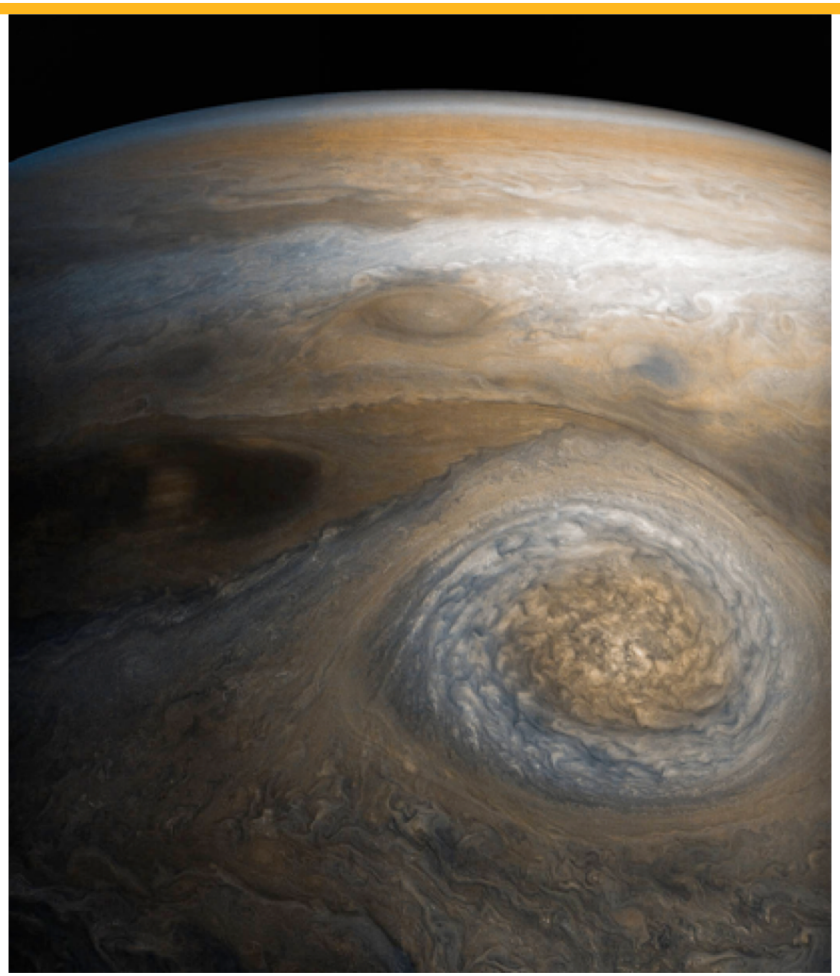
Storms Everywhere, Bigger Than Continents

