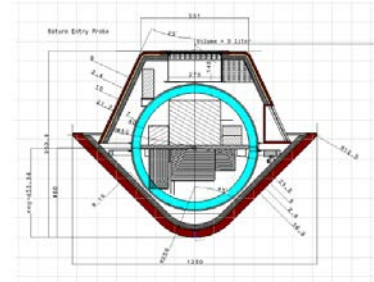
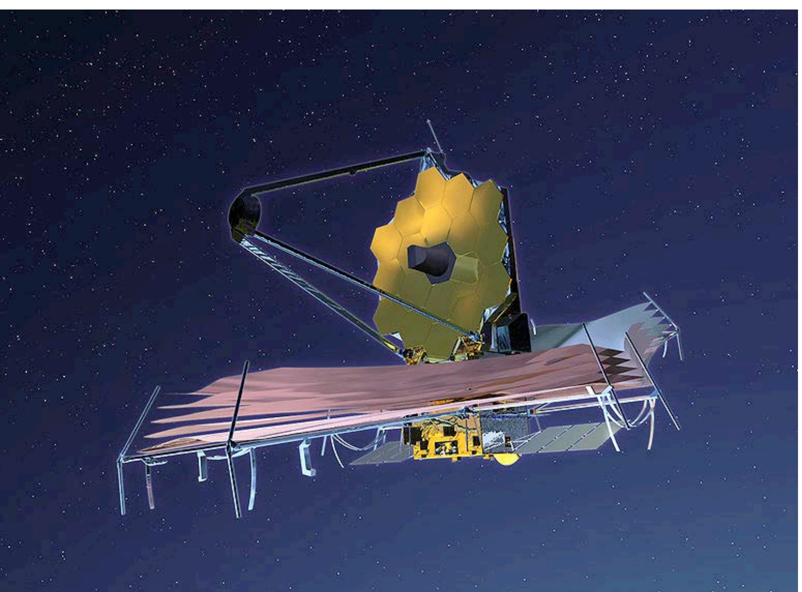
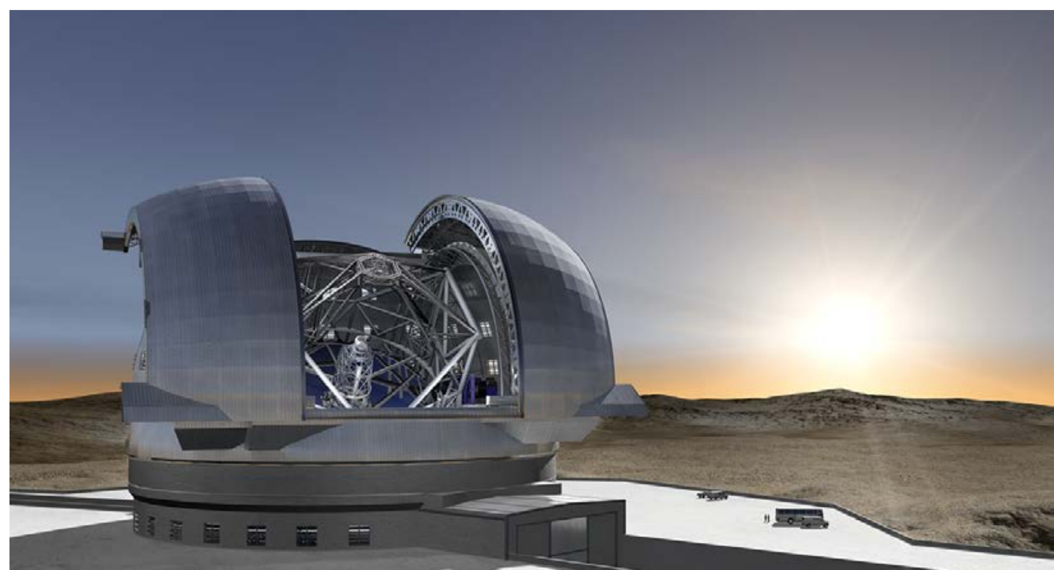


The Future Exploration of Saturn

Chapter 14

Kevin Baines, Sushil Atreya, Frank Crary, Tommy Greathouse,
Henrik Melin,Olivier Mousis, Glenn Orton ,
Thomas R. Spilker, and Anthony Wesley

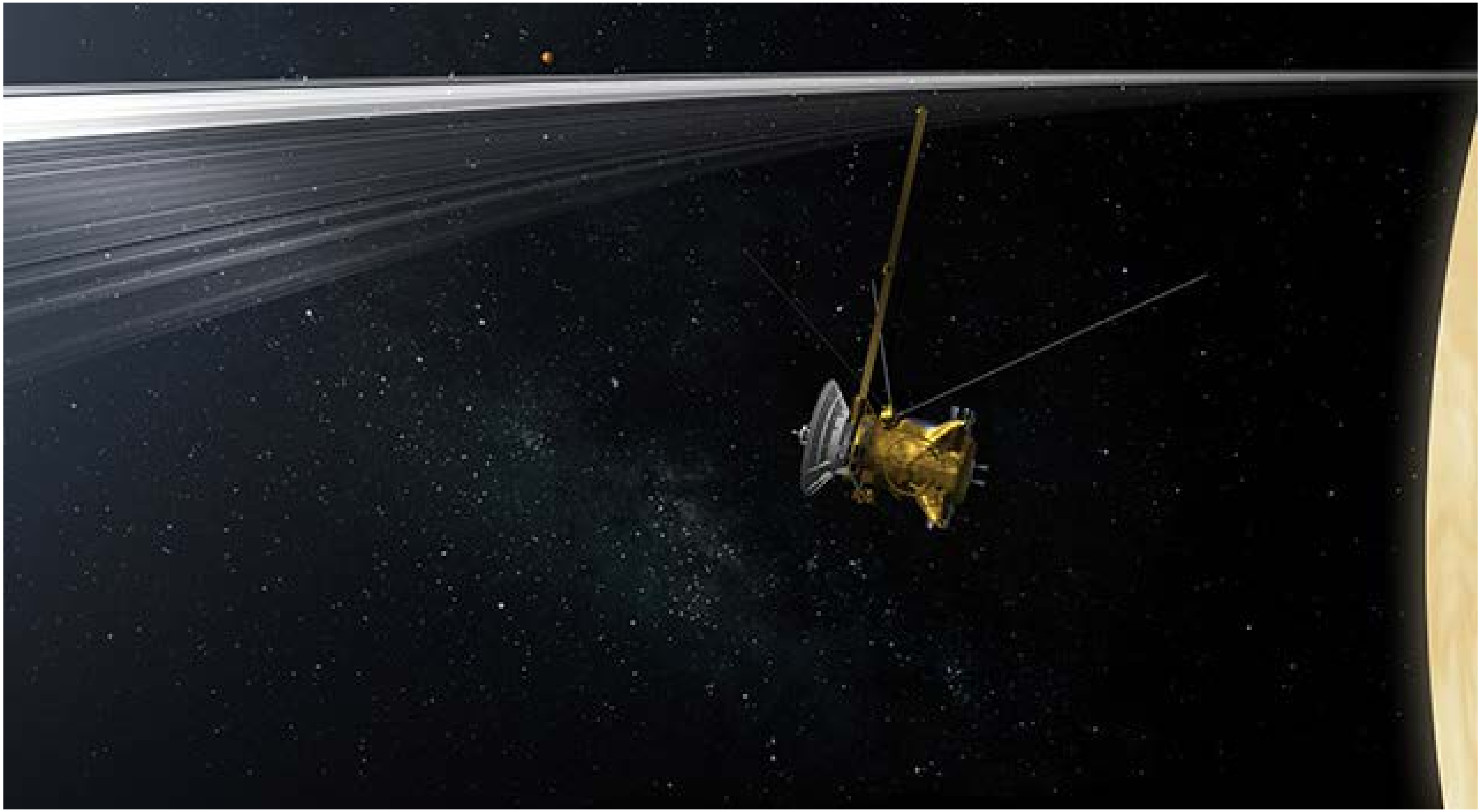




The Future Exploration of Saturn
Chapter and Talk Outline

1. Preview of Grand Finale Mission (Kevin, Frank)
2. Post-Cassini: Outstanding Science Issues (All)
3. Future Planetary Missions: NASA and ESA (Sushil, Olivia, Tom Spilker)
4. Earth-Based Observing Possibilities over the Next Few Decades
   - Airborne and Near-Earth Telescope Facilities (Tommy Greathouse, Henrik Melin, Glenn Orton)
   - Large Telescopes (> 4 meter aperture) (Tommy Greathouse and Glenn)
   - Amateur Observations (Anthony)
4. Summary

Grand Finale Cassini Mission



Cassini-Huygens Project

Cassini-Huygens Mission To Saturn and Titan

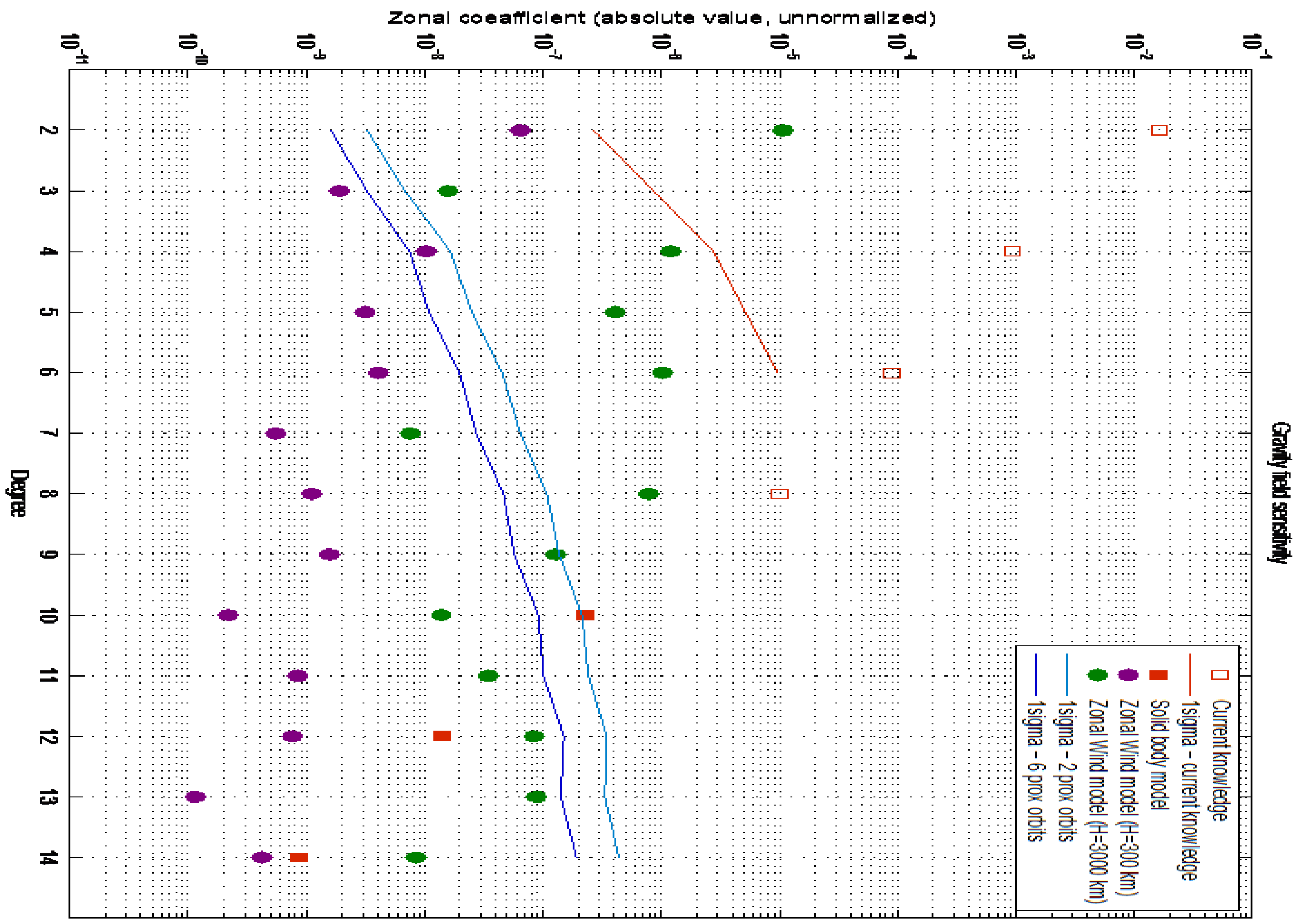
Saturn Science Priorities

- Gravity (RSS) – Planetary formation (core), thermo-chemical evolution (helium rain), heavy elements in the mantle, deep winds (cylinders?). At least 6 good orbits to do the science.
- Magnetic field (MAG) – Depth of the dynamo, rotation of the planetary interior. MAPS is in charge. MAG is on all the time.
- Thermosphere composition (INMS) – Measured values of He/H_2 and HD/H_2 provide clues to these ratios in the lower atmosphere; diffusive separation is a complication. Reactive species and ions. Search for H_2O (ring rain). 3-6 periapse passes (some internal disagreement here).
- Turbulence and small scales (RADAR, ISS) – Up to 50 times higher resolution (ISS ~100 m) to study convective clouds, waves, ammonia-laden updrafts and dry downdrafts. Want 3 pole-to-pole scans for RADAR, 3 for ISS, but could drop to one each.

