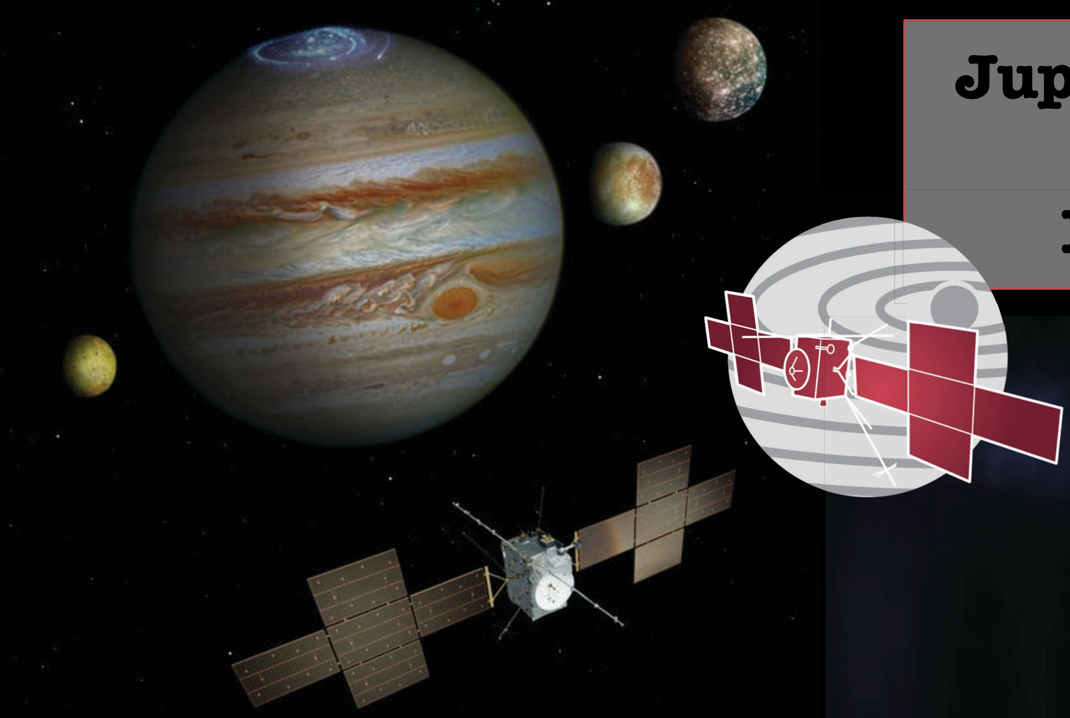
Jupiter Science in the Next Decade: From Juno to JUICE



@LeighFletcher
(w/thanks to D. Grassi, M. Galand, T. Cavalie, R. Hueso, O. Witasse & JUICE Science Working Team)

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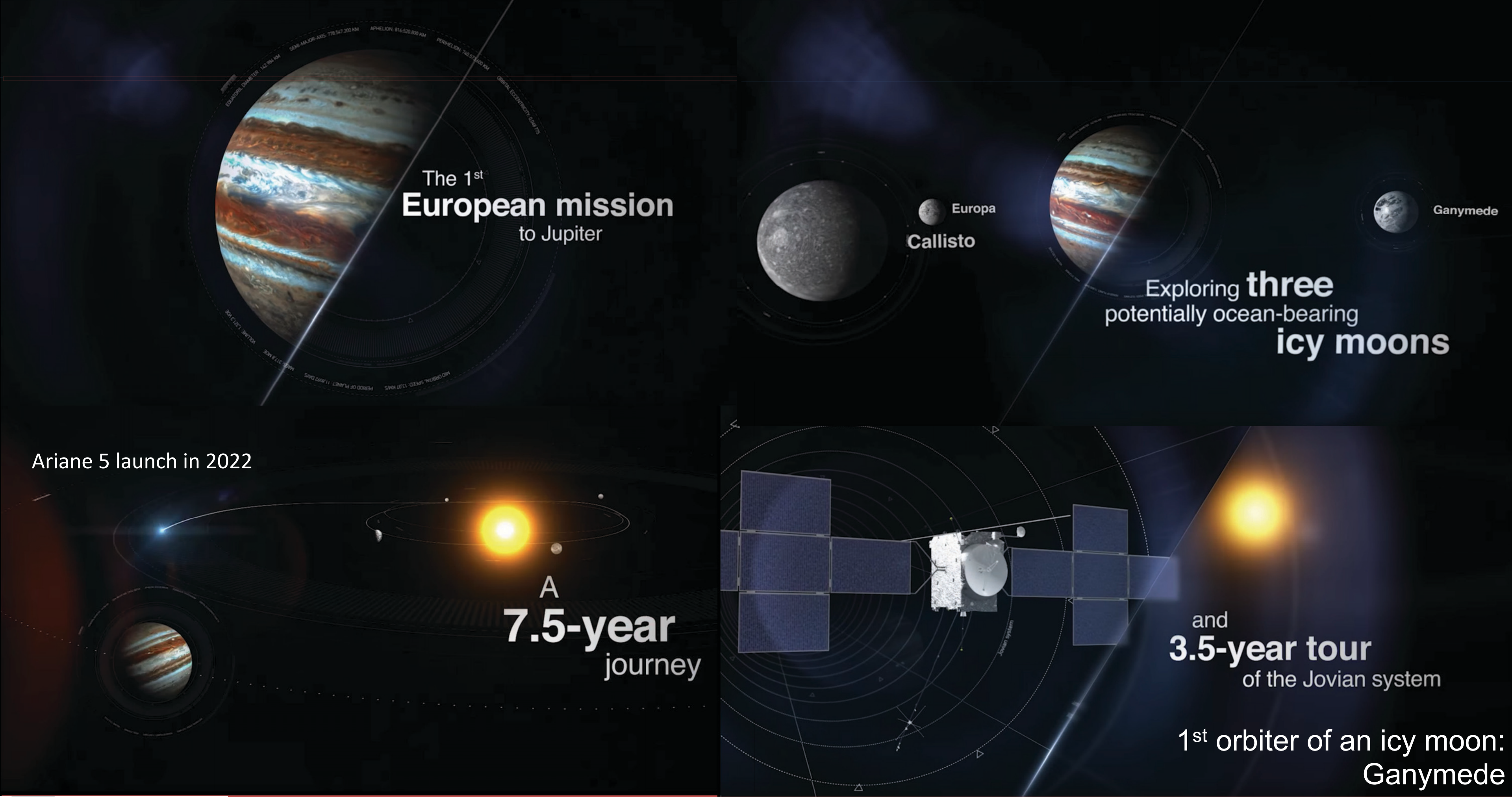
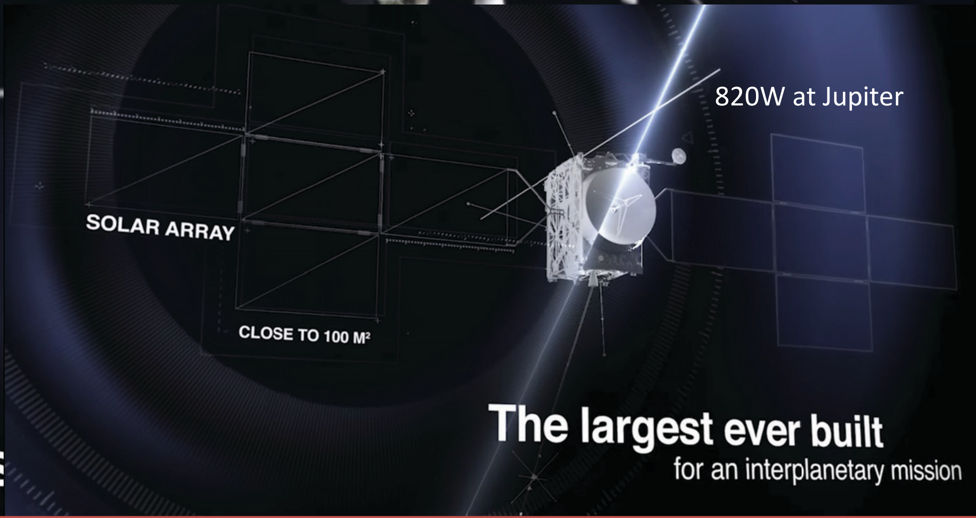
THE ROYAL SOCIETY


The 1st
European mission
to Jupiter
Europa
Callisto
Ganymede
Exploring three
potentially ocean-bearing
icy moons
Ariane 5 launch in 2022
A
7.5-year
journey
and
3.5-year tour
of the Jovian system
1st orbiter of an icy moon:
Ganymede

