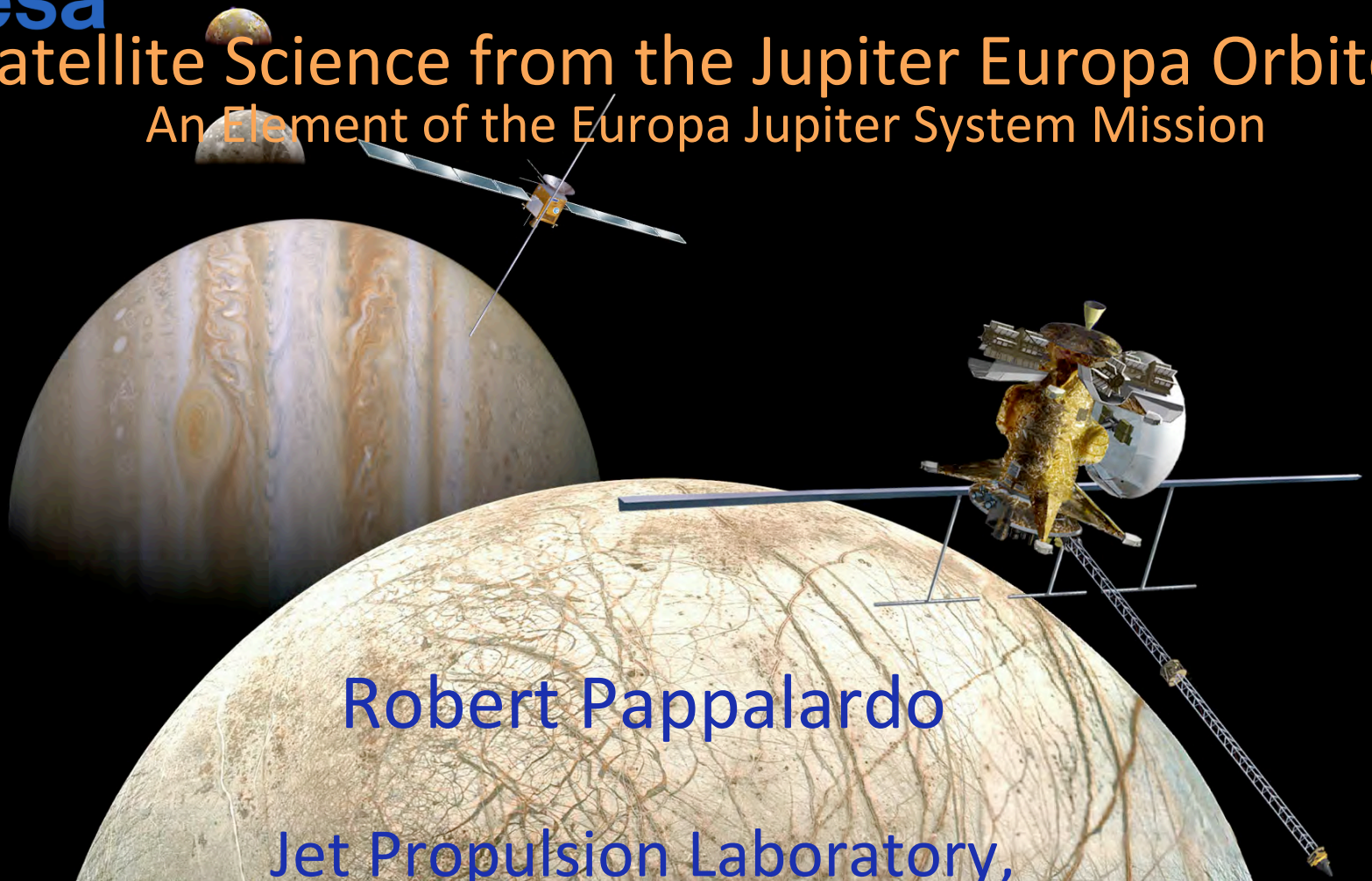
Satellite Science from the Jupiter Europa Orbiter:
An Element of the Europa Jupiter System Mission



Robert Pappalardo

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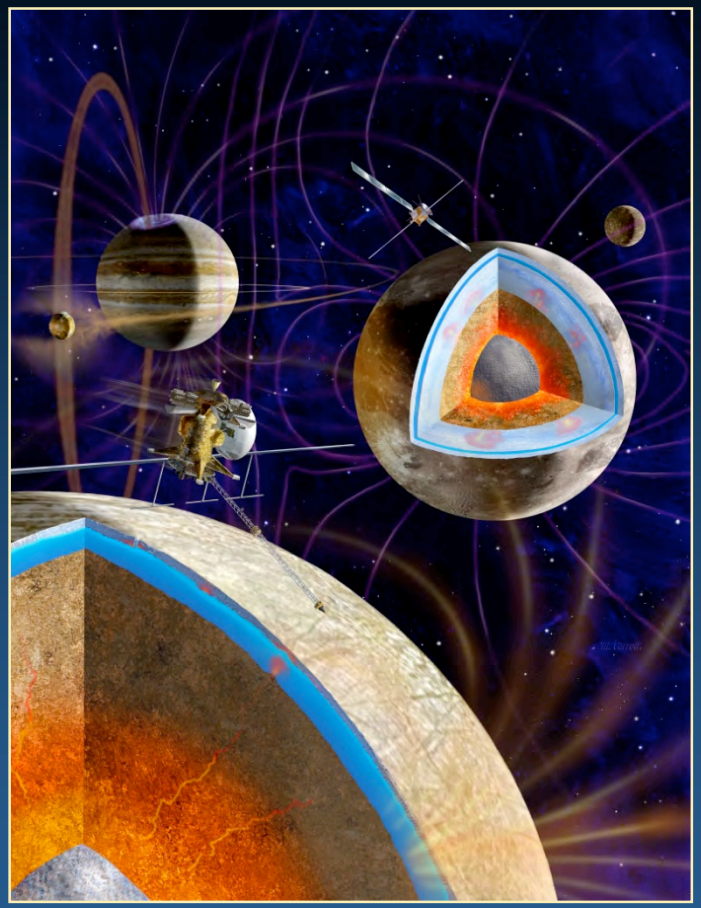
A Joint NASA-ESA Outer Planet Mission Study

2002 Decadal Survey: Galilean Satellite Science

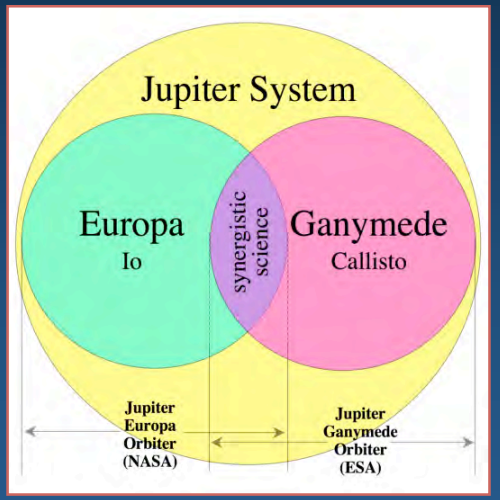
- Steering Group's "Science Themes" and associated "Fundamental Science Questions" point to Europa:
  - The Origin and Evolution of Habitable Worlds:
    7. How do planetary processes give rise to habitable zones and worlds?
  - Processes: How Planetary Systems Work:
    11. How do processes that shape planetary bodies operate and interact?
- Large Satellites Panel recommendations:
  - Robust Europa Orbiter with Jupiter system science is strongly recommended
  - Addresses 3 of 4 Large Satellites Panel panel themes and associated key questions
  - Next decade: Ganymede Orbiter, Io Explorer

2002 Decadal Survey recommended Europa as top flagship priority

Europa Jupiter Science Mission (EJSM)

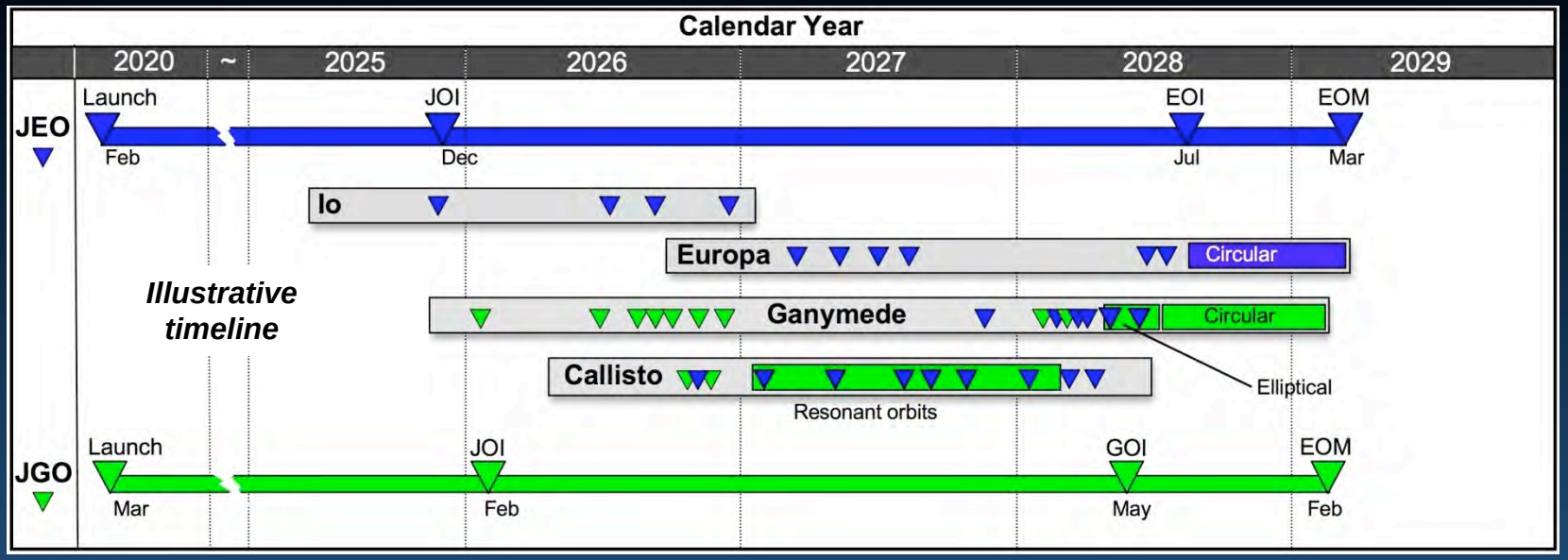


- NASA and ESA: Shared mission leadership
- Independently launched and operated orbiters
  - NASA-led Jupiter Europa Orbiter (JEO)
  - ESA-led Jupiter Ganymede Orbiter (JGO)
- Complementary science and payloads
  - JEO concentrates on Europa and Io
  - JGO concentrates on Ganymede and Callisto
  - Synergistic overlap
  - 11-12 instruments each
- Science goals:
  - Icy world habitability
  - Jupiter system processes



Synergistic science: The sum of JEO + JGO is greater than the parts

Nominal EJSM Timeline

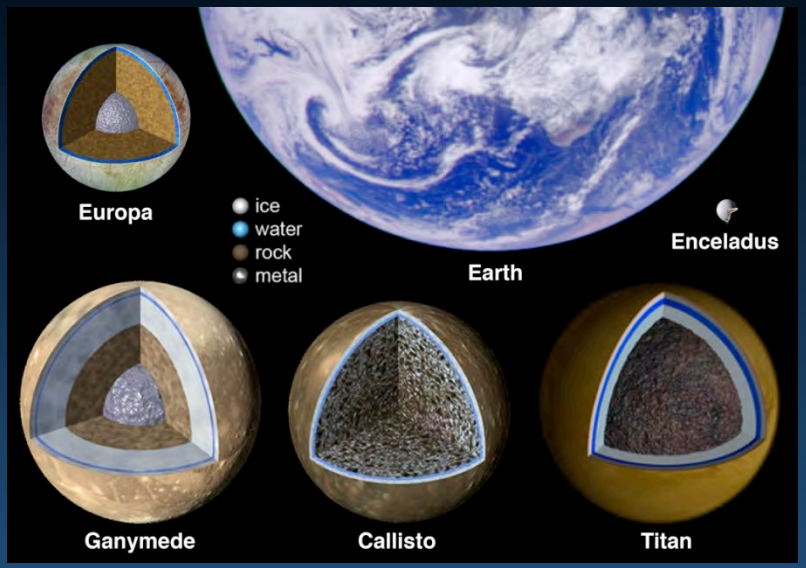


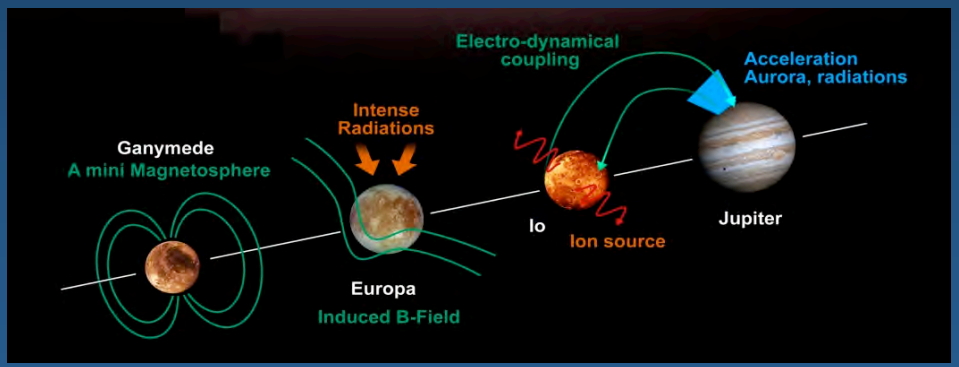
- Launches: 2020
- Jovian system tour phases: 2–3 years
- Moon orbital phases: 6–12 months
- End of Prime Missions: 2029
- Flexibility if either flight element is delayed or advanced

Coordinated timelines ensure synergistic science

EJSM Theme:
The Emergence of Habitable Worlds Around Gas Giants

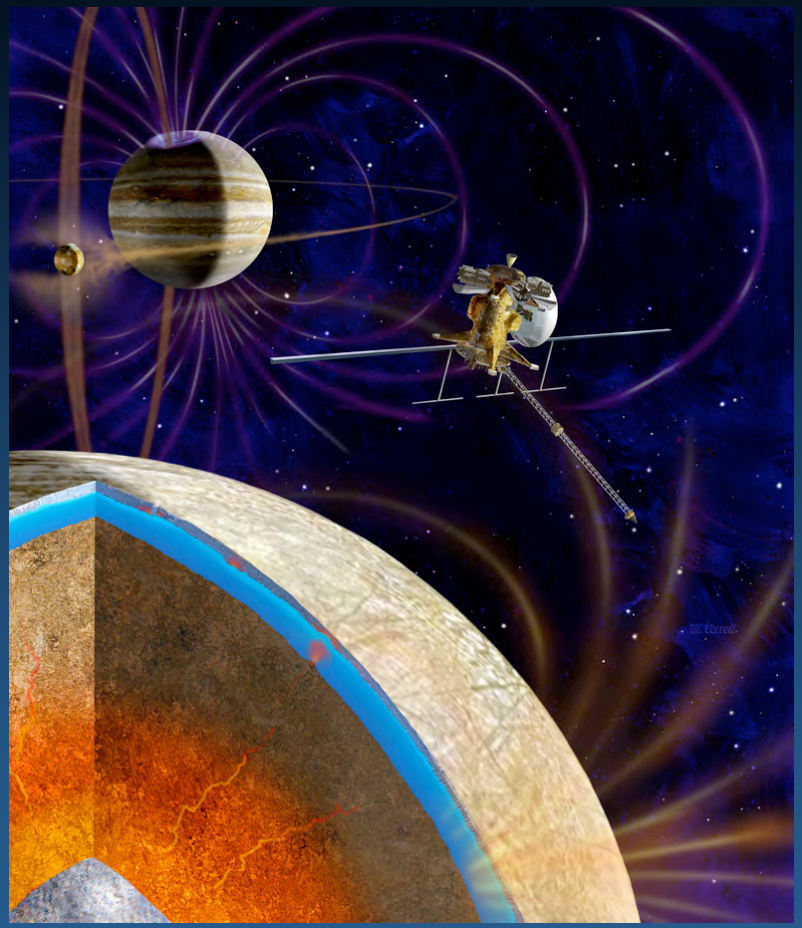
- *Goal 1:* Determine if the Jupiter system harbors habitable worlds
  - Ocean characteristics
  - Ice shells and subsurface water
  - Deep internal structure, and (for Ganymede) intrinsic magnetic field
  - External environments
  - Global surface compositions
  - Surface features and future landing sites
- *Goal 2:* Characterize Jupiter system processes
  - Satellite system
  - Jupiter atmosphere
  - Magnetodisk/magnetosphere
  - Jovian system Interactions
  - Jovian system origin





Emphasis on icy moon habitability and Jupiter system processes

JEO Goal:
Explore Europa to Investigate Its Habitability

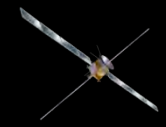


Habitability

Objectives (prioritized):

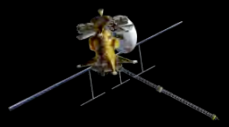
- Ocean and Interior
- Ice Shell
- Chemistry and Composition
- Geology and Landing Sites
- Jupiter System
  - Satellite surfaces and interiors
  - Satellite atmospheres
  - Plasma and magnetospheres
  - Jupiter atmosphere
  - Rings

Characterizing the archetype of icy world habitability









JEO Traceability: Europa

Goal	Science Objective		Science Investigation	
Explore Europa to investigate its habitability.	A. Ocean	**Characterize the extent of the ocean and its relation to the deeper interior.**	A1.	Determine the amplitude and phase of the gravitational tides.
			A2.	Characterize the magnetic environment (including plasma) to determine the induction response from the ocean over multiple frequencies.
			A3.	Characterize surface motion over the tidal cycle.
			A4.	Determine the satellite's dynamical rotation state.
			A5.	Investigate the core, rocky mantle, and rock-ocean interface.
	B. Ice	**Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange.**	B1.	Characterize the distribution of any shallow subsurface water.
			B2.	Search for an ice-ocean interface.
			B3.	Correlate surface features and subsurface structure to investigate processes governing material exchange among the surface, ice shell, and ocean.
			B4.	Characterize regional and global heat flow variations.
	C. Chemistry	**Determine global surface compositions and chemistry, especially as related to habitability.**	C1.	Characterize surface organic and inorganic chemistry, including abundances and distributions of materials, with emphasis on indicators of habitability and potential biosignatures.
			C2.	Relate compositions to geological processes, especially material exchange with the interior.
			C3.	Characterize the global radiation environment and the effects of radiation on surface composition, atmospheric composition, albedo, sputtering, sublimation, and redox chemistry.
			C4.	Characterize the nature of exogenic materials.
	D. Geology	**Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future *in situ* exploration.**	D1.	Determine the formation history and three-dimensional characteristics of magmatic, tectonic, and impact landforms.
			D2.	Determine sites of most recent geological activity, and evaluate future landing sites.
			D3.	Investigate processes of erosion and deposition and their effects on the physical properties of the surface debris.