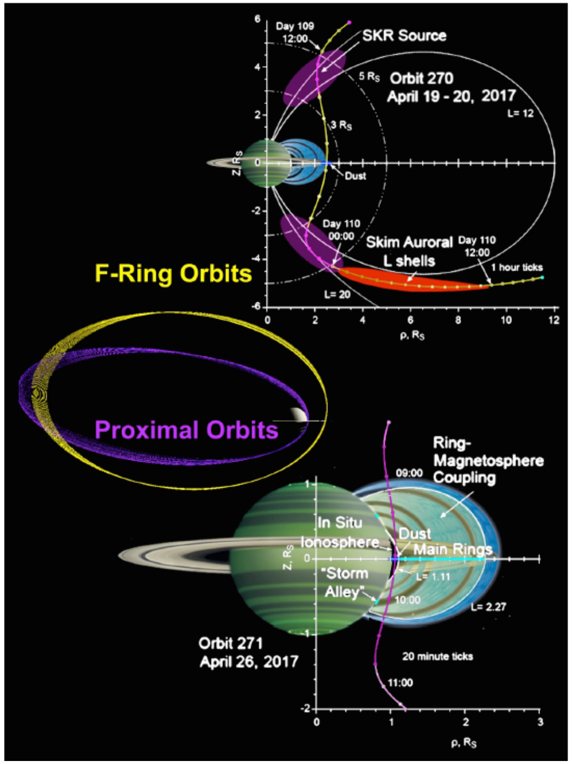
Gravity Measurements

- Current measurements are limited to J_2, J_4, J_6, and J_8
  - Do not yet allow an estimate of the extent of a possible high-density core, the depth of Saturn's zonal winds, or the mass of Saturn's classical ring system.
  - All of these will be possible with the planned RSS gravity experiments during the Cassini Grand Finale.
- The absolute accuracy of the gravity field measurements will be improved by a factor of several hundred over current values, and extended to both even and odd harmonics up to 14 with an absolute error below 2×10^{-7}.

Expected Cassini Sensitivity to Zonal Gravity Harmonics during Proximal Orbits.



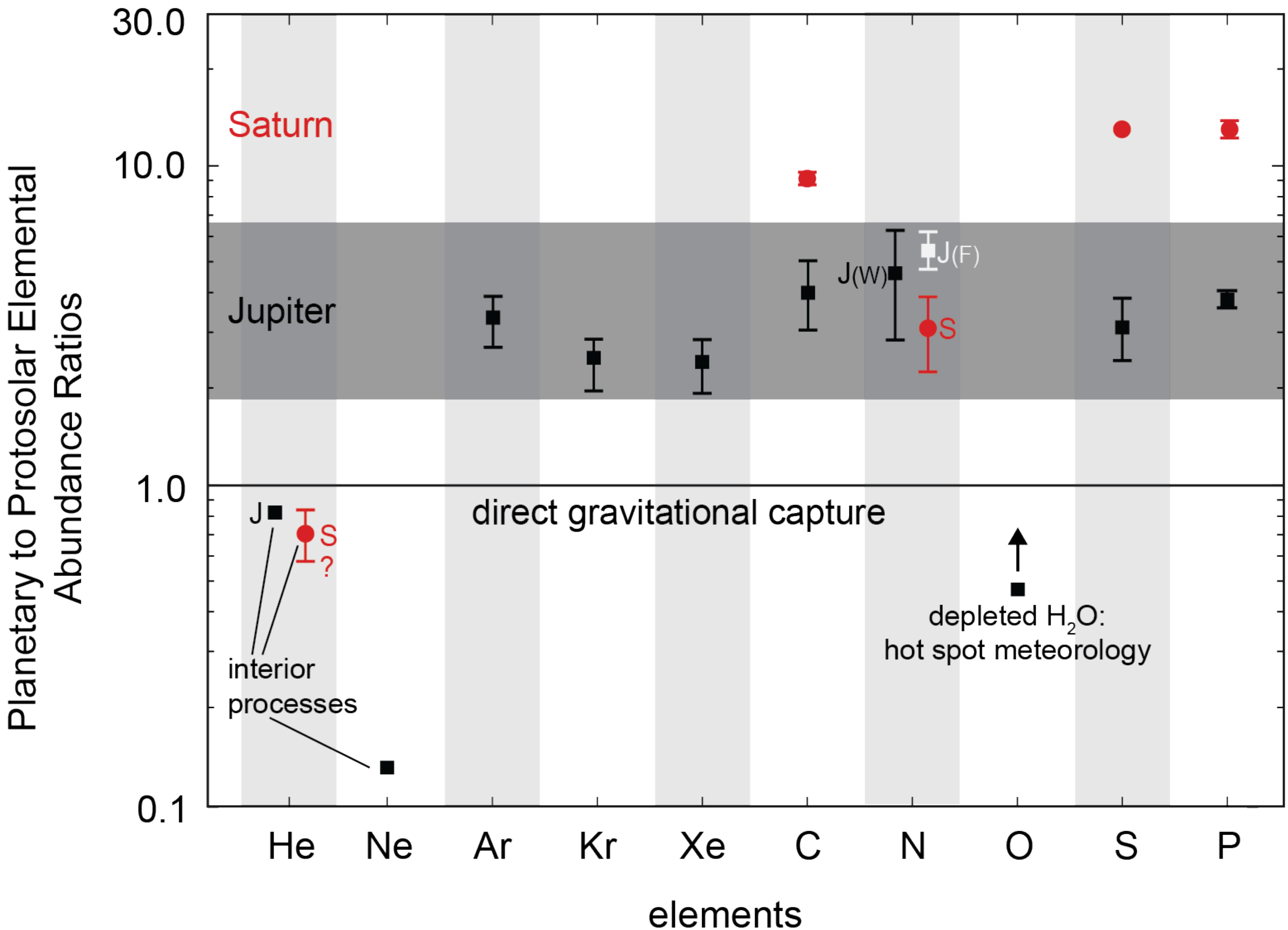
Cassini Grand Finale



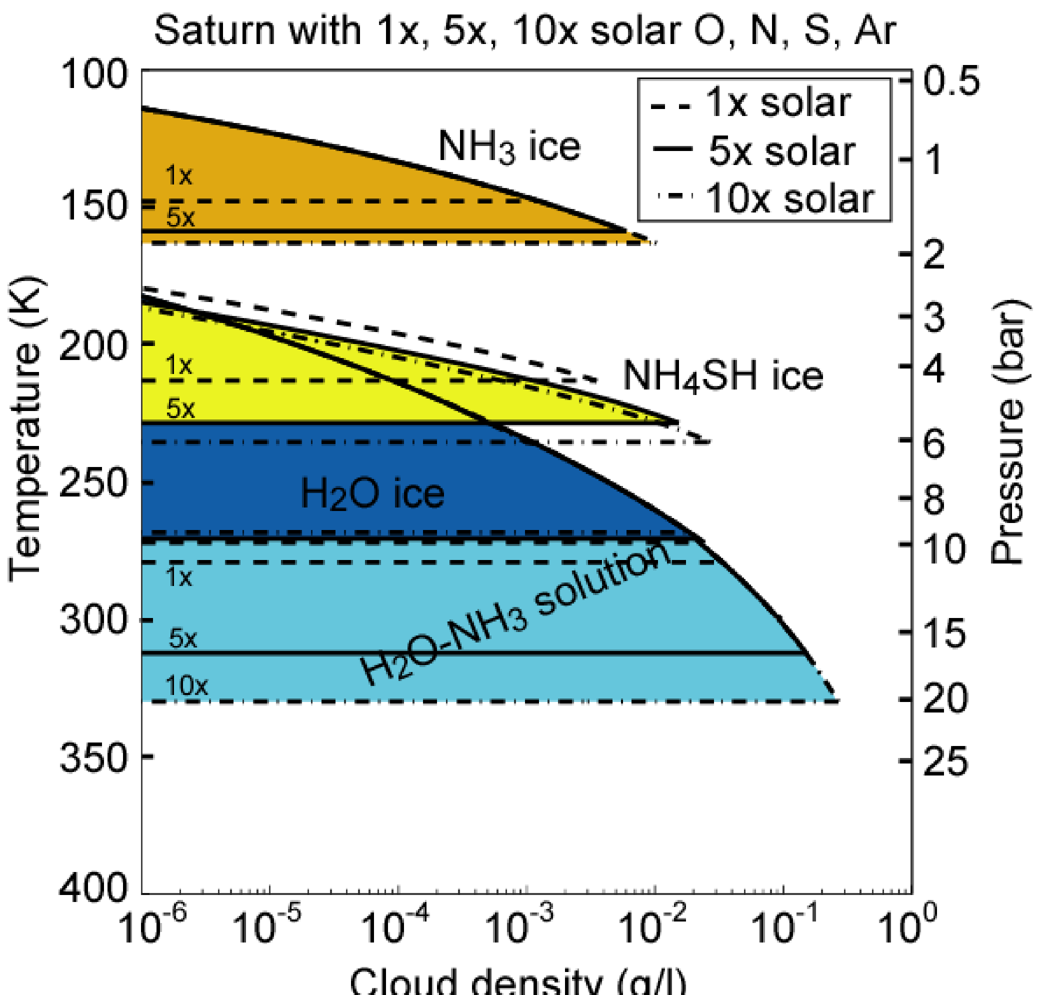
- Saturn's ionosphere (INMS and RPWS)
  - Measurements near noon
    - Radio occultations only sample near dawn or dusk
  - Electron density (RPWS), electron & ion temperatures (RPWS-LP)
  - First composition measurements of an outer planet ionosphere
- Internal magnetic field (MAG)
  - Higher order terms for dynamo theory
  - Asymmetric terms (if any) for core rotation rate
- Aurora (VIMS and UVIS)
  - Highest spatial resolution of Cassini mission (50 km TBC)
- Lightning: Whistlers and Sprites (RPWS and MIMI)
  - Radio signals and energetic electron beams produced by lightning