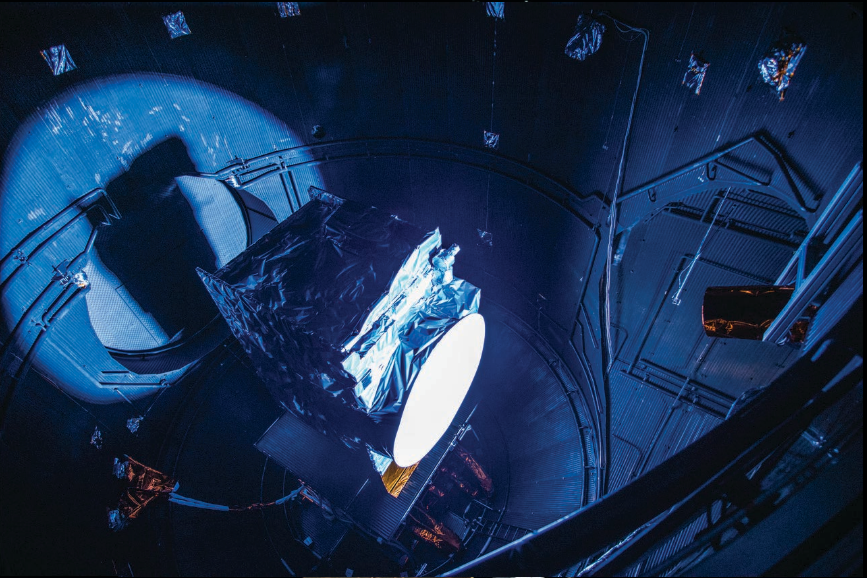

5.3 tonne spacecraft
Carrying 10
scientific
instruments


Unprecedented electromagnetic
cleanliness level


All electronics housed in
shielded vaults

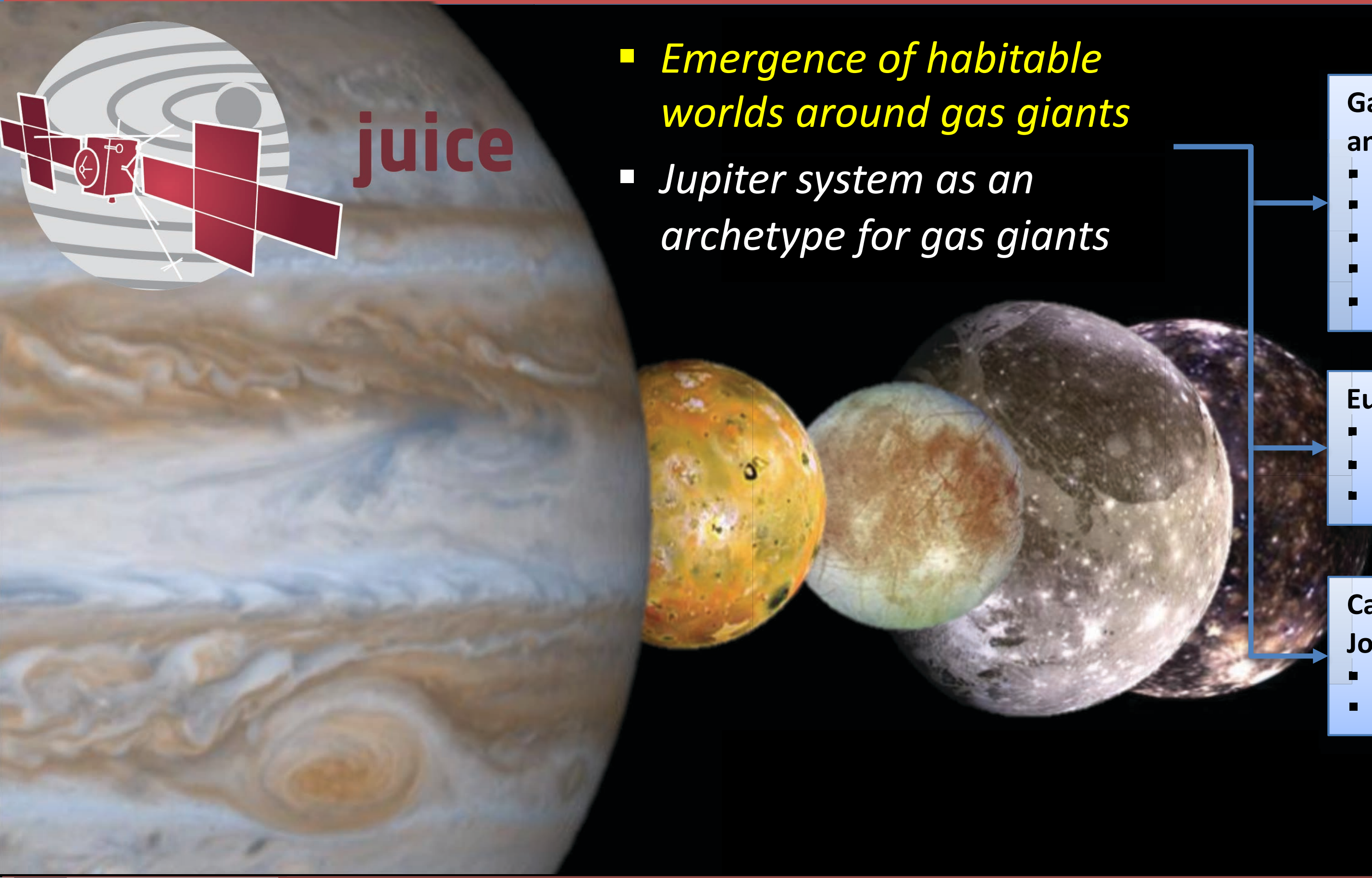

820W at Jupiter
SOLAR ARRAY
CLOSE TO 100 M²
The largest ever built
for an interplanetary mission

How Did We Get Here?



- ESA **Cosmic Vision** 2007 – Laplace
- JGO+JEO=EJSM (Europa-Jupiter System Mission) 2008-2011.
- NASA Withdrawal led JGO->JUICE 2011-2012.
- Officially selected as L1 in May 2012.
- Phase A/B1 (prelim definition) to formal adoption Nov 2014.
- Airbus D&S selected July 2015.
- Passed PDR and into Phase C (detailed definition) March 2017, prototype units under construction.
- Upcoming CDR to move into Phase D (2.5yrs, Q2 2019).
- Launch May-June 2022.

JUICE Science Themes



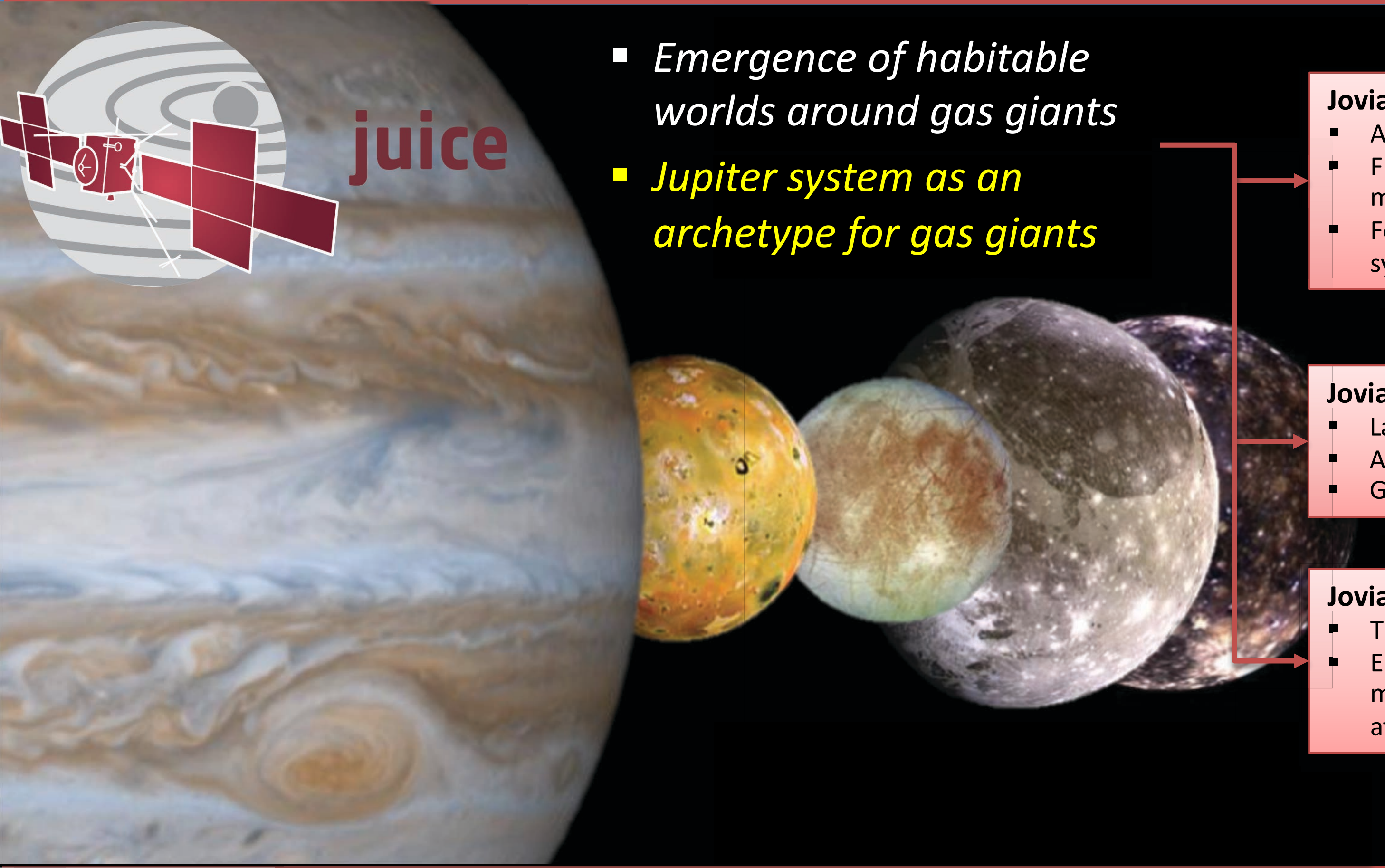
- *Emergence of habitable worlds around gas giants*
- *Jupiter system as an archetype for gas giants*

Ganymede as a planetary object and possible habitat
- Largest satellite in the solar system
- Ocean between icy layers
- Internal dynamo
- Richest crater morphologies
- Archetype of waterworlds

Europa's recently active zones
- Impactor history
- Enigmatic differentiation
- Witness of early ages

Callisto as a remnant of the early Jovian system
- An active world?
- Ocean in contact with silicates

JUICE Science Themes



- *Emergence of habitable worlds around gas giants*
- *Jupiter system as an archetype for gas giants*

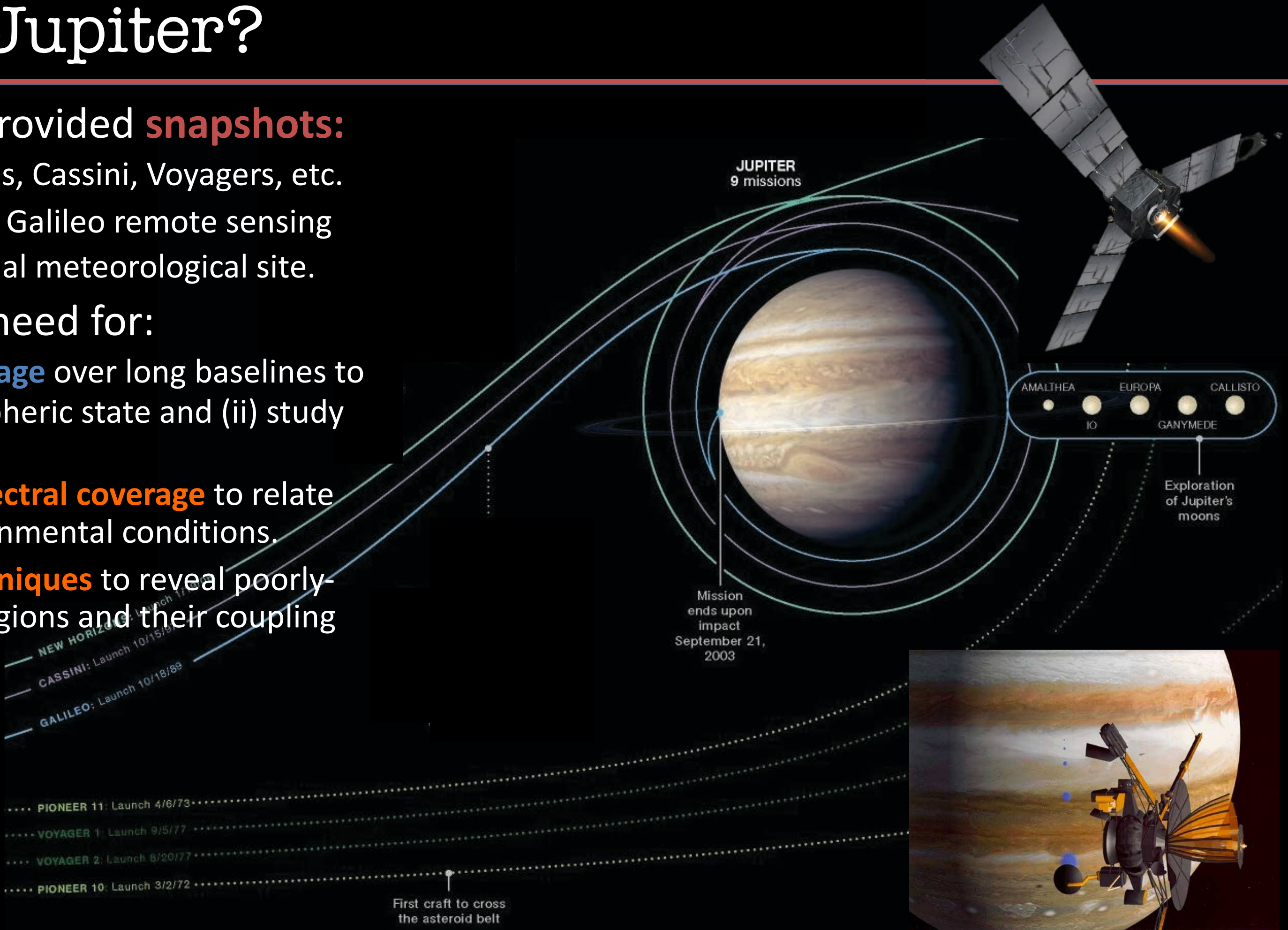
Jovian atmosphere
- Archetype for giant planets
- Fluid dynamics, chemistry, meteorology,...
- Formational history of planetary system