No Belts and Zones At Poles

Close Up Images Of Jupiter

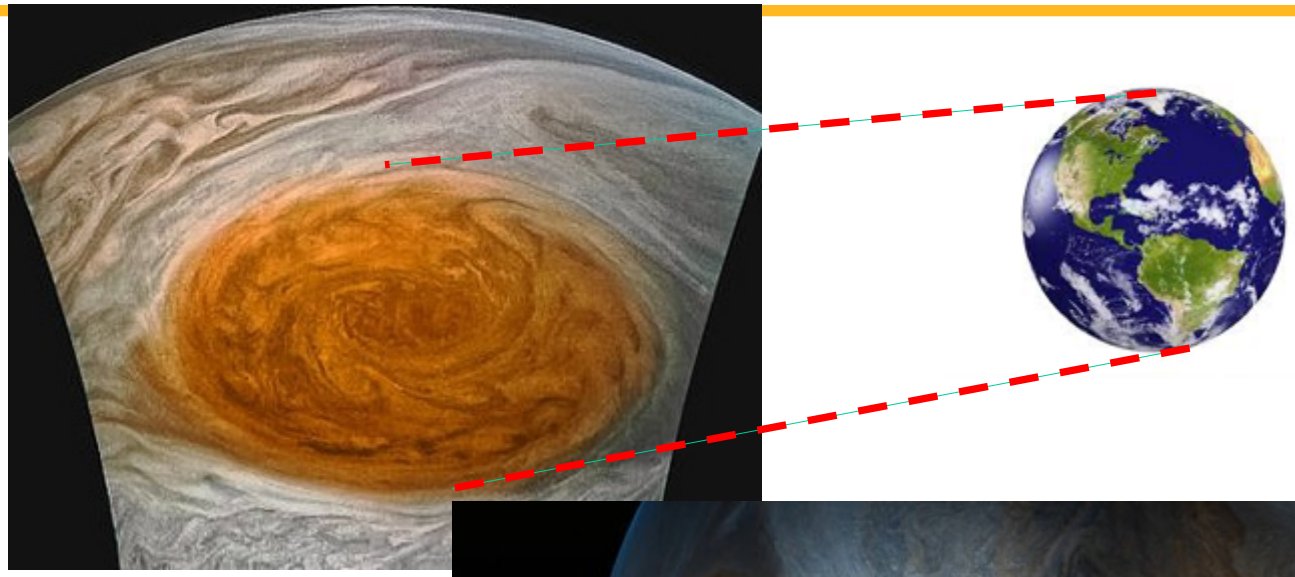




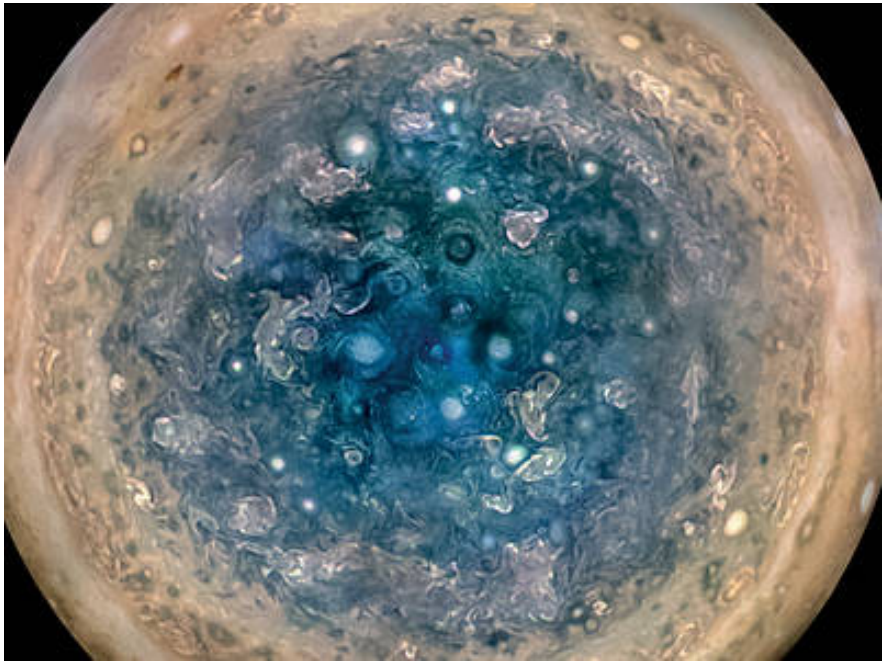
Want to find out what is in the core

Close Up Images Of Jupiter

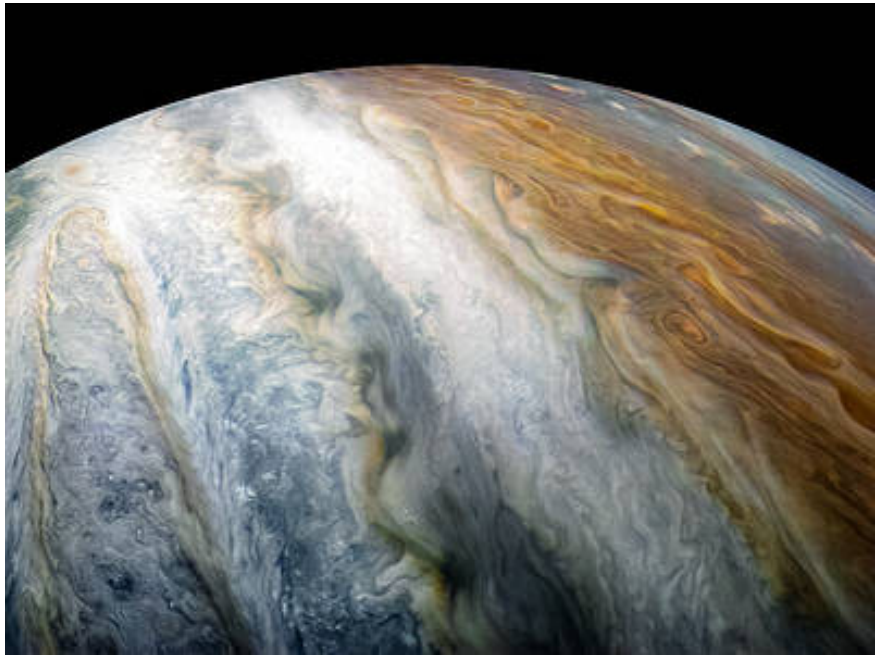
Close Up Images Of Jupiter



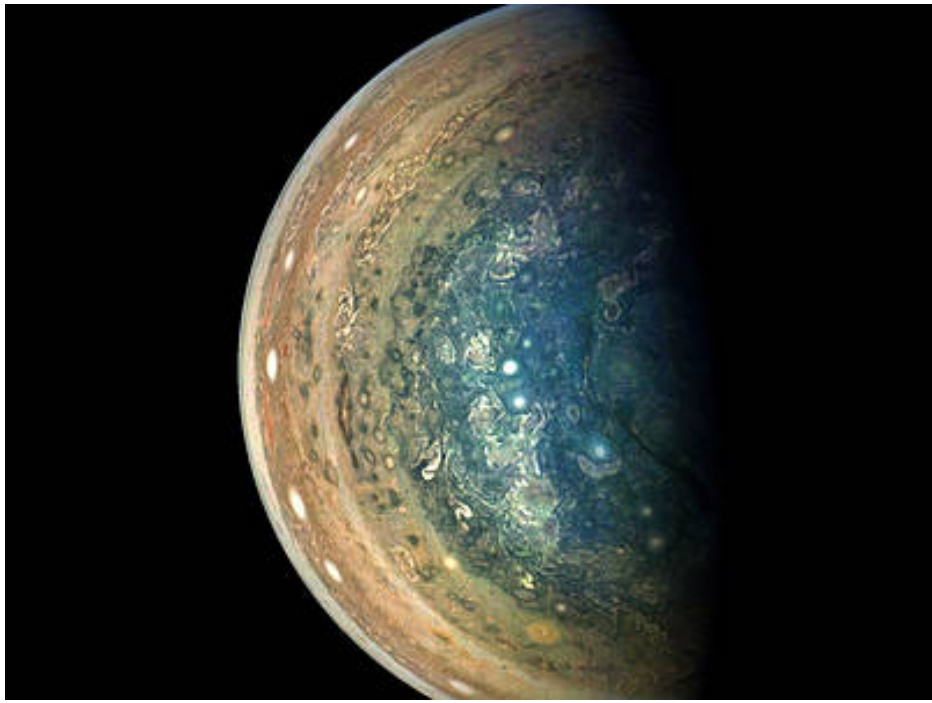
Close Up Images Of Jupiter



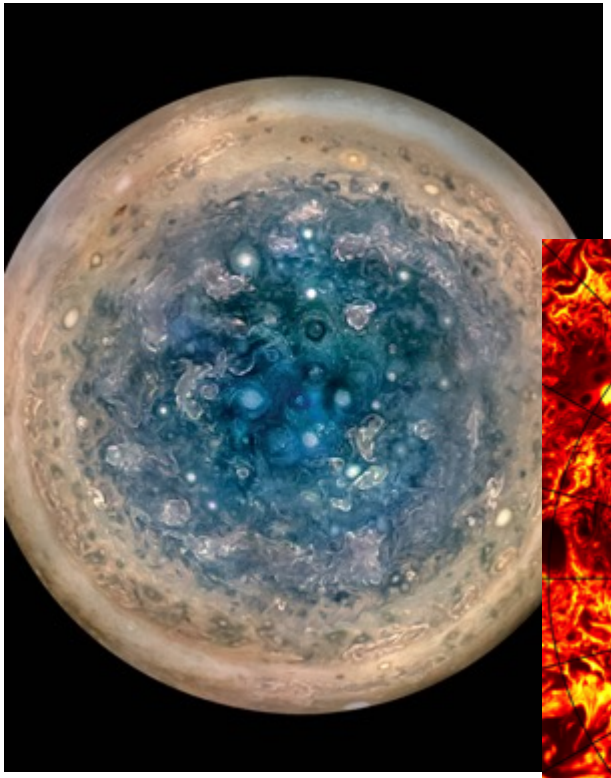
Close Up Images Of Jupiter



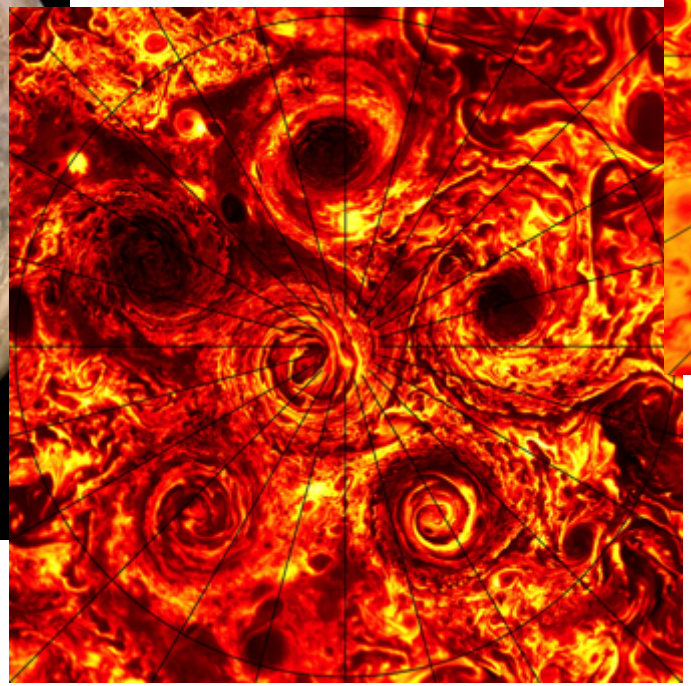
Close Up Images Of Jupiter

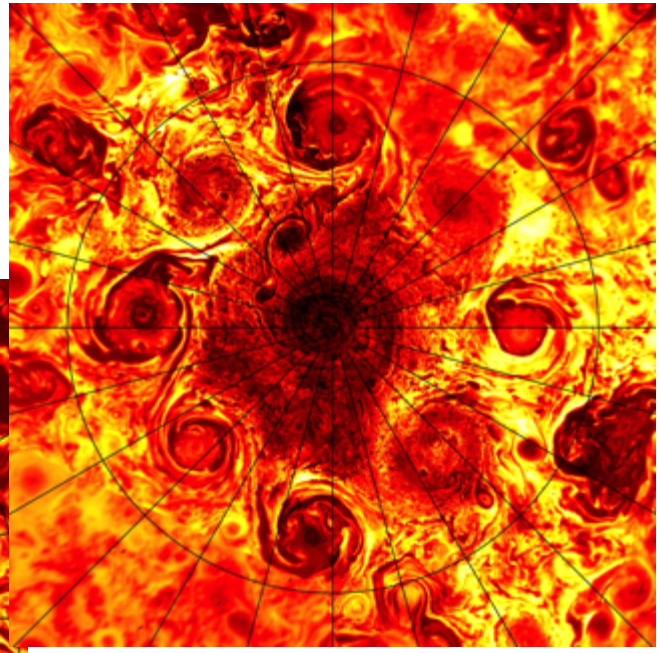


Circumpolar Cyclones



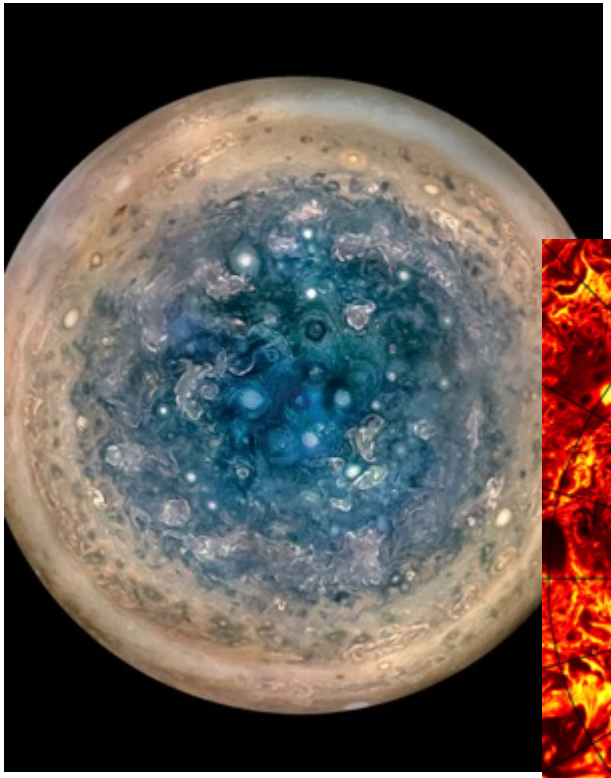
South Pole
Bluer In Poles



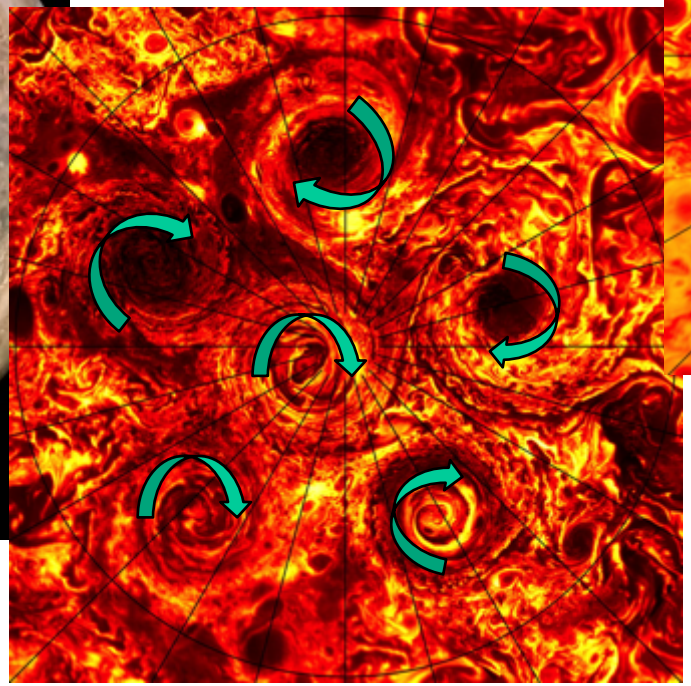


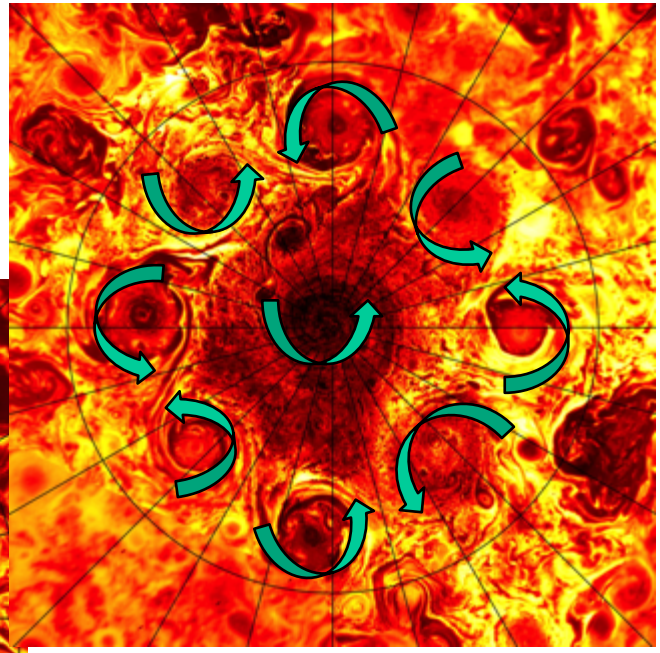
Cyclones Taken With Infrared Camera

Circumpolar Cyclones



8 Cyclones Gathered
In The North Pole With
One In Center
All Counterclockwise
And Stable Over 2 Yrs



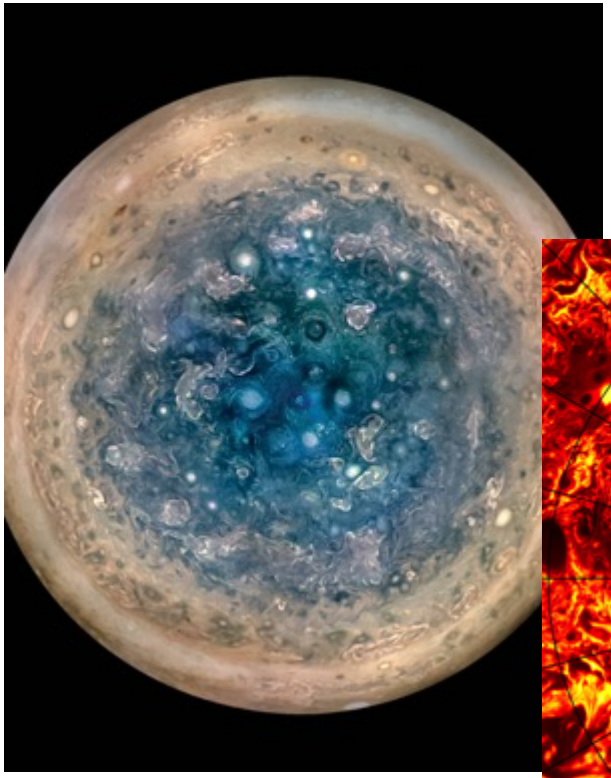


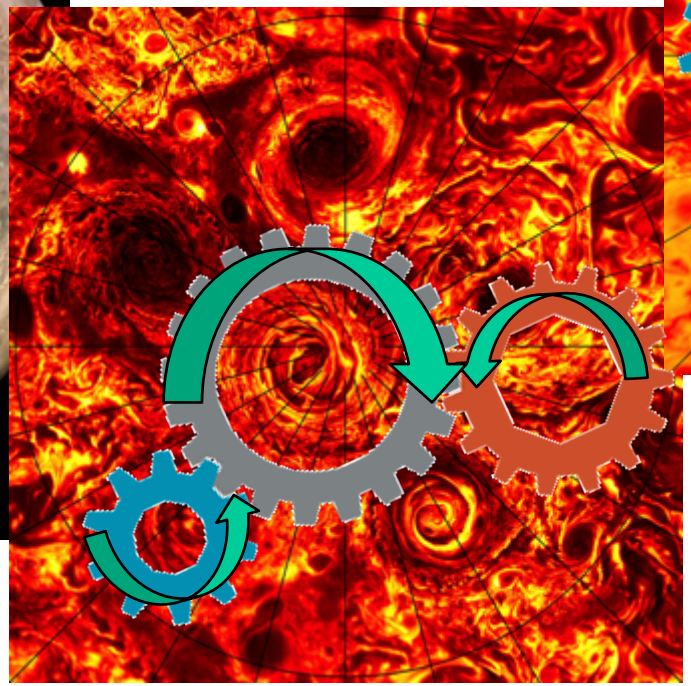
Drift Only A Bit Over Time But Very Stable.

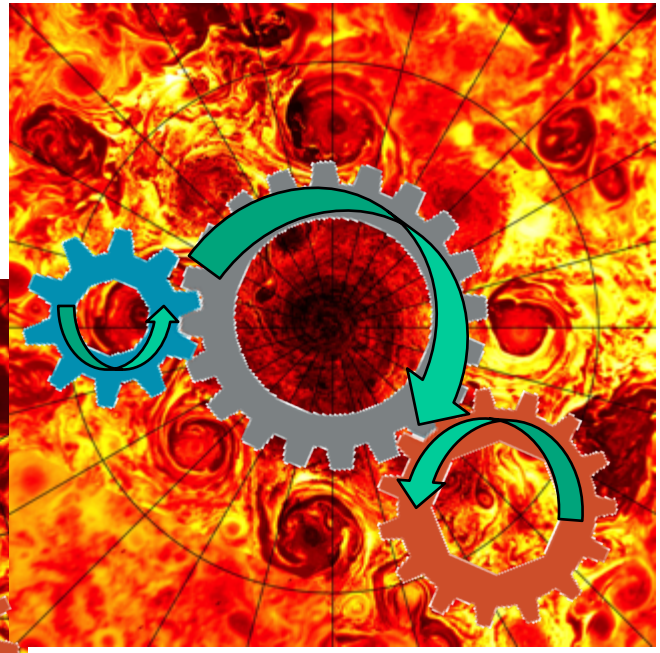
With Infrared camera we can see temperature and see warmer gases with brighter zones. Jupiter is warmer on inside that outside, so still cooling off 4.5 billion years after it formed.