Post-Cassini Outstanding Science Issues

Element abundances in Saturn & Jupiter



Look for heavy elements below the clouds

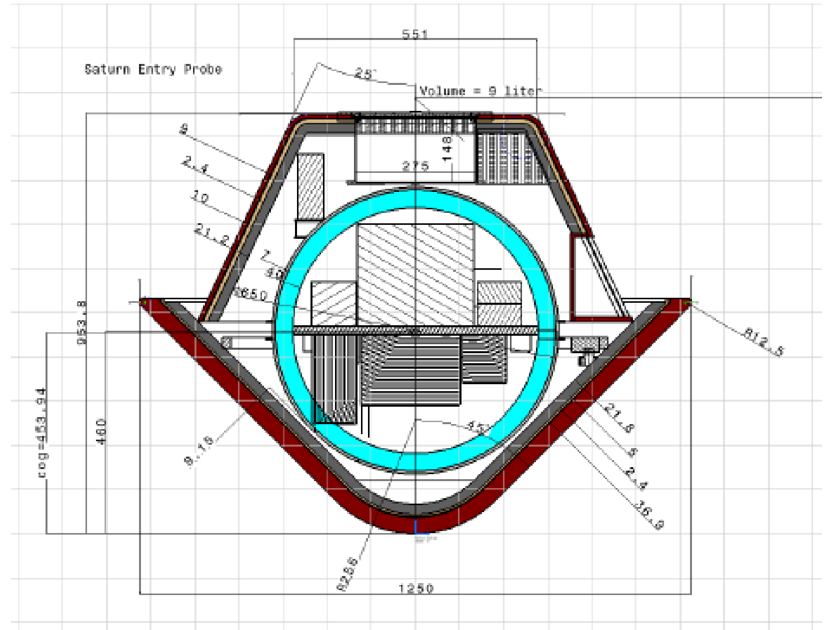


Upper limits

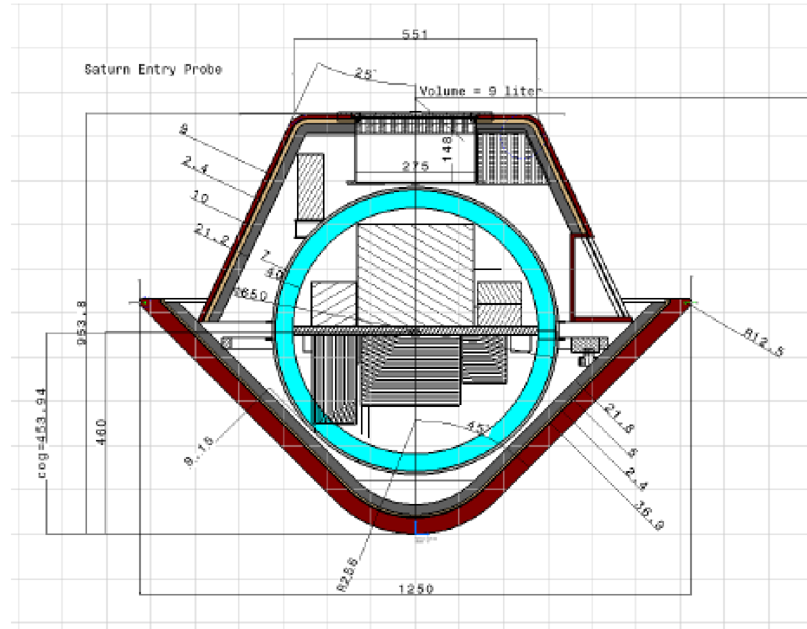
S A T U R N

S.K. Atreya, 2007

Future Planetary Missions

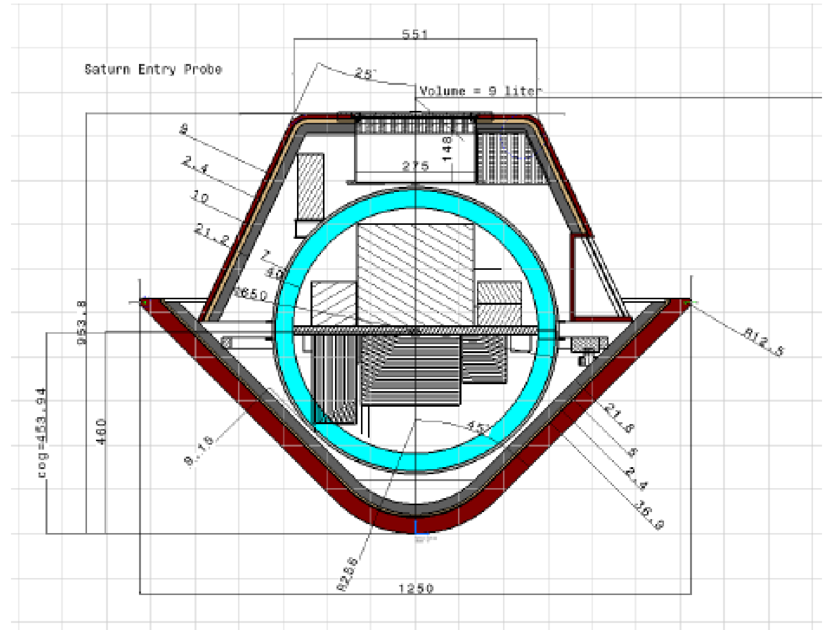


Future Planetary Missions



No new missions currently approved
But several proposals are underway:

Future Planetary Missions



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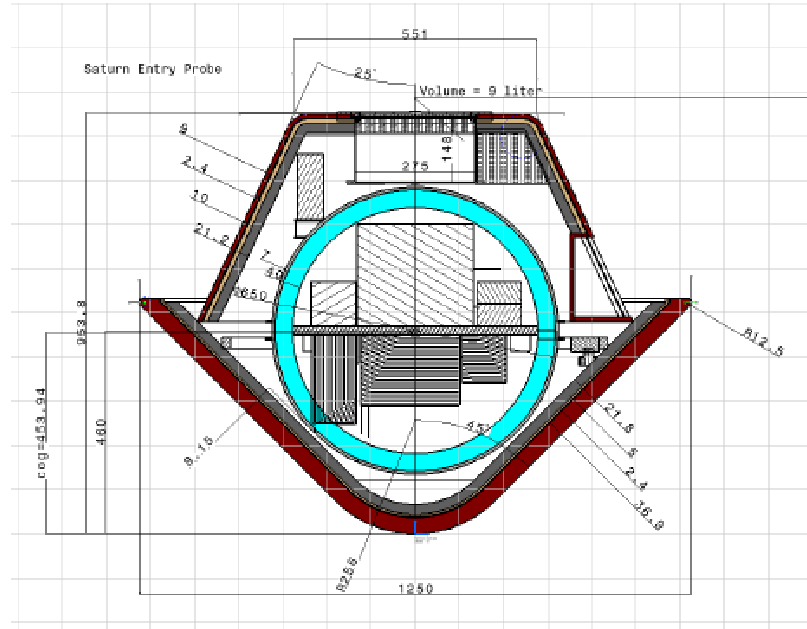
But several proposals are underway

1. New Frontiers Saturn Probe: Recommended by Decadal Study

Future Planetary Missions



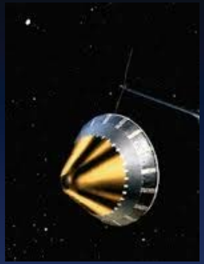
No new missions currently approved
But several proposals are underway

1. New Frontiers Saturn Probe: Recommended by Decadal Study
2. ESA Cosmic Vision Call: Probe mission proposal being developed

Decadal Study

Atmospheric Entry Probe Missions

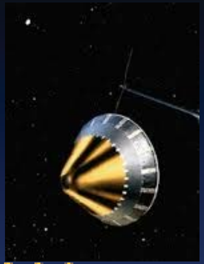
Decadal Survey Saturn Probe Studies



- Conducted in early 2010 at JPL
- Primary objective: test for fit within New Frontiers Program
  - Secondary objective: would a two-probe mission fit?
- Giant Planets Panel: address only Tier 1 science objectives
  - Determine the noble gas abundances and isotopic ratios of H, C, N, and O in Saturn's atmosphere
  - Determine the atmospheric structure at the probe descent location(s)
- Tier 2 objectives for prospective PI & team to customize
  - Clouds, winds & circulation, radiative balance, spatial variability, …
- NASA requirement: include 50% development cost reserve
  - Competed missions usually include 30-35% development cost reserve
- *Success!* : mission fit within New Frontiers limits (just barely)

Atmospheric Entry Probe Missions

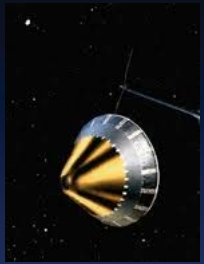
Comparison: Saturn Probe and *Galileo Probe* (Jupiter)



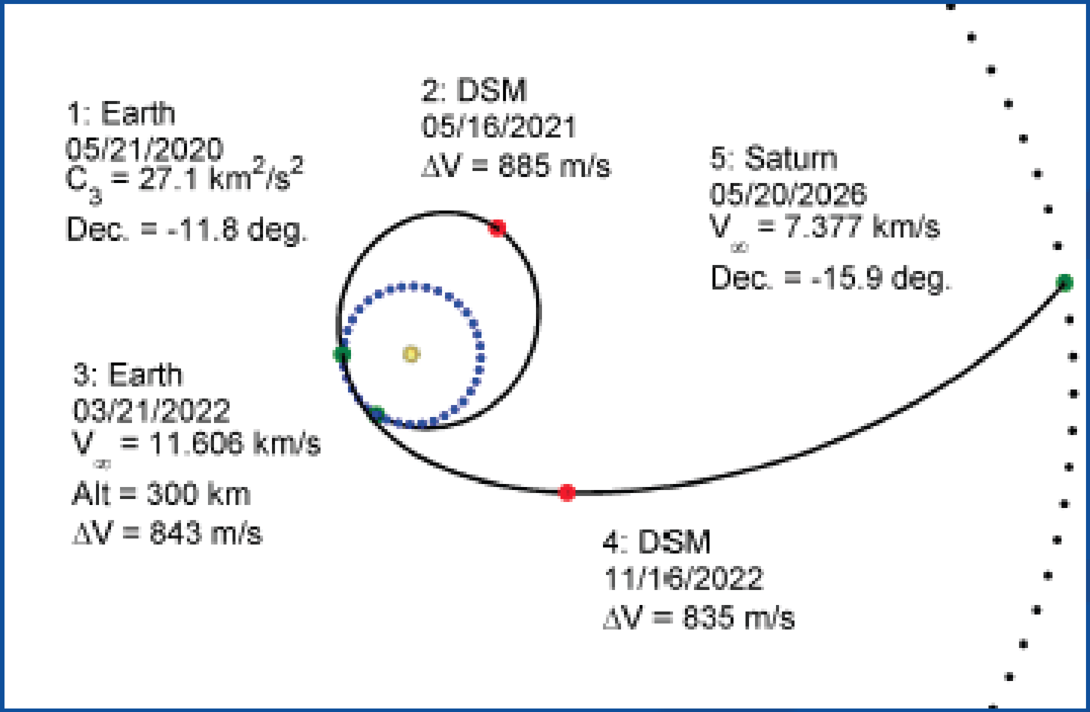
- Saturn at ~10 AU heliocentric distance, Jupiter at ~5 AU
  - Typically longer cruise times -> greater operations costs
  - More energy needed for Saturn transfer
    - Larger launch vehicle and/or more gravity assists -> greater costs
  - Solar electric power more problematic at Saturn distance
- Saturn has less than 1/3 Jupiter's mass
  - Shallower gravity well; entry speeds lower for given trajectory types
    - *Minimum* Jupiter entry: ~47 km/s; many useful Saturn entries 26-30 km/s
    - Smaller inertial loads from deceleration
  - Allows lower-performance thermal protection systems -> lower costs
- Saturn's rings absorb energetic particles
  - Much more benign radiation environment -> lower flight system costs
- Saturn probe mission has far fewer non-probe requirements
  - Allows better optimization of probe mission & mission support
  - Along with less radiation, allows much better data relay geometries

Atmospheric Entry Probe Missions

Transfer to Saturn: Many Different Options



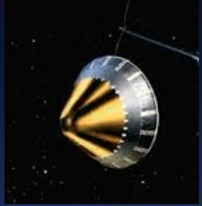
- Inner solar system gravity assists to Saturn, without Jupiter
  - Many different ways to do this, usually using Venus & Earth
  - Earth departure energy much lower
    - Can be as low as ~5 x 10^6 J/kg (C3 ~10 km^2/s^2)
  - Usually includes leveraged propulsive maneuvers (ex.: ΔVEGA)
  - Cruise durations 6-10 years or more



Trajectory from Decadal Survey Saturn Probe study; rejected due to large propulsive requirements, stemming from Saturn being far out of ecliptic plane