Jovian magnetosphere
- Largest object in our Solar System
- Astrophysical mechanisms at work
- Giant particle accelerator

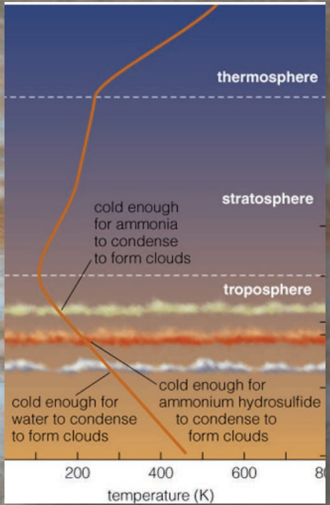
Jovian satellite and ring systems
- Tidal forces: Laplace resonance
- Electromagnetic interactions to magnetosphere and upper atmosphere of Jupiter

Context: Why Jupiter?

- Previous exploration provided **snapshots:**
  - Flybys from New Horizons, Cassini, Voyagers, etc.
  - Limited data return from Galileo remote sensing
  - In situ sampling of unusual meteorological site.
- Literature reveals the need for:
  - **Continuity of data coverage** over long baselines to (i) define a mean atmospheric state and (ii) study departures from it.
  - **Broad, simultaneous spectral coverage** to relate visible changes to environmental conditions.
  - **Novel instrumental techniques** to reveal poorly-explored atmospheric regions and their coupling processes.

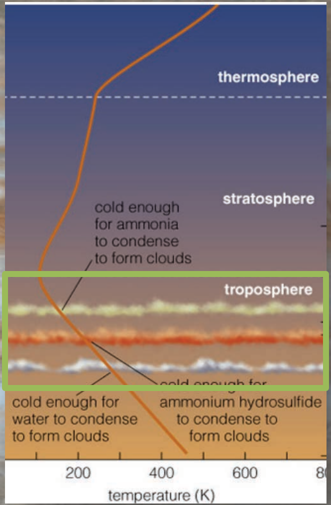


JUICE Jupiter Science Questions



- External Env.
- Upper Atmos.
- Middle Atmos.
- Troposphere
- Interior/Origin

JUICE Jupiter Science Questions



External Env.

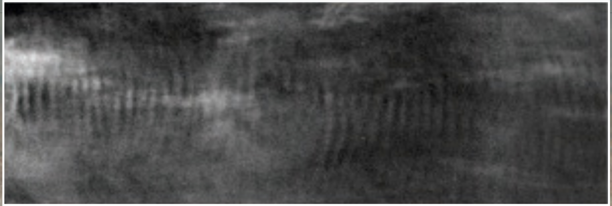
Upper Atmos.

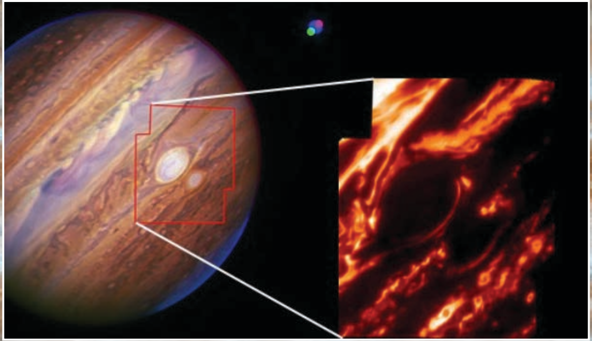
Middle Atmos.

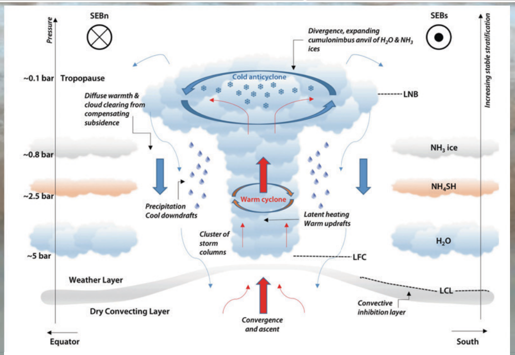
Troposphere

Interior/Origin

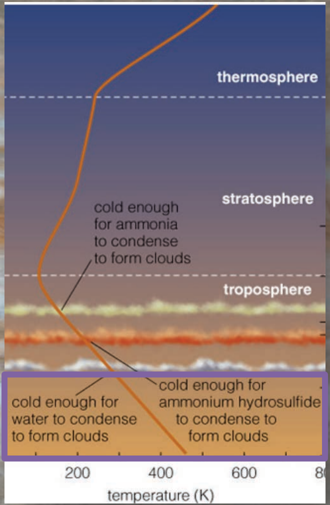
- Stability, maintenance, energetics of zonal winds (eddies, waves, energy cascade)
- Influence of (moist) convection/lightning
- Temporal variability of belt/zone structure
- Evolution and structure of discrete phenomena (e.g., GRS, vortices, plumes)
- Compositional tracers of vertical/meridional mixing
- Structure & composition of clouds and hazes







JUICE Jupiter Science Questions



External Env.

Upper Atmos.

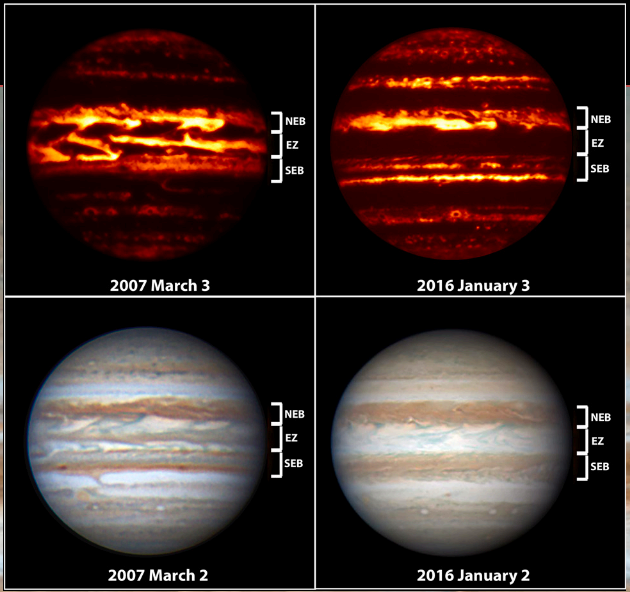
Middle Atmos.

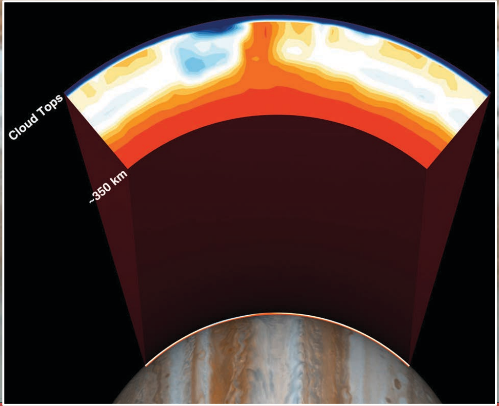
Troposphere

Interior/Origin

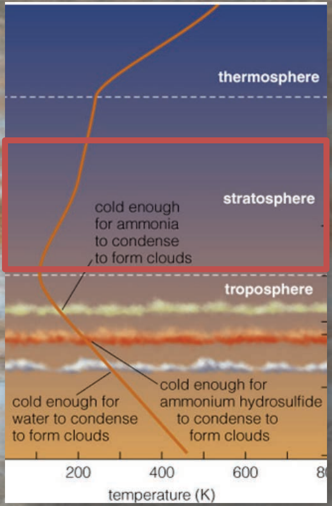
Elemental abundances & isotopic ratios

Coupling of weather layer to deep interior





JUICE Jupiter Science Questions



External Env.

Upper Atmos.

Middle Atmos.

Troposphere

Interior/Origin

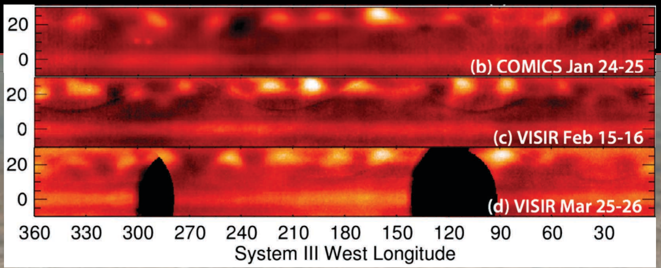
Global circulation of the middle atmosphere and zonal winds

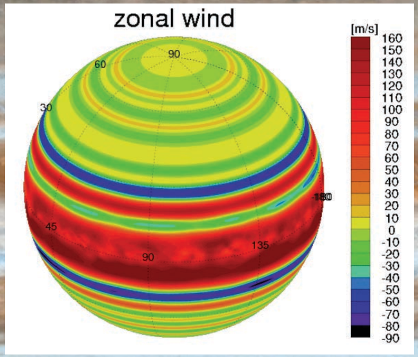
Stratospheric composition (esp. H2O) and photochemistry

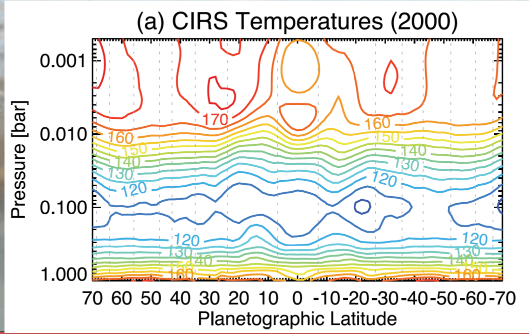
Exogenic sources (cometary, IDPs, rings, satellites)

Dynamics of the QQO (quasi-quadrennial oscillation)

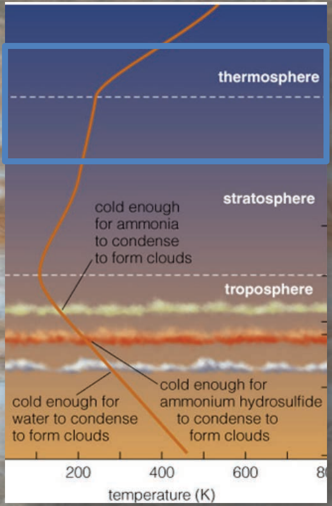
Thermal wave phenomena & coupling to tropospheric meteorology







JUICE Jupiter Science Questions



External Env.