5 Cyclones Gathered
In The South Pole With
One In Center, All Spinning In
Same Clockwise Direction
And Stable Over 2 Yrs

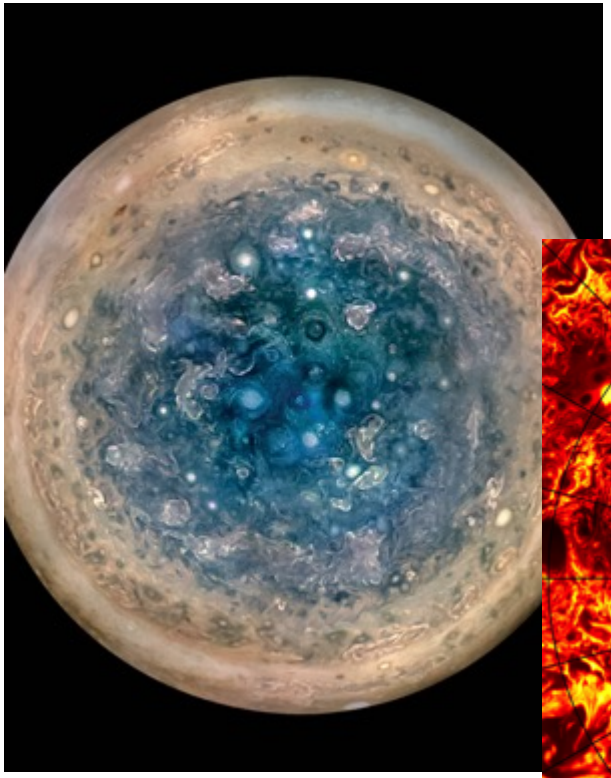
Circumpolar Cyclones

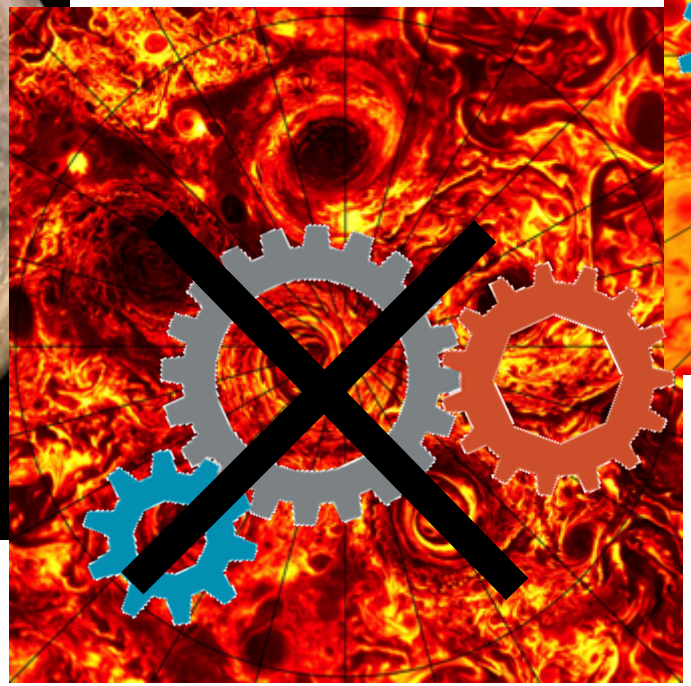




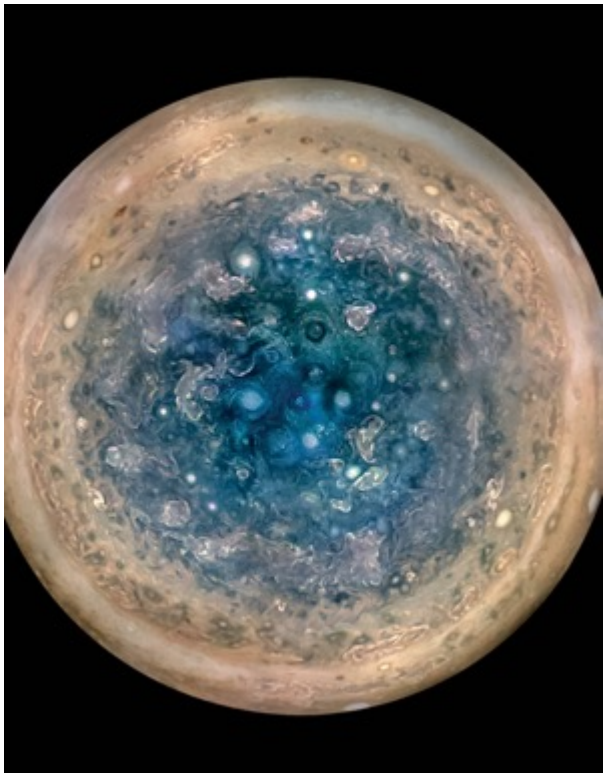


Circumpolar Cyclones





Circumpolar Cyclones



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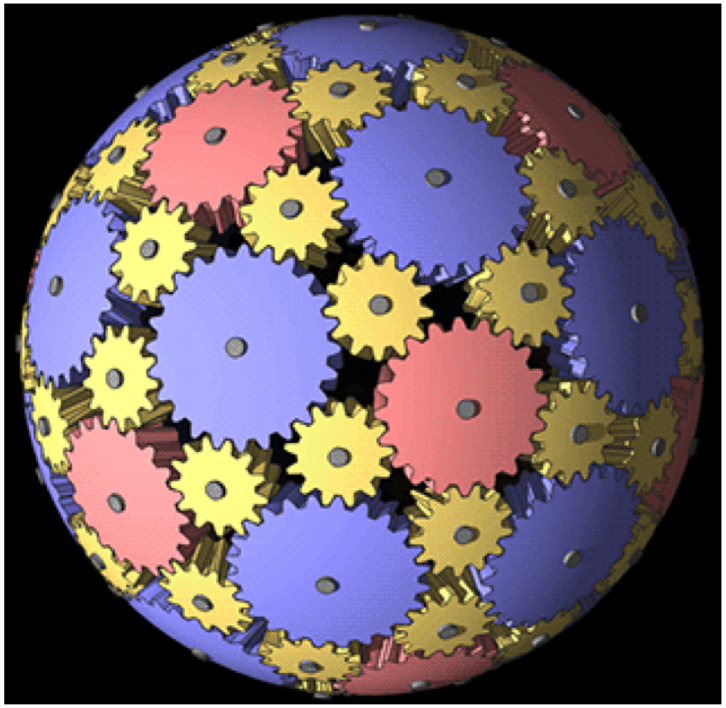
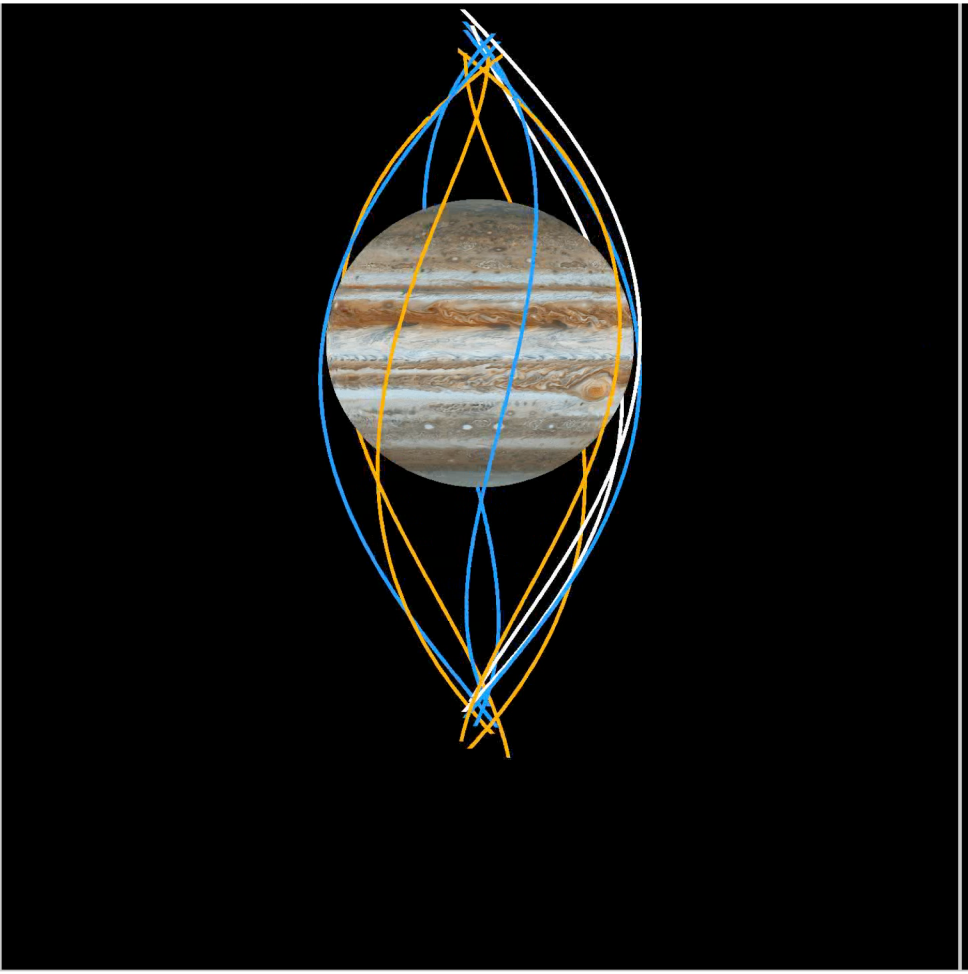
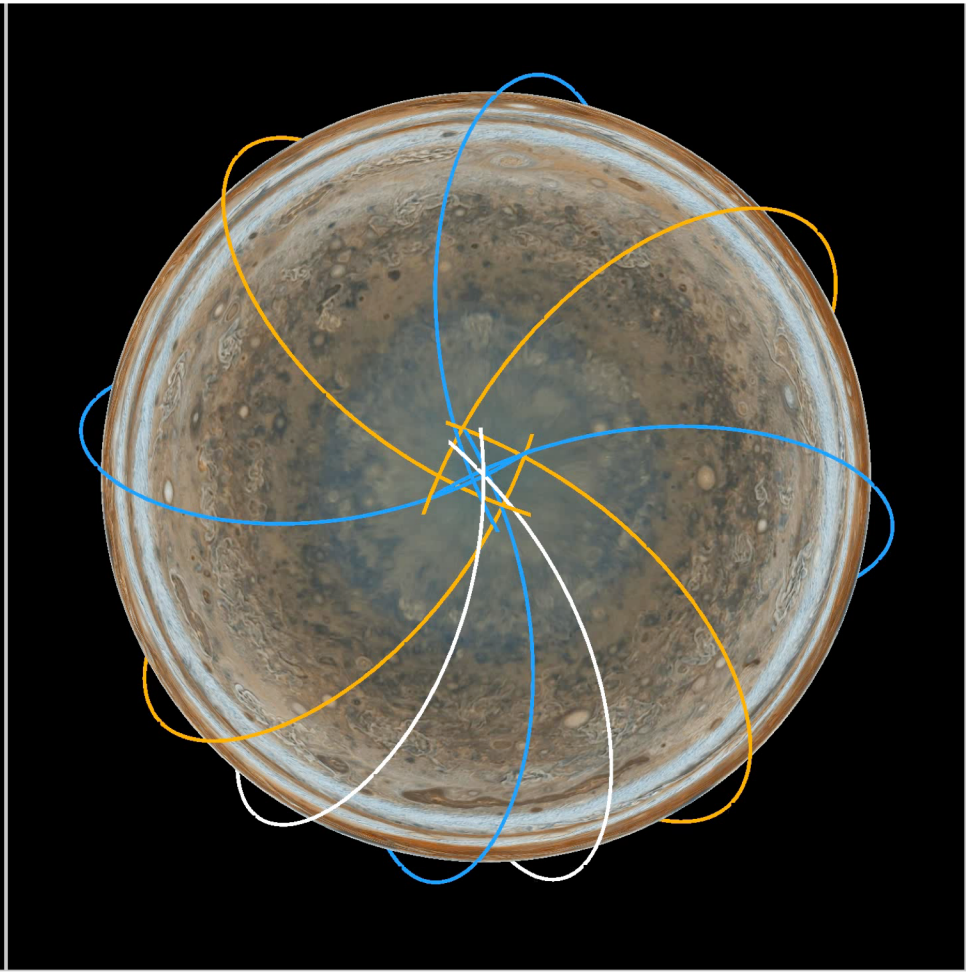
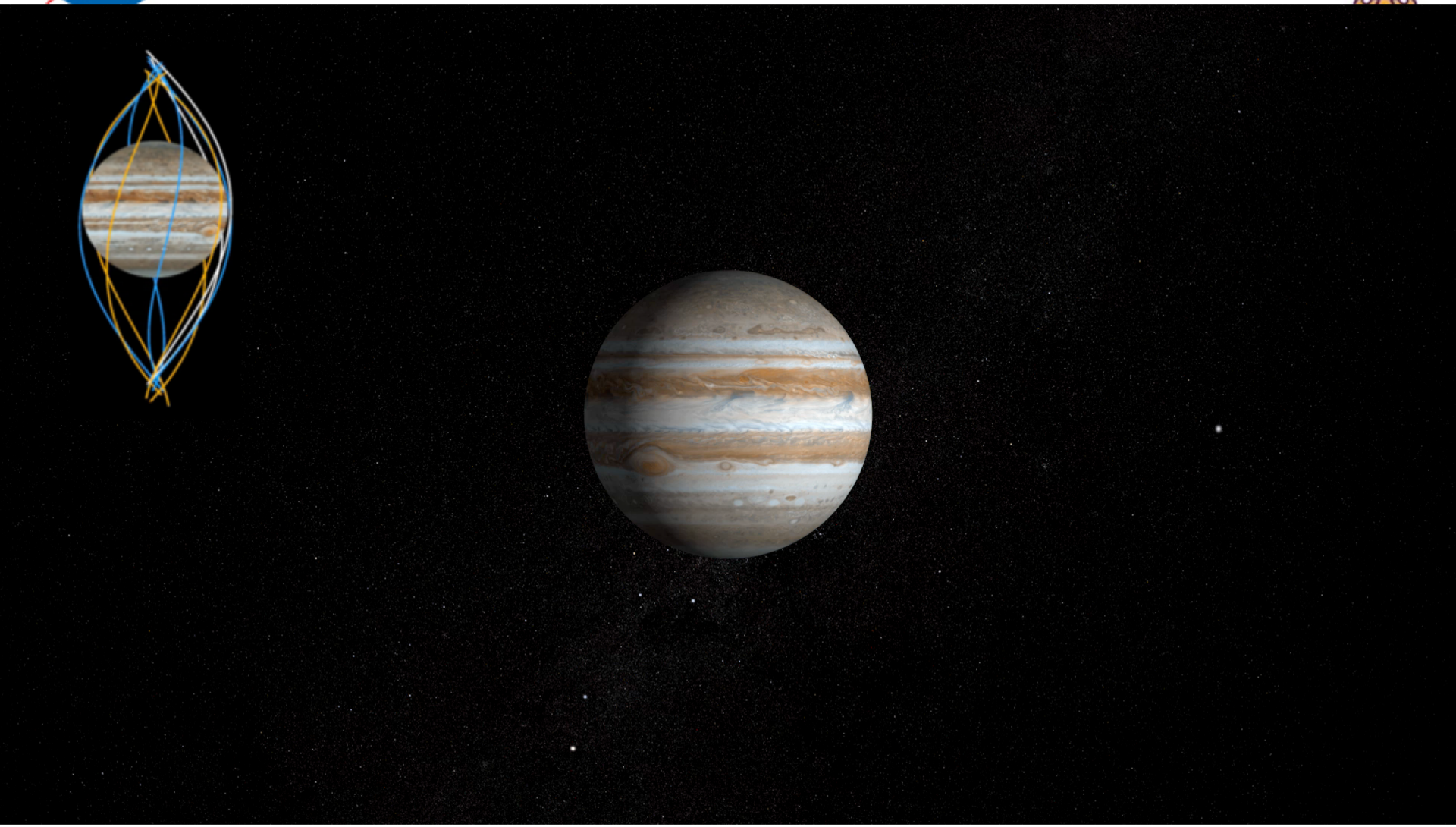


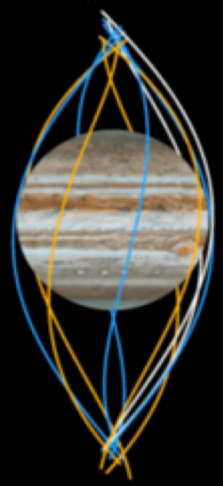
FLYOVER OF JUPITER'S
NORTH POLE IN INFRARED