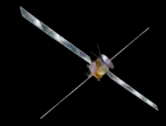
JEO Themes: **Origins** | **Evolution** | **Processes** | **Habitability** | **Life**

Based on 2002 Decadal's "objectives of solar system exploration"

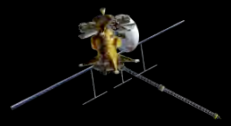
JEO Traceability: Jupiter System Science

Goal	Science Objective		Science Investigation	
Explore Europa to investigate its habitability.	E. Jupiter system science **Understand Europa in the context of the Jupiter system.**	Satellite surfaces and interiors	E1.	Investigate the nature and magnitude of tidal dissipation and heat loss on the Galilean satellites, particularly Io
			E2.	Investigate Io's active volcanism for insight into its geological history and evolution (particularly of its silicate crust)
			E3.	Investigate the presence and location of water within Ganymede and Callisto.
			E4.	Determine the composition, physical characteristics, distribution and evolution of surface materials on Ganymede.
			E5.	Determine the composition, physical characteristics, distribution and evolution of surface materials on Callisto.
			E6.	Identify the dynamical processes that cause internal evolution and near-surface tectonics of Ganymede and Callisto.
		Satellite Atms.	E7.	Characterize the composition, variability and dynamics of Europa's atmosphere and ionosphere
			E8.	Understand the sources and sinks of Io's crustal volatiles and atmosphere.
			E9.	Determine the sources and sinks of the Ganymede and Callisto atmospheres.
		Plasma and magnetospheres	E10.	Characterize the neutral atoms and molecules escaping Europa's gravity.
			E11.	Characterize the composition of and transport in Io's plasma torus.
			E12.	Study the pickup and charge exchange processes in the Jupiter system plasma and neutral tori.
			E13.	Study the interactions between Jupiter's magnetosphere and Io, Ganymede and Callisto (incl. characterize Ganymede's magnetic field)
			E14.	Understand the structure, composition and stress balance of Jupiter's magnetosphere.
			E15.	Determine how plasma and magnetic flux are transported in Jupiter's magnetosphere.
		Jupiter atm.	E16.	Characterize the abundance of minor species (especially water and ammonia) in Jupiter's atmosphere to understand the evolution of the Jovian system, including Europa.
			E17.	Characterize Jovian atmospheric dynamics and structure.
		Rings	E18.	Characterize the properites of the small moons, ring source bodies and dust
			E19.	Identify the dynamical processes that define the origin and dynamics of ring dust.

Giant Planets Panel





JEO Model Payload

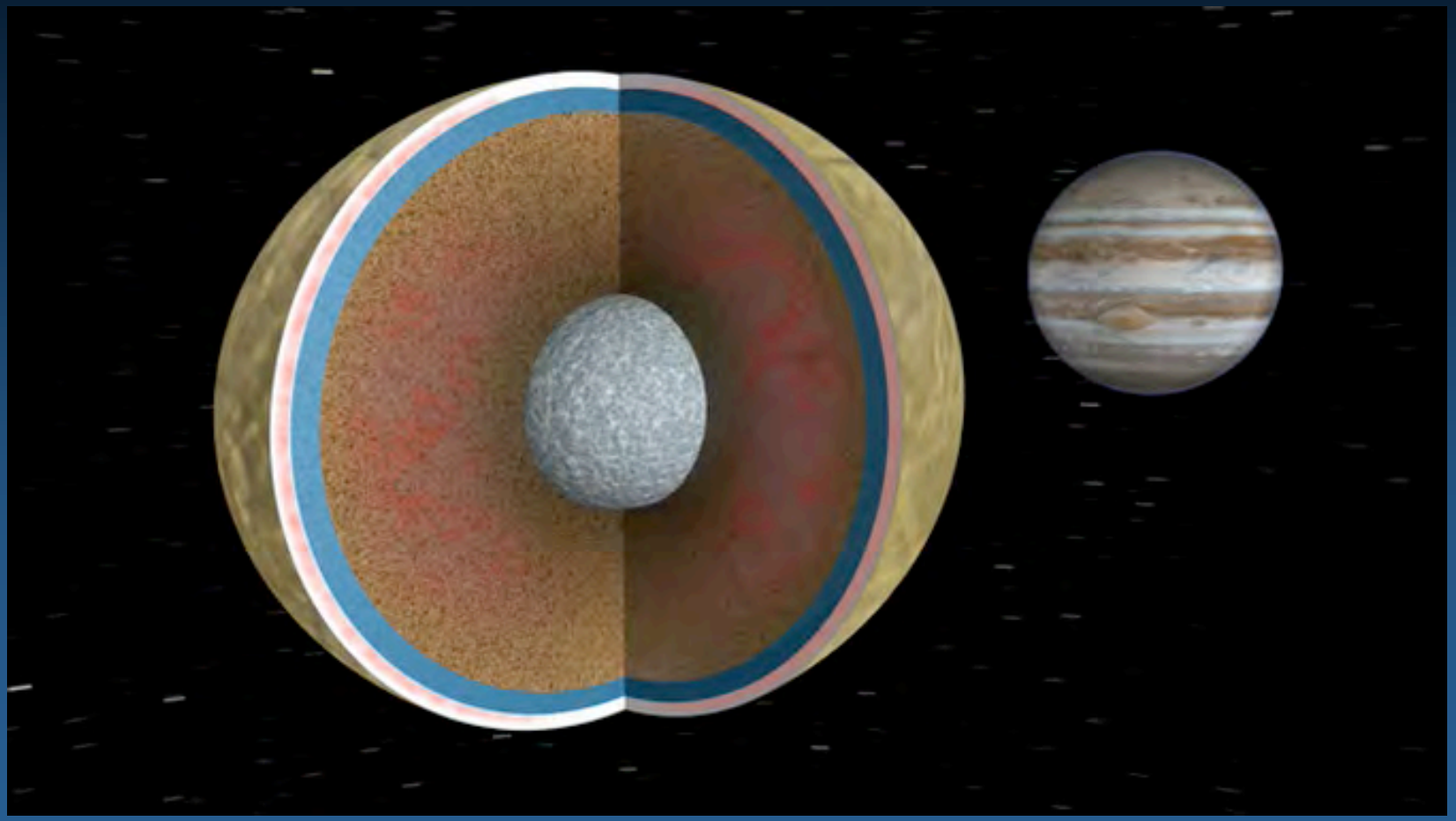
Ocean		
	Laser Altimeter	**LA**
	Radio Science	**RS**
Ice		
	Ice Penetrating Radar	**IPR**
Chemistry		
	Vis-IR Imaging Spectrometer	**VIRIS**
	UV Spectrometer	**UVS**
	Ion and Neutral Mass Spectrometer	**INMS**
Geology		
	Thermal Instrument	**TI**
	Narrow Angle Camera	**NAC**
	Wide Angle Camera and Medium Angle Camera	**WAC + MAC**
Fields and Particles		
	Magnetometer	**MAG**
	Particle and Plasma Instrument	**PPI**

- Model payload is a proof-of-concept example
  - Other instrument choices may be viable
- Emphasizes accomplishing Europa investigations
- Enables robust Jupiter system science
- The final selected payload will almost certainly be different

Capable model payload with a conservative approach

Europa: Ocean • Ice • Chemistry • Geology

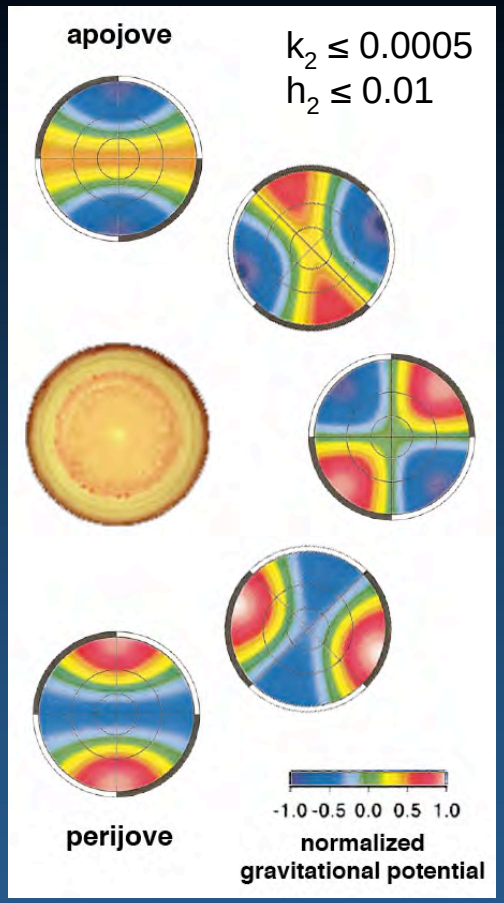
A. Characterize the extent of the ocean and its relation to the deeper interior.



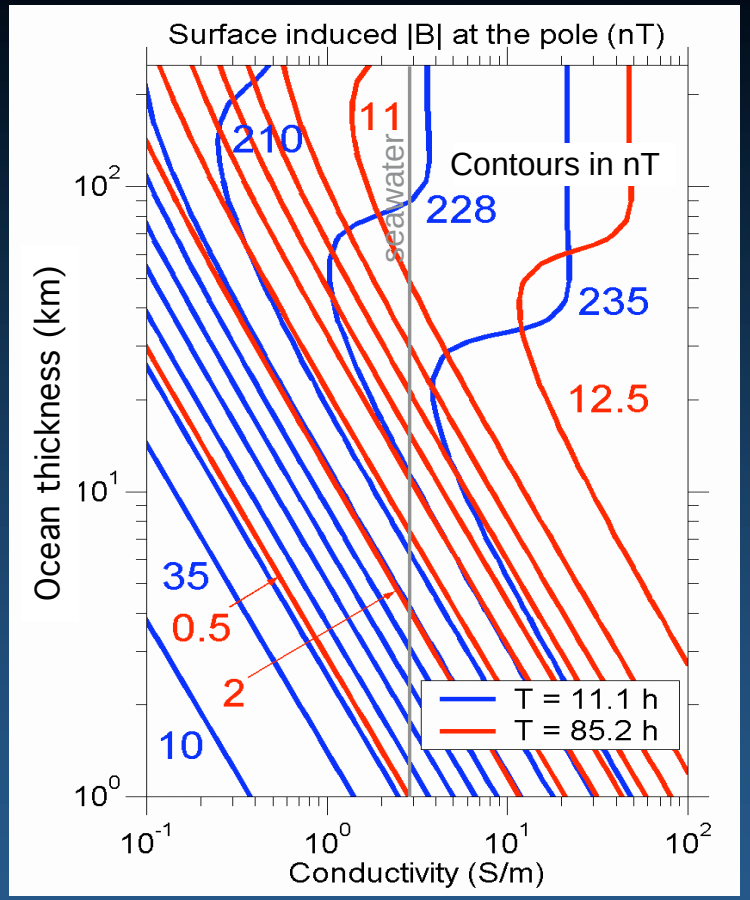
Europa: Ocean • Ice • Chemistry • Geology

A. Ocean & deeper interior:

1. Gravitational tides
2. Magnetic environment (including plasma)
3. Surface motion
4. Dynamical rotation state
5. Core, rocky mantle, & rock-ocean interface



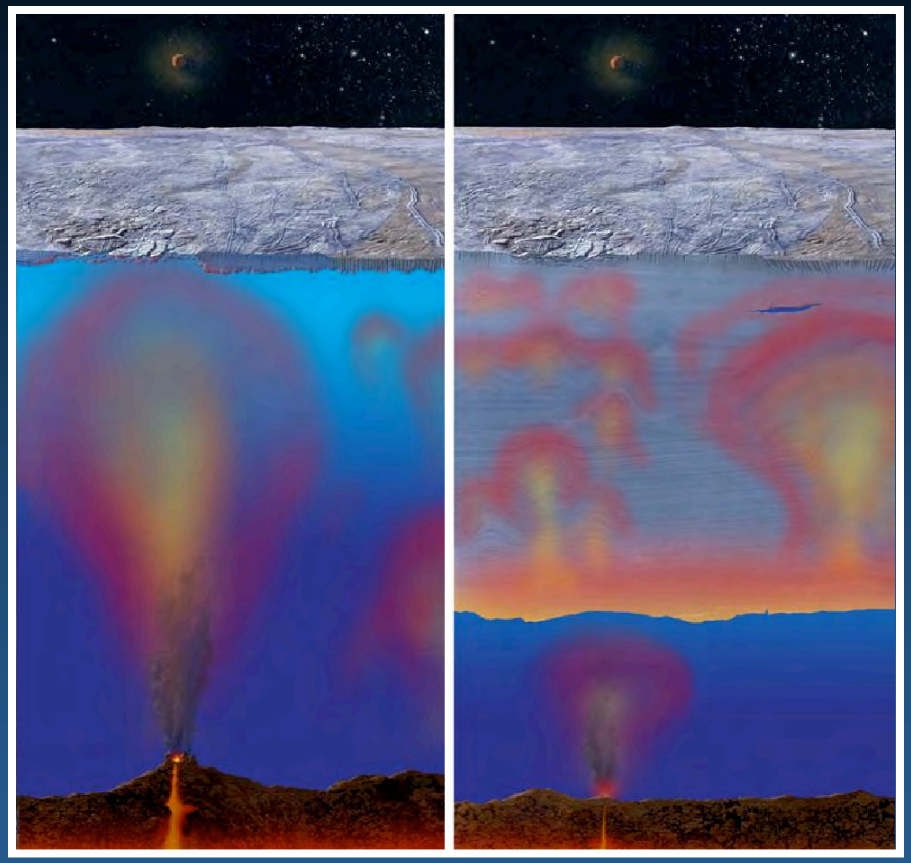
[*Moore & Schubert, 2000*]



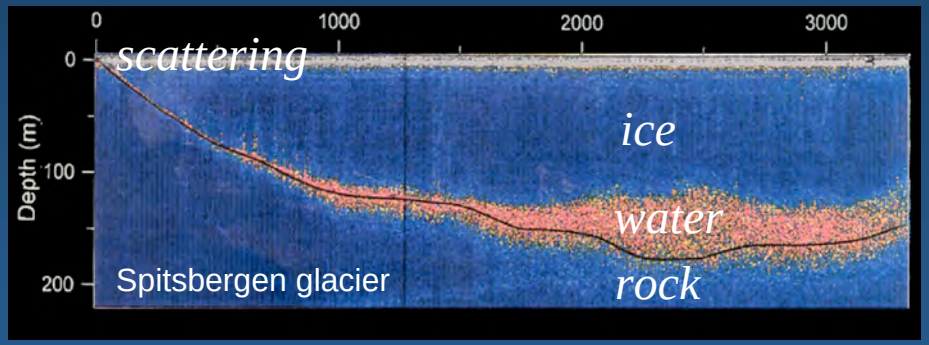
[*Khurana, 2002*]

Geophysical techniques reveal the nature of the interior

Europa: Ocean • Ice • Chemistry • Geology



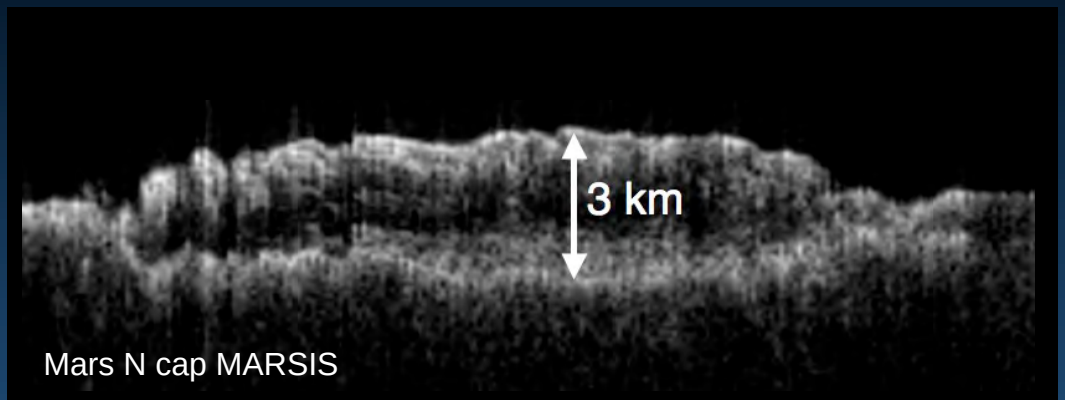
B. Characterize the ice shell and any subsurface water, including their heterogeneity, and the nature of surface-ice-ocean exchange