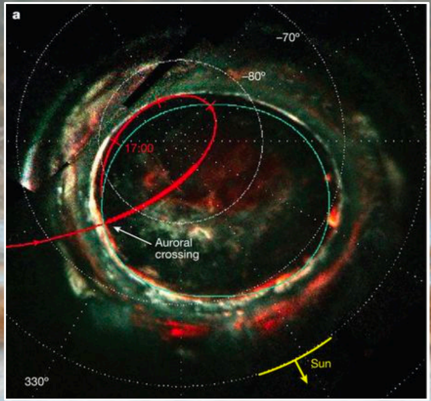
Upper Atmos.

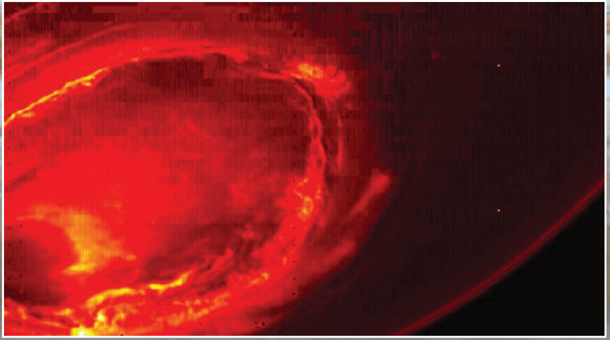
Middle Atmos.

Troposphere

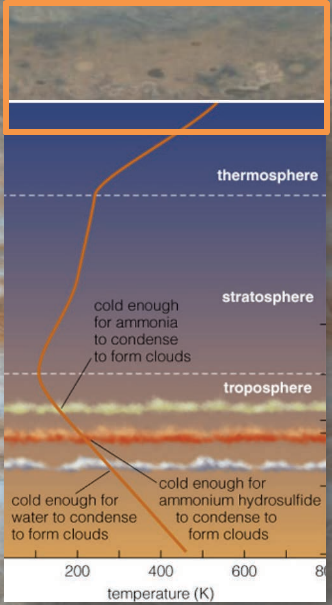
Interior/Origin

- Circulation/composition of thermosphere- ionosphere & exospheric temp.
- Coupling of thermosphere to deeper atmosphere (e.g., waves, homopause)
- Airglow morphology and anomalies
- Ion-neutral chemistry
- Temporal variability and structure of aurora (polar & low-latitude)
- Influence of auroral energy on polar temperatures/winds





JUICE Jupiter Science Questions



External Env.

Upper Atmos.

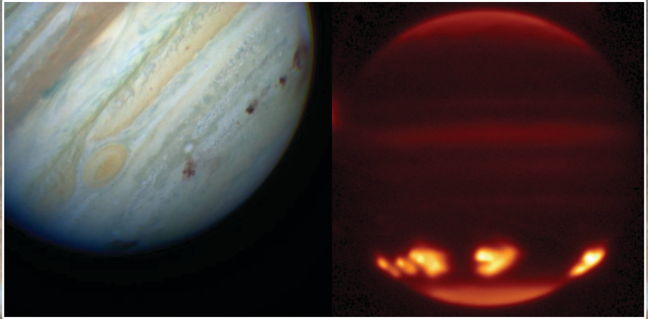
Middle Atmos.

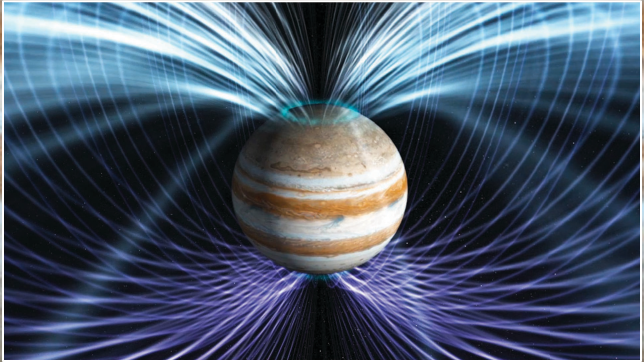
Troposphere

Interior/Origin

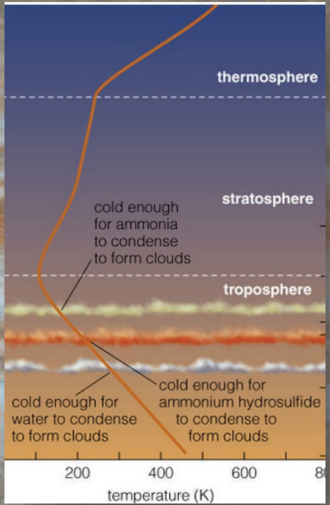
Coupling to external magnetosphere/aurora (precipitating e-, changing torus, inner mag.)

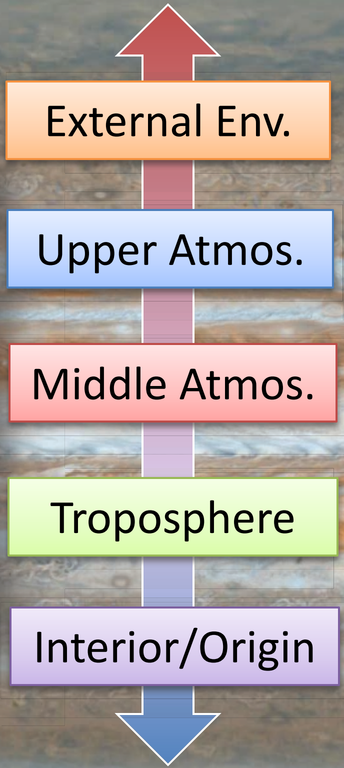
Impacting bodies in the jovian system





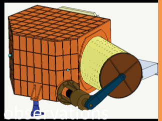
JUICE Jupiter Science Questions





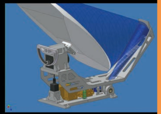
- Require remote sensing across ***broad wavelength range*** to probe vertical structure from the thermosphere to the cloud decks and below.
- Require ***high spatial resolutions and global coverage*** of Jupiter's atmosphere at multiple atmospheric levels.
- Require ***long baseline of observations*** across a broad wavelength range to monitor variability on multiple timescales from hours to years.

JANUS: Visible Camera System
PI: Pasquale Palumbo, Parthenope University, Italy.
Co-PI: Ralf Jaumann, DLR, Germany



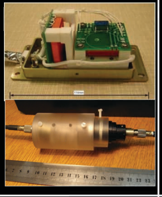
- ≥7.5m/pixel
- Multiband imaging, 380 - 1080 nm
- Icy moon geology
- Io activity monitoring and other moons observations
- Jovian atmosphere dynamics

SWI: Sub-mm Wave Instrument
PI: Paul Hartogh, MPS, Germany



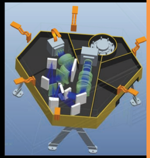
- 600 GHz and 1200 GHz
- Jovian Stratosphere
- Moon atmosphere
- Atmospheric isotopes

JMAG: JUICE Magnetometer
PI: Michele Dougherty, Imperial, UK



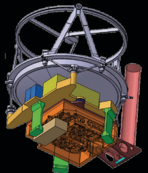
- Dual Fluxgate and Scalar mag
- ±8000 nT range, 0.2 nT accuracy
- Moon interior through induction
- Dynamical plasma processes

MAJIS: Imaging VIS-NIR/IR Spectrograph
PI: Yves Langevin, IAS, France
Co-PI: Guiseppe Piccioni, INAF, Italy



- 0.9-1.9 μm and 1.5-5.7 μm
- ≥62.5 m/pixel
- Surface composition
- Jovian atmosphere

GALA: Laser Altimeter
PI: Hauke Hussmann, DLR, Germany

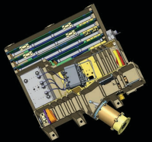


- ≥40 m spot size
- ≥0.1 m accuracy
- Shape and rotational state
- Tidal deformation
- Slopes, roughness, albedo

PEP: Particle Environment Package
PI: Stas Barabash, IRF-K, Sweden
Co-PI: Peter Wurz, UBe, Switzerland

- Six sensor suite
- Ions, electrons, neutral gas (in-situ)
- Remote ENA imaging of plasma and torus

UVS: UV Imaging Spectrograph
PI: Randy Gladstone, SwRI, USA



- 55-210 nm
- 0.04˚-0.16˚
- Aurora and Airglow
- Surface albedos
- Stellar and Solar Occultation

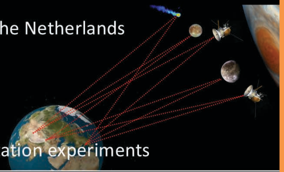
RIME: Ice Penetrating Radar
PI: Lorenzo Bruzzone, Trento, Italy
Co-PI: Jeff Plaut, JPL, USA

- ≥40 m spot size
- ≥0.1 m accuracy
- Shape and rotational state
- Tidal deformation
- Slopes, roughness, albedo

RPWI: Radio and Plasma Wave Investigation
PI: Jan-Erik Wahlund, IRF-U, Sweden

- Langmuir Probes
- Search Coil Magnetometer
- Tri-axial dipole antenna
- E and B-fields
- Ion, electron and charged dust parameters

PRIDE: Planetary Radio Interferometer & Doppler Experiment
PI: Leonid Gurvits, JIVE, EU/The Netherlands



- VLBI Radio Tracking
- S/C state vector
- Ephemerides
- bi-static and radio occultation experiments