Atmospheric Entry Probe Missions

Transfer to Saturn: Many Different Options



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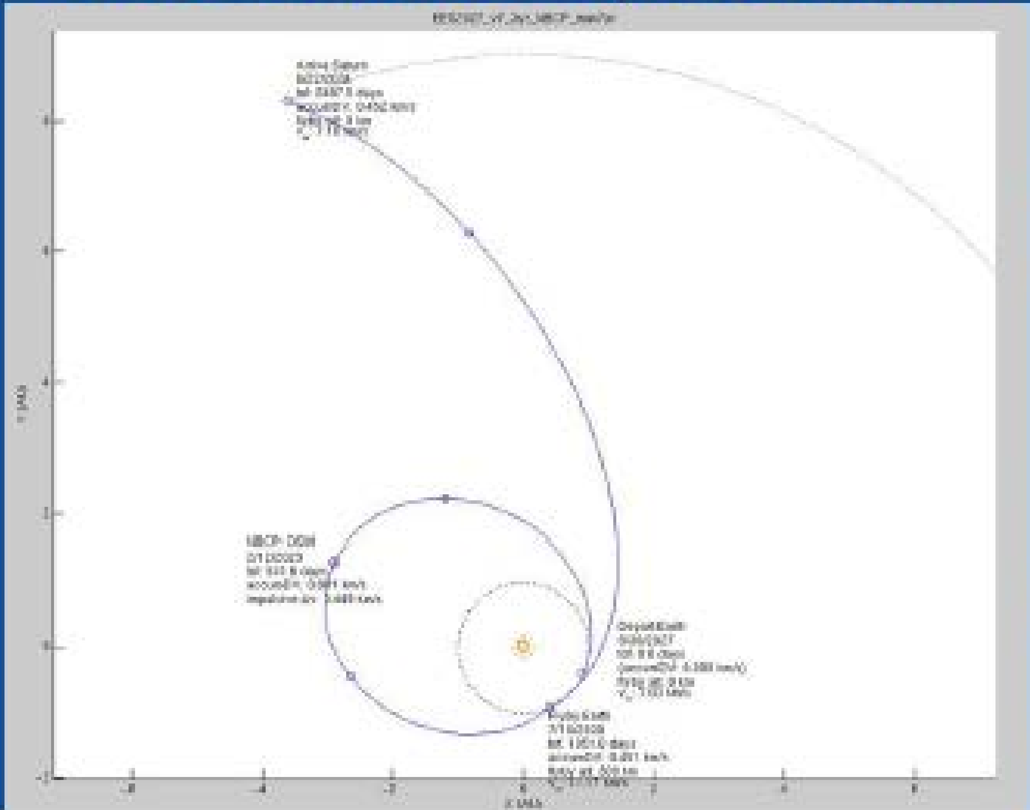
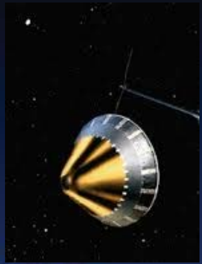


Trajectory used for Decadal Survey Saturn Probe study Final Report; launching 7 years later made Saturn arrival very near ecliptic plane, propulsive requirement less than 1/5 that of rejected trajectory

Atmospheric Entry Probe Missions

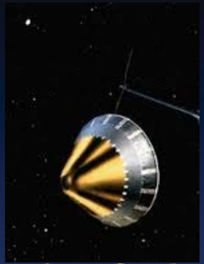


Science Mission at Saturn: Many Useful Options

- Large Saturn obliquity (~27 deg) & arrival circumstances
  - Approach declination (wrt Saturn equatorial plane) from 0 to >30 deg
  - Entry speeds <30 km/s for a variety of approaches & entry latitudes
    - Can be as low as ~26 km/s for equatorial entry, approach declination ~0
  - Outbound arrivals enter on night side
  - Inbound arrivals (for direct-to-Earth data transmission) can enter day side, but add years to cruise time
  - Useful trajectories exist for any arrival, despite ring collision limitations

Atmospheric Entry Probe Missions

Decadal Survey Saturn Probe Studies: Major Conclusions



- Single-probe mission fits New Frontiers Program constraints
- Mission budget varies somewhat with launch year
  - Effects of availability of Jupiter gravity assist, Saturn position wrt ecliptic, etc.
- ASRG nuclear electric power source offered cost *savings*
  - CRSC & probe both use radioisotope heaters; no launch approval cost savings
  - Low intensity [insolation], low temperature (LILT) effects
    - Cell performance uncertainties require testing *each individual cell!*
    - Remaining uncertainties dictate larger-than-usual margins (more cells)
    - Solar arrays must be huge, cell test program is expensive
  - ASRG development program cancelled; MMRTG more expensive?
- Carbon phenolic thermal protection material is unavailable
  - Must develop new material(s), but <30 km/s entry helps
- Useful entry trajectories available essentially any time
- Relay data link affords higher data return than DTE

Science Opportunities From Other Missions

Missions to the Saturn System

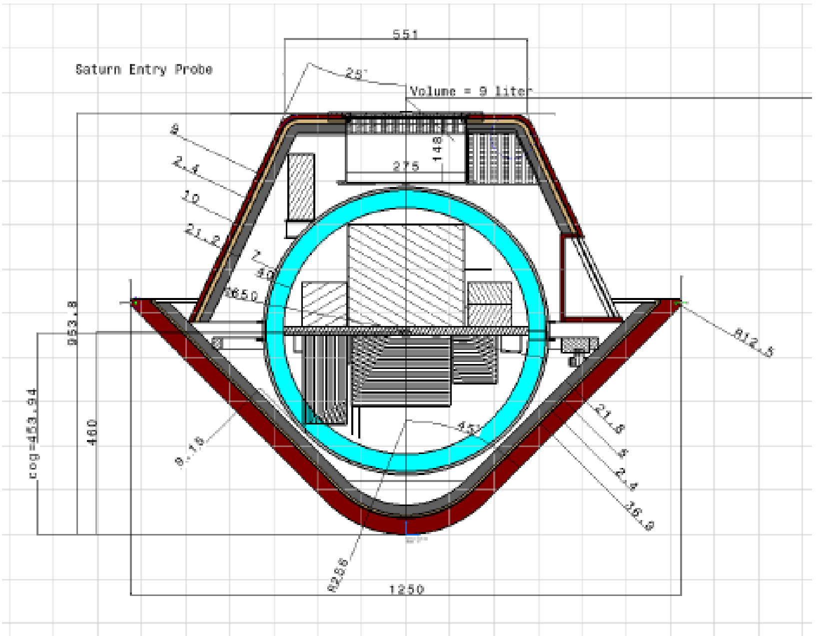
- Any mission that remains in Saturn orbit
  - *Titan Saturn System Mission* (TSSM)
  - Missions that orbit Saturn to yield multiple Titan & Enceladus flybys
  - These likely would have instruments useful for observing Saturn
- Any mission using gravity-assisted pump-down to Titan or Enceladus orbit
  - Titan orbiter
  - Enceladus orbiter
- Less useful missions (but still useful to some degree)
  - Direct insertion into Titan orbit from Saturn approach
  - Direct entry into Titan atmosphere from Saturn approach
  - Instruments not inside an entry heat shield can provide some monitoring during Saturn approach phase
- Missions not useful for Saturn science
  - Missions whose instruments are all inside an entry heat shield until reaching the final (non-Saturn) destination, or for other reasons are unavailable for Saturn observations

Science Opportunities From Other Missions

Missions to Other Destinations

- Saturn can provide a substantial gravity assist
  - Any mission with a destination outside of Saturn's orbit will likely need a Jupiter or Saturn – or both – gravity assist
  - Those using Saturn provide approach and departure opportunities
- Missions providing Saturn science opportunities:
  - Those with instrumentation useful & available for Saturn science
    - Long list of potentially useful instruments & investigations
    - IR, visible, & UV remote sensing (including spectrometry)
    - Fields & particles: magnetometry, charged particles, ENA, plasma, dust, …
  - Those that perform a Saturn flyby en route to another destination
    - Uranus, Neptune, KBO, Centaur
    - Approach geometry would be similar to *Cassini* or *Voyager*
      - Approach from dawn side, disk mostly lit
    - Departure geometry would be similar to *Voyager 2* departure, unless headed well out of Saturn's orbit plane
      - Departure between midnight & dawn, disk mostly unlit
    - Obscuration by rings dependent on approach trajectory & season
    - *Potentially* could deliver & support a Saturn entry probe

Concept of Saturn Probe Under Development for the ESA M4 call



Mission concepts: entry probe that would descend through Saturn's stratosphere and troposphere under parachute down to a **minimum of 10 bars**.

Three possible mission configurations:

- **Configuration 1: Probe + Carrier.** After probe delivery, the carrier would follow its path and be destroyed during atmospheric entry, but could perform pre-entry science. The probe would transmit its data via DTE link;
- **Configuration 2: Probe + Carrier/Relay.** The probe would detach from the carrier several months prior to probe entry. The carrier trajectory would be designed to enable probe data relay during over-flight and flyby science;
- **Configuration 3: Probe + Orbiter** (similar to Galileo). As for Config. 2, but after probe relay during over-flight, the orbiter would transit to a Saturn orbit and continue to perform orbital science.

In all three configurations, the carrier/orbiter would be equipped with a combination of solar panels, secondary batteries and possibly a set of primary batteries for phases that require a high power demand, for example during the probe entry phase.

Concept of Saturn probe to be submitted to the ESA M4 call

Example of model payload

Instrument	Measurement
Mass Spectrometer	Elemental and chemical composition
	Isotopic composition
	High molecular mass organics
Tunable Laser Spectrometer	Stable isotope ratios
Helium Abundance Detector	Accurate He/H_2 ratio
Atmospheric Structure Instrument	Pressure, temperature, density, molecular weight profile
Doppler Wind Experiment	Measure winds, speed and direction
Nephelometer	Cloud structure
	Solid/liquid particles
Net-flux radiometer	Thermal/solar energy

Juno will map Jupiter’s water in July 2016

Launched August 2011

Earth flyby 9 October 2013

Juno will map Jupiter’s water in July 2016

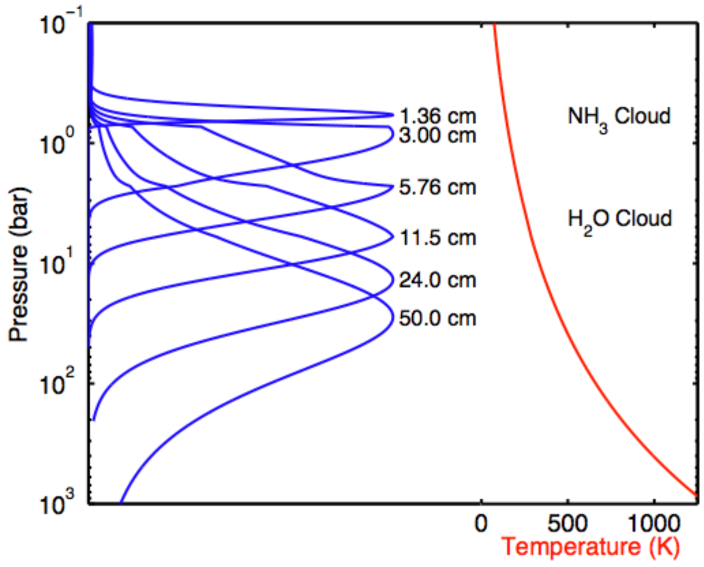
What about Saturn?