[*Bjornsson et al., 1996*]

Exchange processes are critical to Europa's habitability

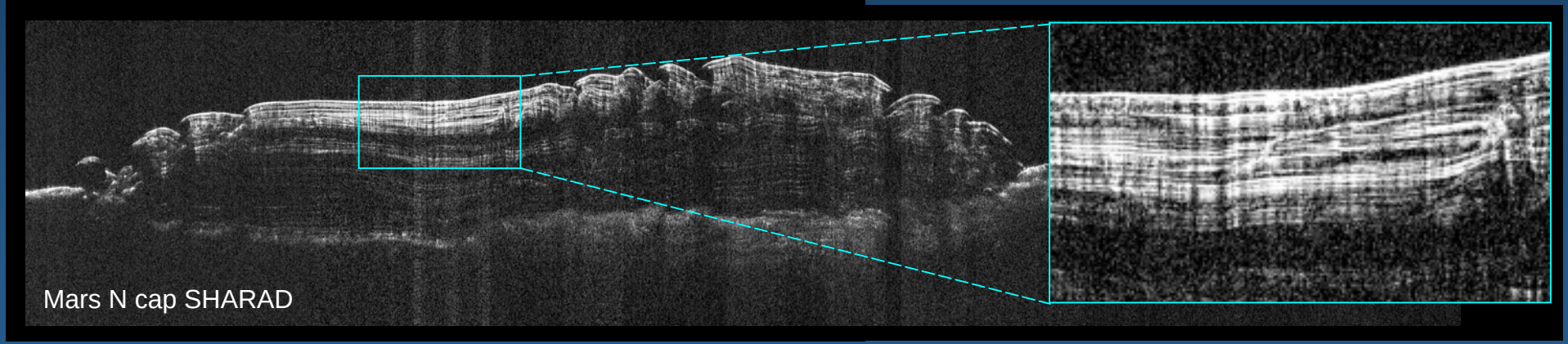
Europa: Ocean • Ice • Chemistry • Geology



Mars N cap MARSIS

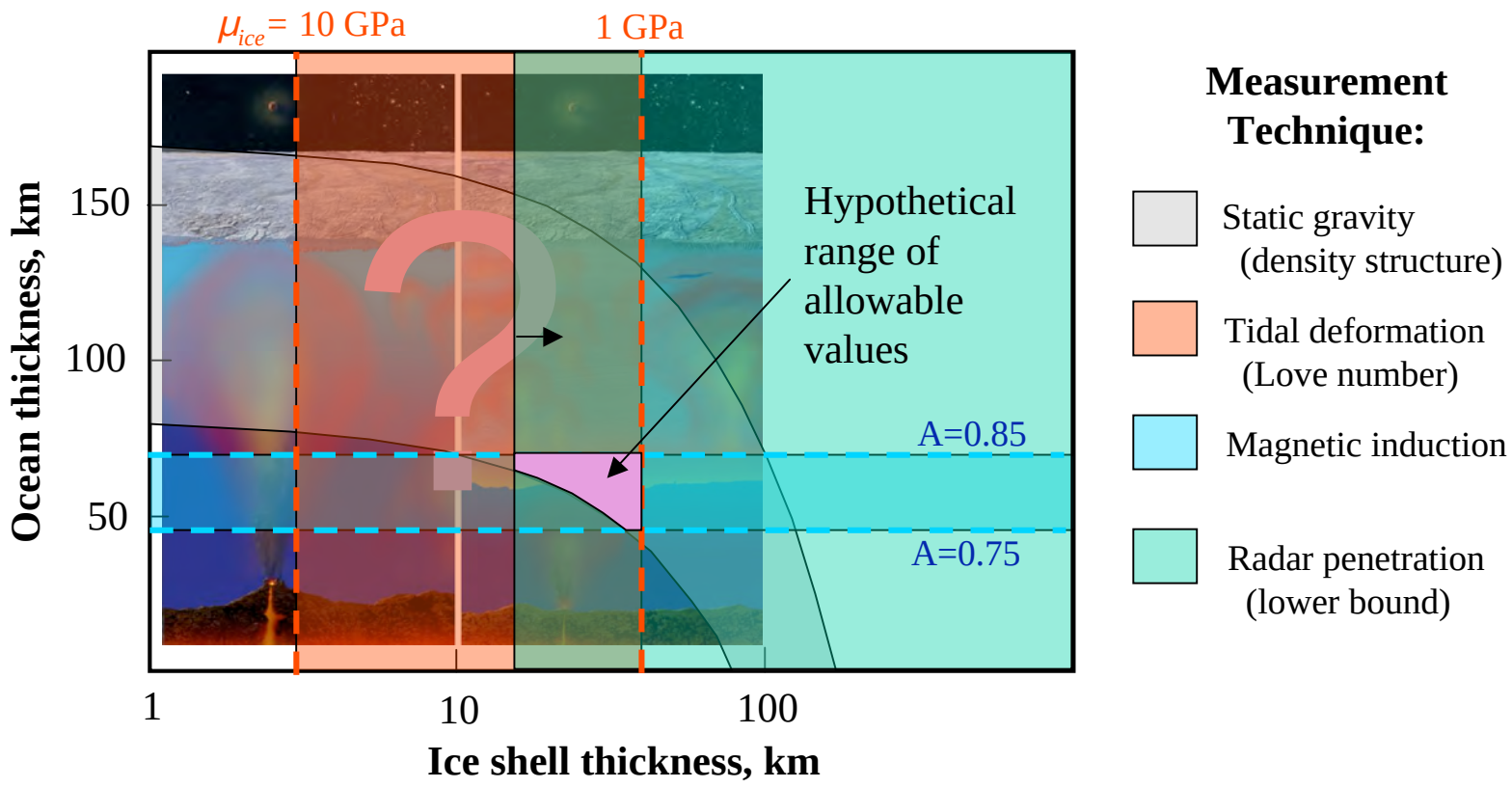
B. Ice shell & subsurface water:

1. Shallow water
2. Ice-ocean interface
3. Material exchange
4. Heat flow variations


Mars N cap SHARAD

Radar sounding would characterize the ice shell in 3 dimensions

Constraining Ice Shell Thickness: *Hypothetical Example*



Multiple techniques constrain ice shell thickness

Europa: Ocean • Ice • Chemistry • Geology

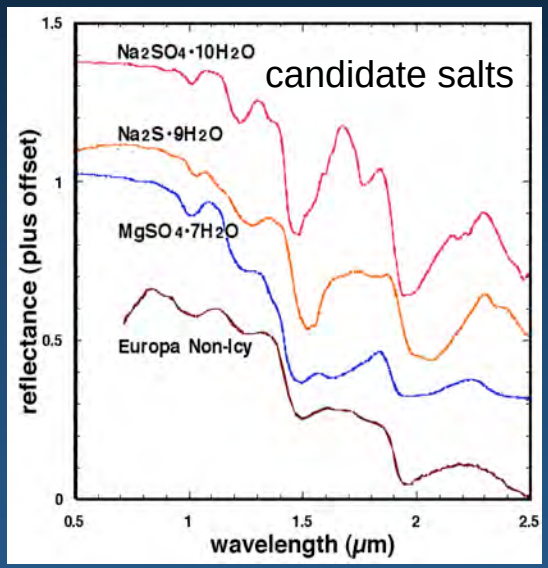
C. Determine global surface compositions and chemistry, especially as related to habitability

Composition is key to understanding ocean habitability

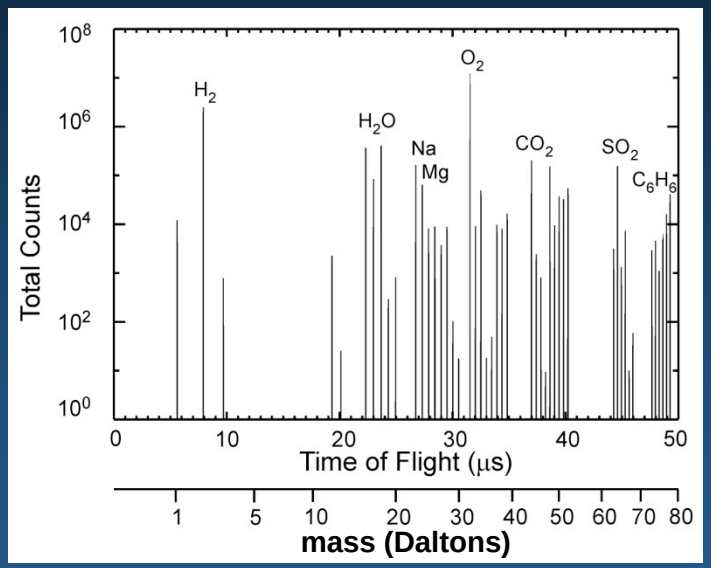
Europa: Ocean • Ice • Chemistry • Geology

C. Global surface composition & chemistry:

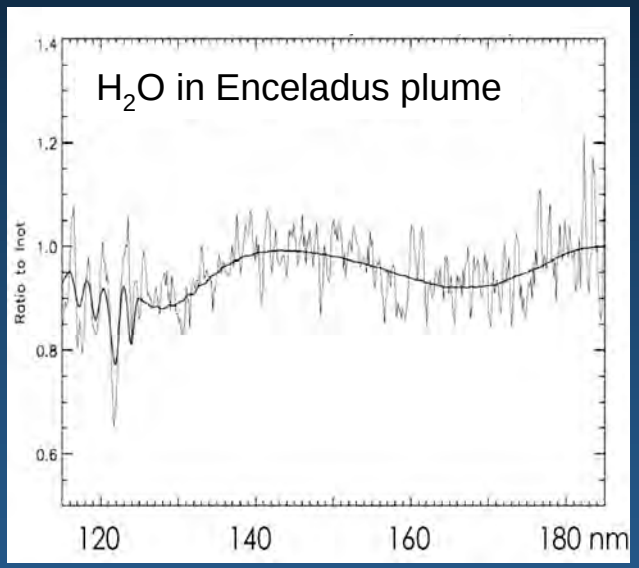
1. Organic & inorganic chemistry
2. Relation to geologic processes
3. Radiation effects
4. Exogenic materials



IR spectroscopy:
surface constituents



INMS:
sputtered particles

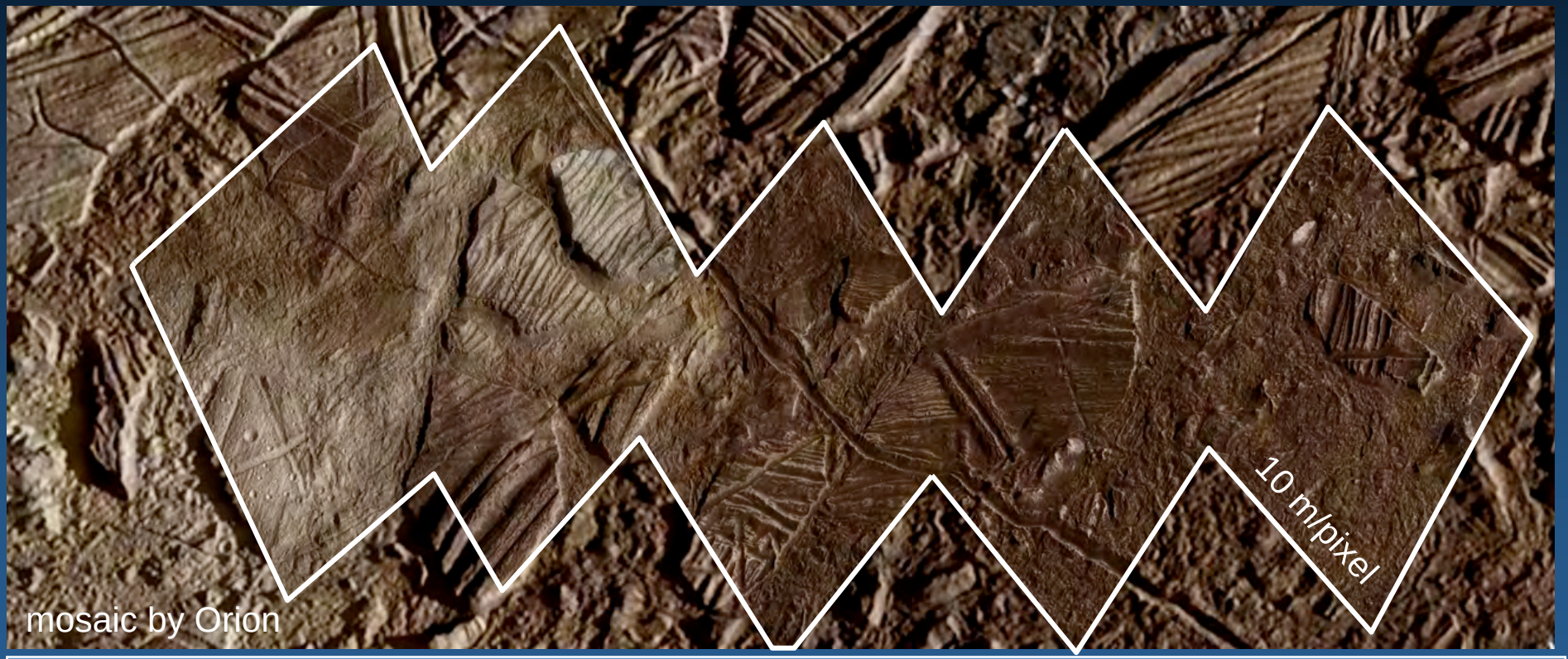


Stellar occultations:
atmospheric species

Multiple techniques characterize and map composition

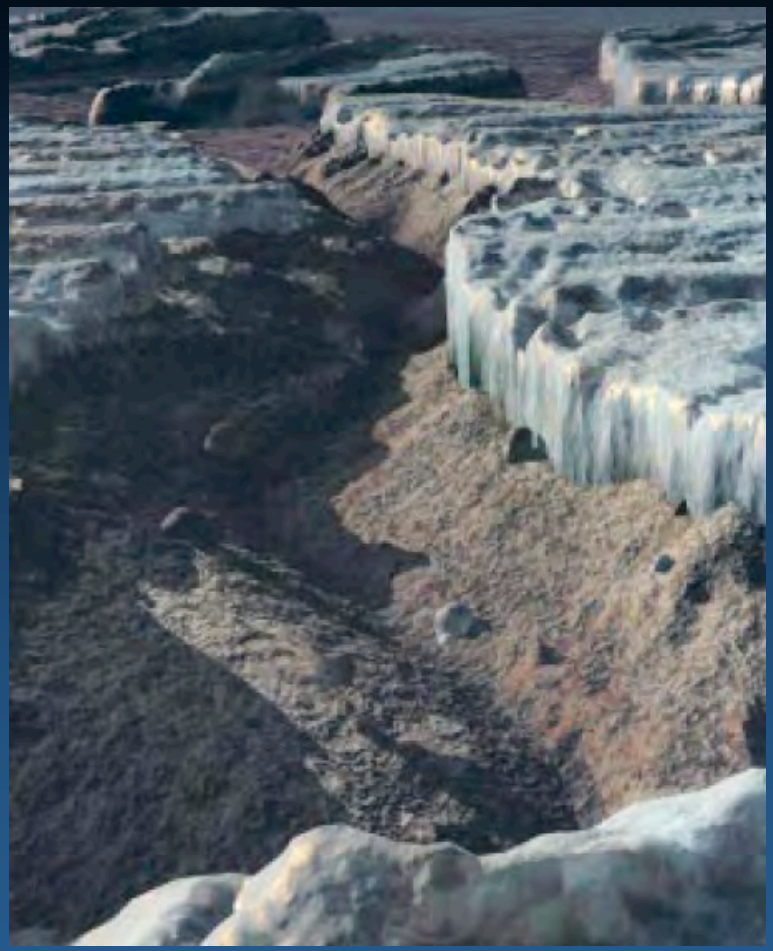
Europa: Ocean • Ice • Chemistry • Geology

D. Understand the formation of surface features, including sites of recent or current activity, and identify and characterize candidate sites for future in situ exploration



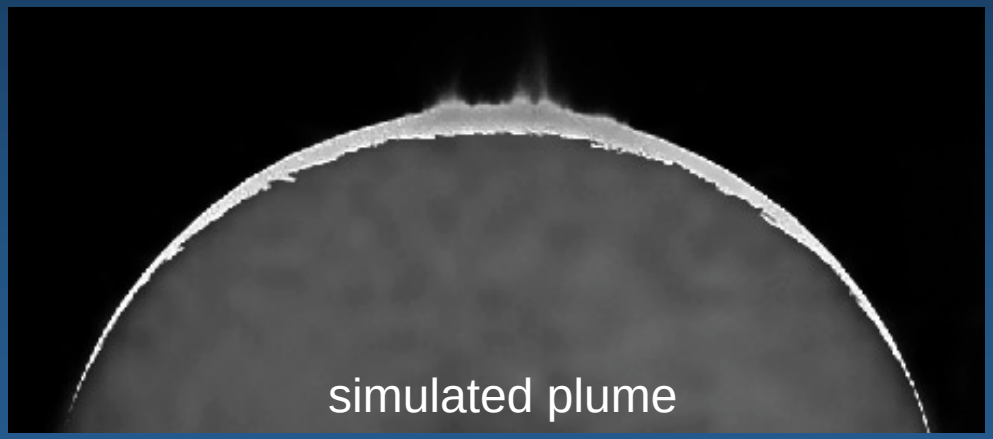
JEO would increase 10-20 m/pixel image coverage from 0.03% to 7%