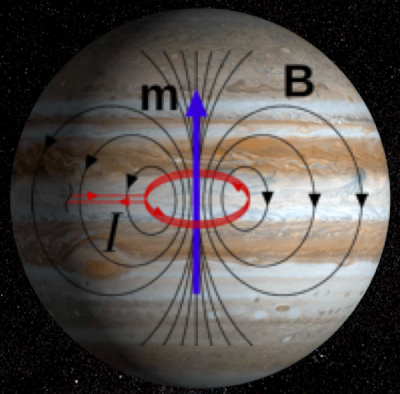
Mapping Jupiter's Magnetic Field







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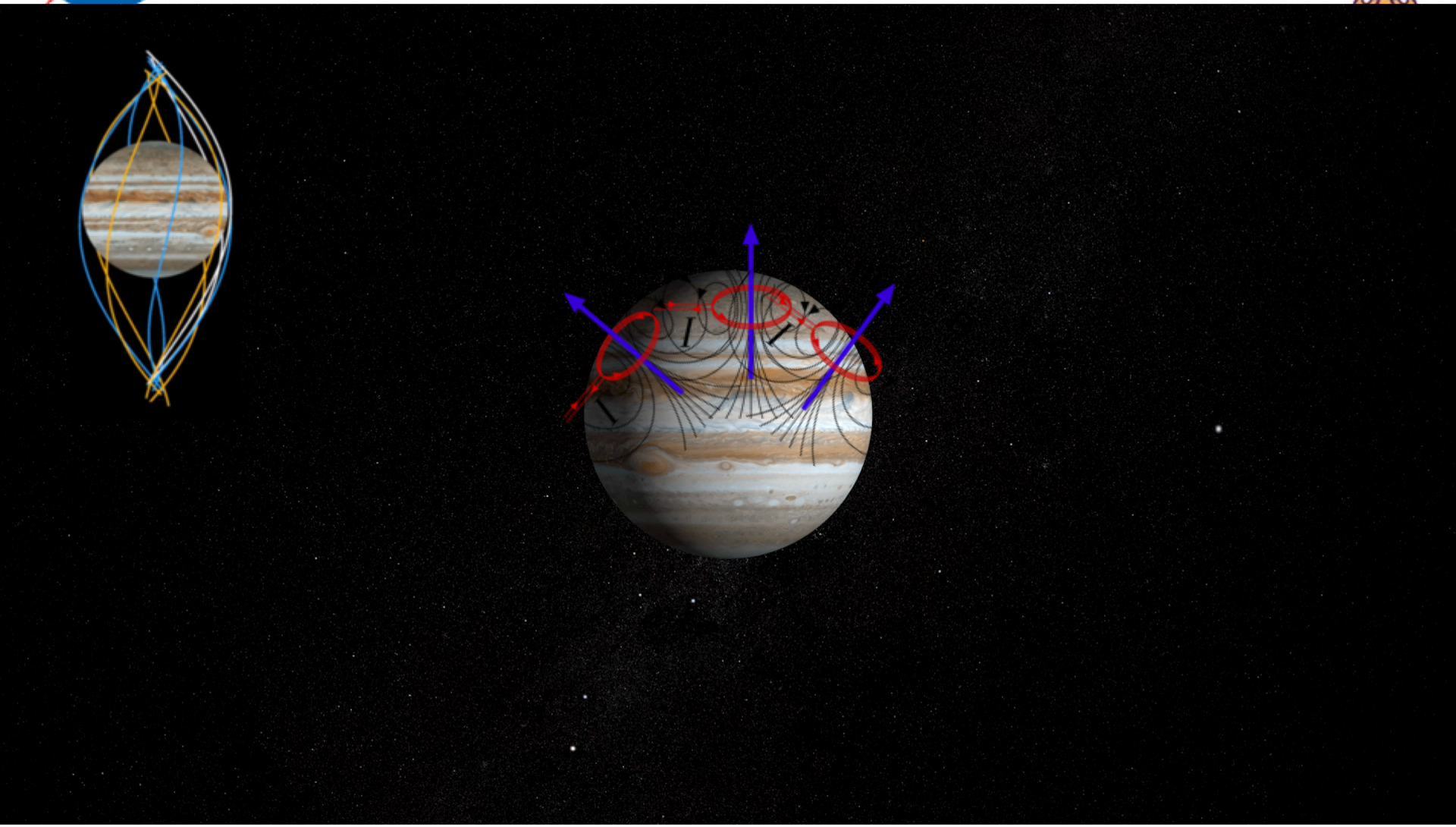
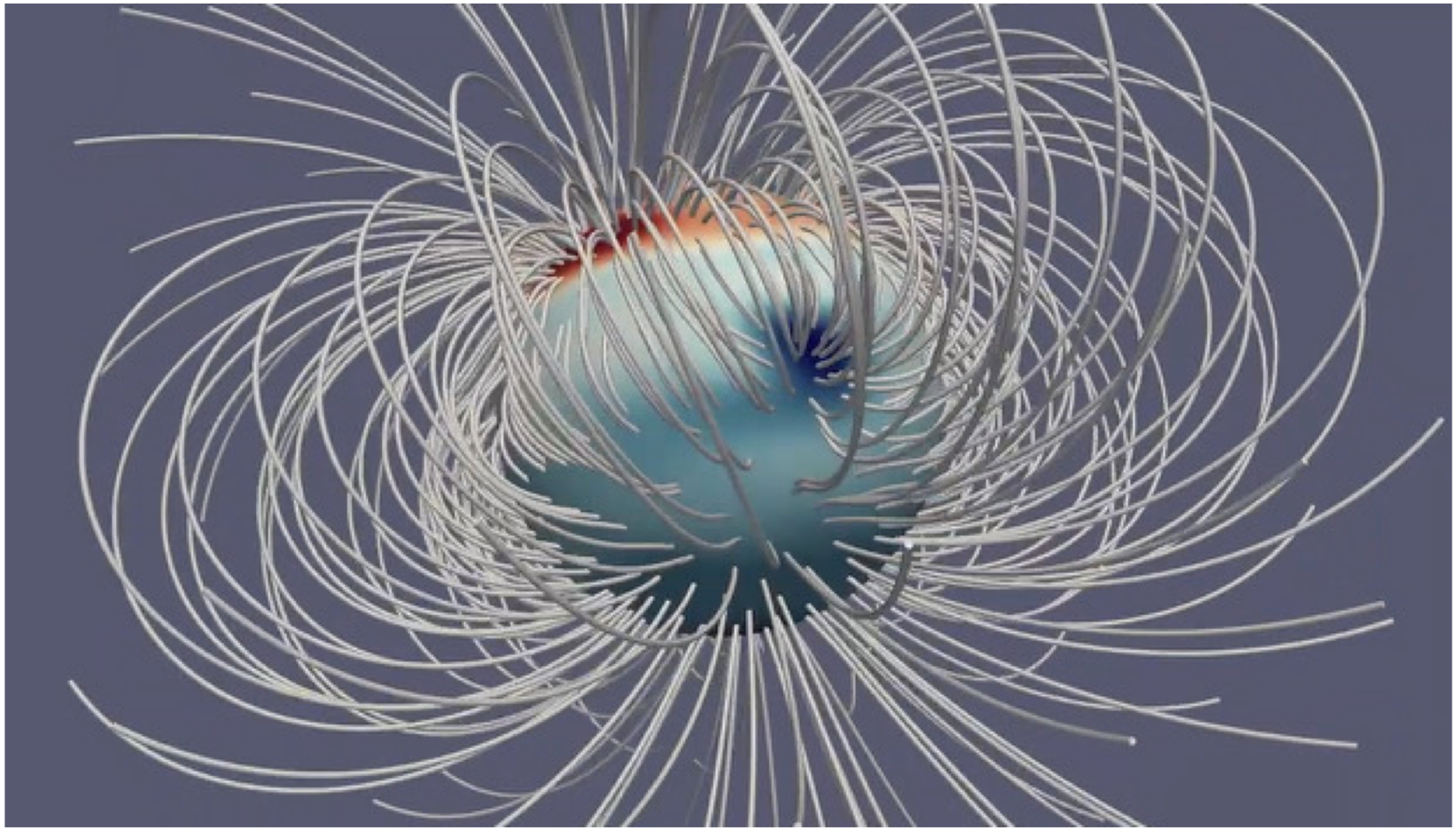
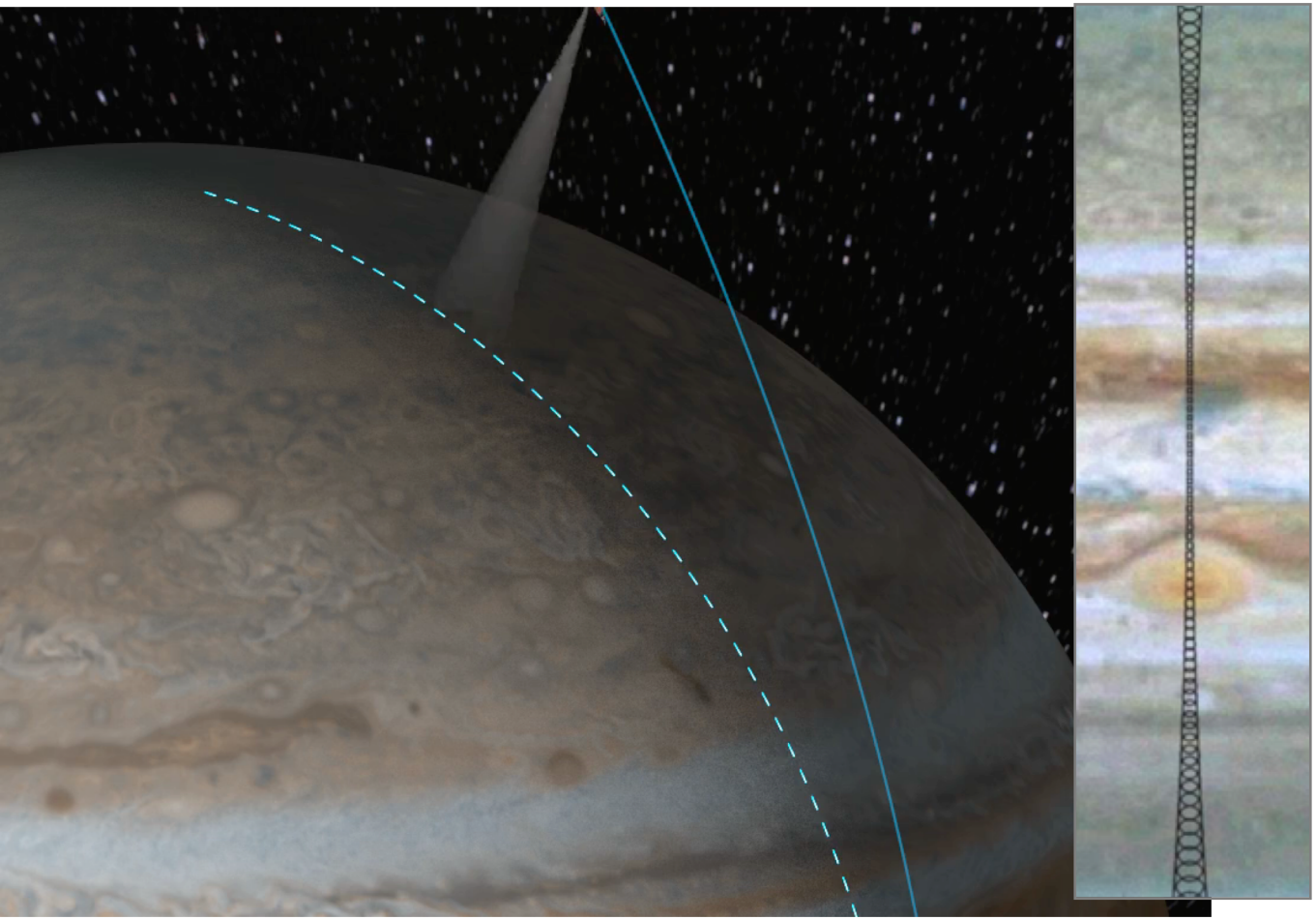
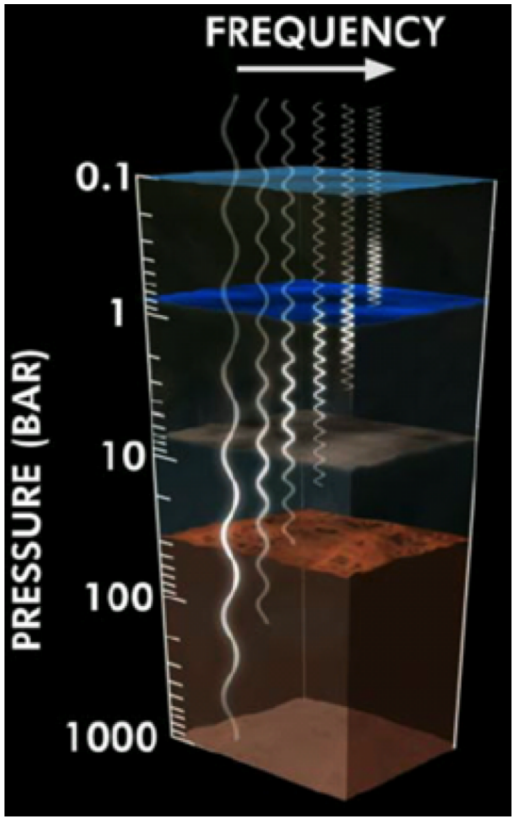




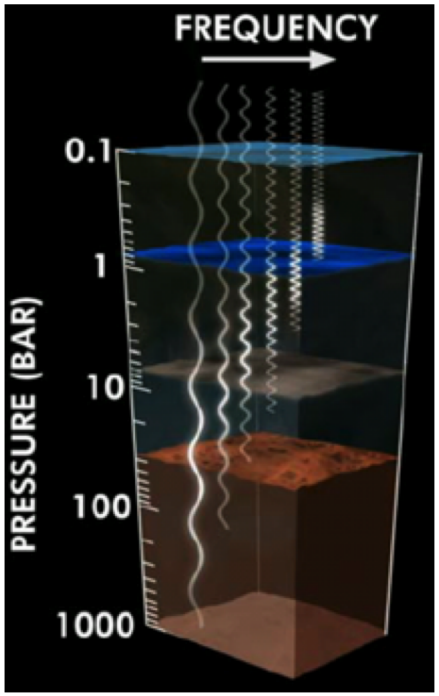
MWR Sees Beneath The Clouds...

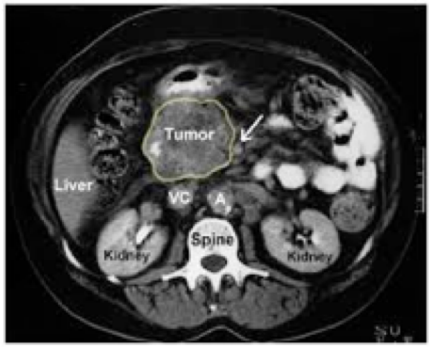


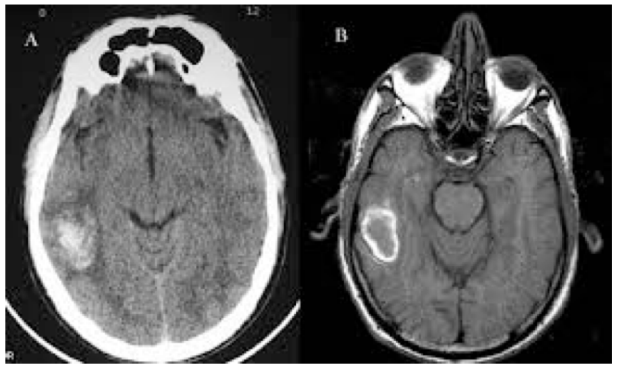


Looks at natural radial emission in different 6 channels, looks at six different depths into Jupiter like a CAT scan, dissect what is going on inside Jupiter.

MWR Sees Beneath The Clouds...







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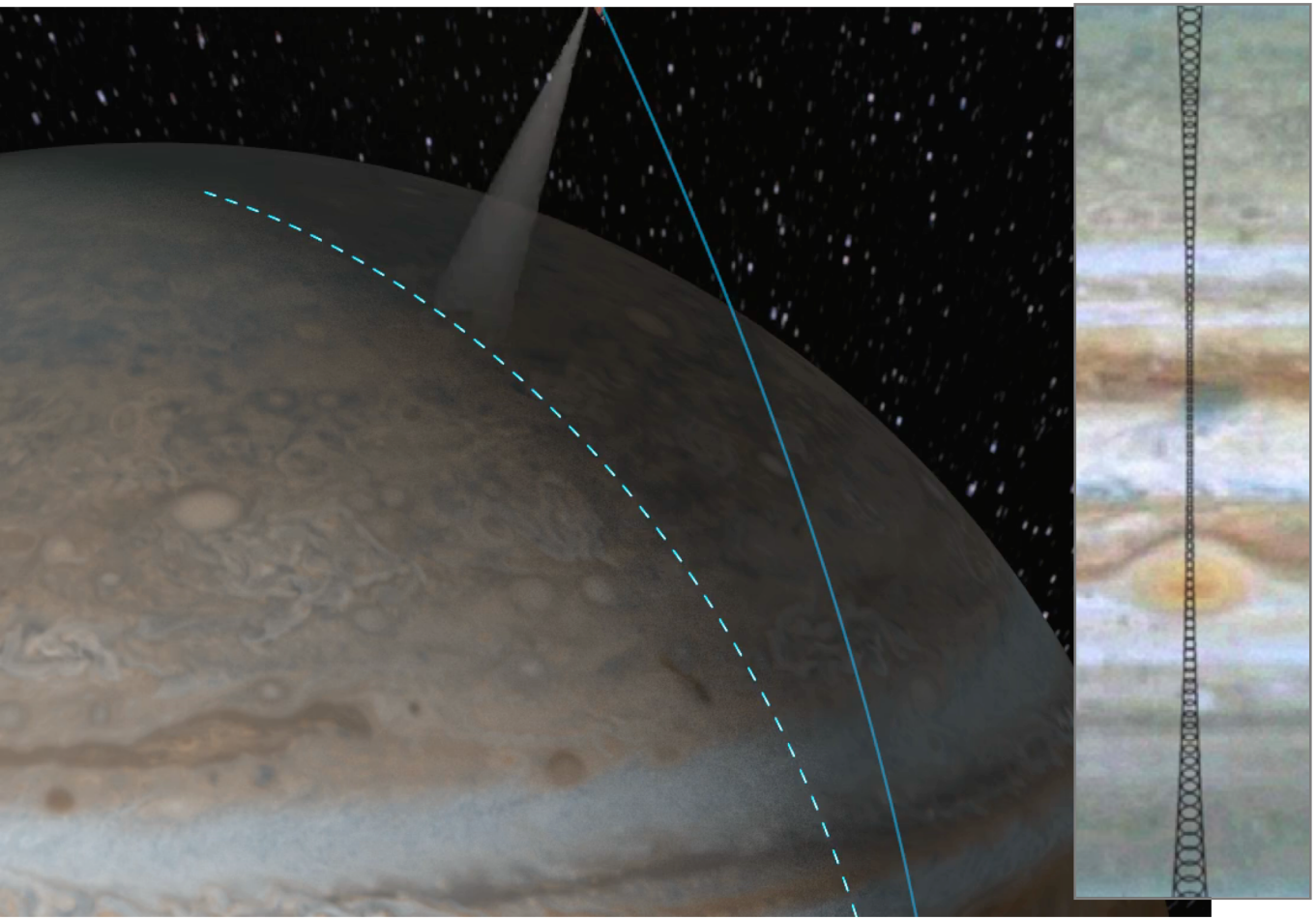
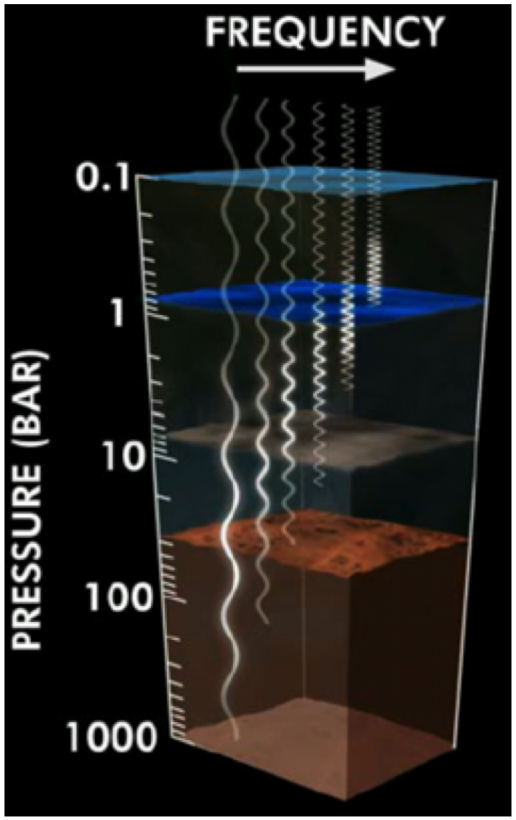
MWR Sees Beneath The Clouds...