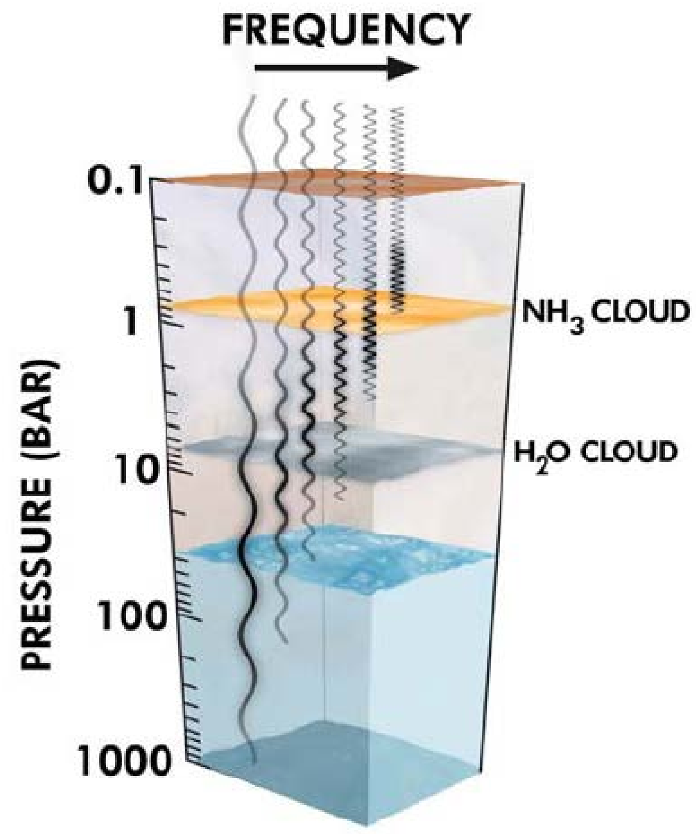
Launched August 2011

Earth flyby 9 October 2013

Juno Microwave Radiometry maps Jupiter's water and ammonia

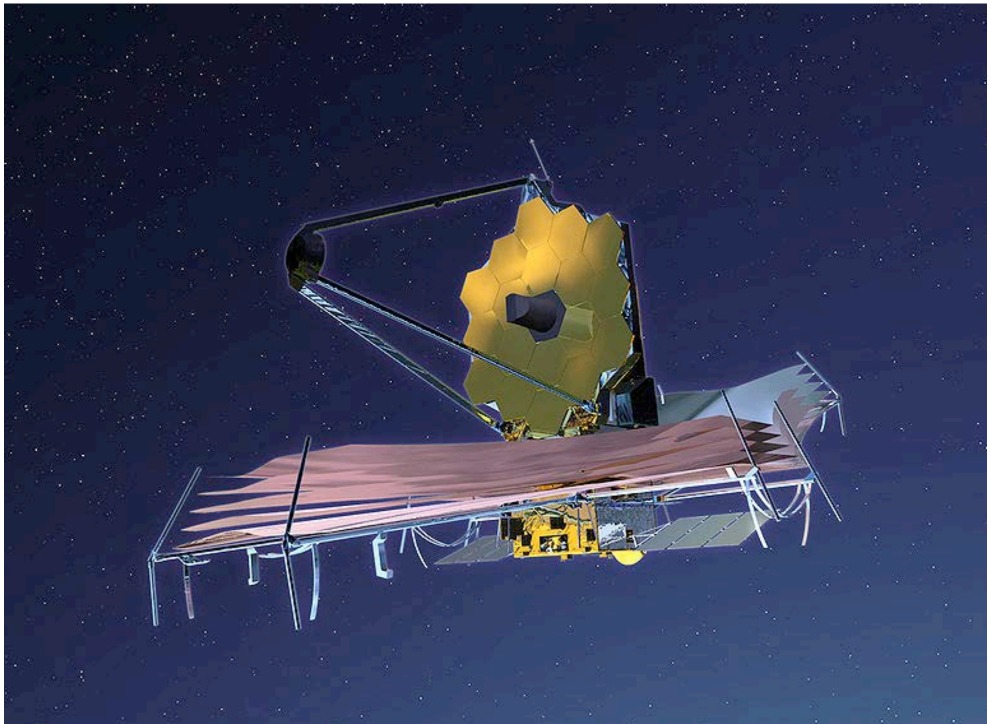
- Radiometry sounds the deep atmosphere
- Six wavelengths: 1- 50 cm
- Determines and *maps* H_2O and NH_3 abundances to ≥100 bars globally

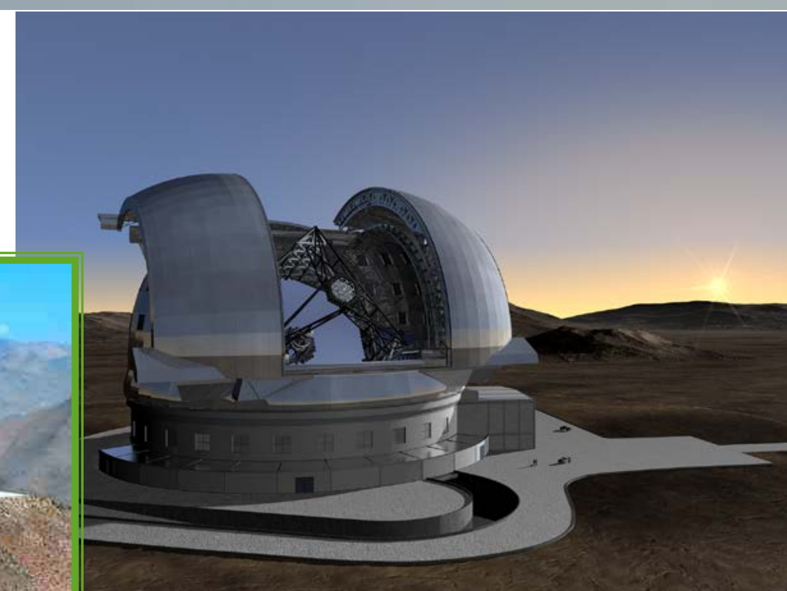


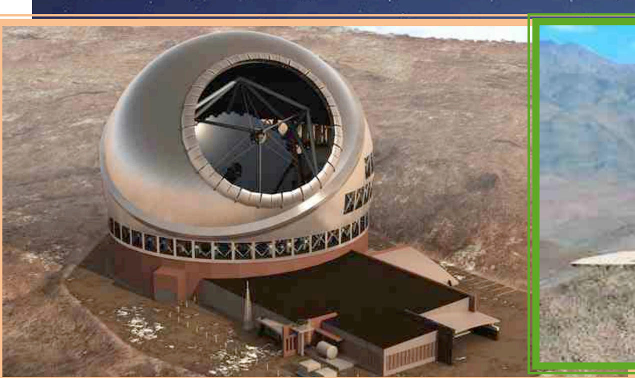


Use same technique on Saturn

Ground-Based and Earth-Proximal Telescopic Facilities







Near-Term Questions

- What is the reaction of the atmospheres of Saturn or Titan to seasonal forcing?
- What is the behavior of the SSAO in view of what is likely to be storm interference?
- How long does it take Saturn's atmosphere to relax back into pre-storm conditions?
- What is the behavior of atmospheric thermal waves: Are their properties driven by seasonal variability or the storm aftermath?

Near-Term Questions

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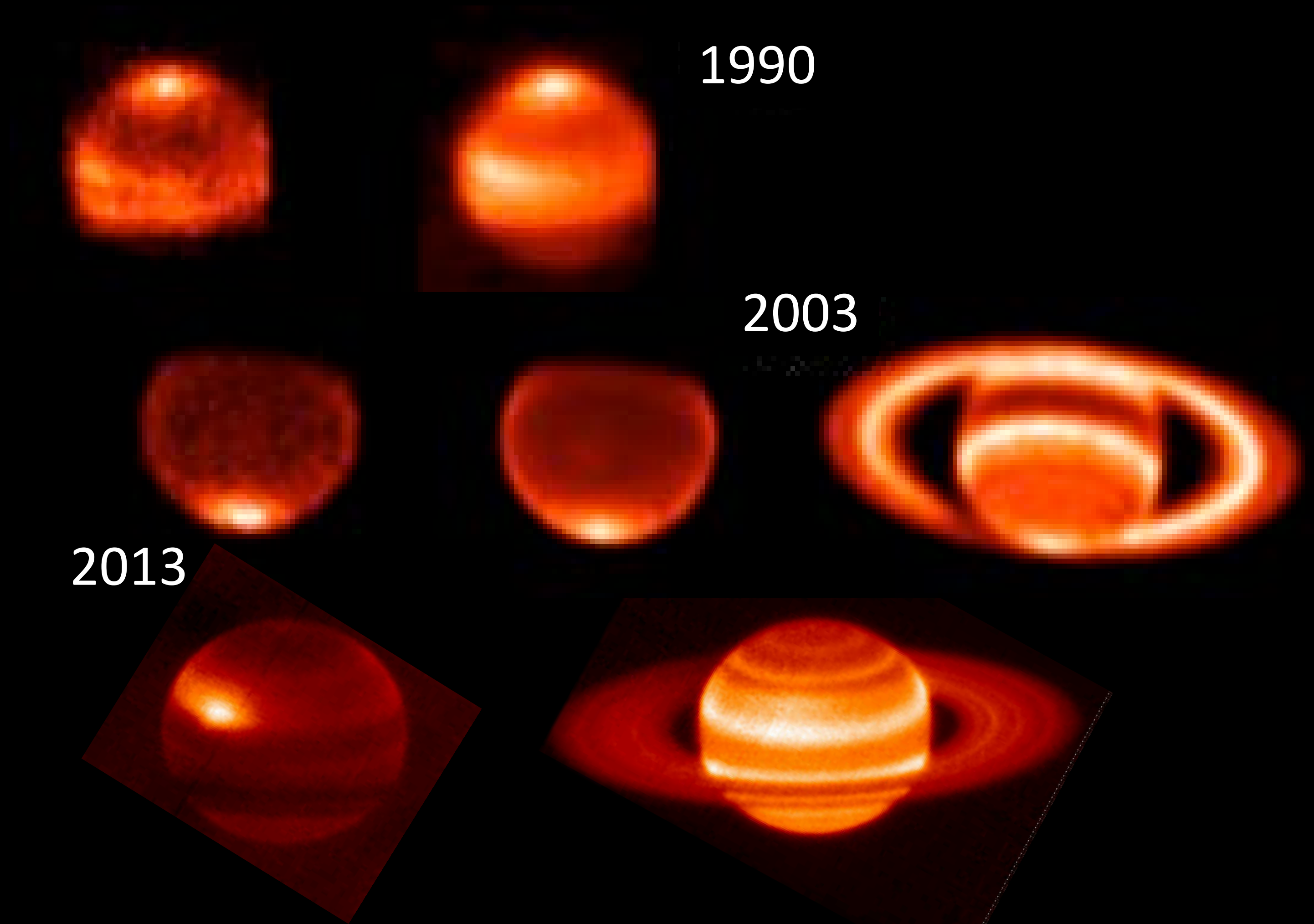
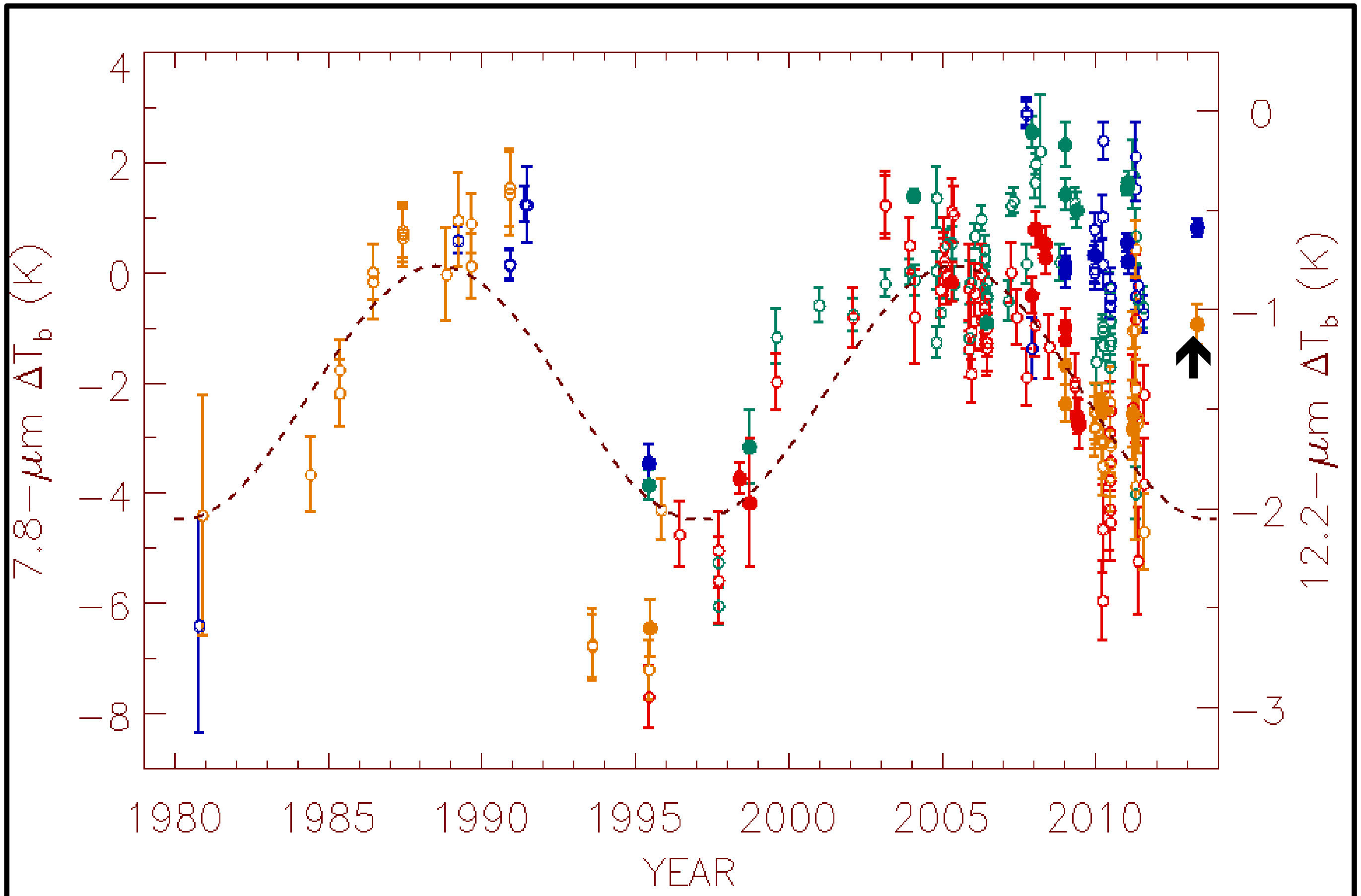