Europa: Ocean • Ice • Chemistry • Geology



D. Surface features, activity, & landing sites:

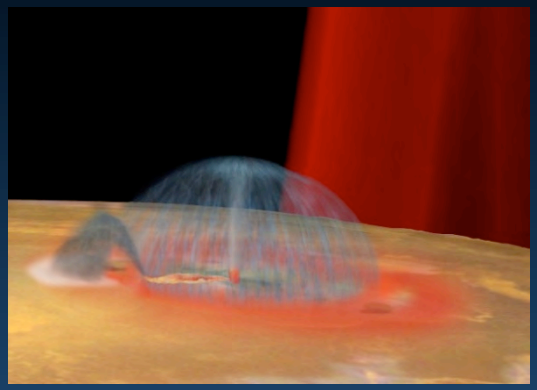
1. Formation history & 3-D character
2. Recent activity & potential future landing sites
3. Erosion & deposition



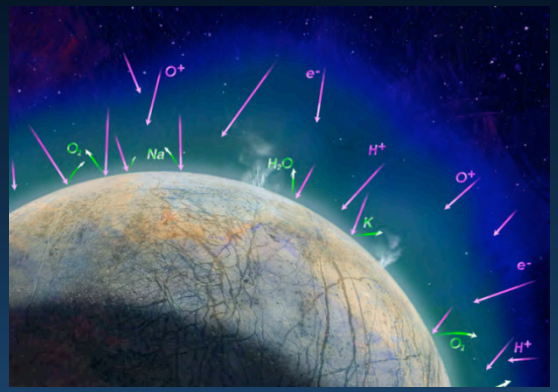
JEO would decipher Europa's varied and complex geology

Jupiter System: Sats • Atm • Mag • Jupiter • Rings

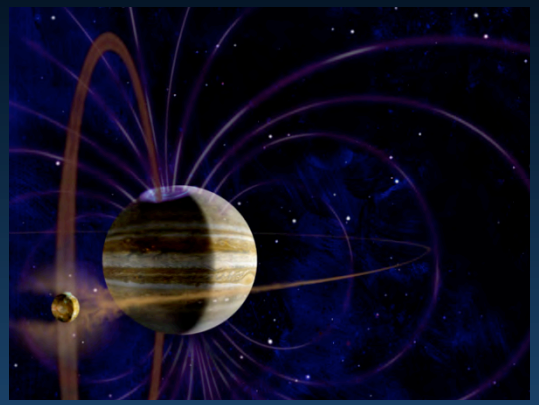
E. Understand Europa in the context of the Jupiter system



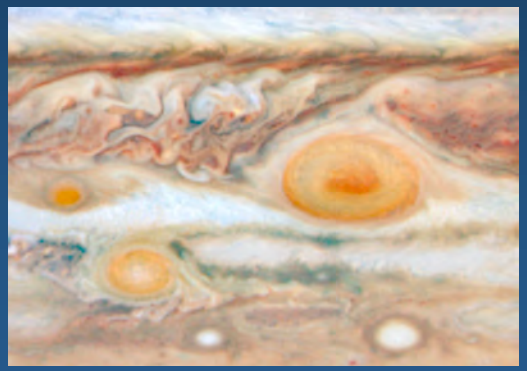
Satellite surfaces & interiors



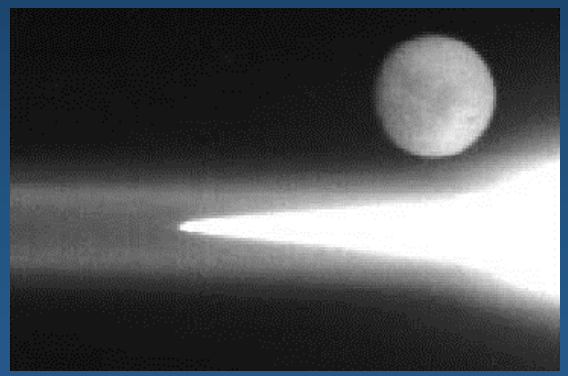
Satellite atmospheres



Plasma & magnetospheres



Jupiter atmosphere



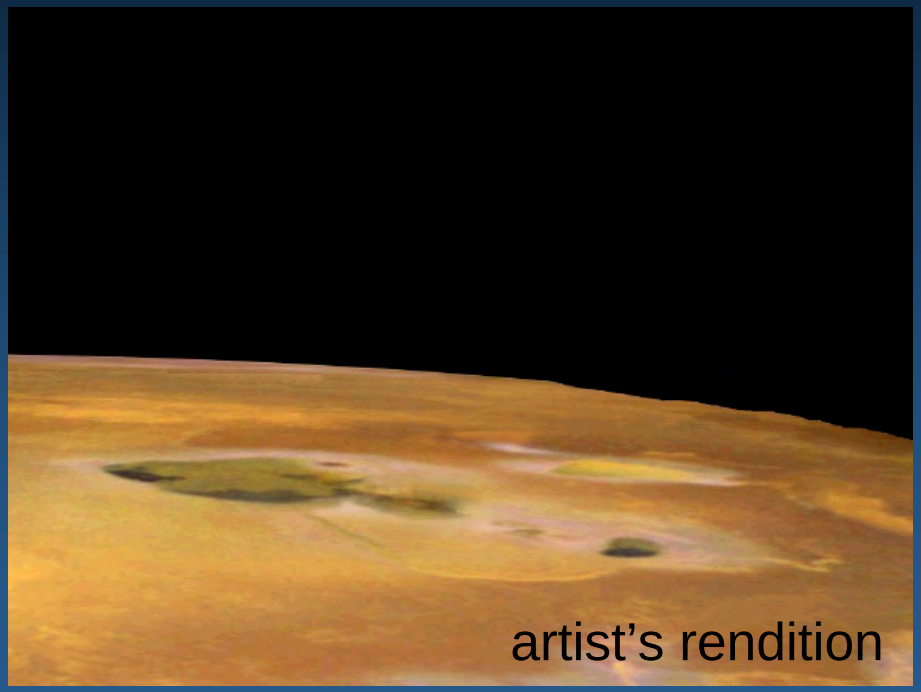
Rings

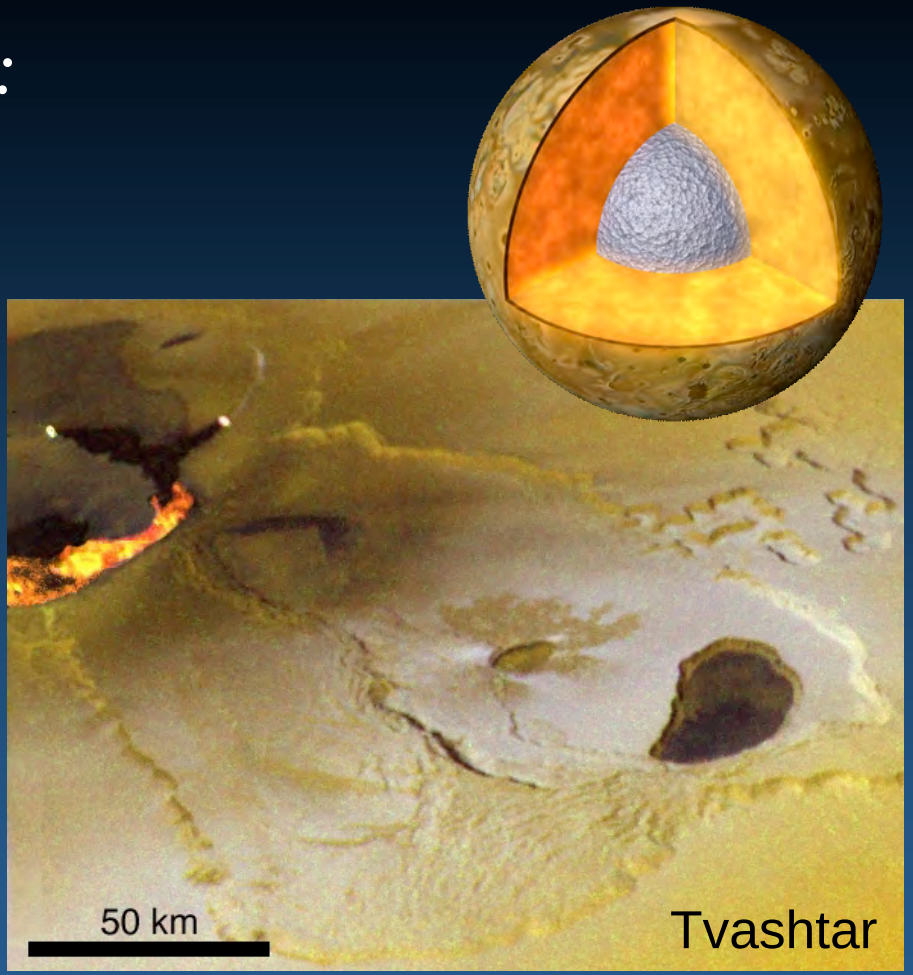
The Jupiter system is rich in dynamic and coupled processes

Jupiter System: Sats • Atm • Mag • Jupiter • Rings

Satellite surfaces & interiors:

1. Io's tidal heating & heat loss
2. Io's active volcanism



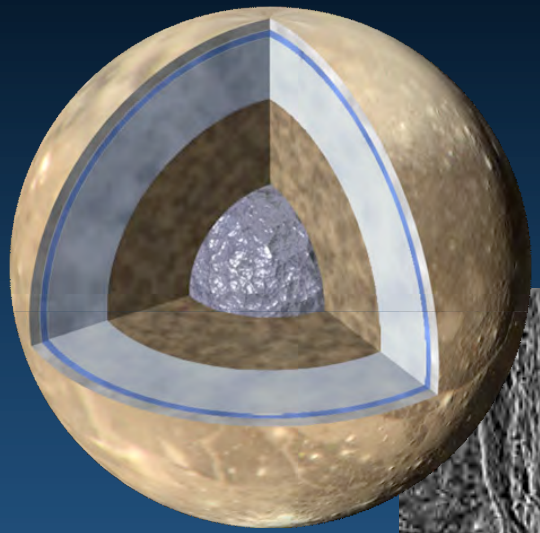


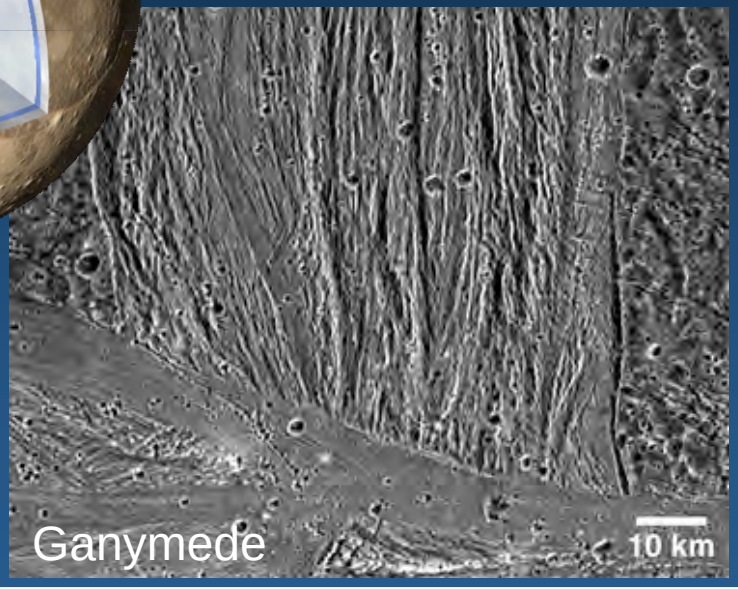
Io is the tidal engine of the Laplace resonance

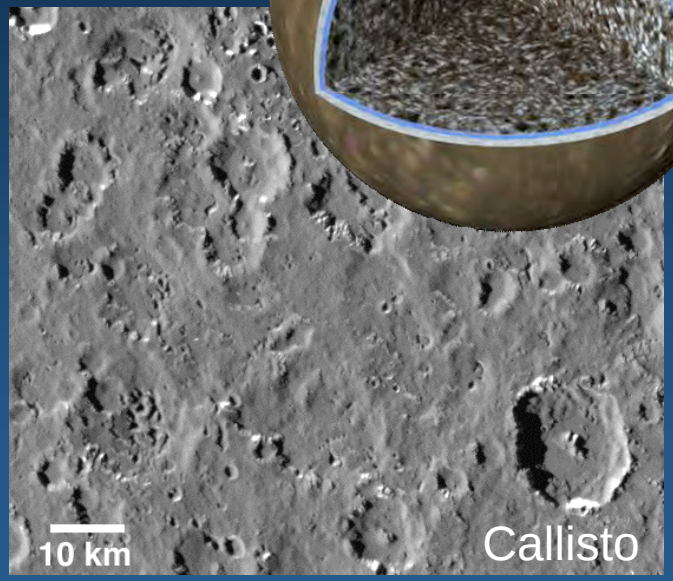
Jupiter System: Sats • Atm • Mag • Jupiter • Rings

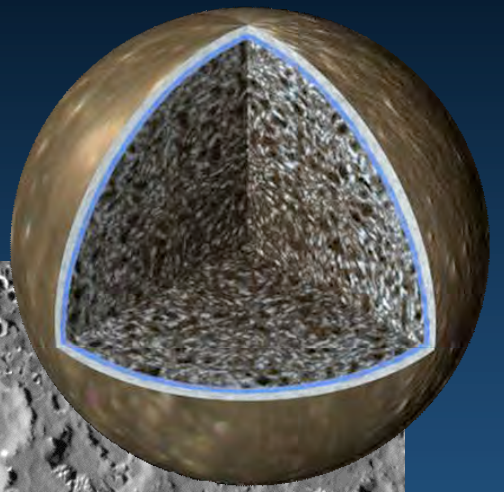
Satellite surfaces & interiors (cont.):

3. Water in Ganymede & Callisto
4. Ganymede's surface materials
5. Callisto's surface materials
6. Internal evolution & tectonics







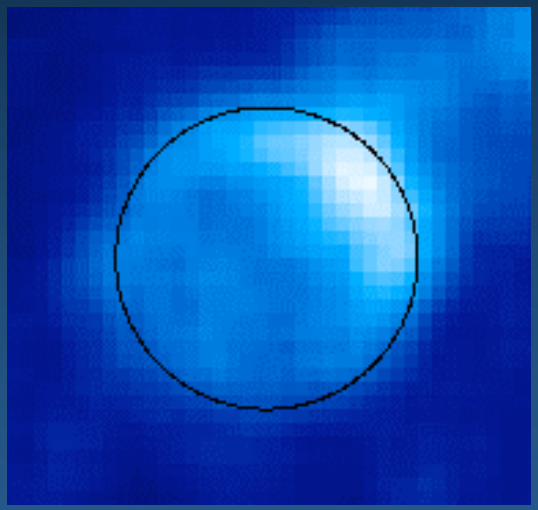


The icy Galilean satellites provide context for Europa

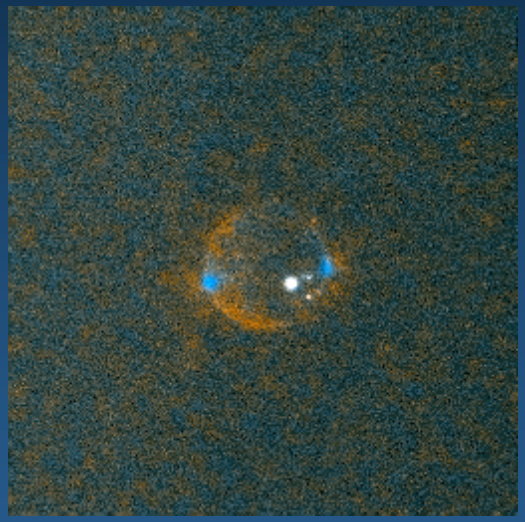
Jupiter System: Sats • Atm • Mag • Jupiter • Rings

Satellite atmospheres:

7. Europa: Composition, variability, and dynamics
8. Io: Composition, sources, and evolution
9. Ganymede and Callisto: Sources and sinks



Europa atm. (HST O 1356Å)

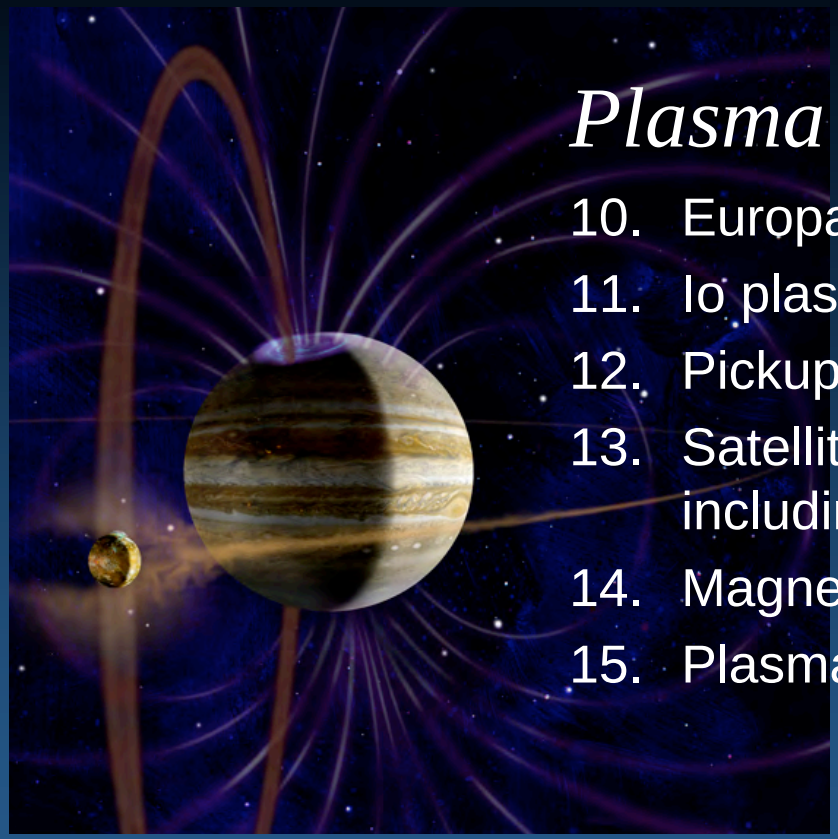


Io atm. & aurora (Cassini)