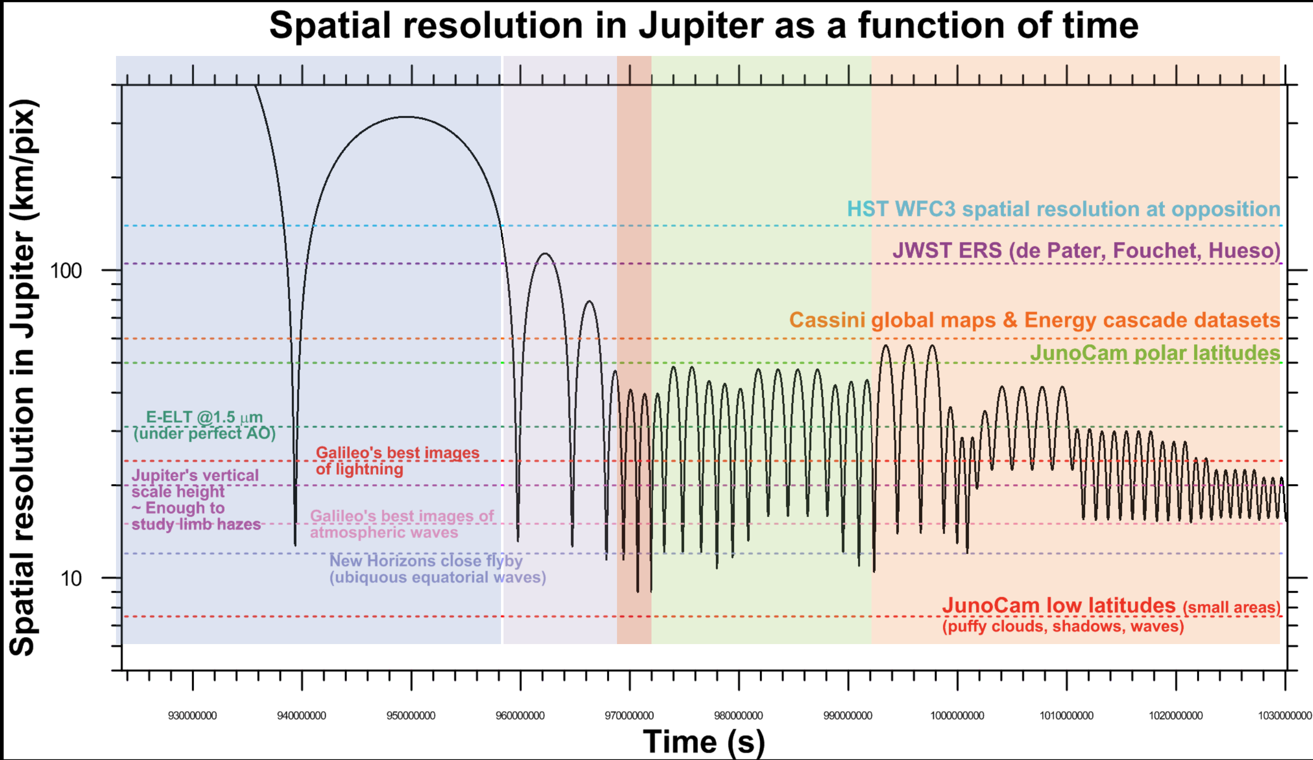
3GM: Gravity, Geophysics, Galilean Moons
PI: Luciano Iess, Rome, Italy
Co-PI: David J. Stevenson, CalTech, USA
Co-PI: Yohai Kaspi, Israel

- Ranging by radio tracking **+ USO**
- 2 μm/s range rate
- 20 cm range accuracy
- Gravity fields and tidal deformation

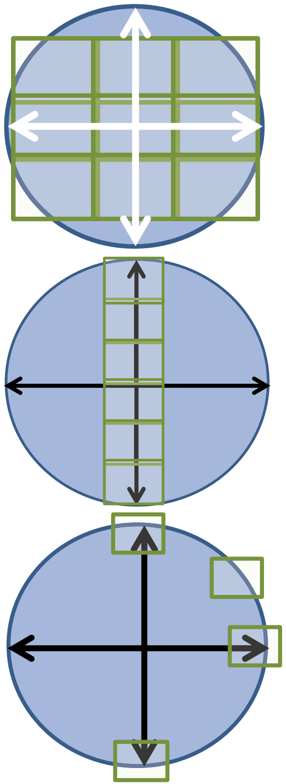
JUICE Payload

JANUS: Visible Camera System

Filter id.	λ / width [nm] (tbc)	Note
FPAN	650/500	Panchromatic – monochromatic imaging
FBLUE	450/60	Blue – satellite colours
FGREEN	530/60	Green, background for Na – satellite colours
FRED	656/60	Red, background for Ha– satellite colours
CMT medium	750/20	Continuum for strong Methane band on Jupiter, geology
Na	590/10	Sodium D-lines in exospheres
MT strong	889/20	Strong Methane band on Jupiter
CMT strong	940/20	Continuum for medium Methane band on Jupiter, Fe^{2+} on satellites
MT medium	727/10	Medium Methane band on Jupiter
Violet	410/80	UV slope of satellites surfaces
NIR 1	910/80	Fe^{2+}, Io lava spots
NIR 2	1000/ 150	Fe^{2+}, Io lava spots
Ha	656/10	Hα-line for aurorae and lightnings



JANUS



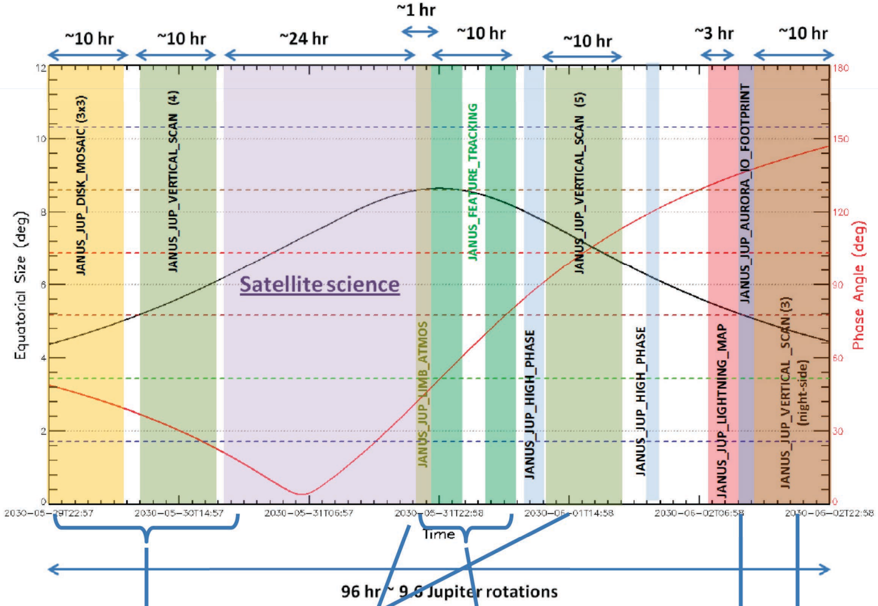
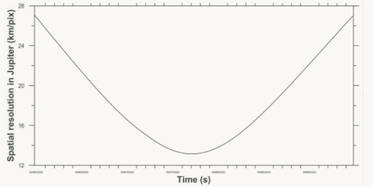


Figure 9 Example of JANUS perijove operations. Angular diameter of Jupiter (black-line, left axis) and phase angle (red line, right axis) surrounding PJ2 and 2G2.

EARLY WG Science

PJ2: Spatial resolution from 13 to 27 km/pix (2-5 better than JunoCam over the pole and comparable to JunoCam over the GRS)



Day-side: Global maps wind noise measurement level: ~ 1 m/s

NEVER ACHIEVED BEFORE

Limb views at 12 km/pix (low data required)

NEVER ACHIVED BEFORE

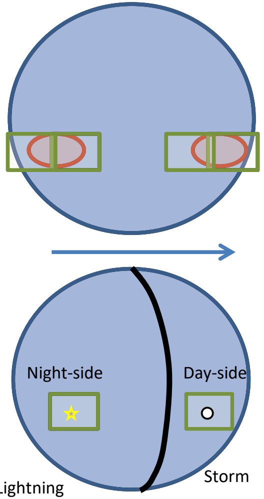
Juno high-clouds from views on the terminator (60 km)

Feature tracking wind noise measurement level: ~ 0.3 m/s
Moderate DV required
NEVER ACHIEVED BEFORE

Resolution 22 km/pix
Size of Io footprint depend on magnetic projection of Io 200-800 km (10-33 resolution elements)

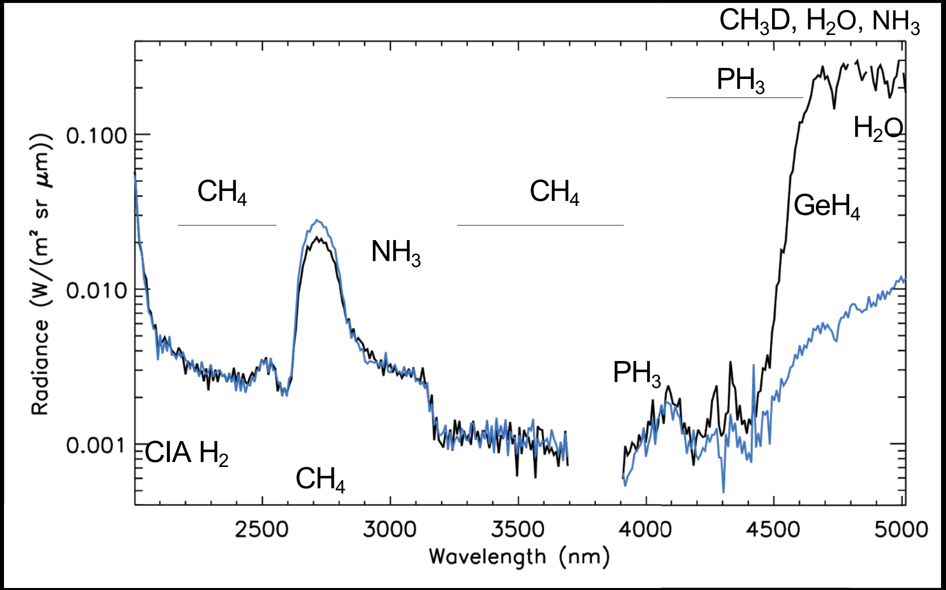
Lightning flashes size depends on its depth. For lightning in water condensation clouds 5 pixels width lightning strokes are expected.