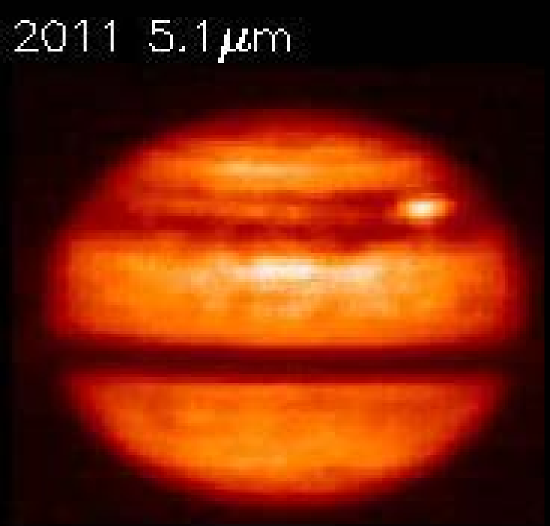
Near-Term Questions

- What is the behavior of the Saturnian Semi-Annual Oscillation in view of what is likely to be storm interference?
  - Recent observations show an exception to the 14.7-year SSAO period.



Near-Term Questions

- How long does it take Saturn’s atmosphere to relax back into pre-storm conditions?
  - e.g. relaxation of deep clouds sensed in the 5-m window to pre-storm cloudy state



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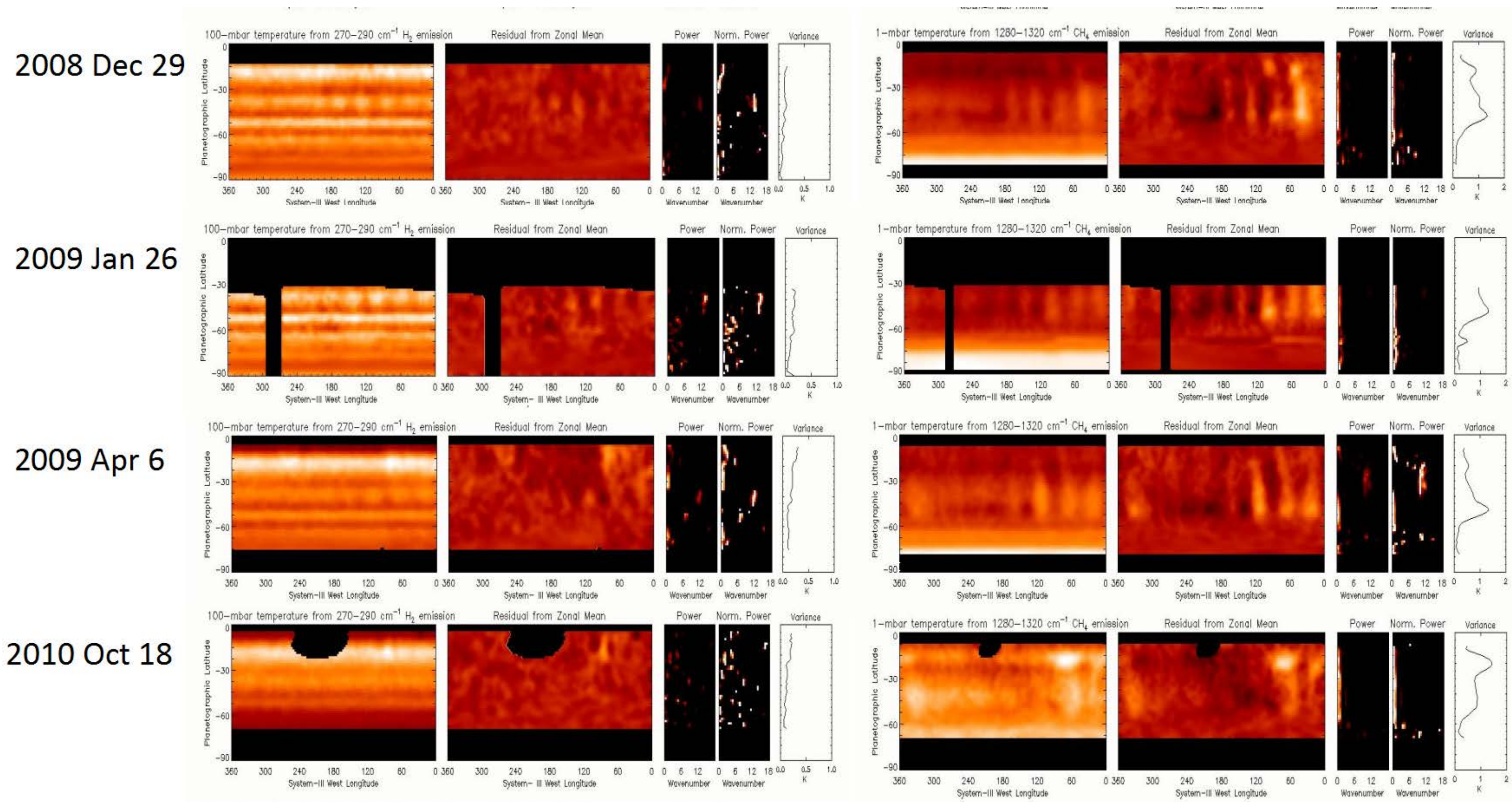


Long-Term Questions

- Are there other non-seasonal variations in the atmospheres of Saturn or Titan?
- What is the collision rate at Saturn – do we see bolides flashes or evidence for any impact events?
- What is the long-term behavior of waves?
  - Slowly moving waves
  - Low-latitude waves, such as the SSAO
- Are the effects of great storms similar for both the mid-latitudes and low-latitudes?
  - Clearing of deep clouds
  - Establishment of a stratospheric "beacon" vortex

Questions probed by Ground-based Facilities

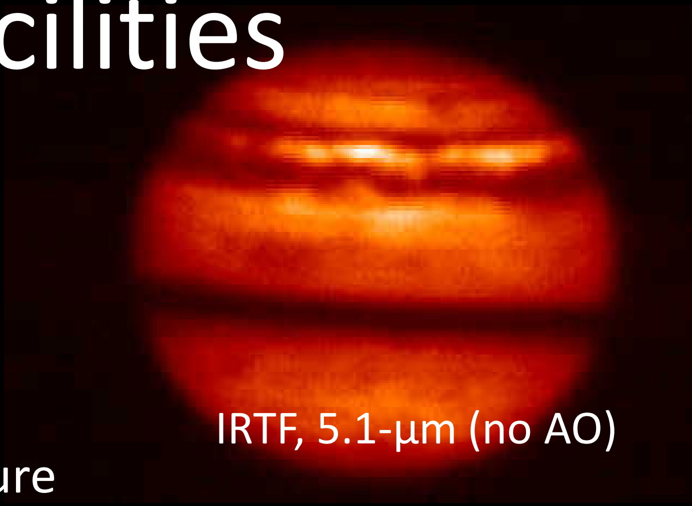
- Seasonal variability
  - Saturn (15-19 arcsec diameter)
    - Seasonal monitoring of temperatures and hydrocarbon abundances can be performed on 3+ meter telescopes at all wavelengths.

Diffraction Limit

Wavelength / Diameter	1 μm	5 μm	14 μm	28 μm
3-meter	0.083	0.41	1.17	2.35
8-meter	0.032	0.16	0.44	0.88
30-meter	0.0083	0.041	0.117	0.24

Ground-based Facilities

- Current facilities < 4 meter
  - NASA IRTF
    - Seeing often at 0.5” or better
    - Possibility of AO-guided imaging in future
    - Mid-ir diffraction ~2” still useful for seasonal variability, waves
  - Calar Alto
    - PlanetCam using “lucky imaging”
  - University of Hawaii 88”
    - Tip-tilt available, AO being implemented
  - Other professional,
    - e.g. Palomar 60” using “Robo-AO”
  - Amateur community



IRTF, 5.1-µm (no AO)

Calar Alto, RGB composite
(lucky imaging)

Ground-based Facilities

- Current telescopes, 8-10 meter class
    - Gemini North and South
    - Subaru
    - Keck 1 and Keck 2
    - Very Large Telescope (4 telescopes)
    - Gran Telescopio Canarias (aka GranTeCan or GTC)
  - Routine availability of adaptive optics for near-ir
  - Mid-IR diffraction limit to ~0.4”

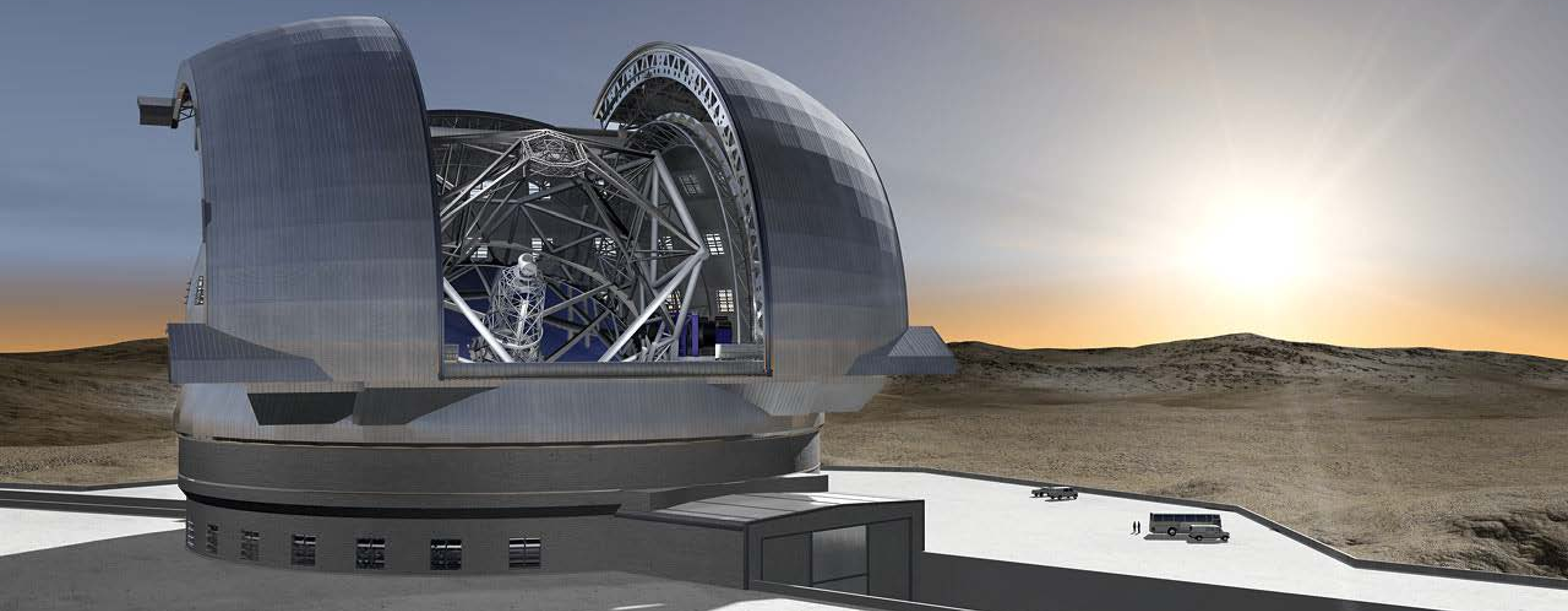
Keck with AO, near-IR

Gemini N with AO, JHK composite

Keck, 17.8-µm mosaic

Ground-based Facilities

- Future large aperture telescopes:
  - E-ELT : European Extremely Large Telescope at Cerro Armazones (39-m, operations planned early 2020s)
  - Groundbreaking has taken place