Ganymede aurora (HST)

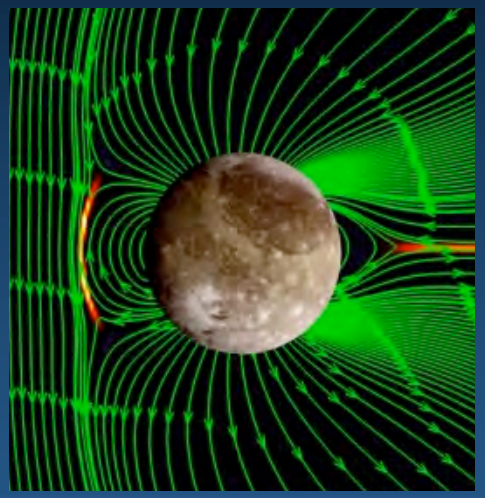
Understanding atmospheric interactions and processes

Jupiter System: Sats • Atm • Mag • Jupiter • Rings



Plasma & magnetospheres:

10. Europa's escaping neutrals
11. Io plasma torus
12. Pickup & charge exchange
13. Satellite interactions including Ganymede's field
14. Magnetospheric structure
15. Plasma transport

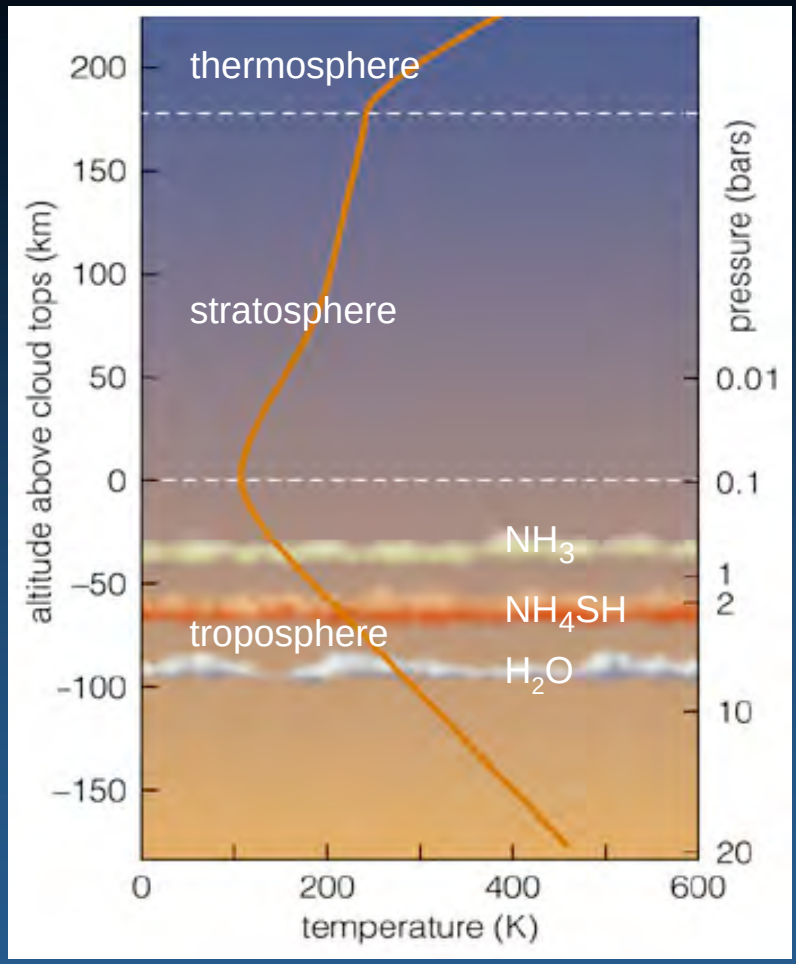


Probing the Solar System's largest magnetosphere and its unique satellite-magnetosphere interactions

Jupiter System: Sats • Atm • Mag • Jupiter • Rings

E. Jupiter atmosphere:

16. Minor species abundances
17. Dynamics & structure

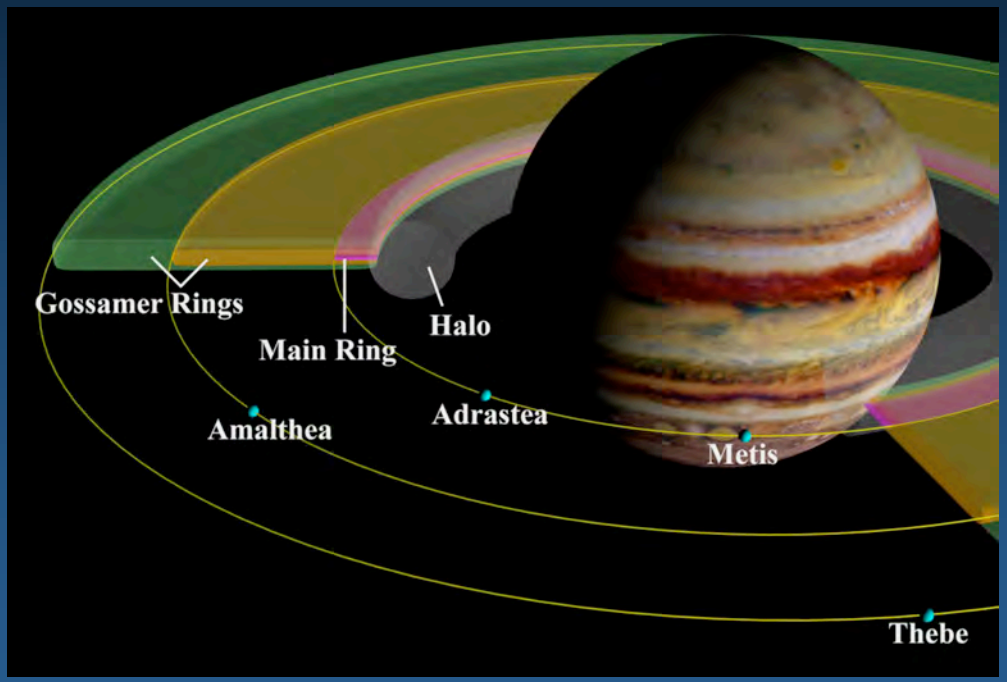


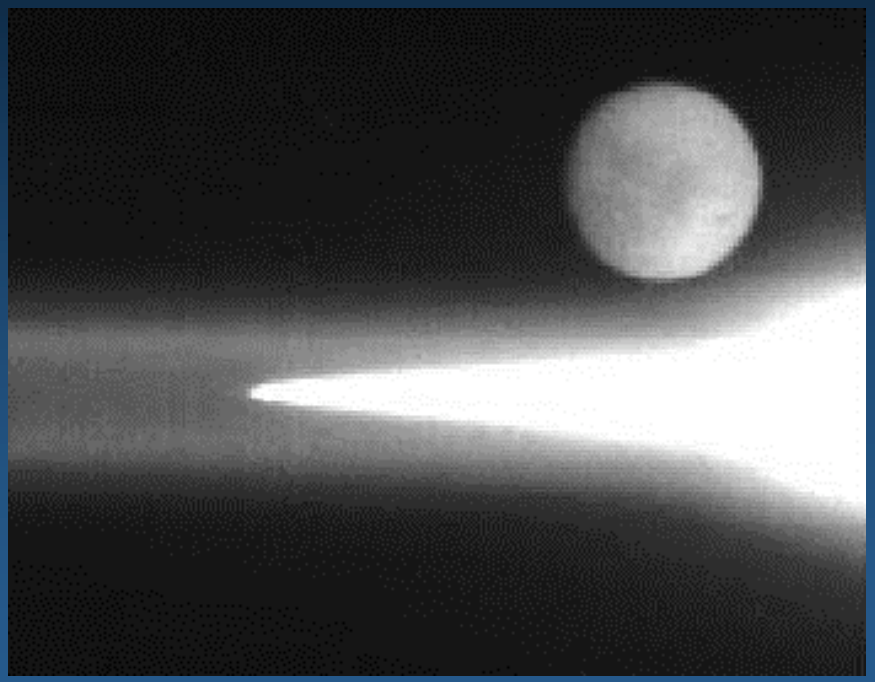
Addresses unanswered questions and complements Juno

Jupiter System: Sats • Atm • Mag • Jupiter • Rings

E. Rings:

18. Ring source bodies
19. Dynamical processes





Comparative studies of ring dynamics and evolution

Jupiter Europa Orbiter Science

Habitability

Objectives Summary:

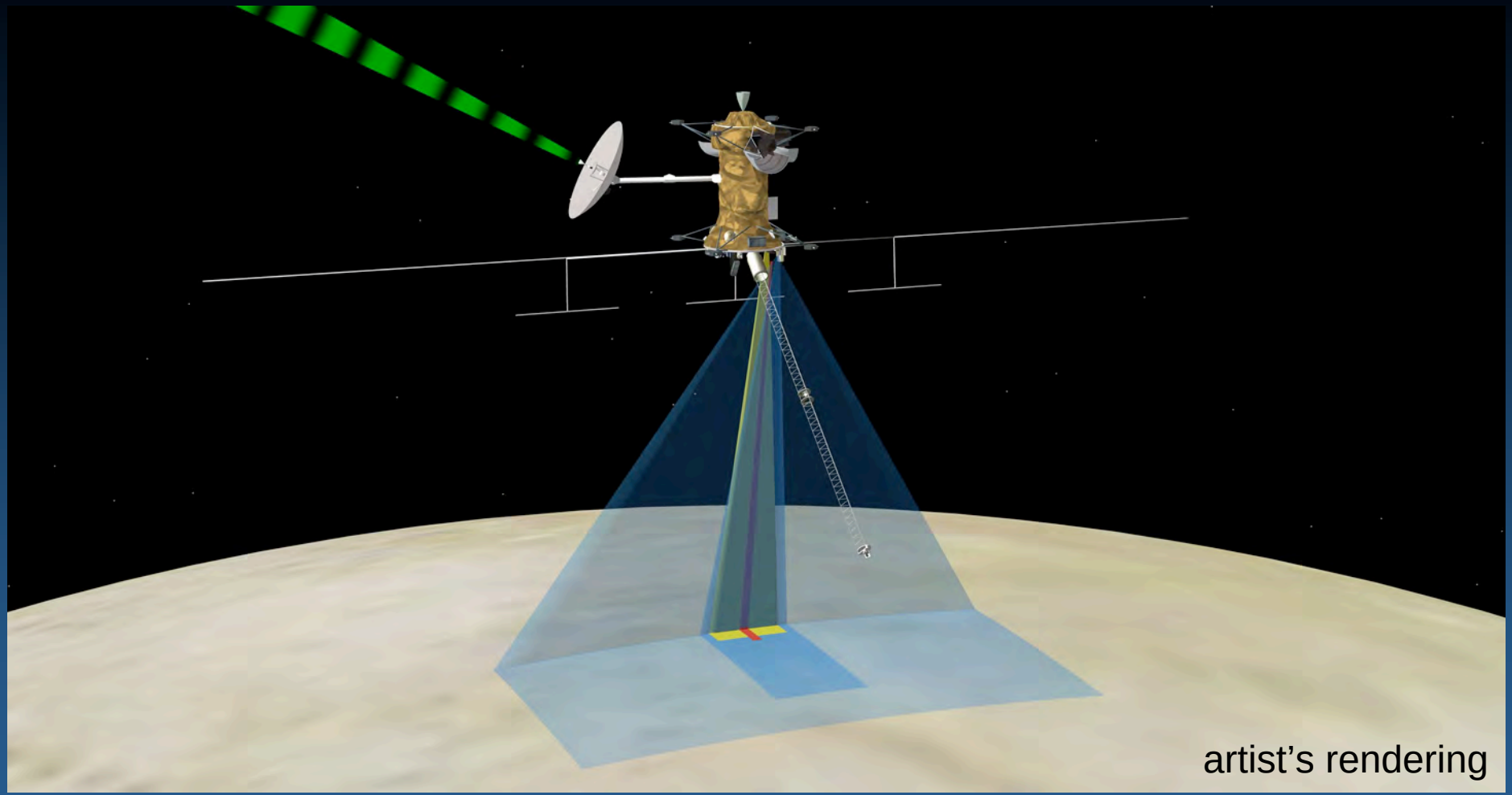
- Ocean characterization
- Surface-ice-ocean exchange
- Compositional makeup
- Geological evolution
- Jupiter system science
  - Galilean satellite evolution
  - Sat. atmospheric interactions
  - Magnetospheric physics
  - Jupiter atmospheric dynamics
  - Ring system dynamics

Rich and robust science of Europa and the Jupiter system

JEO Baseline Mission Overview

- Launch vehicle: Atlas V 551
- Power source: 5 MMRTG or 5 ASRG
- Mission timeline:
  - Launch: 2020
  - Jovian system tour phase: 30 mo.
  - Europa orbital phase: 9 mo.
  - End of prime mission: 2029
  - Spacecraft final disposition is Europa impact
- Radiation dose: 2.9 Mrad (behind 100 mils Al)
  - Handled using a combination of rad-hard parts and tailored component shielding
  - Key rad-hard parts are available, with the required heritage
  - Team is developing and providing design information and approved parts list for prospective suppliers of components, including instruments

Orbital Operability



Articulated antenna would permit simultaneous observations and downlink

Europa Science Campaigns

JOI to EOI	Jul 2028	Aug 2028	Sep 2028	Oct 2028

JOI

Satellite & Jupiter Science

EOI

Initial Europa Orbit
Altitude: 200 km
Inclination: 95–100° (~85° N lat)
Lighting: 2:30 PM LST
Repeat: 4 Eurosols

After Campaign 1
Altitude: 100 km
Repeat: 6 Eurosols

Europa Campaigns 1–3 total 99 days

Observing Strategies for Europa Campaigns 1–3
- Always on: LA, MAG, PPI, TI, INMS (50%)
- 2-orbit ops scenario permits power/data rate equalization:
  - Even orbits emphasize optical remote sensing
  - Odd orbits emphasize radar sounding to locate water
- Targets collected with residual data volume

Checkout (6 days)

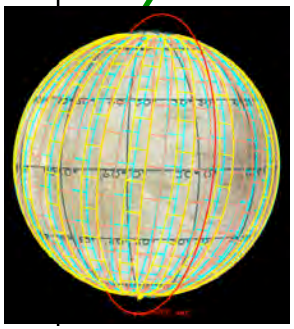
1A | 1B

2A | 2B

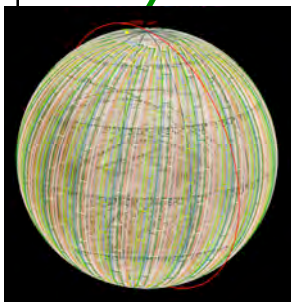
3

Focused Science

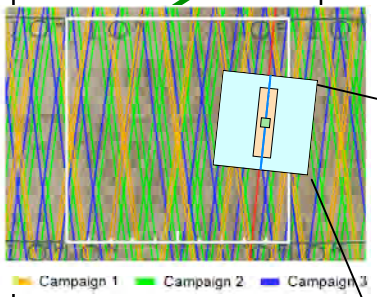
4



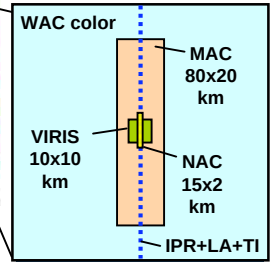
Global Framework
200 km altitude
(200 m/pixel WAC)
8 eurosols ≈ 28 days



Regional Processes
100 km altitude
(100 m/pixel WAC)
12 eurosols ≈ 43 days



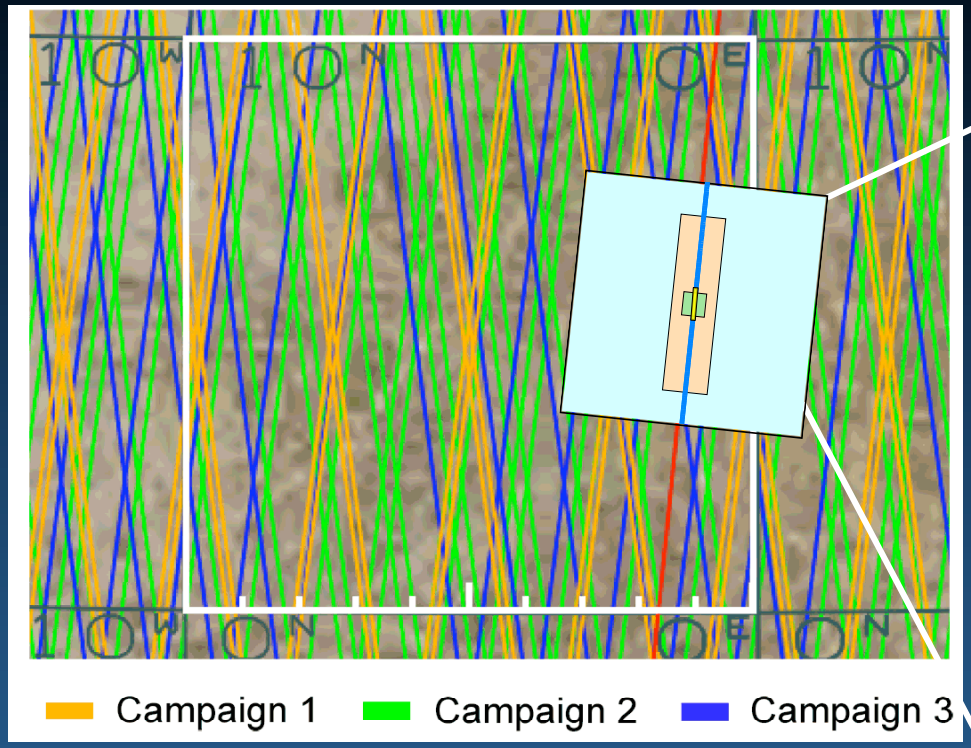
Targeted Processes
100 km altitude
8 eurosols ≈ 28 days