NEVER ACHIEVED BEFORE

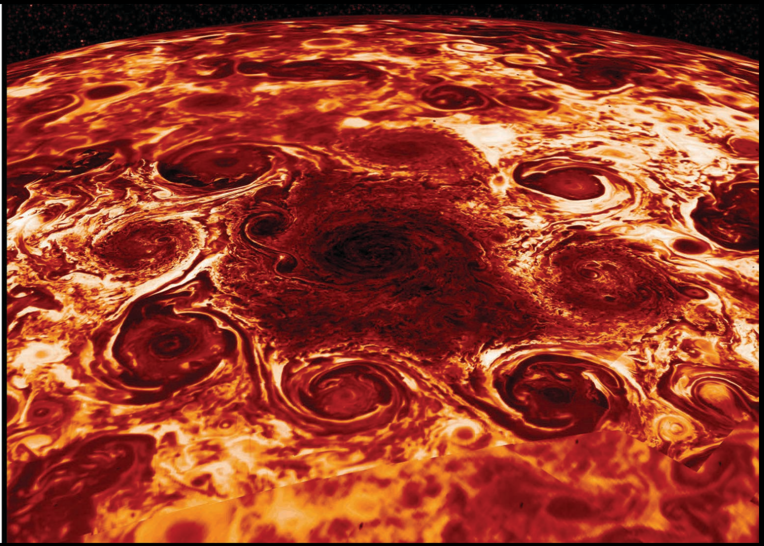


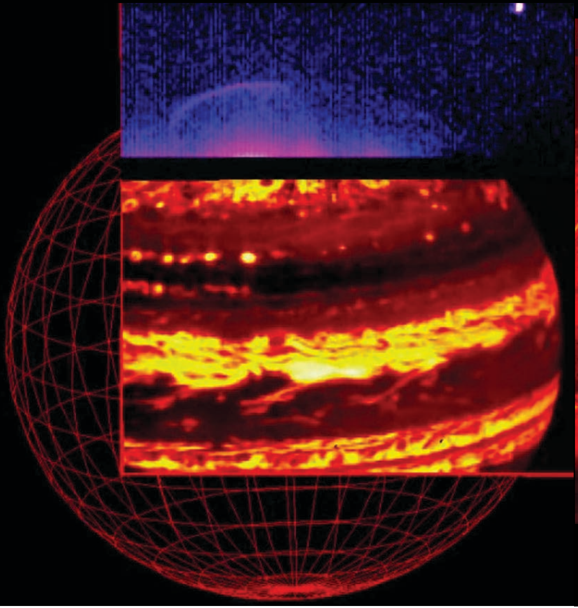
MAJIS: Vis/NIR Spectrograph

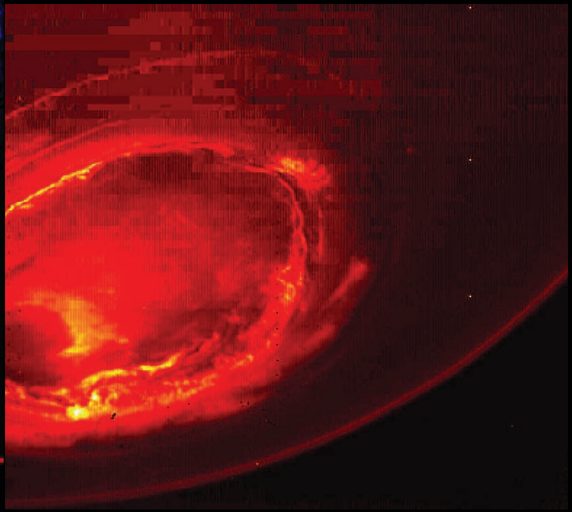
- Pushbroom – 400-pixel long line, spectrum in each.
- **Two channels**
  - VIS-NIR: range 0.5-2.35 μm with a spectral sampling of 3.64 nm
  - IR: range 2.25-5.54 μm with a spectral sampling of 6.48 nm
- **Compared to previous (VIMS, NIMS, JIRAM):**
  - Longer wavelengths (better water/NH_3 discrimination)
  - Shorter wavelengths (CH_4 bands for cloud tomography).
  - Higher resolution (break degeneracies, measure H_3^+).

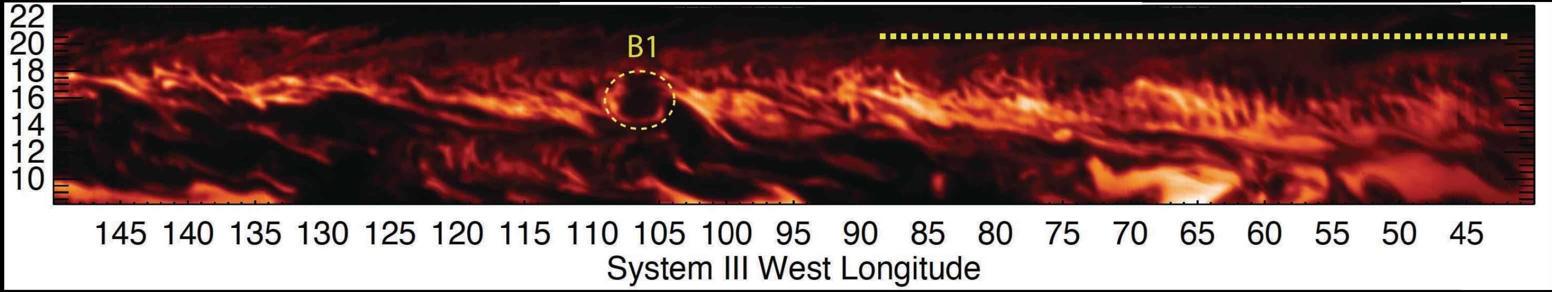


From JIRAM to MAJIS

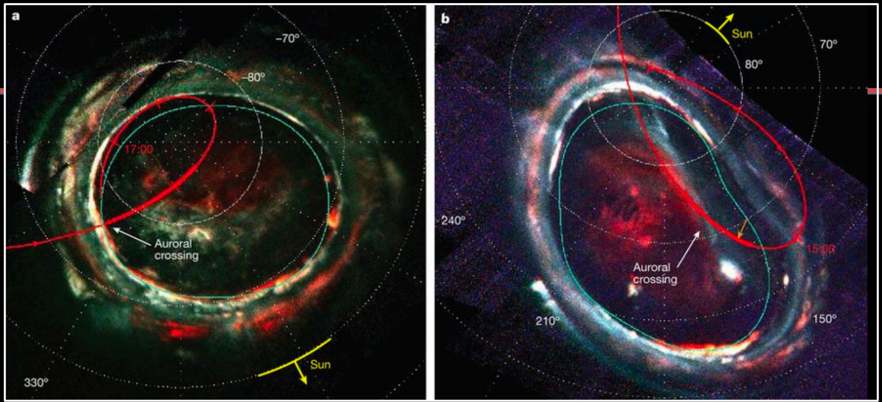




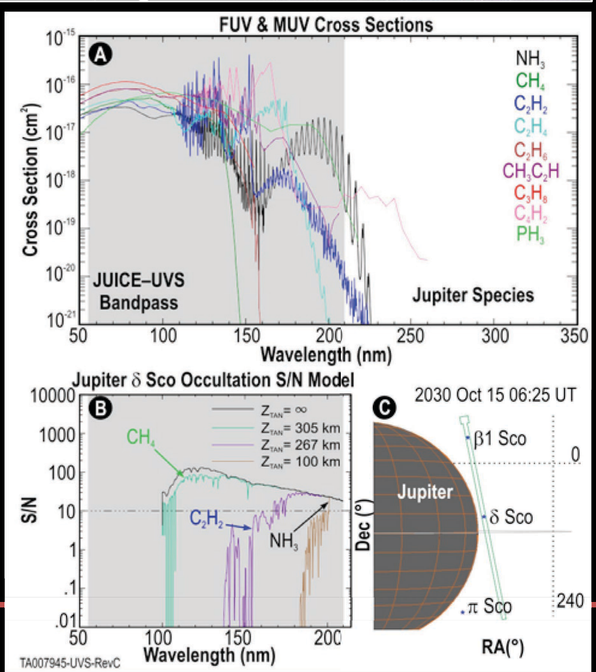


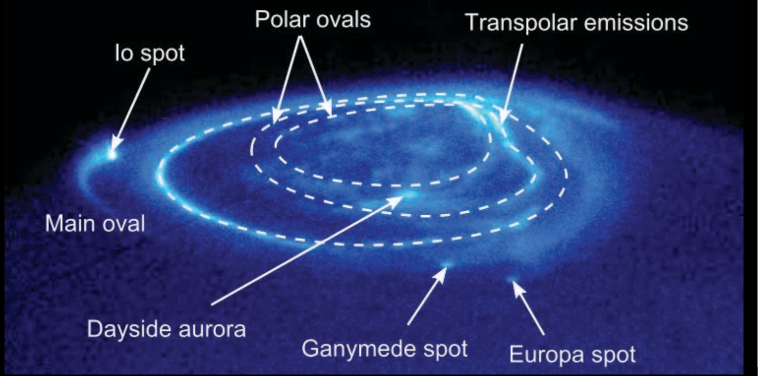


UVS: Imaging Spectrograph

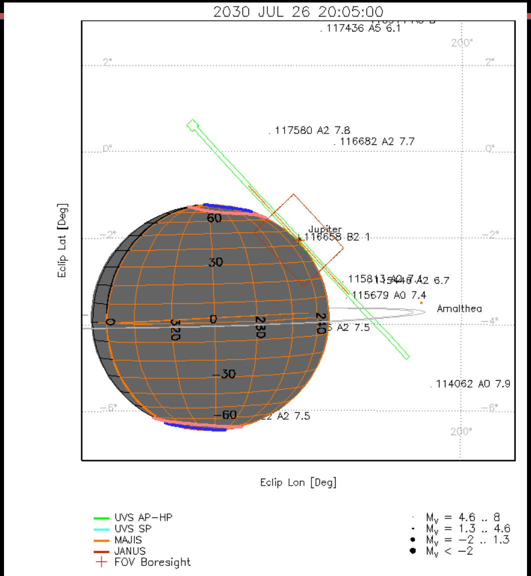


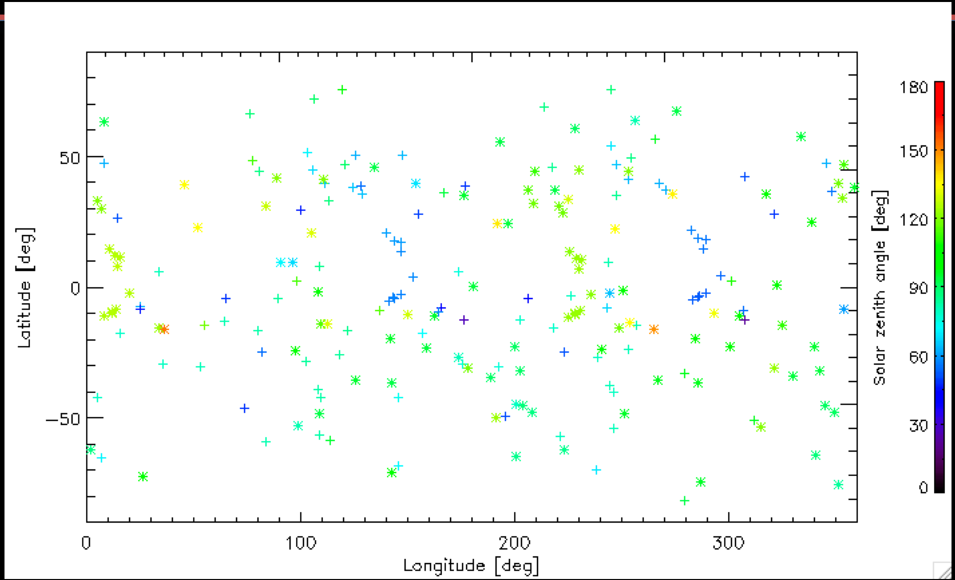
- Updated design compared to Juno/UVS.
- EUV and FUV: 55 – 210 nm (e.g., emissions: H_2 bands, H-Lyman series; absorption: H_2, hydrocarbons, NH_3)
- **Primary modes:**
  - UV atmospheric emissions (airglow/aurora) & scattered sunlight
  - UV transmission in stellar & solar occultations.