Ground-based Facilities

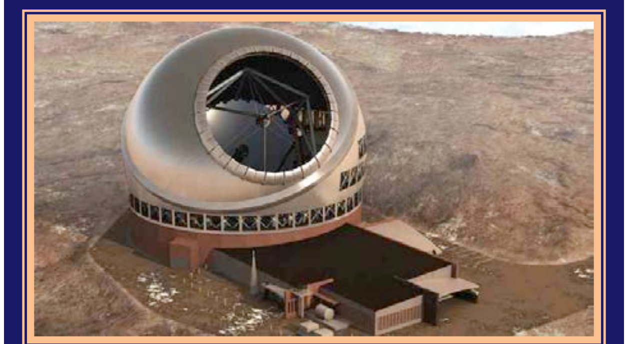
- Future large aperture telescopes:
  - GMT : Giant Magellan Telescope at Las Campanas Observatory (24.5-m, commissioning planned to start in 2020)

Ground-based Facilities

- Future large aperture telescopes:
  - TMT : Thirty Meter Telescope on Mauna Kea (30-m, planned completion 2022)
  - E-ELT : European Extremely Large Telescope at Cerro Armazones (39-m, operations planned early 2020s)
  - GMT : Giant Magellan Telescope at Las Campanas Observatory (24.5-m, commissioning planned to start in 2020)
  - Diffraction limit for mid-IR down to size of current limit for near-IR (<0.17”), e.g. image mid-IR variations on Titan

	λ (μm)	Field size	Max resolution	Brown Dwarfs	Exo-planets	Ice Giants	Saturn
IRIS	<2.5	2.2x4.55"	4000				
WIRC	0.8-5	30”	100				
NIRES	1-5	2”	100,000				
HARMONI	<2.45	5x10”	20,000				
METIS-IFU	3-5.3	0.4 x 1.5"	100,000				
SIMPLE	<2.5	4”	100,000				
GMTNIRS	1-5	1.2”	100,000				
MIISE	3-28	2’x2’	2000				

Thirty Meter Telescope - 2018



European Extremely Large Telescope – 2020s

Giant Magellan Telescope - 2020

Earth-Proximal Telescopes

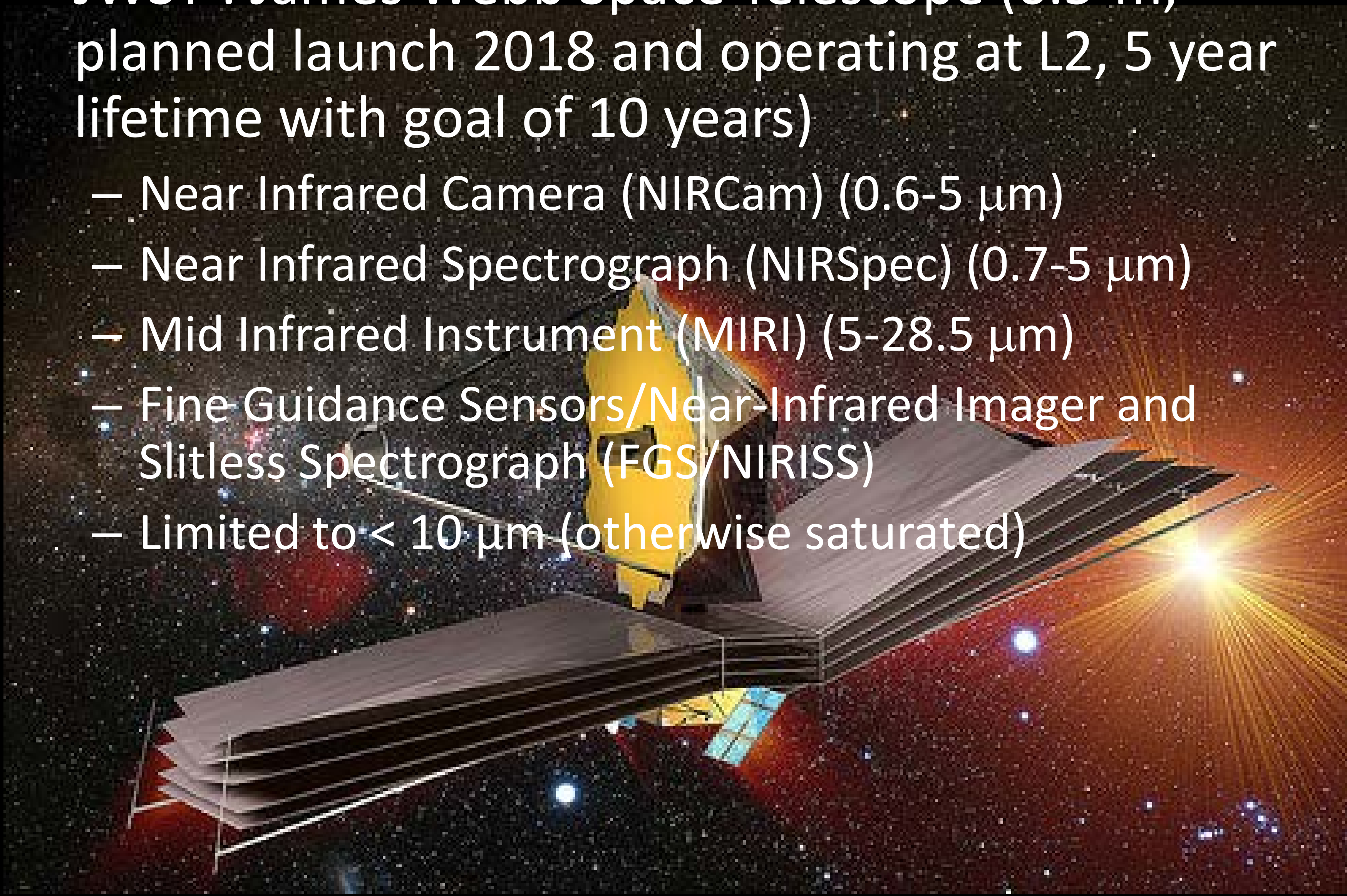
- HST: Hubble Space Telescope (2.4-m, 1990-present)
  – Detailed cloud motions
  – Access to UV spectrum
- JWST: James Webb Space Telescope (6.5-m, planned launch 2018 and operating at L2, 5 year lifetime with goal of 10 years)

Earth-Proximal Telescopes

- **HST : Hubble Space Telescope (2.4-m, 1990-present)**
  - Expected operations through 2020, 2-year overlap with JWST
  - Wide Field Camera 3 (WFC3) (Near-UV to Near-IR)
  - Cosmic Origins Spectrograph (COS) (UV)
  - Advanced Camera for Surveys (ACS) (Far-UV to Visible)
  - Space Telescope Imaging Spectrograph (STIS) (UV to Near-IR)
  - Near Infrared Camera and Multi-Object Spectrometer (NICMOS) (Near-IR)
  - Fine Guidance Sensors (FGS) (Visible)
  - Need to push for planetary support from the community

Earth-Proximal Telescopes

- JWST : James Webb Space Telescope (6.5-m, planned launch 2018 and operating at L2, 5 year lifetime with goal of 10 years)
  - Near Infrared Camera (NIRCam) (0.6-5 μm)
  - Near Infrared Spectrograph (NIRSpec) (0.7-5 μm)
  - Mid Infrared Instrument (MIRI) (5-28.5 μm)
  - Fine Guidance Sensors/Near-Infrared Imager and Slitless Spectrograph (FGS/NIRISS)
  - Limited to < 10 μm (otherwise saturated)