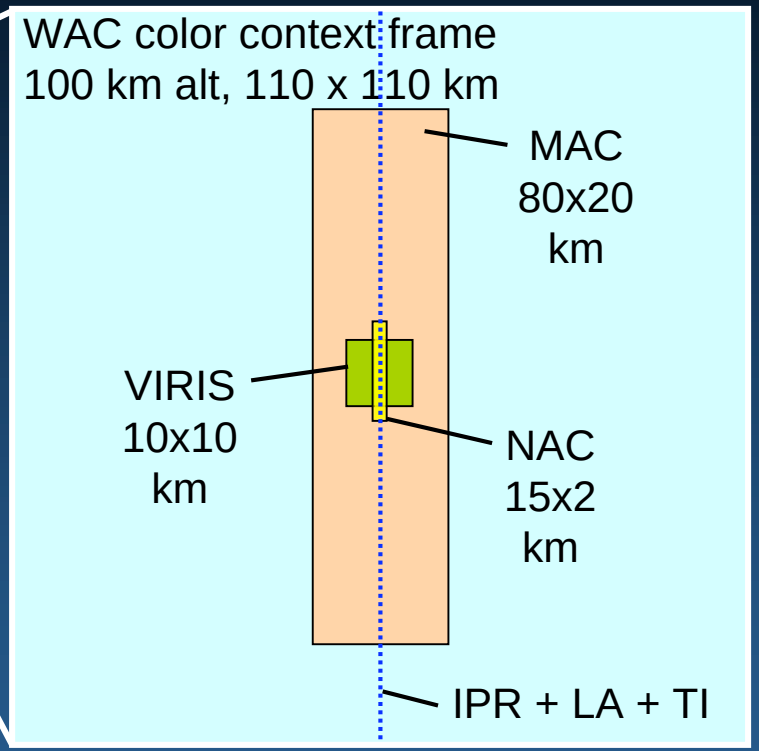
Coordinated Targets

Europa science objectives addressed in first 100 days in orbit

Europa Science Campaigns: Profiling and Targeted Observations



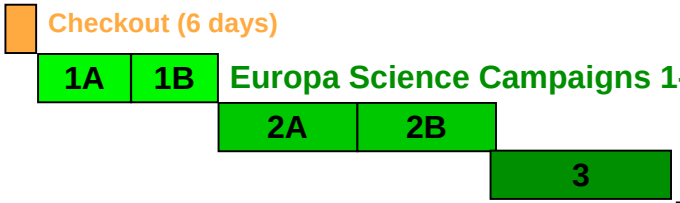
≤18 km groundtrack separation after 100 dy



290 Mb coordinated targets

~1700 coordinated targeted observations obtained after 9 mo.

Europa Science Campaigns



Campaign 4: Focused Science (5.5 mo.)

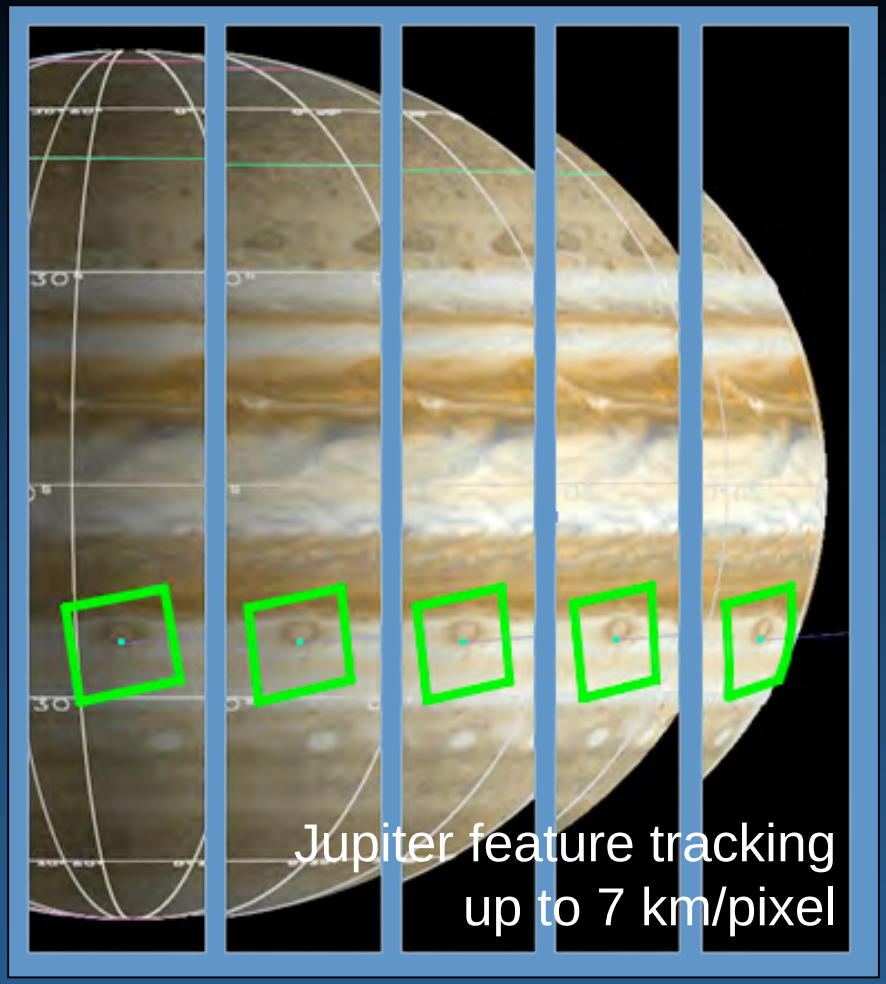
By end of Europa Campaign 3:

- 99 days orbital science
- 4 global maps
  - 2 @ 200 m Color + Stereo
  - 2 @ 100 m Stereo
- 730 imaging and radar targets
- 18 km profile separation for LA, TI
- 35 km spacing for IPR, VIRIS
- 400 UVS stellar occultations
- 700 Gb data return

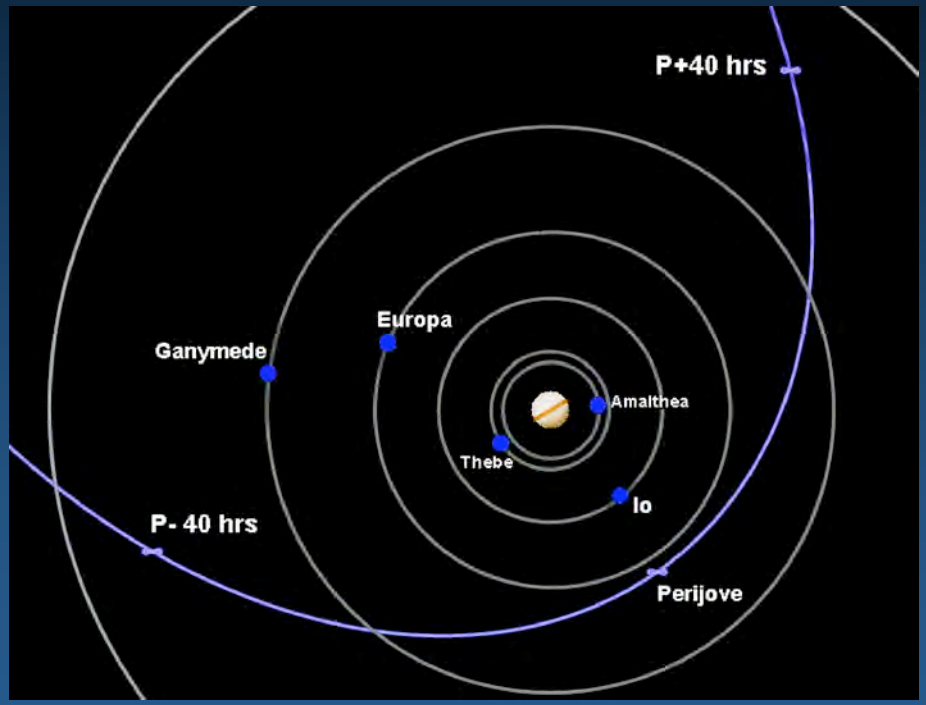
- Follow up on discoveries
- Finer global and regional grid of profiling observations (IPR, VIRIS, TI)
- Continue gravity, laser altimetry, and fields and particles measurements
- Additional coordinated target sets
  - Investigate new discoveries and priorities
  - Characterize candidate future landing sites
- Off-nadir NAC stereo images
- Lower-altitude operations
- Monitor Io and Jupiter, 1 to 2 times per week

Focused Science Campaign would allow follow-up on discoveries

Jupiter System Science

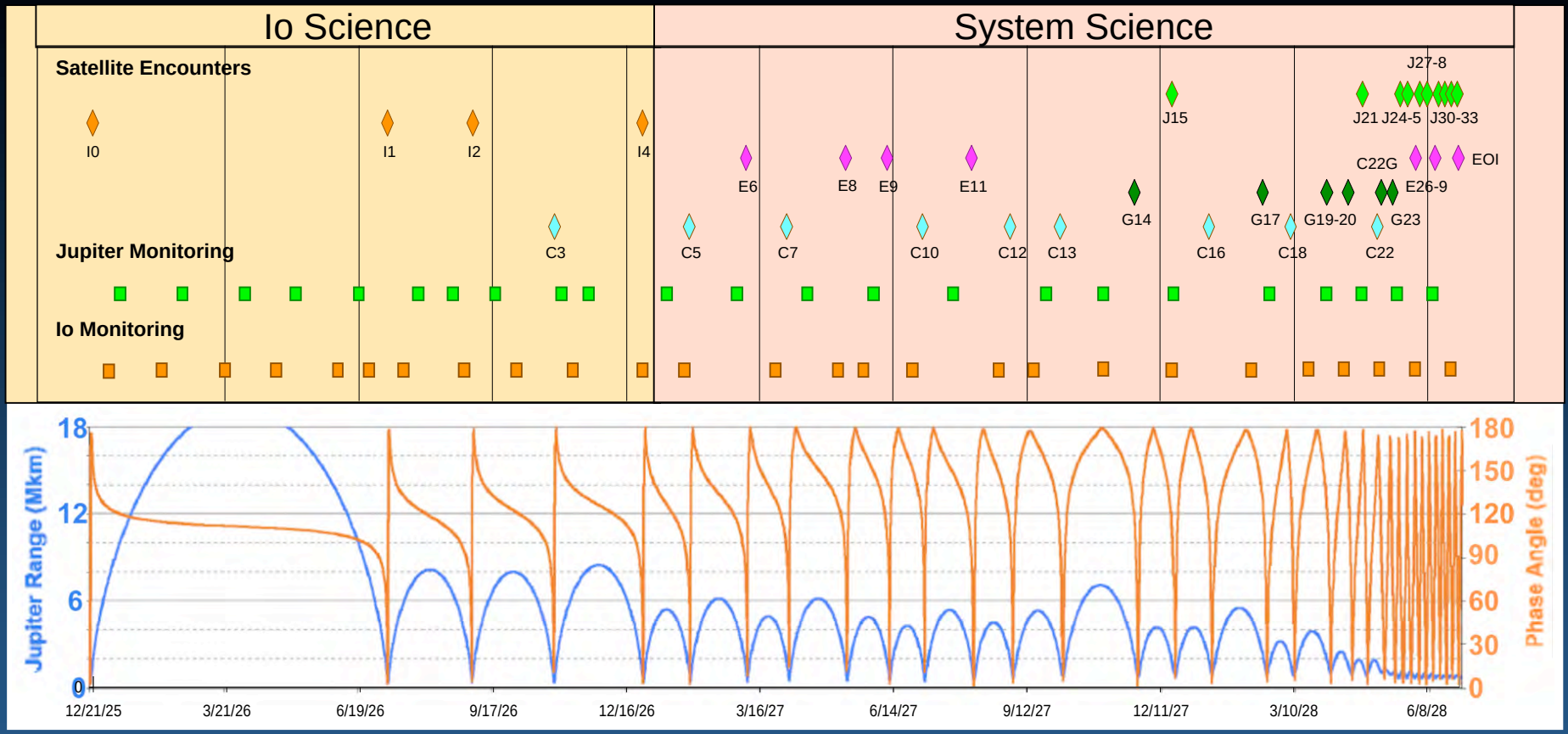


- ~25 Gb collected each perijove
- ~3.2 Tb available during Jovian tour
- ~1000 times Galileo data return



Jovian Tour would enable in-depth Jupiter system exploration

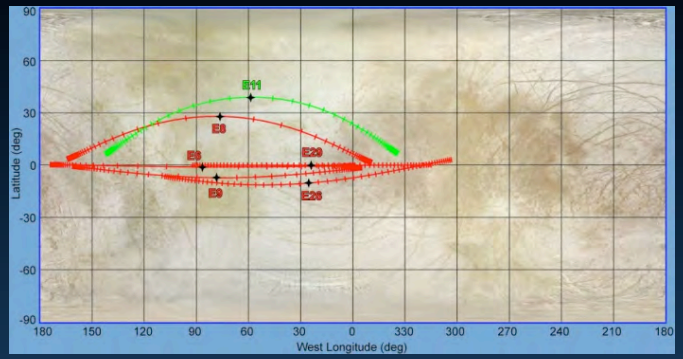
Jovian Tour Example

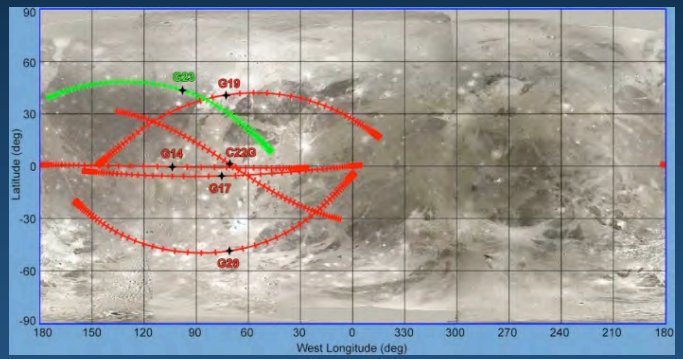


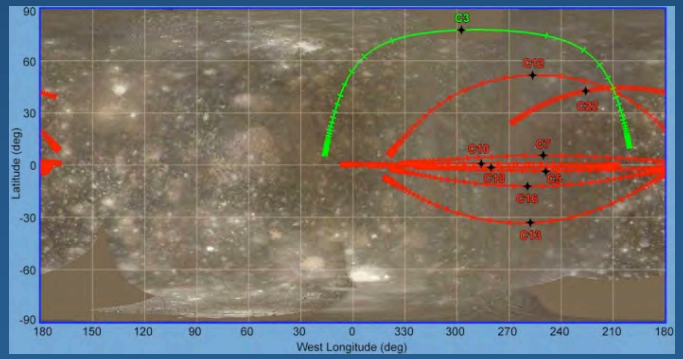
- 33 perijoves during Jovian Tour
  - 23 with satellite flybys
  - 22 permit JEO-Earth radio occultations