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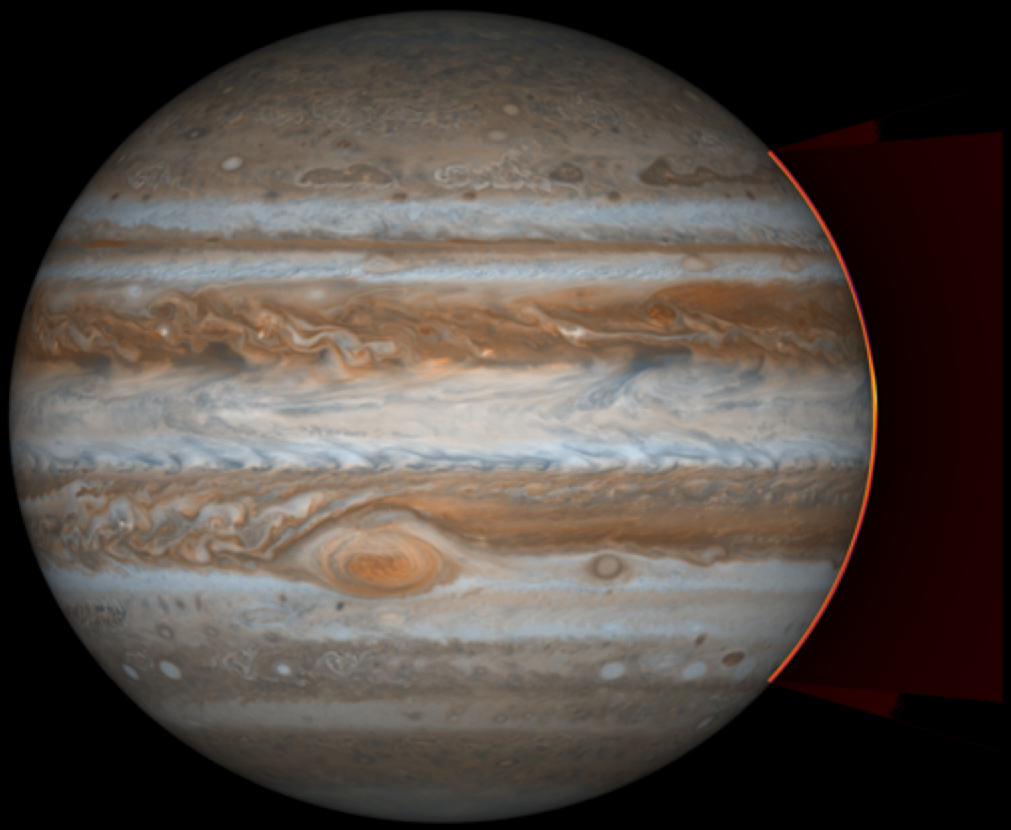
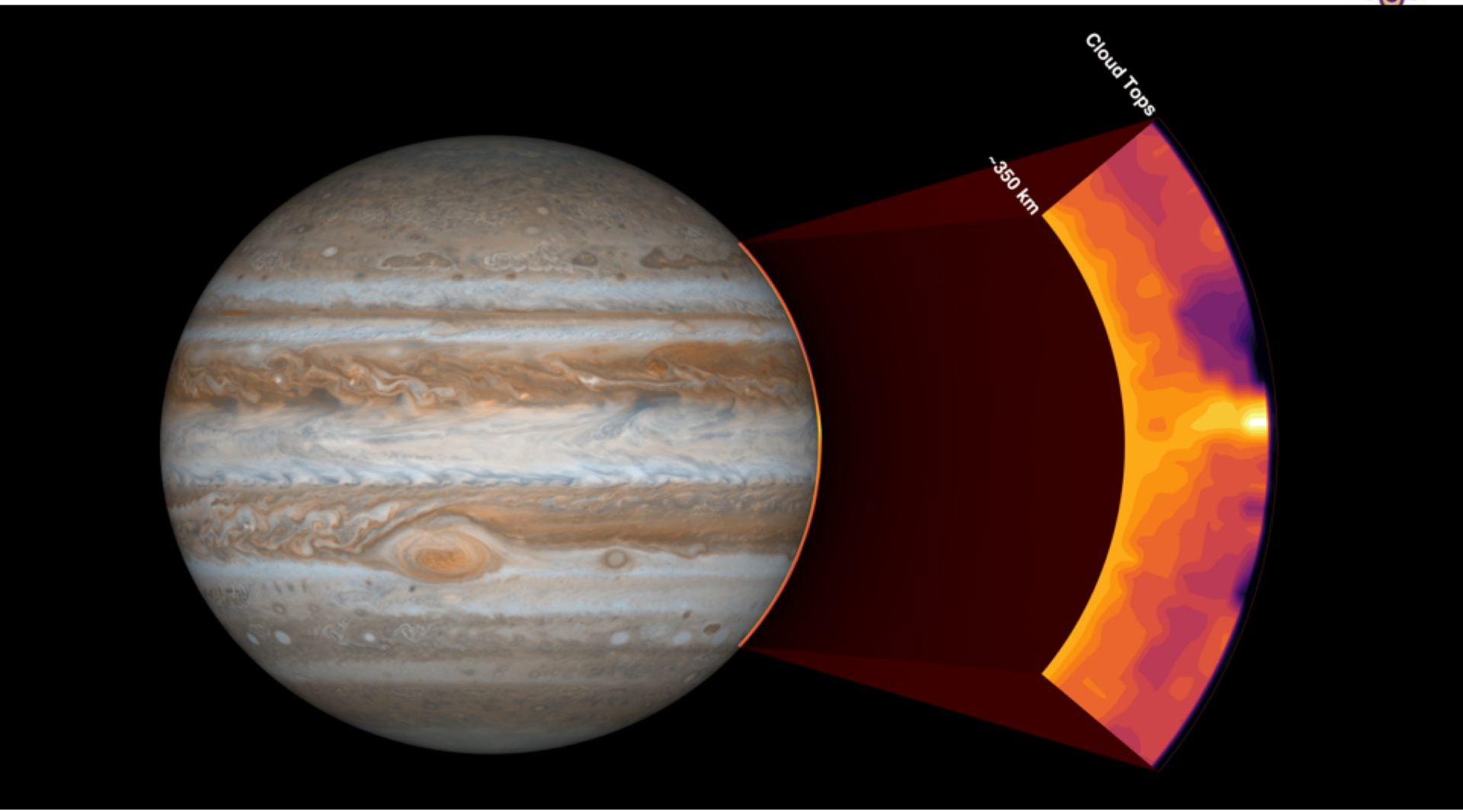
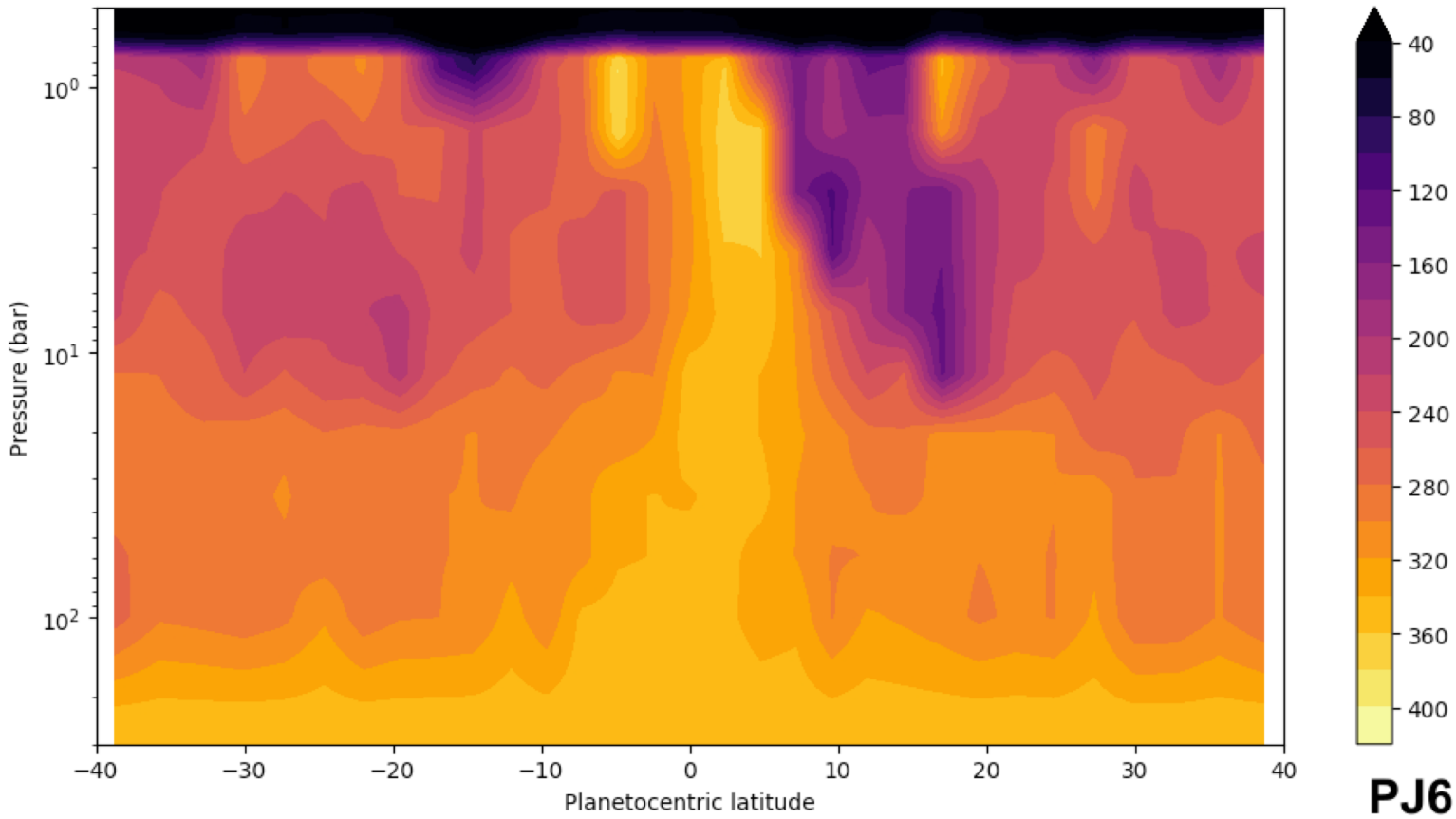
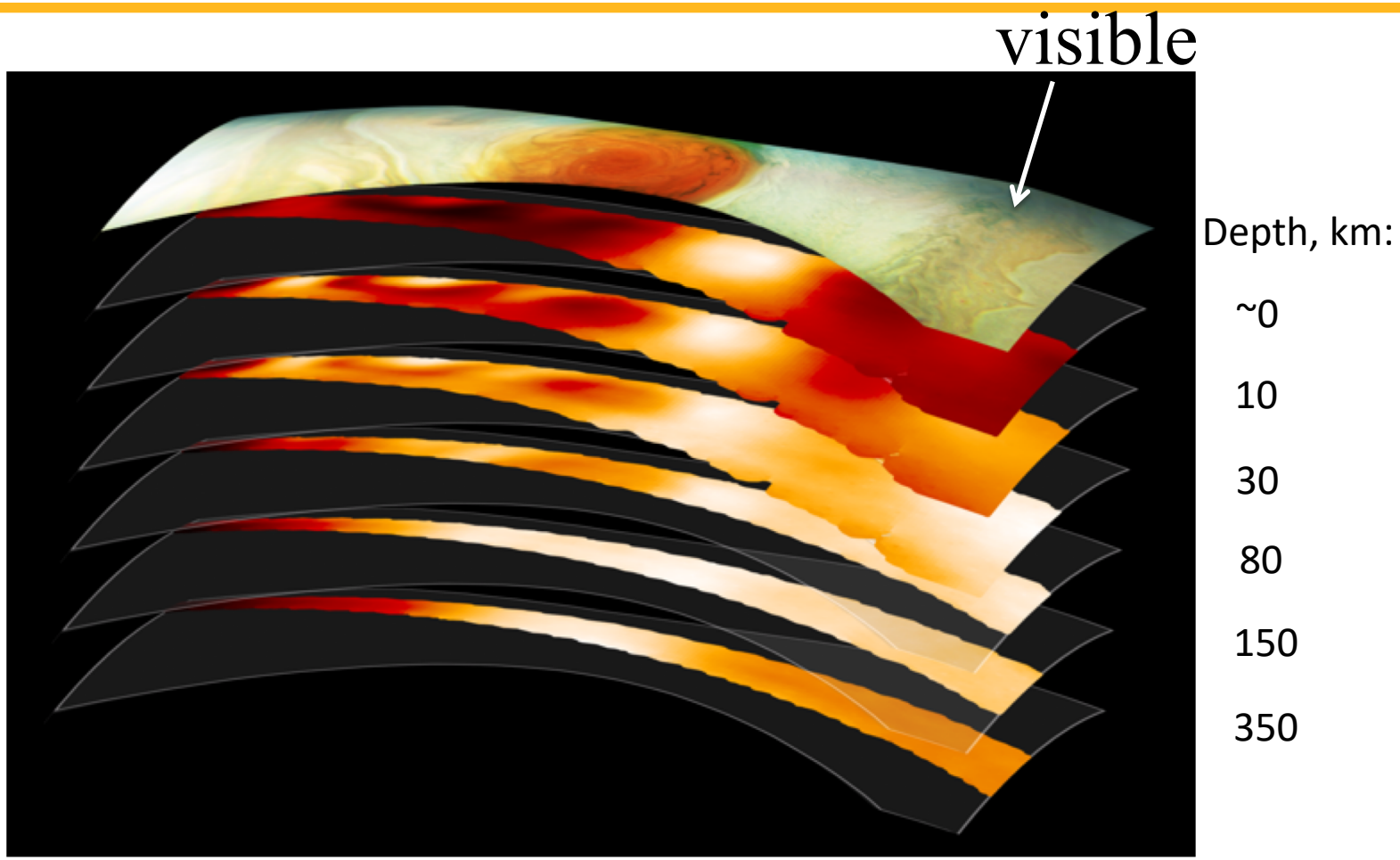
Jupiter's Deep Atmosphere Is Surprisingly Complex!