Advantages of JUICE/UVS

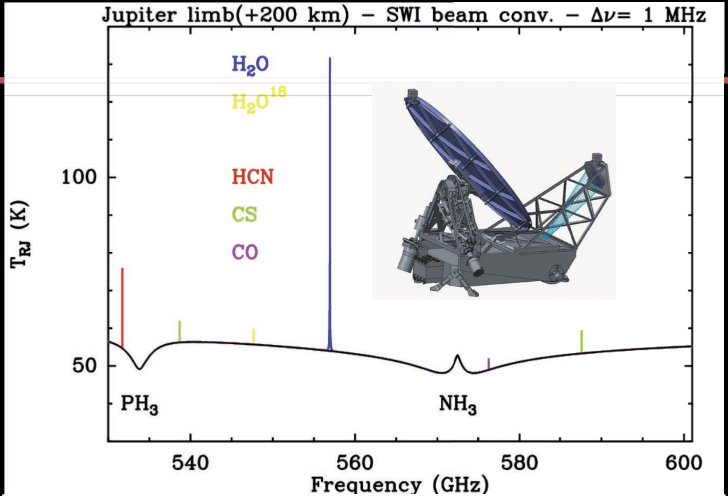


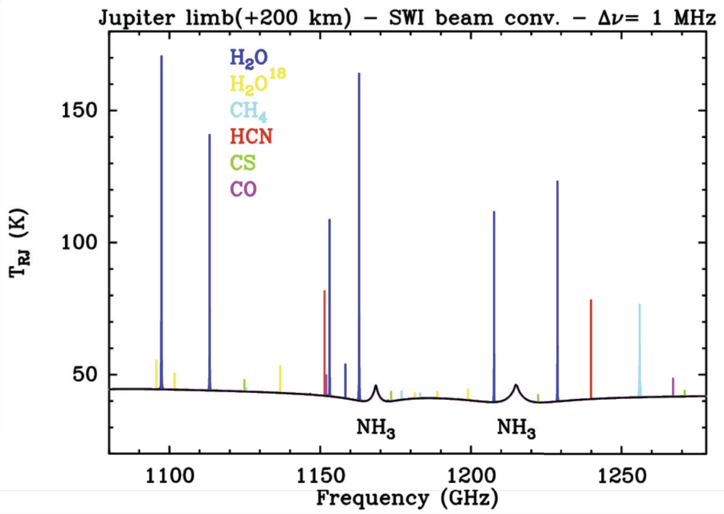


- Juno focus on aurora, JUICE focus on middle and upper atmosphere globally.
- Juno narrow observing windows near perijove; JUICE extensive long-term monitoring throughout the orbital tour.
- Juno orbits constraints time of day (dawn/dusk), JUICE samples at a broad range of local times.
- JUICE capabilities for stellar and solar occultations.

SWI: Sub-mm Wave Instrument

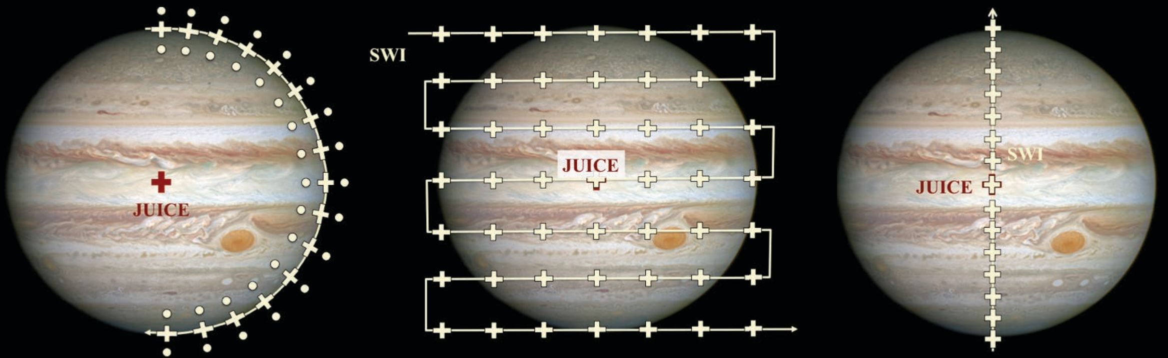
- Never done before:
  - Direct measurement of middle atmospheric winds.
  - Temperature measurements from CH4.
  - Tracing composition from exogenic sources (H2O, HCN, CO)
  - Water isotopologues and para-H2 fraction for origins.
- Two passively cooled (140 K) Schottky receivers
  - 530 – 625 GHz (600-900 K DSB)
  - 1080 – 1275 GHz (3000-4000 K DSB)
  - IF-range: 3.5 – 8.5 GHz

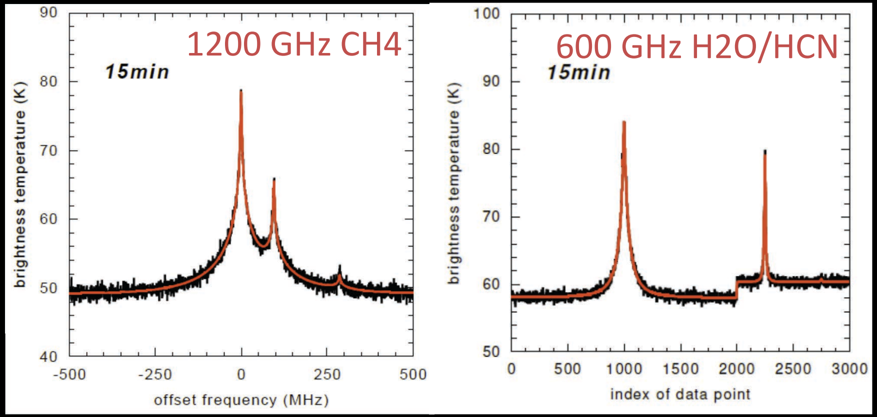




SWI: Observing Strategy

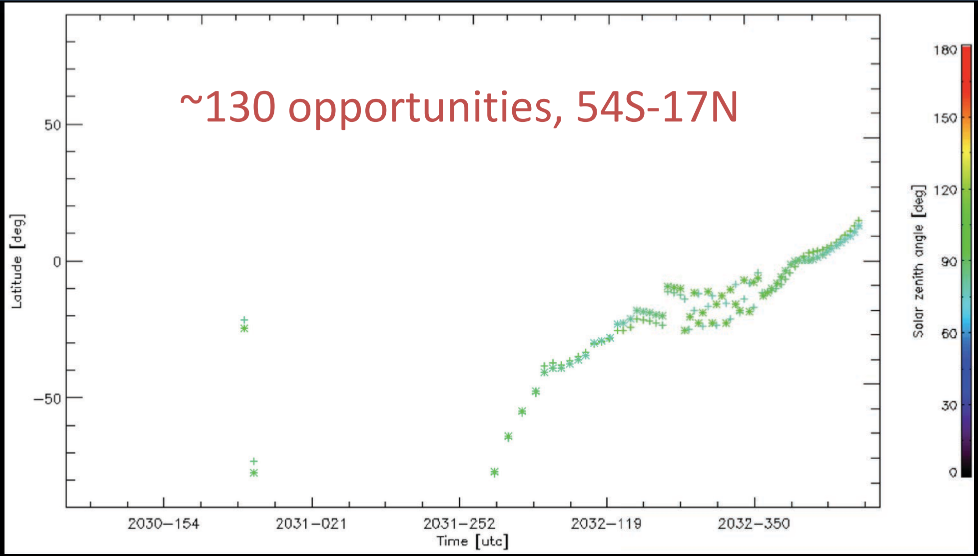
- Scan single point over disc, 30 cm aperture elliptic antenna, movable ±72 and ±4.3 deg (antenna and rocker mechanisms)
- Continuous operations 16h/day, using moveable mirror to perform scans and rasters.
- CH_4/HCN for T retrieval; H_2O for composition; Doppler shift for direct winds.

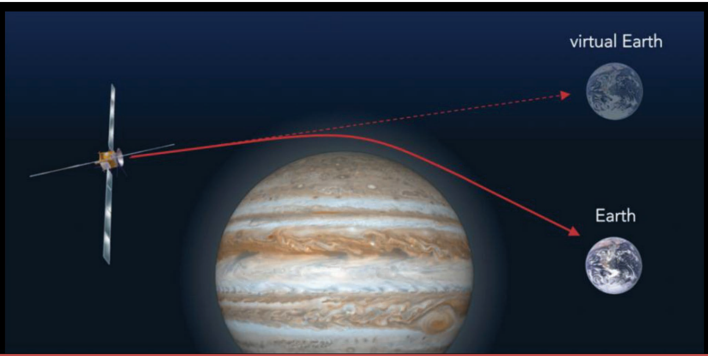




3GM: Jupiter Radio Occultations

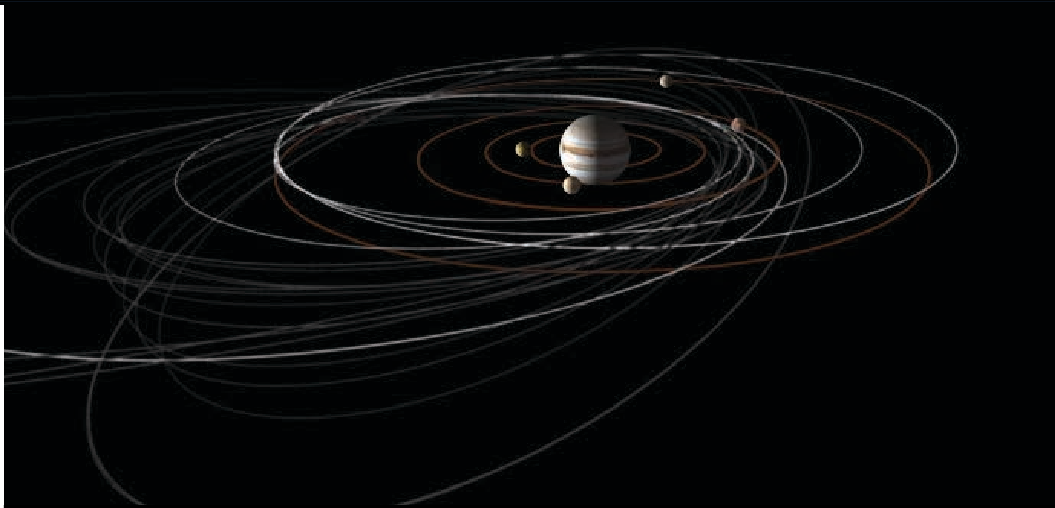
- **Three components:**
  - High performance dual-frequency radio links (X and Ka-band)
  - Steerable medium gain antenna (MGA),
  - Ultra-stable oscillator (USO).
- **Radio occultations of neutral atmosphere and ionosphere:**
  - Retrieve vertical profiles of density, pressure, temperature, and NH3.
  - Measure ionospheric electron densities in auroral to study auroral structure and energy transport.
  - Study the relation between vertically propagating waves and the heating mechanisms for the thermosphere.
  - Inference of zonal winds.