Rich opportunities to acquire Jupiter System Science

Jovian Tour Satellite Science



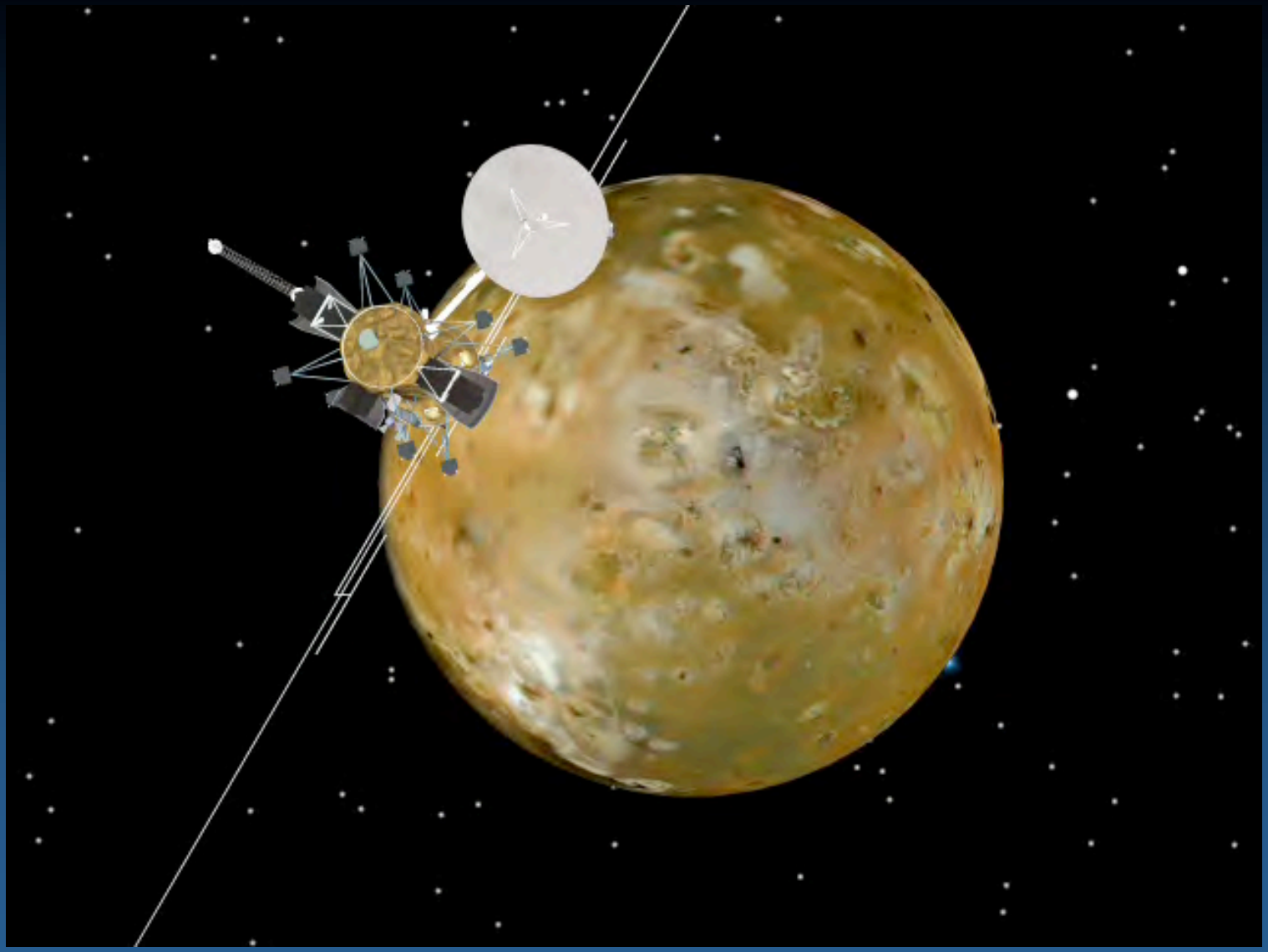




- Io: 3 flybys
  - Opportunities for imaging, IR spectroscopy, and altimetry
  - *In situ* analysis of extended atmosphere with INMS at 75 km
- Europa: 6 flybys
  - Radar and altimetry characterization and calibration
  - Imaging at up to 10–50 m resolution, NIR 250–1250 m
- Ganymede: 6 flybys
  - Radar sounding of grooved and dark terrains
  - Range of lats, lons for magnetosphere sampling
- Callisto: 9 flybys
  - High-latitude flyby for gravity field determination
  - Ocean characterization with magnetometer
  - Radar for subsurface structure of ancient cratered terrain

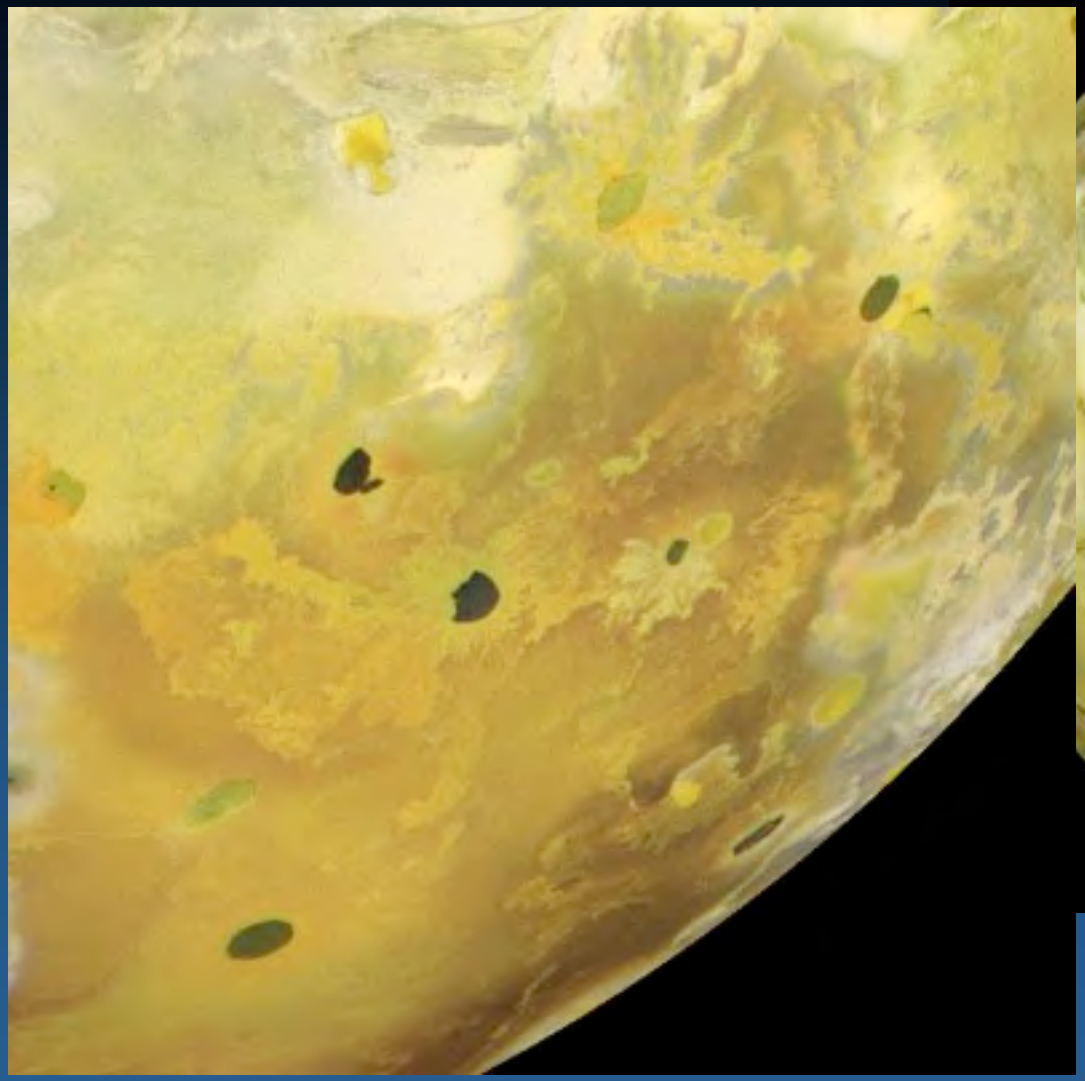
Satellite	≤1000m	≤200m	≤50m	≤10m	Length IPR (km)	Length LA (km)
Io	30%	20%	5%	-	1000	7400
Europa	60%	60%	15%	0.01%	6600	19000
Ganymede	50%	50%	10%	0.02%	17000	28000
Callisto	85%	75%	5%	0.01%	15000	30000

Io Flyby Example

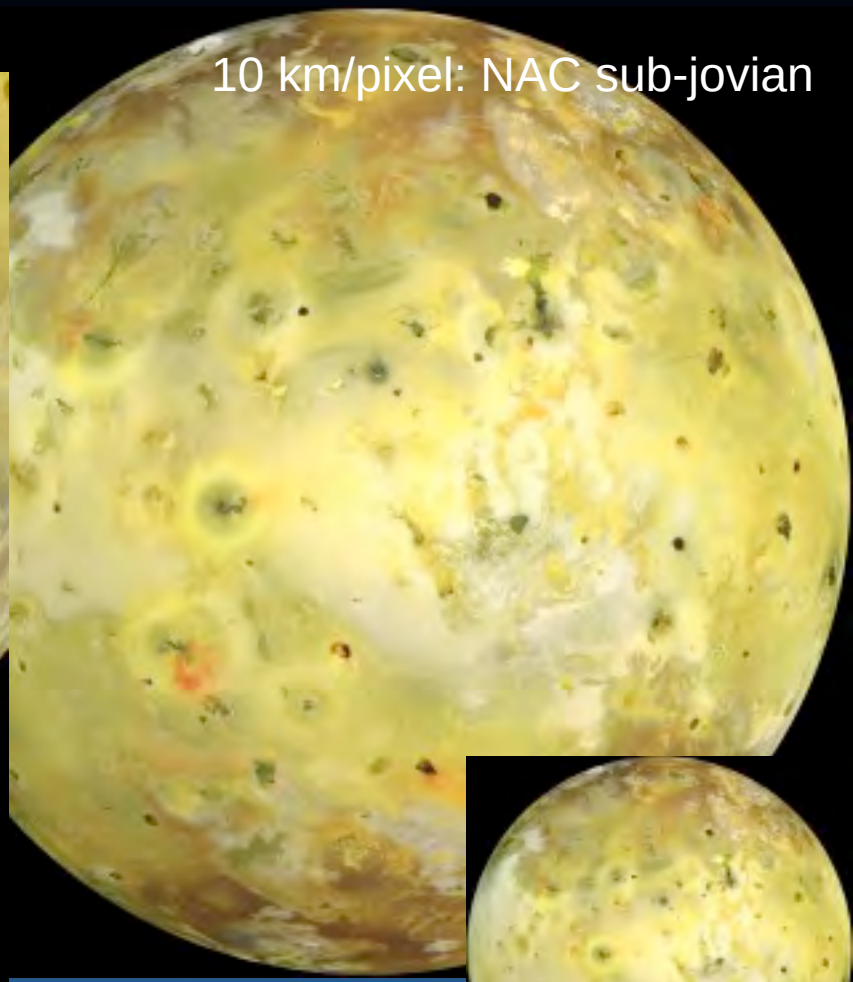


Io Resolution Examples from Europa Distance

2.5 km/pixel: NAC anti-jovian



10 km/pixel: NAC sub-jovian

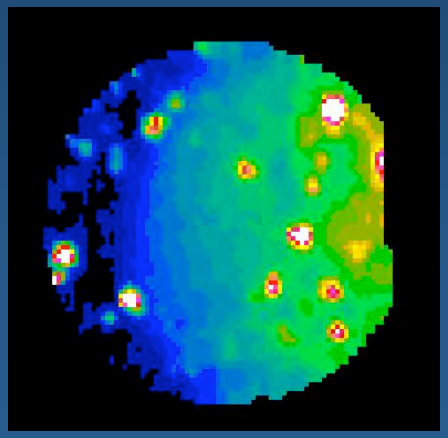


25 km/pixel:
MAC anti-jovian

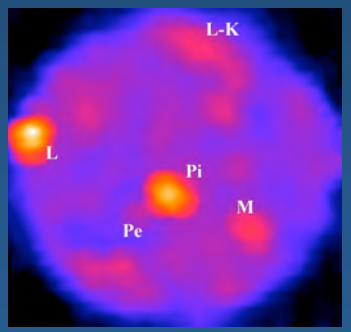
Io Resolution Examples from Europa (cont.)

Eclipse, 55 km/pixel:
MAC leading/trailing

High phase, 25 km/pixel:
MAC anti-jovian



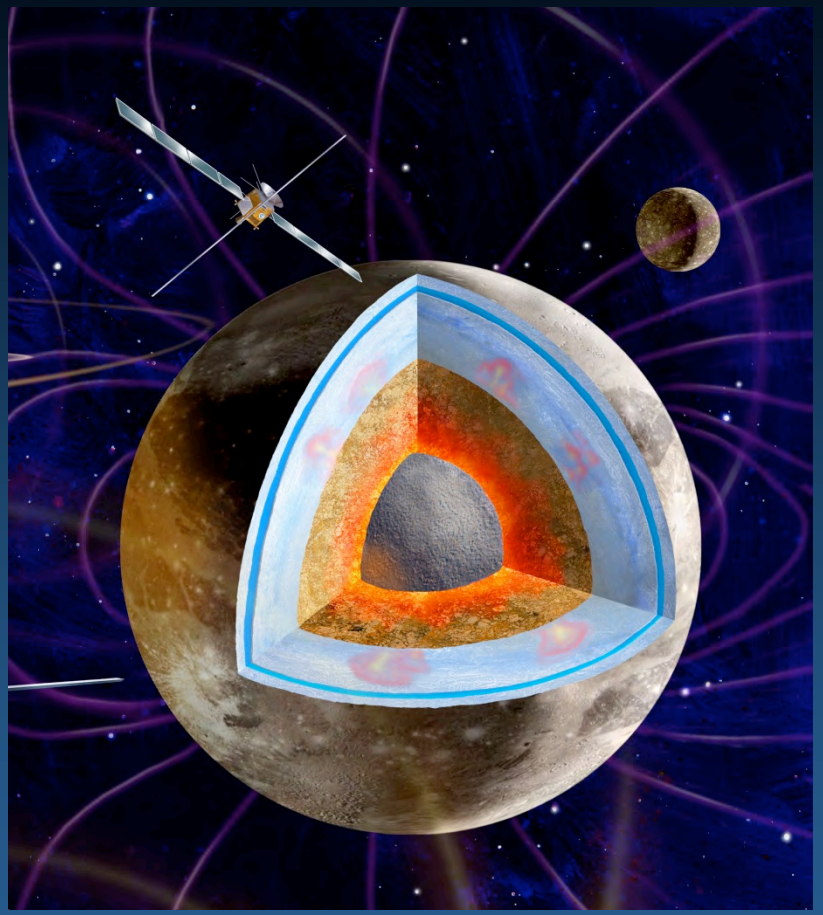
Near IR (5 μm),
85 km/pixel:
VIRIS ~anti-jovian



Thermal IR
(~30 μm),
350 km/pixel:
anti-jovian
[Twice as good as
JEO thermal mapper]

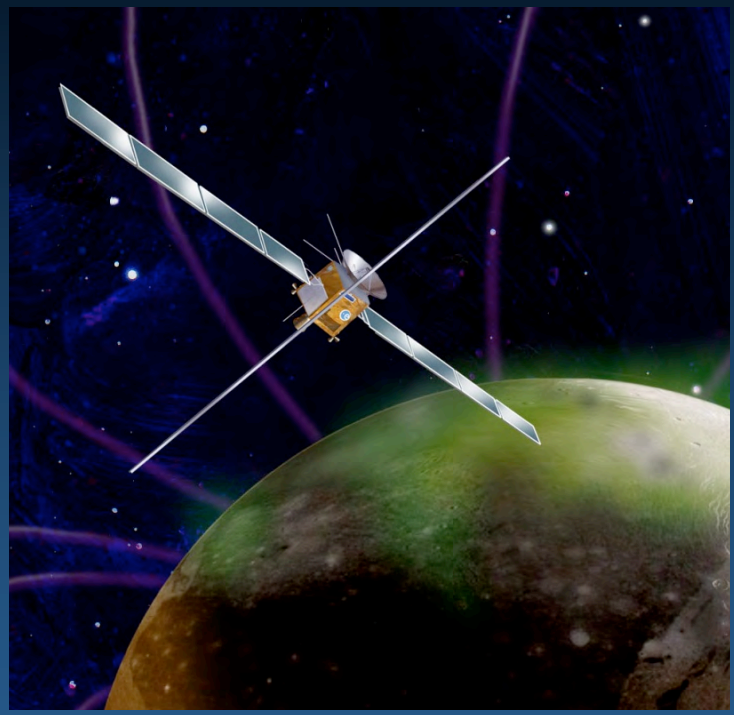
JGO Science: Overview

- Key JGO science phases
  - **Jupiter system:** In-depth exploration
    - From Jupiter orbit, synergistically with JEO
  - **Callisto:** In-depth study and mapping
    - Multiple flybys using a resonant orbit
  - **Ganymede:** Detailed orbital study
    - Elliptical orbit first, then circular orbit
- Science Objectives:
  - **Ganymede:** Characterize Ganymede as a planetary object, including its potential habitability
  - **Satellite System:** Study the Jovian satellite system
  - **Jupiter:** Study the Jovian atmosphere
  - **Magnetosphere:** Study the Jovian magnetodisk / magnetosphere
  - **Jupiter system:** Study the interactions occurring in the Jovian system