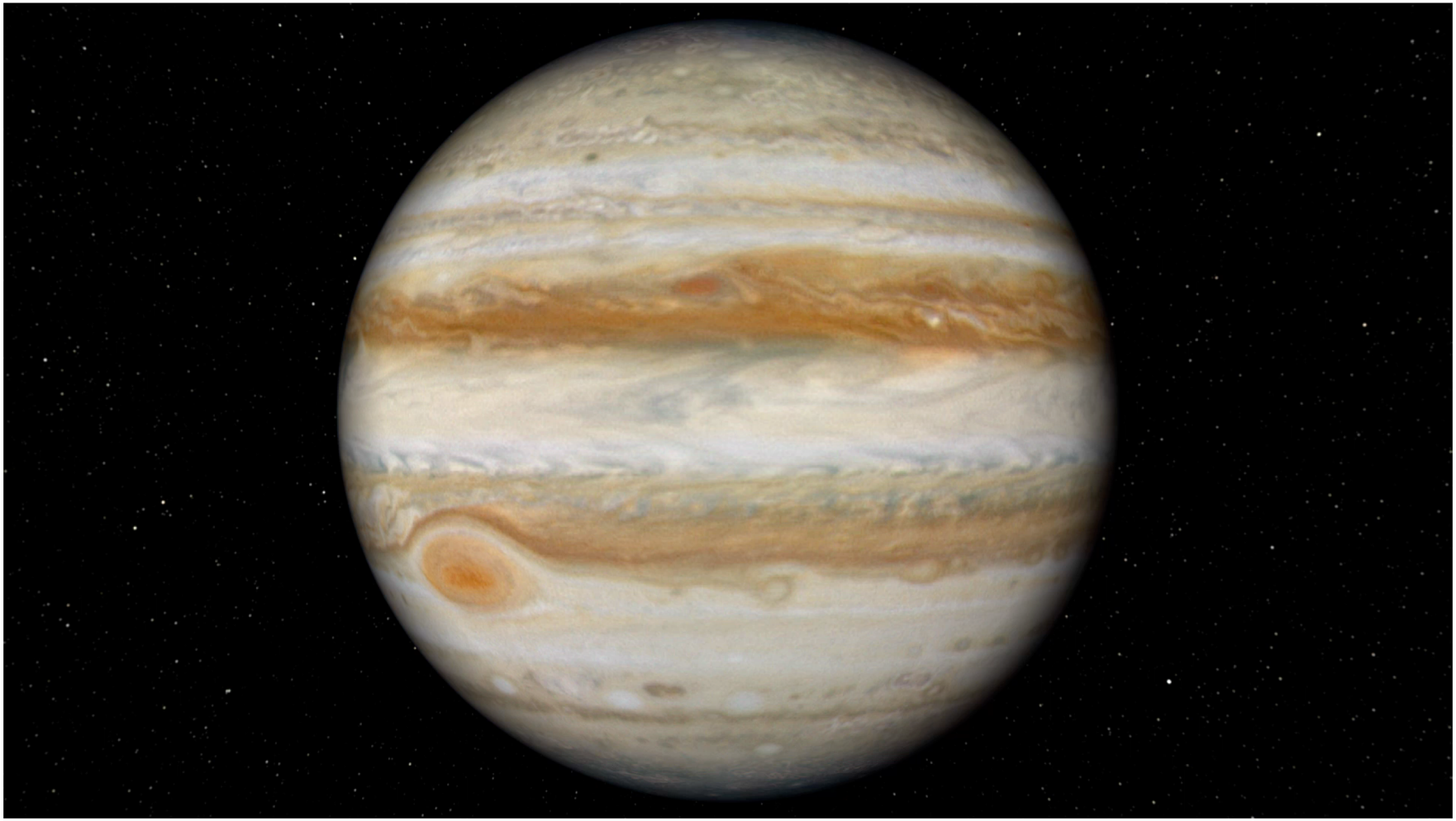

Cloud Tops
~350 km



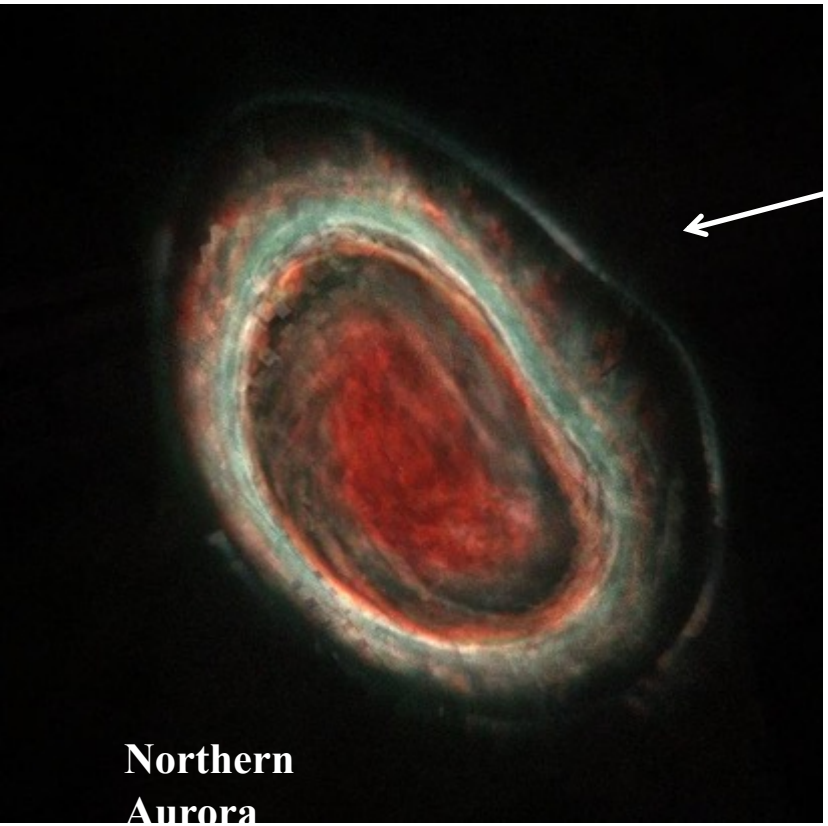
Jupiter's Deep Atmosphere Is Surprisingly Complex!

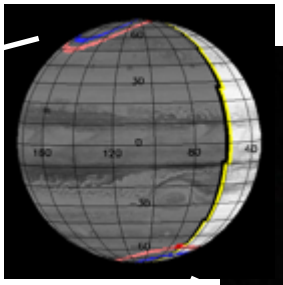


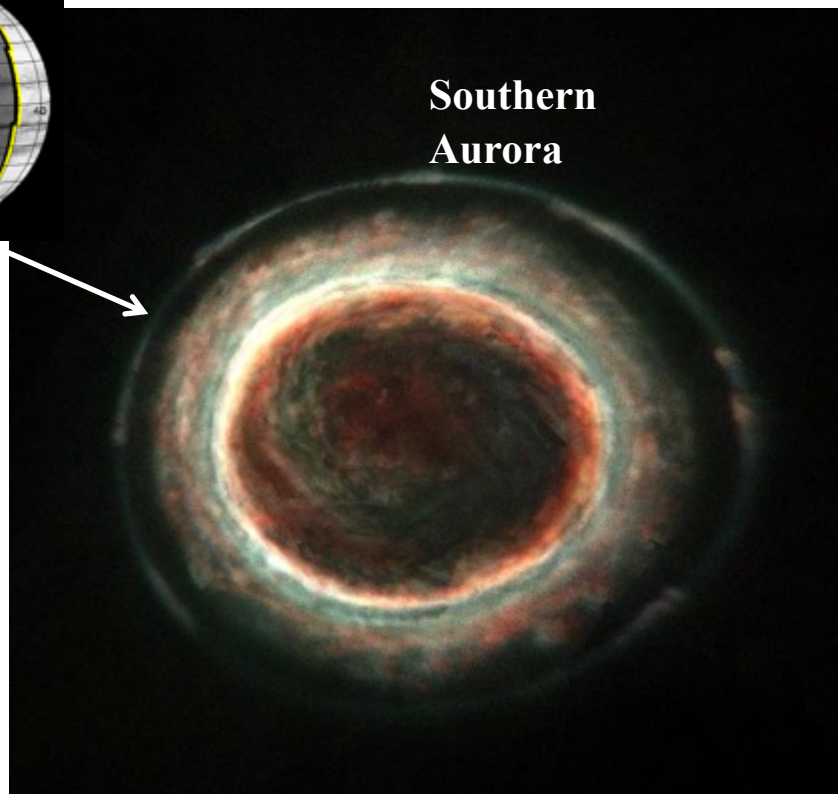
Jupiter's Great Red Spot Is Surprisingly Deep!



The Belts and Zones Are 3000 km Deep!

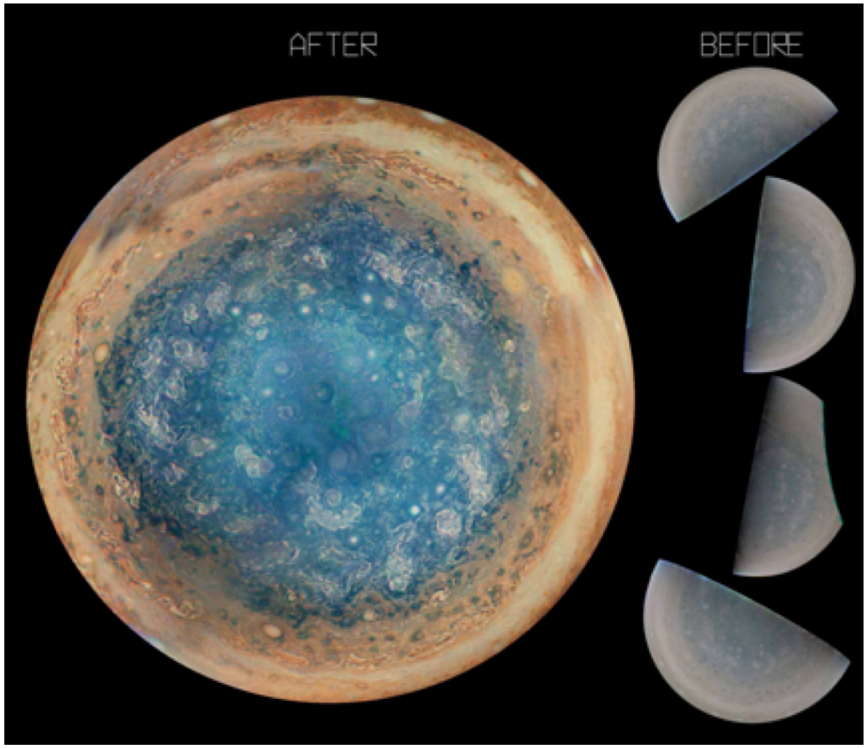




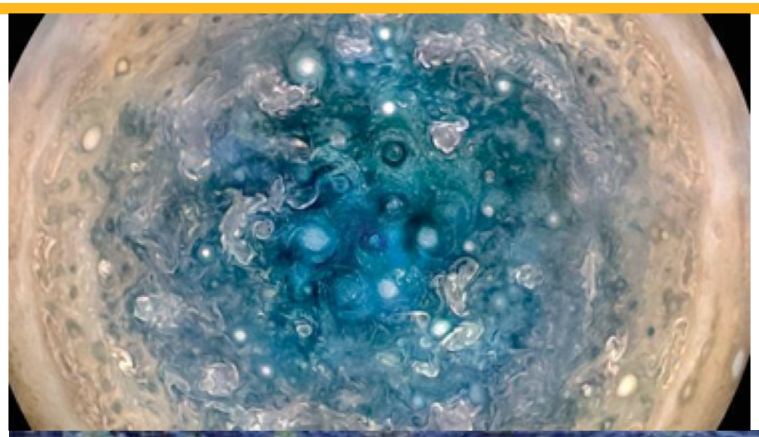


Juno Observes Jupiter's Stunning Aurora

Images From JUNOCAM



Huge Cyclones at Jupiter's Poles

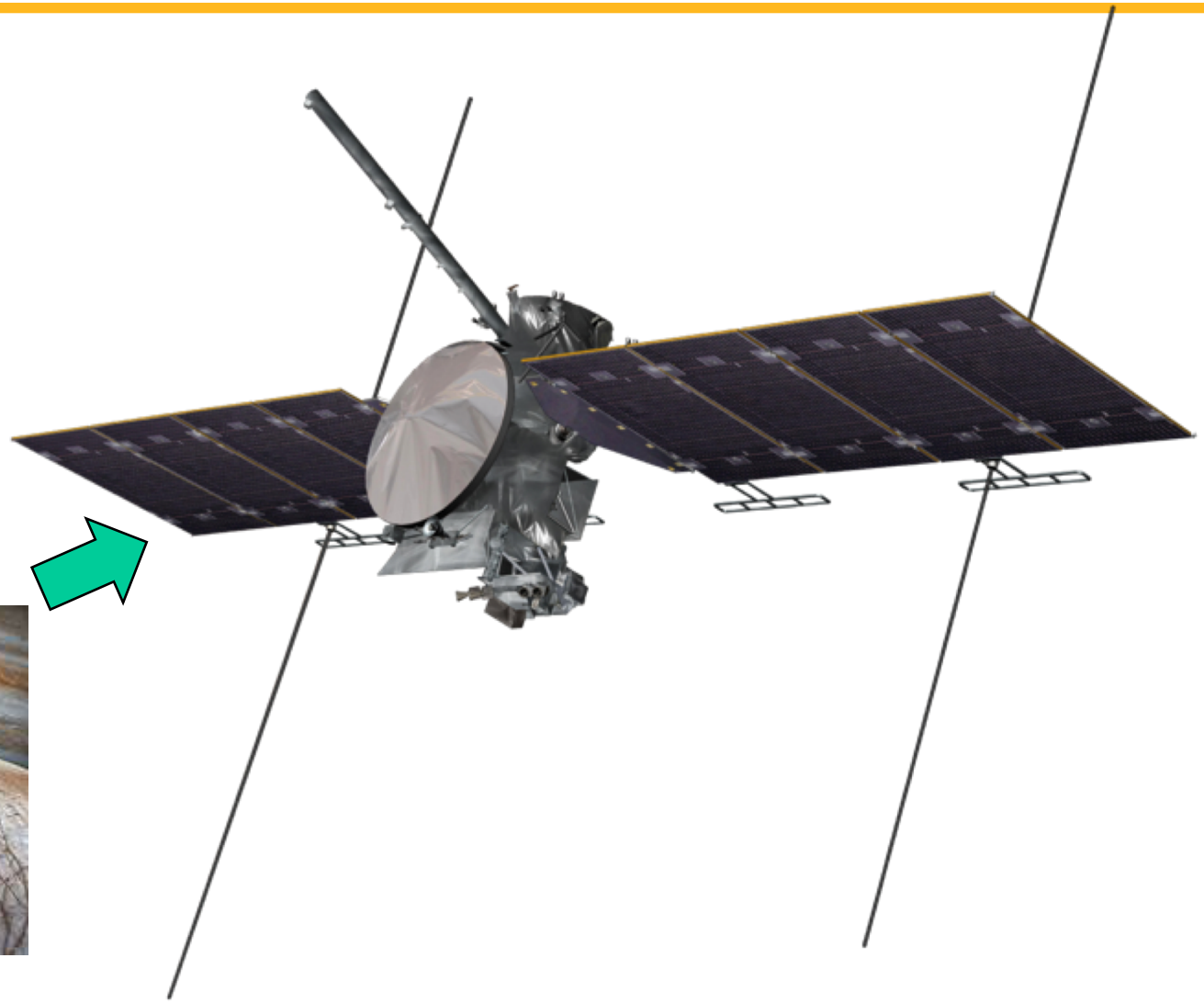


Vincent Van Gogh

Europa

Clipper

The Europa Clipper Spacecraft



Exploring Europa's Habitability: Ingredients for Life

Water:

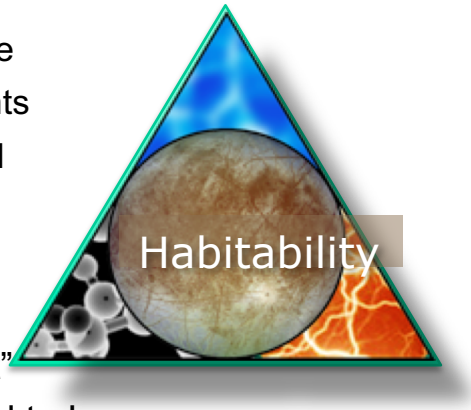
- Probable saltwater ocean, implied by surface geology and magnetic field
- Possible lakes within the ice shell, produced by local melting

Chemistry:

- Ocean in direct contact with mantle rock, promoting chemical leaching
- Dark red surface materials contain salts, probably from the ocean

Energy:

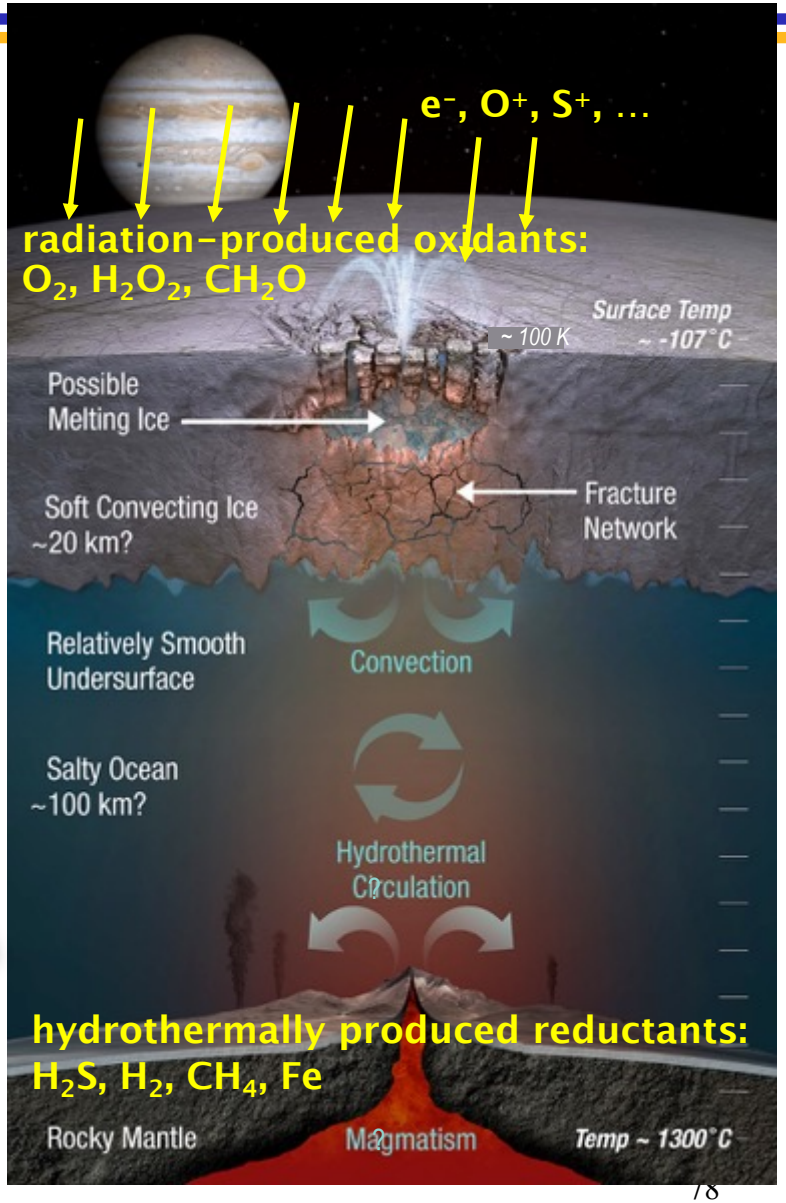
- Chemical energy might sustain life
- Surface irradiation creates oxidants
- Mantle rock-water reactions could create reductants (hydrothermal or serpentinization)



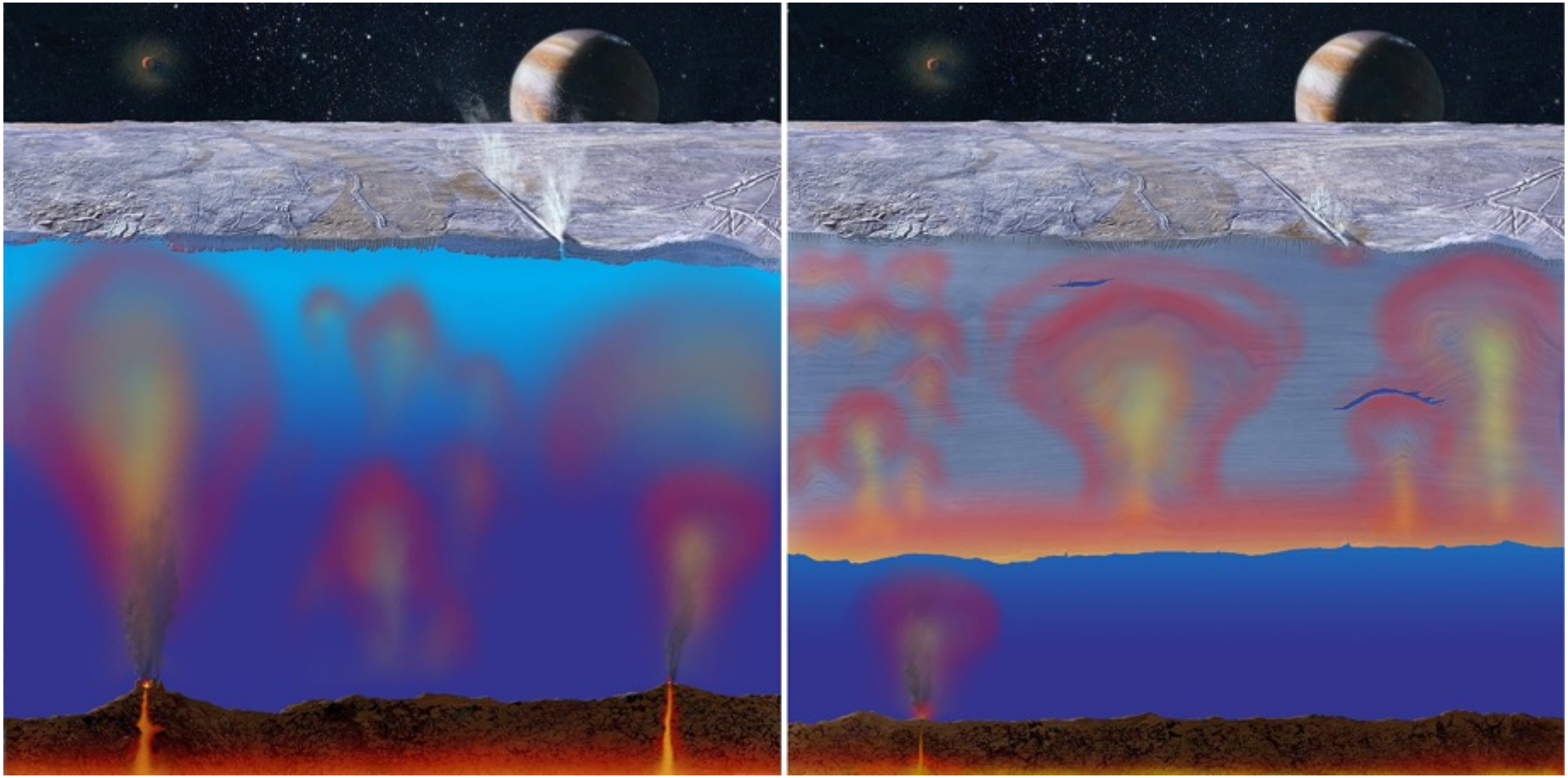
Activity:

- Geological activity "stirs the pot"
- Activity could be cyclical, as tied to Io

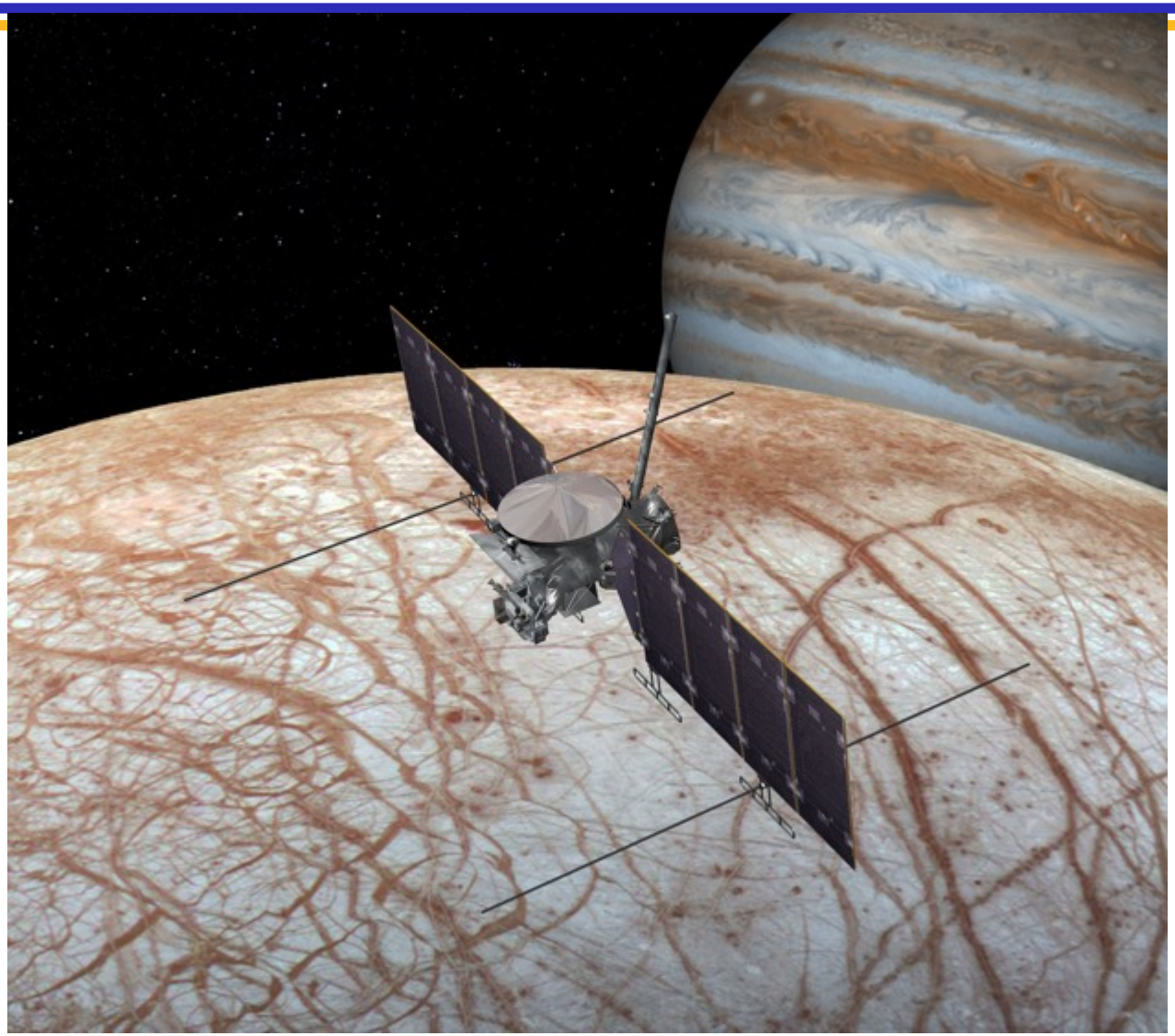
Europa Flyby Mission will test key habitability hypotheses



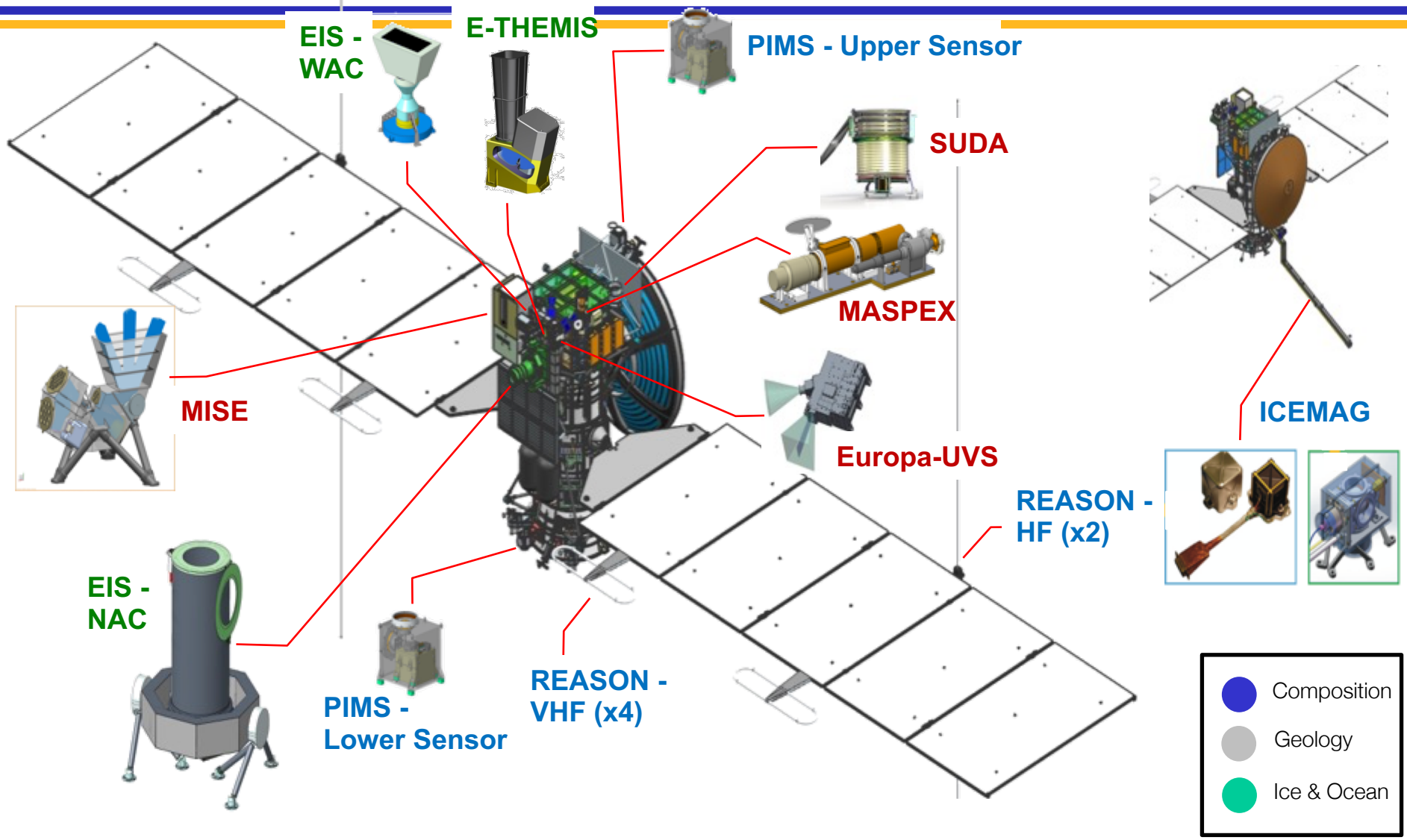
The Europa Clipper Spacecraft



The Europa Clipper Spacecraft



Europa Clipper Payload



Europa Clipper
Science Instruments

- **Plasma Instrument for Magnetic Sounding (PIMS)** -- This instrument works in conjunction with a magnetometer and is key to determining Europa's ice shell thickness, ocean depth, and salinity by correcting the magnetic induction signal for plasma currents around Europa.
- **Interior Characterization of Europa using Magnetometry (ICEMAG)** -- This magnetometer will measure the magnetic field near Europa and - in conjunction with the PIMS instrument - infer the location, thickness and salinity of Europa's subsurface ocean using multi-frequency electromagnetic sounding.
- **Mapping Imaging Spectrometer for Europa (MISE)** -- This instrument will probe the composition of Europa, identifying and mapping the distributions of organics, salts, acid hydrates, water ice phases, and other materials to determine the habitability of Europa's ocean.