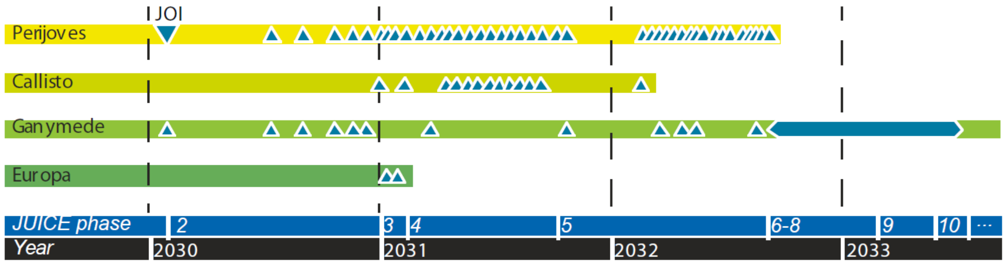




JUICE Tour

Date	Event or phase
June 2022	Launch from Kourou with Ariane 5
May 2023	Earth flyby #1
October 2023	Venus flyby
September 2024	Earth flyby #2
February 2025	Mars flyby
November 2026	Earth flyby #3
October 2029	Jupiter orbit insertion
October 2029-October 2030	Energy reduction phase
October 2030	2 Europa flybys
October 2030-August 2031	Jupiter inclined phase - Callisto flybys
September 2031-November 2032	Phase "transfer to Ganymede"
December 2032	Ganymede orbit insertion
December 2032-September 2033	Elliptical and circular orbits (5000/500 km)
September 2033	End of mission

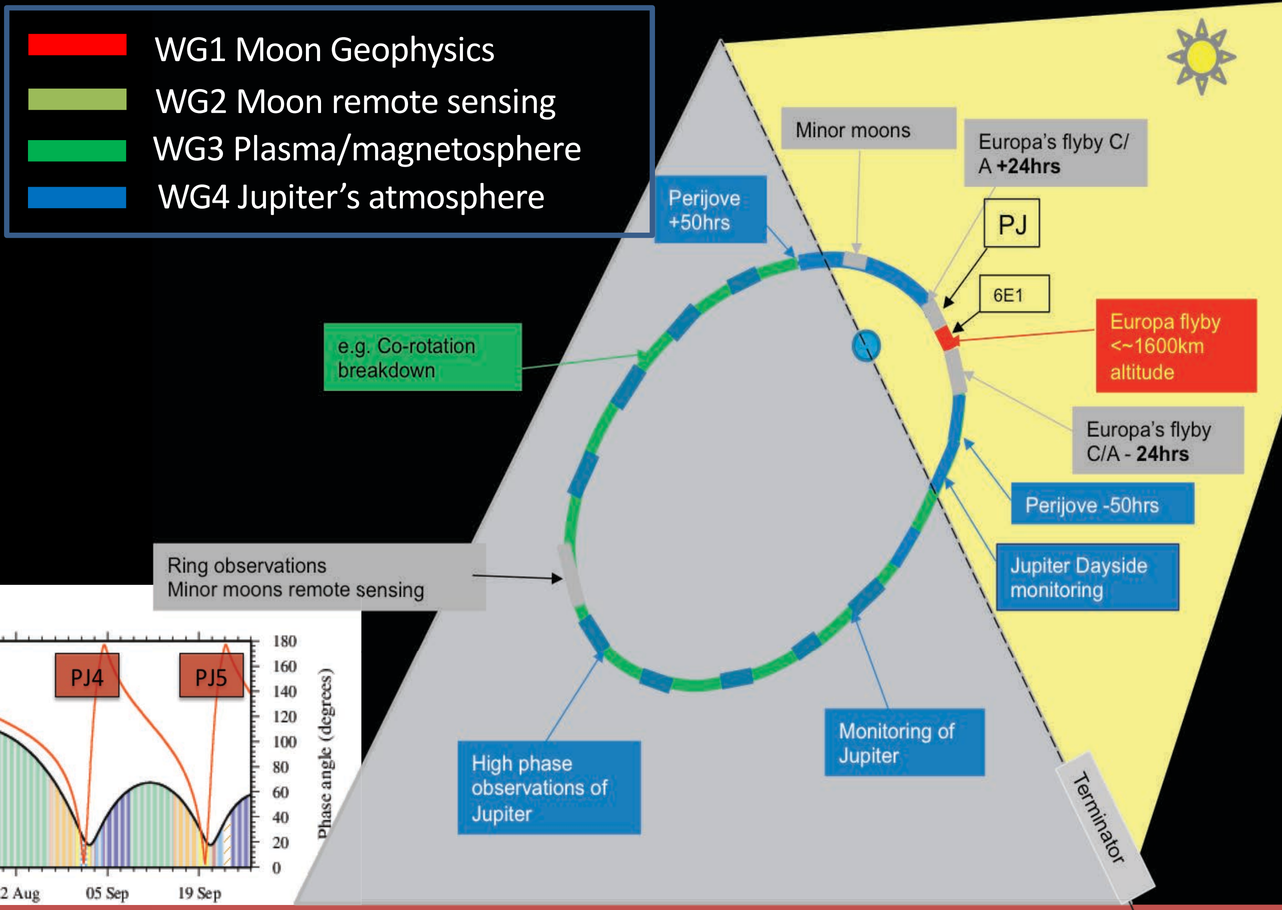


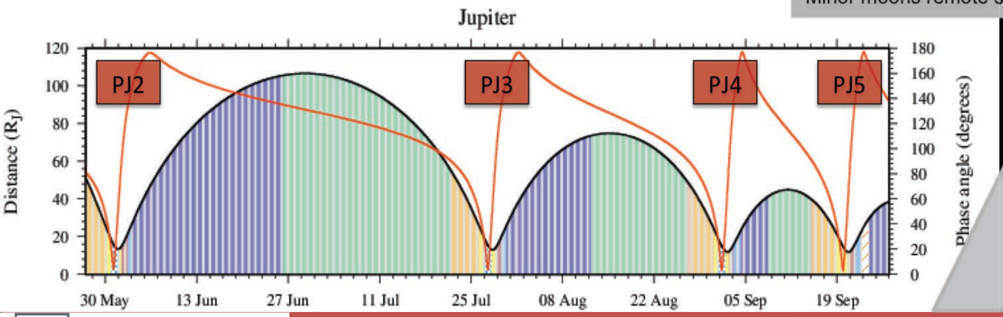


1. Pre-JOI and first ellipse, from 7 April 2029 to 27 May 2030 (PJ1)
2. Energy reduction phase, from 27 May 2030 to 28 September 2030 (PJ2-5)
3. Europa flybys, from 28 September 2030 to 26 October 2030 (PJ6-7)
4. High latitude, from 26 October 2030 to 25 June 2031 (PJ8-20)
5. Low energy phase, from 24 June 2031 to 24 August 2032 (PJ21-51)

Current Status (Phase C)

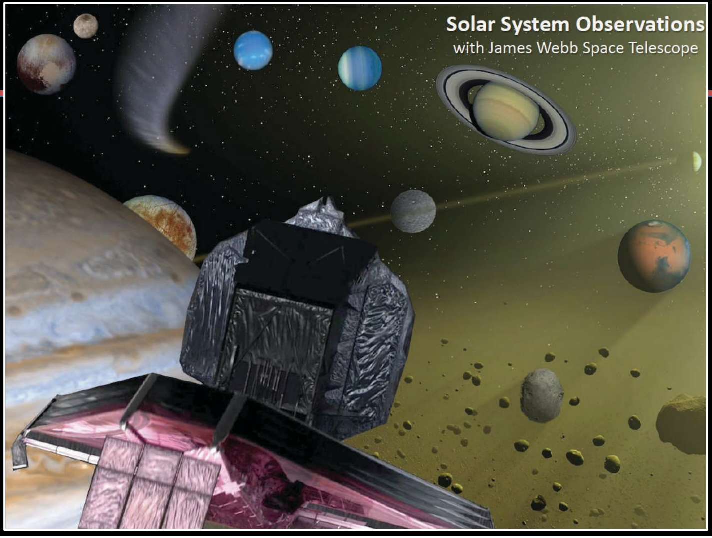
- Four working groups assessing tour opportunities.
- Segmentation of tour based on science priorities (Level-0 planning).
- Level-1 planning in the coming years.

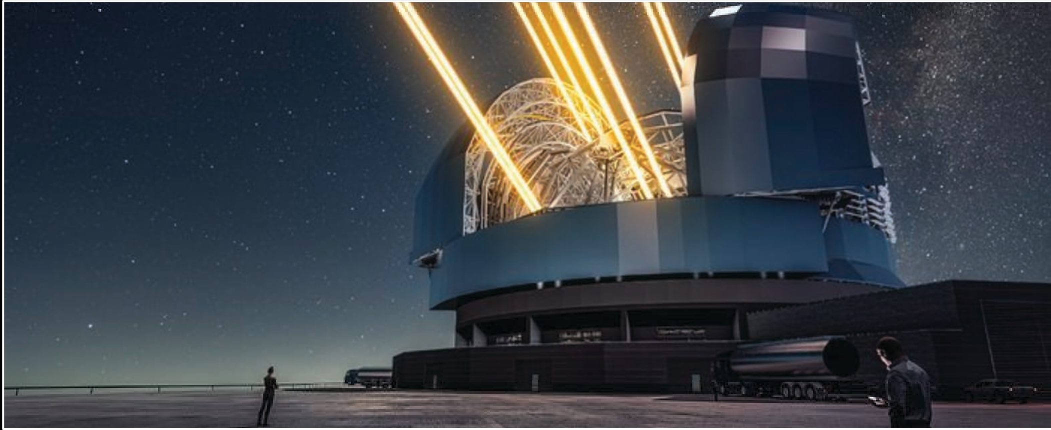




JUICE in Wider Context

- **Juno** extension to ~2021.
- **JWST** launch in ~2021 (0.6-28.5 micron):
  - Near Infrared Camera (NIRCam)
  - Near Infrared Spectrograph (NIRSpec)
  - Mid-Infrared Instrument (MIRI)
  - GTO programme for Jupiter, Saturn, Uranus, Neptune (Hammel, Fletcher)
  - ERS programme for Jupiter (de Pater, Fouchet)
- **ELT** first light ~2024.
  - HARMONI IFS 0.5-2.5 µm
  - METIS Mid-IR spectrograph 3-20 µm
  - MICADO Near-IR imager/spectrograph 0.8-2.4 µm
- **Europa Clipper** ~2023
  - Launch on SLS?
  - Focused on Europa, but could be persuaded to look at some “calibration” objects….





Summary & Perspectives

- **JUICE 2.5-year tour** achieves:
  - Multi-wave remote sensing to probe atmosphere in 3D from clouds to thermosphere.
  - Long baseline of observations.
  - Novel instrument techniques.
  - Simultaneity of data to understand coupling processes.
- Tour and payload specifics continue to evolve.
- Complements continued **Earth- and space-based** programmes.
- On course for **2022 launch** on one of the last Ariane 5s.
  - ~180 weeks away….