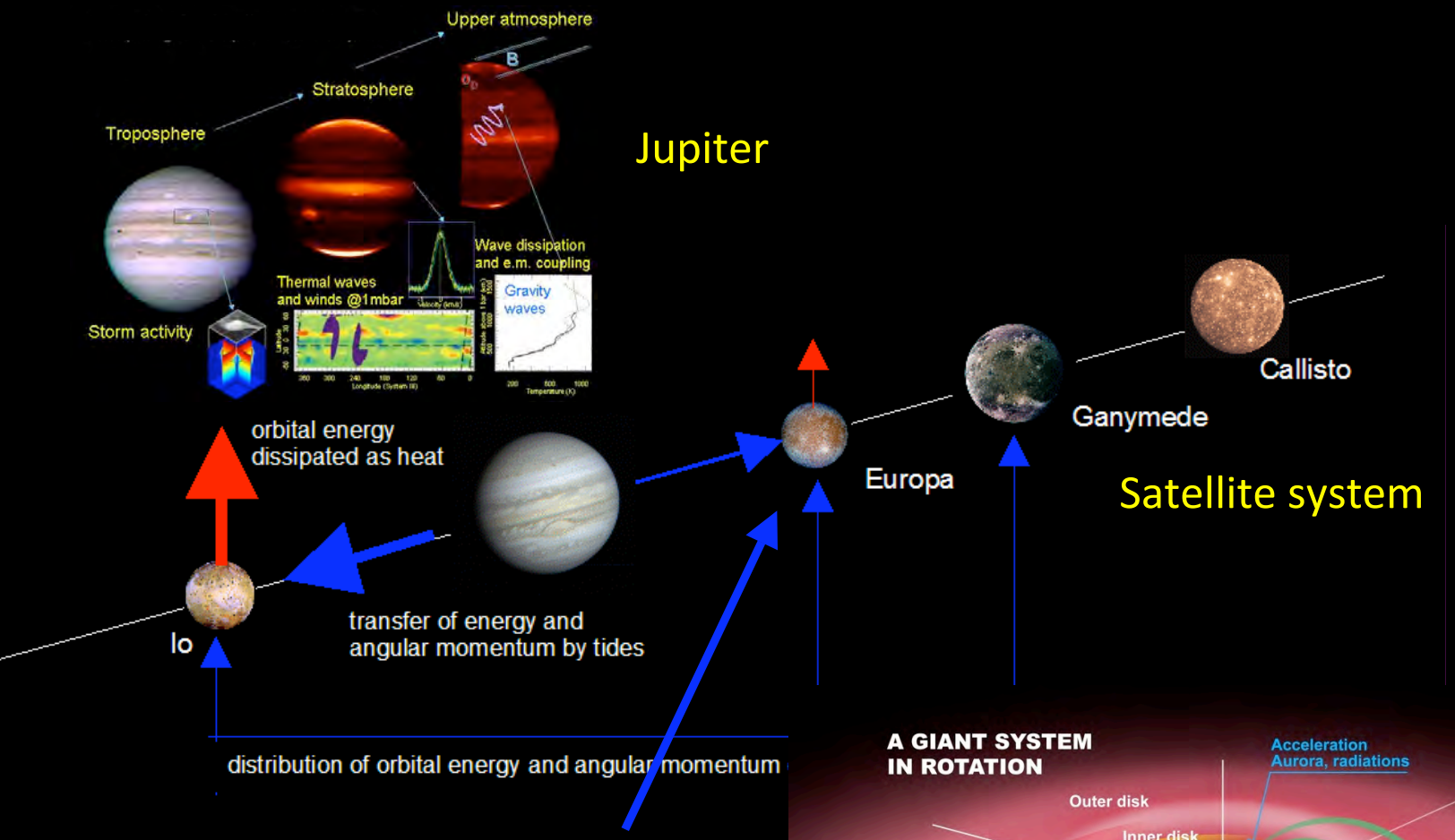


JGO Payload Definition Document (PDD) Study Model Payload

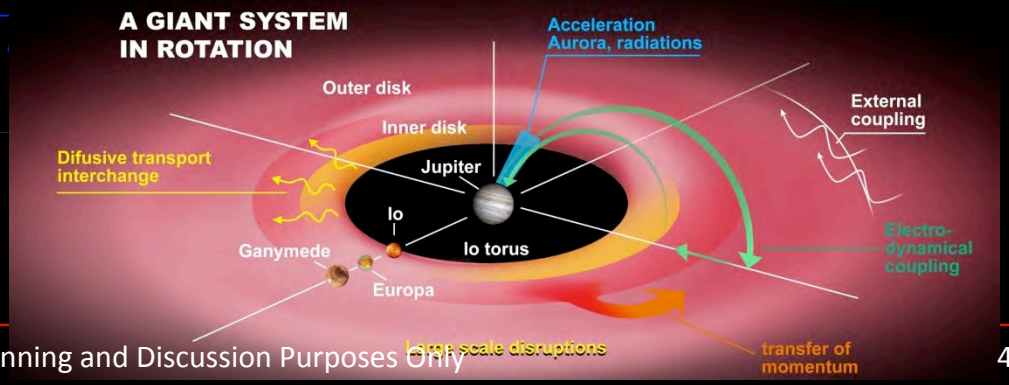
PDD Model Instrument Name	Acronym
Medium-Res Camera & Wide Angle Camera	WAC+MRC
Magnetometer	MAG
Radio Science Transponder and USO	JRST+USO
Visible InfraRed Hyperspectral Imaging Spectrometer	VIRHIS
Plasma Package & Ion and Neutral Mass Spectrometer	PLP/INMS
Sub-mm Instrument	SWI
Radio and Plasma Wave Instrument	RPWI
Narrow Angle Camera	HRC
Sub-Surface Radar	SSR
Laser Altimeter	LA
UV Imaging Spectrometer	UVIS



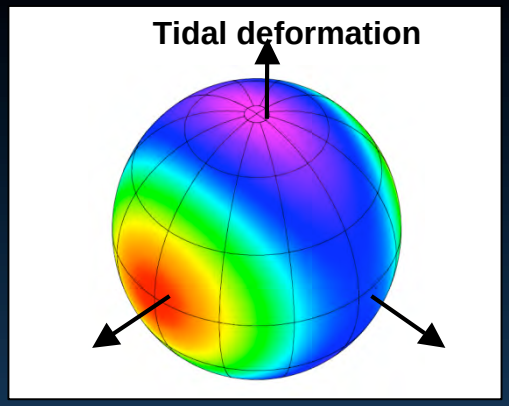
The Jupiter System: Three Coupled Components

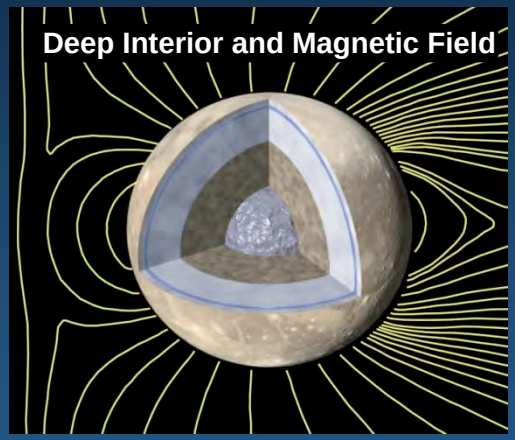


Magnetodisk/
radiation belts

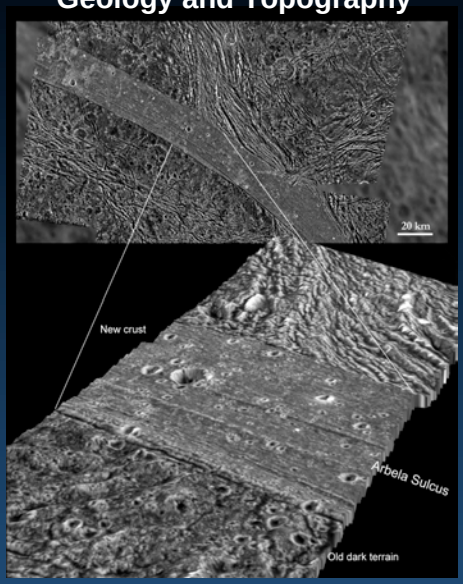


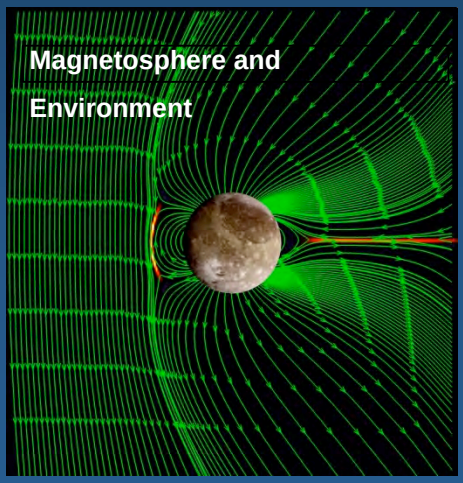
Ganymede: Europa's "False Twin"

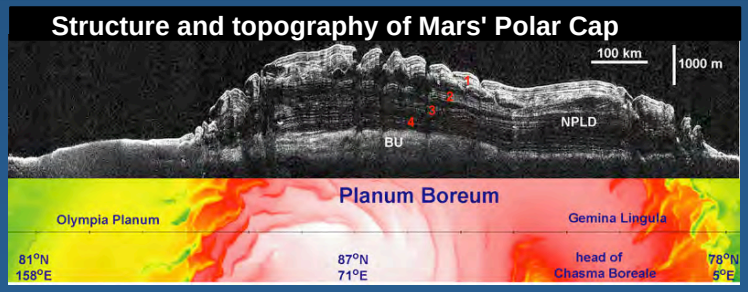


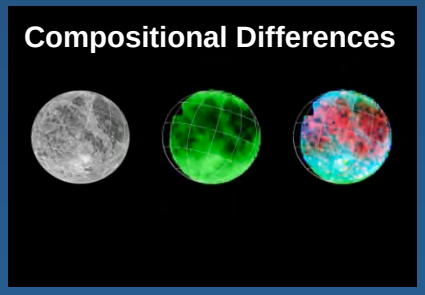


- Presence and extent of a subsurface ocean
- Ice shell and subsurface water
- Deep internal structure, dynamo, magnetic field
- Coupling among surface, exosphere, and magnetosphere
- Surface composition and chemistry
- Surface features, tectonic processes
- Thermal evolution, geology, and the Laplace resonance





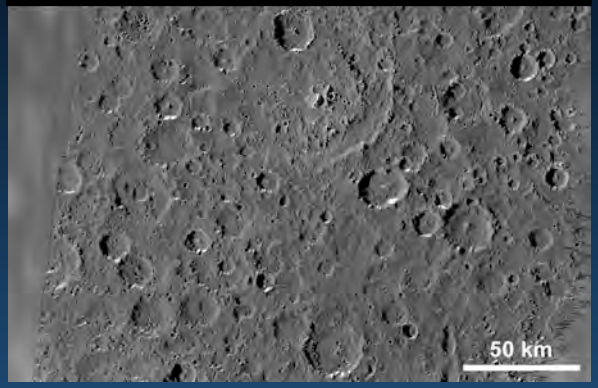




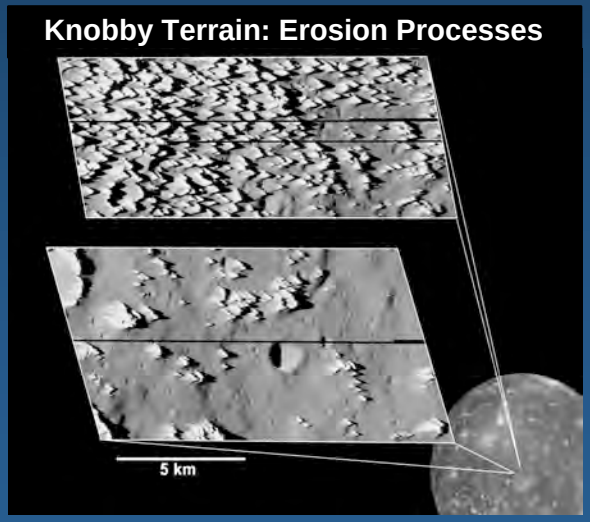
Callisto: A Witness of the Early Ages

- Presence and extent of a subsurface ocean
- Ice shell and subsurface water
- Deep internal structure, including degree of differentiation
- Cratering record and early geological history
- Surface composition, including organics and CO_2
- Surface degradational processes (erosion and sublimation)

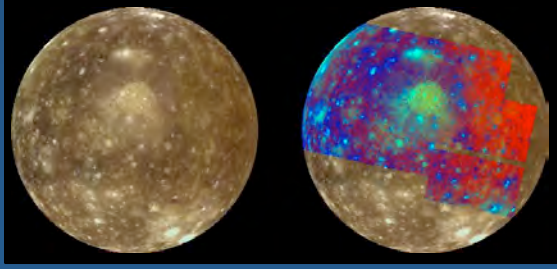
Crater Distribution and Morphology

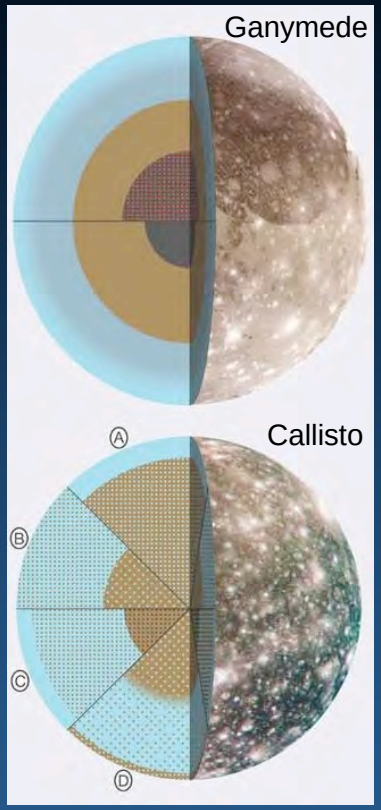


Knobby Terrain: Erosion Processes



Compositional Heterogeneities

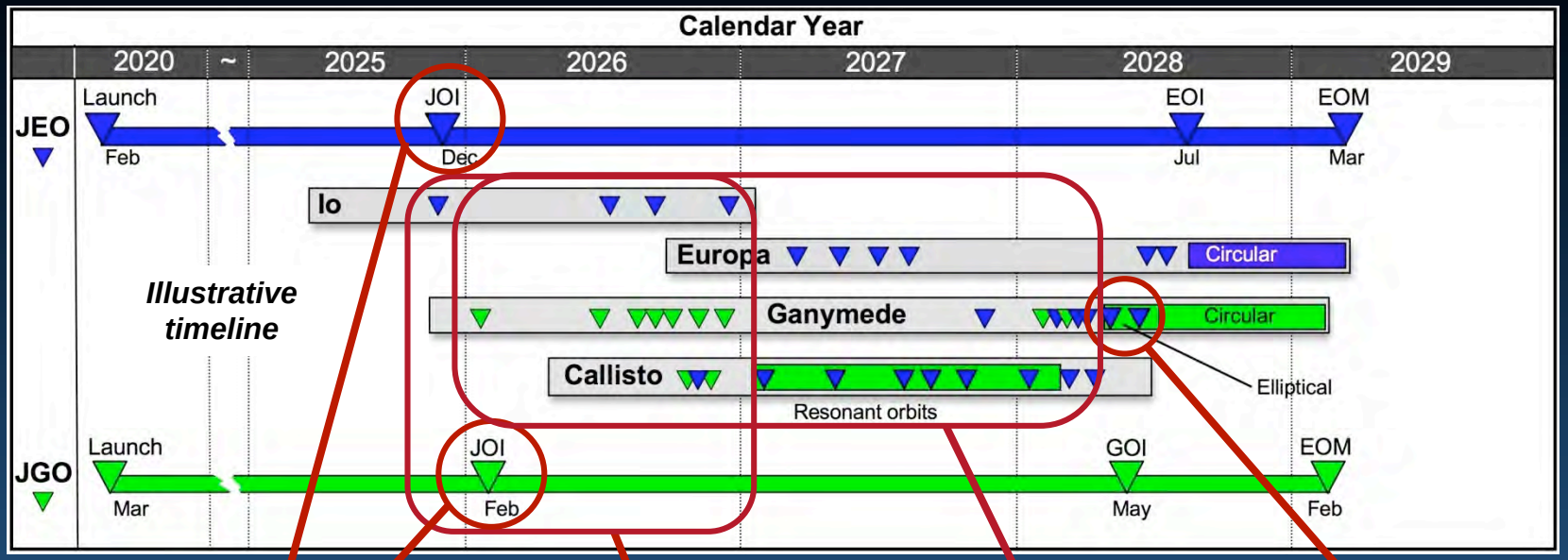




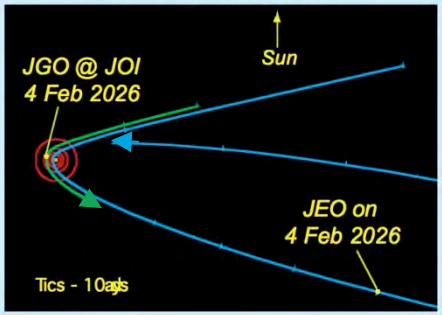
Internal differentiation: Where is Callisto ?

Image after Bagenal et al. [2004]

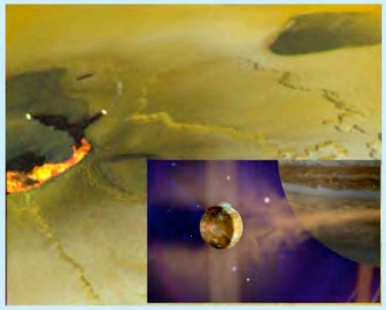
EJSM Synergistic Science



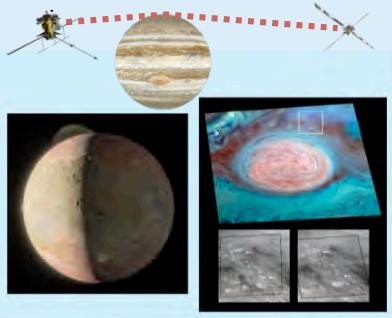
Jupiter Magnetosphere Studies



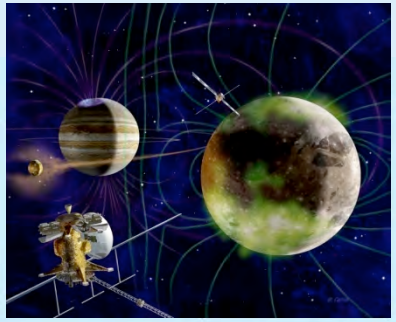
Io Volcanism & Io Torus Dynamics



Satellite & Jupiter Monitoring; Radio Occultation Science?



Ganymede Magnetosphere Studies



JEO: Untangling Fundamental Mysteries

- Science objectives have been honed for over a decade
- Science and technical teams have worked together closely to optimize the JEO science return
- JEO would achieve outstanding Decadal Survey science
- JEO would fundamentally alter our understanding of the nature of habitable worlds around gas giants
- EJSM has the science, technology, and "opportunity"

Solving fundamental mysteries of Europa and the Jupiter system

For More Information…

A wealth of resources are available at the OPFM website

The Europa Jupiter System Mission:
The Emergence of Habitable Worlds Around Gas Giants