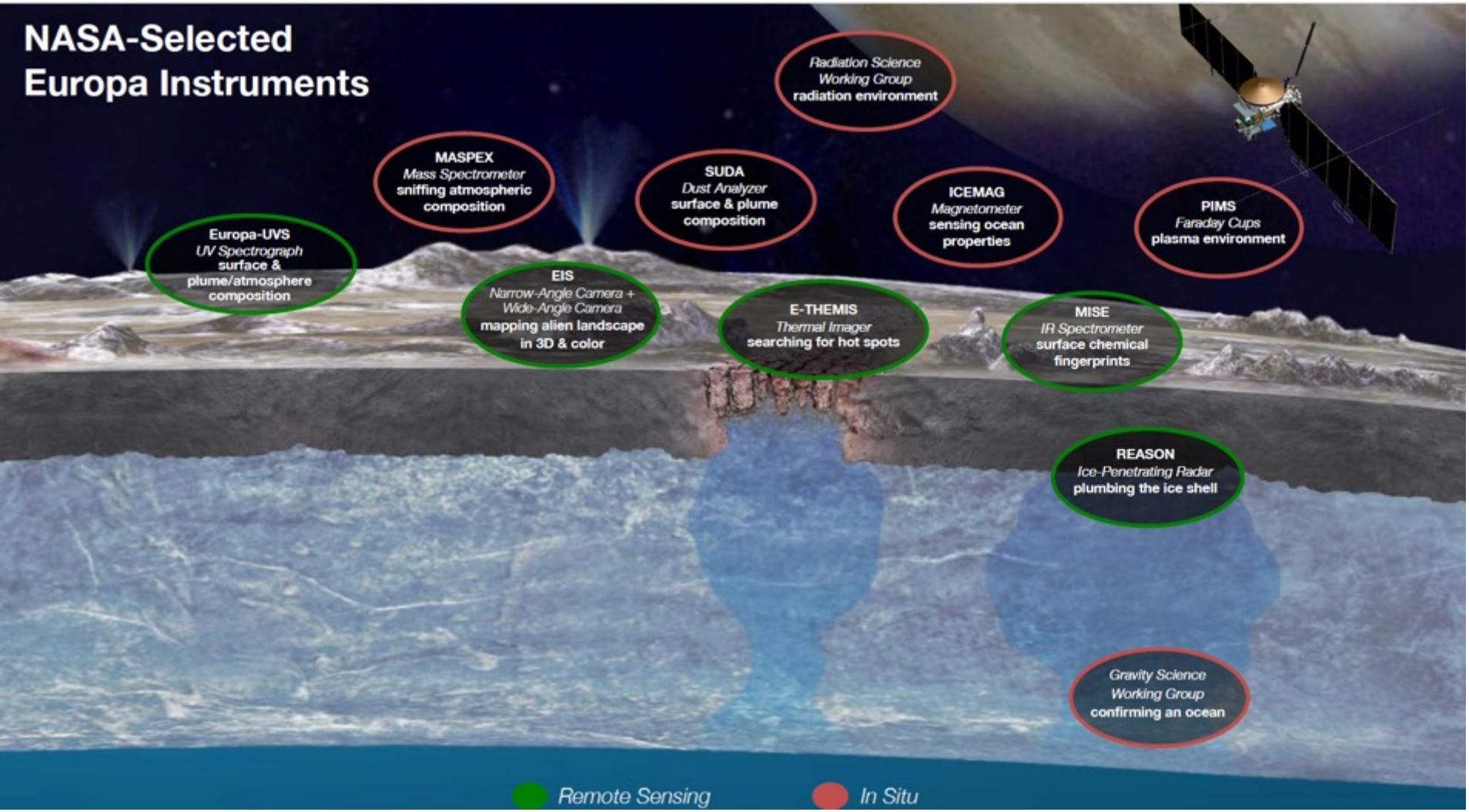
Europa Clipper
Science Instruments

- **Europa Imaging System (EIS)** -- The wide and narrow angle cameras on this instrument will map most of Europa at 50 meter (164 foot) resolution, and will provide images of areas of Europa's surface at up to 100 times higher resolution.
- **Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)** -- This dual-frequency ice penetrating radar instrument is designed to characterize and sound Europa's icy crust from the near-surface to the ocean, revealing the hidden structure of Europa's ice shell and potential water within.
- **SUrface Dust Mass Analyzer (SUDA)** -- This instrument will measure the composition of small, solid particles ejected from Europa, providing the opportunity to directly sample the surface and potential plumes on low-altitude flybys.

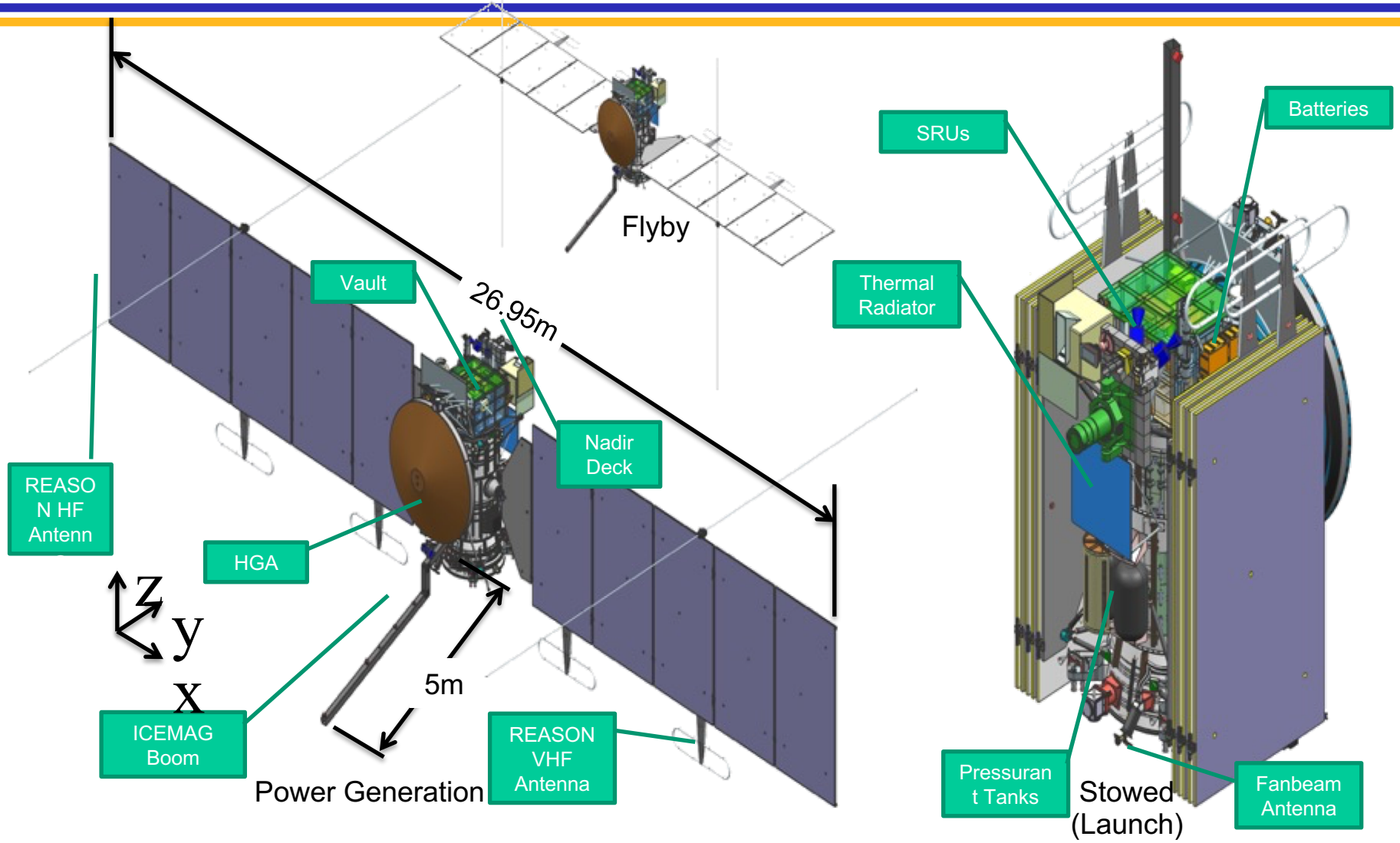
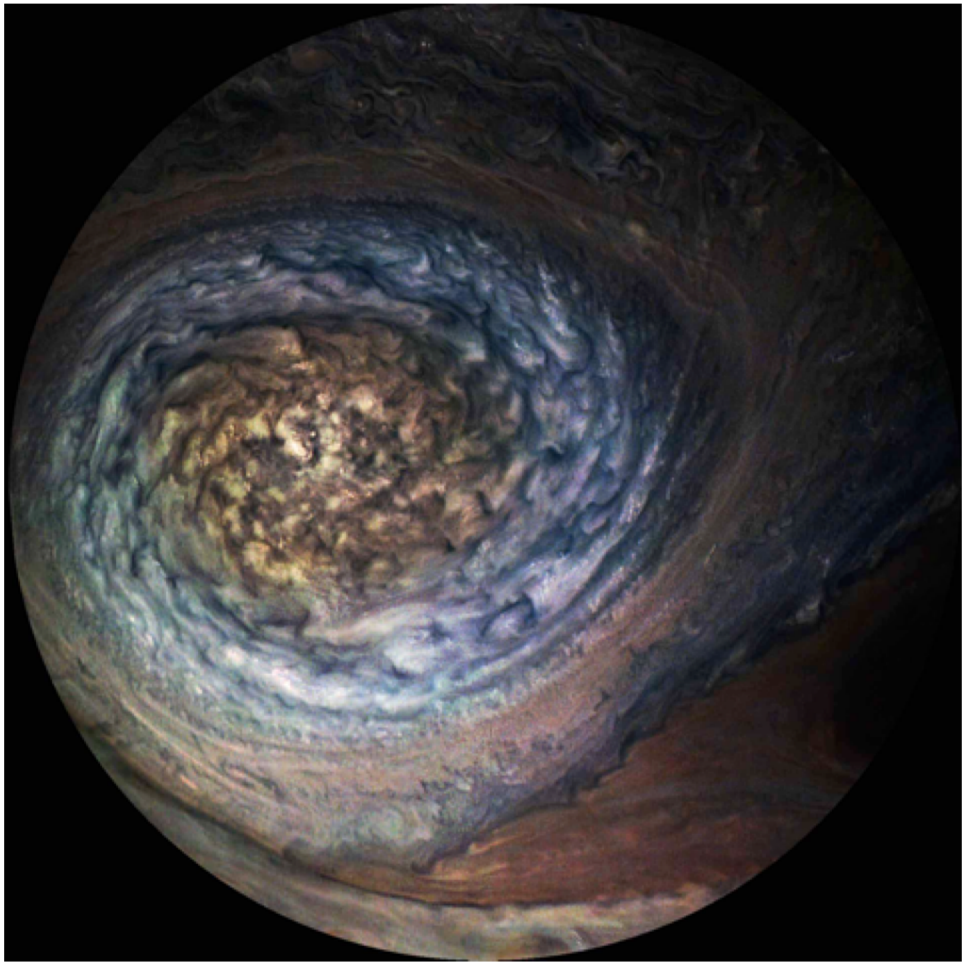
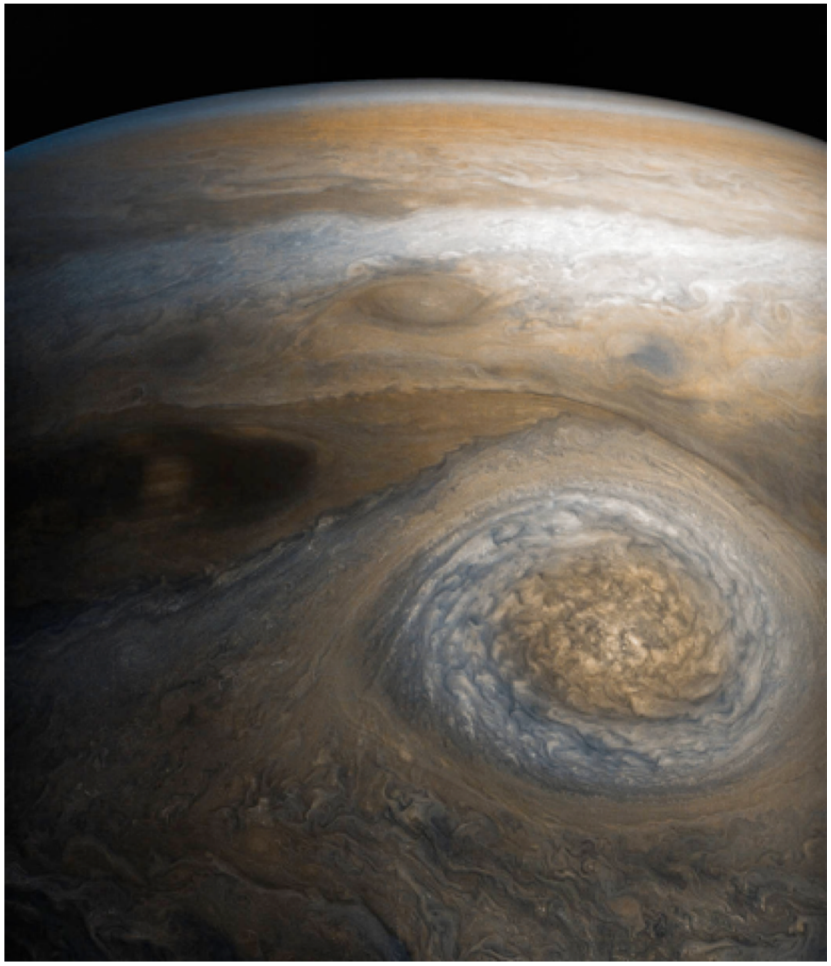
Europa Clipper Science Instruments

- **Europa Thermal Emission Imaging System (E-THEMIS)** -- This "heat detector" will provide high spatial resolution, multi-spectral thermal imaging of Europa to help detect active sites, such as potential vents erupting plumes of water into space.
- **MAss SPectrometer for Planetary EXploration/Europa (MASPEX)** -- This instrument will determine the composition of the surface and subsurface ocean by measuring Europa's extremely tenuous atmosphere and any surface material ejected into space.
- **Ultraviolet Spectrograph/Europa (UVS)** -- This instrument will adopt the same technique used by the Hubble Space Telescope to detect the likely presence of water plumes erupting from Europa's surface. UVS will be able to detect small plumes and will provide valuable data about the composition and dynamics of the moon's rarefied atmosphere.

The Europa Clipper Spacecraft



Configuration



THANK YOU!