Solar System Observations with JWST

Norwood et al.,

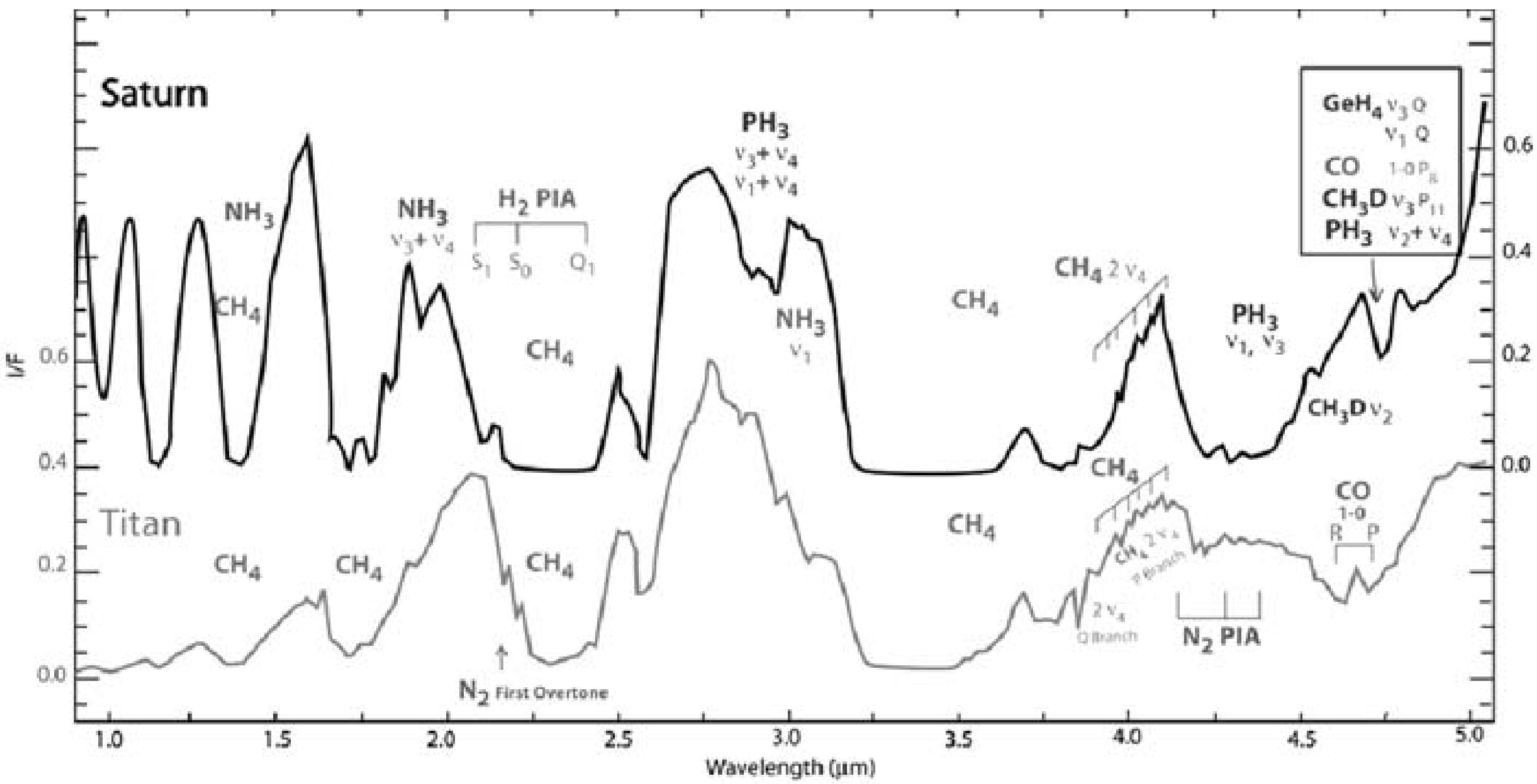
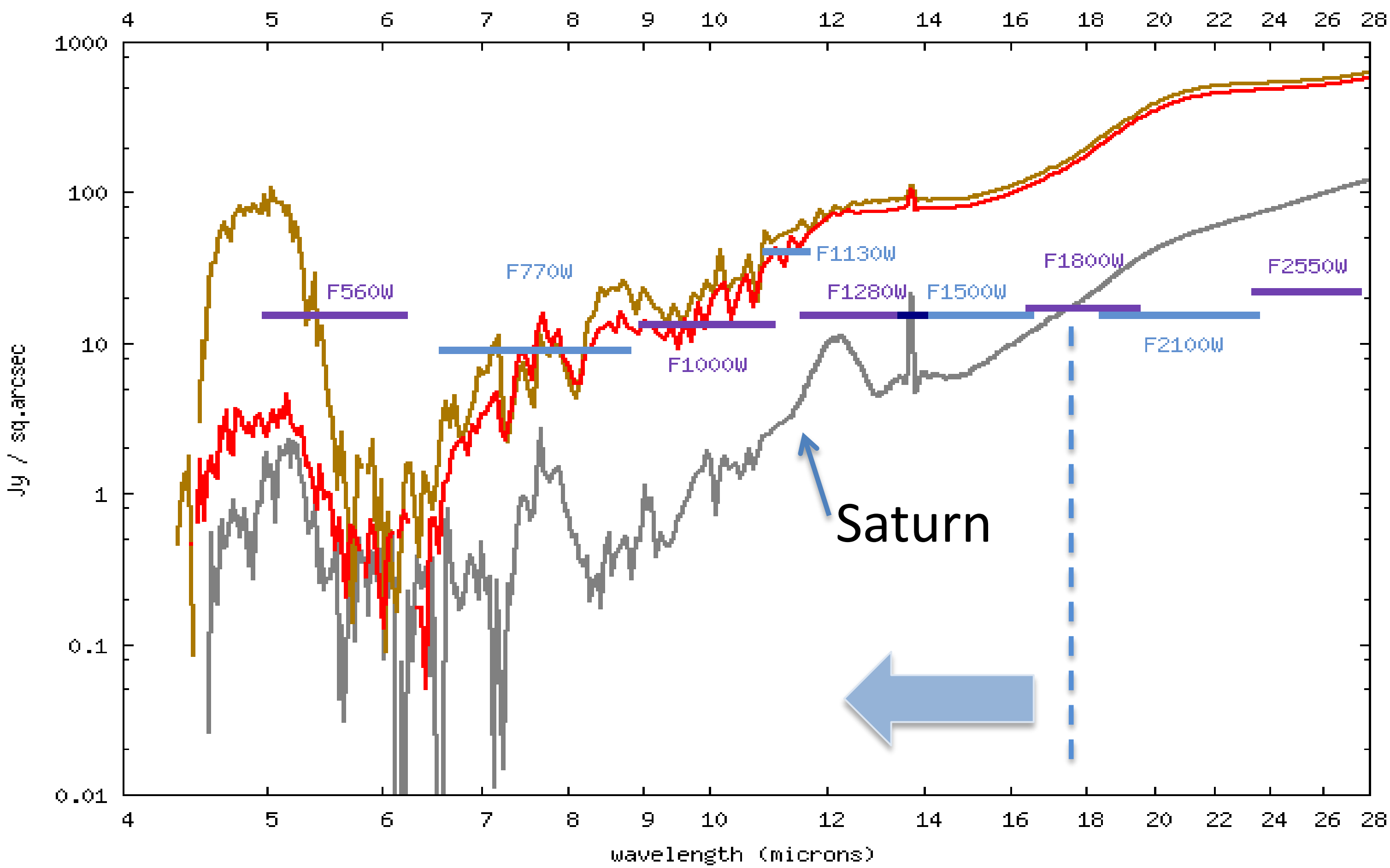


Figure 6. VIMS spectrum of Saturn (darker line) over a spectral region comparable to that of NIRSpec. The spectral resolution of the VIMS data is ~200; NIRSpec will be able to match or exceed this, providing a more detailed understanding of the chemistry and dynamics in the giant planet atmospheres. Figure from Baines et al. (2005).

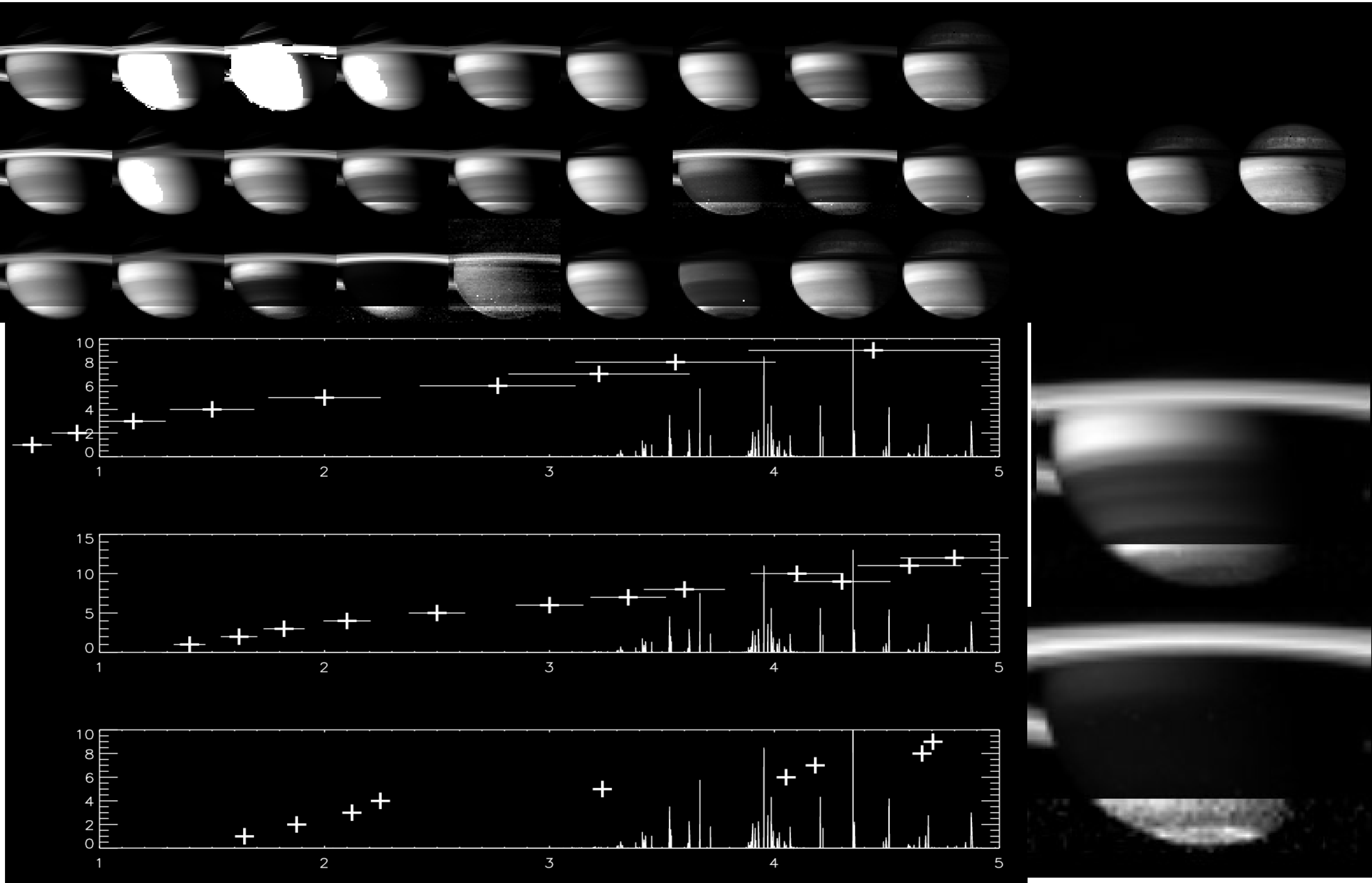
JWST MIRI Saturn Spectrum Prediction

Viable for Wavelengths < 18 μm



Saturation Limits

Auroral Observations



SOFIA: Stratospheric Observatory for Infrared Astronomy

SOFIA: Stratospheric Observatory for Infrared Astronomy

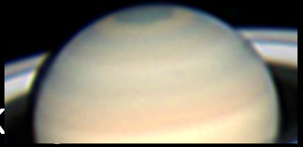
- EXES : Echelon-Cross –Echelle Spectrograph (4.8-28.3 μm) (R=10^5, 15,000, or 4,000)
- FIFI-LS : Field Imaging Far-Infrared Line Spectrometer (42-210 μm)
- FLITECAM : First Light Infrared Test Experiment CAMera (1-5 μm)
- FORCAST : Faint Object InfraRed Camera for the SOFIA Telescope (5-40 μm)
- GREAT : German Receiver for Astronomy at Terahertz Frequencies (60-200 μm)
- HAWC : High-resolution Airborne Wideband Camera (50-240 μm) (bolometer camera and polarimeter)
- HIPO : High-speed Imaging Photometer for Occultation (0.3-1.1 μm)

Observations from Amateur Observers

Current State-of-the Art in Amateur Planetary Imaging

The Current Evolution of High Speed / Low Noise Video Cameras Available to Amateurs Allow them to Contribute to Planetary Imaging in Three Distinct Ways:

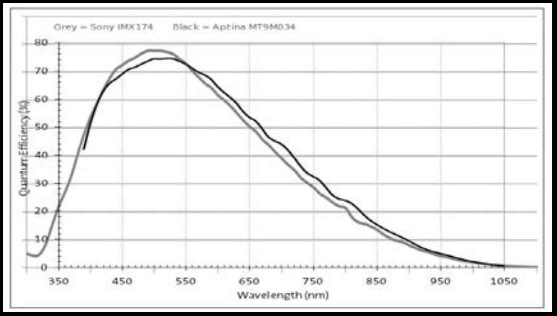
- Visible Light Feature Detection and Tracking



- Visible Light Color Changes, Ddetection and Track

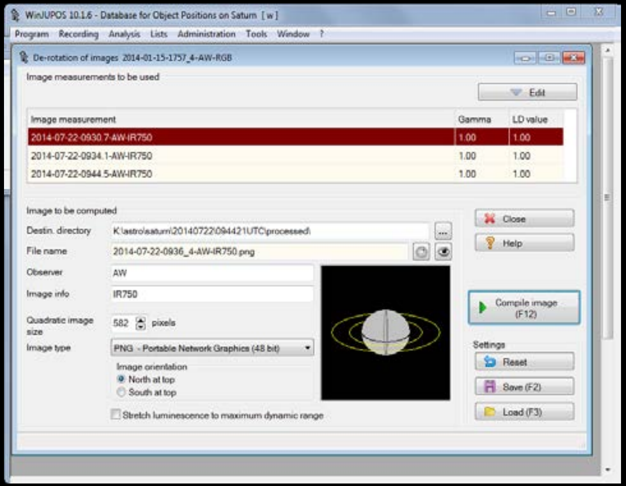
- Impact / Flash / Bolide Detection

The Future of Amateur Planetary Imaging



- Camera Technology Evolving and Improving Faster Every Year, Improvements in Sensitivity and Reduced Noise.

- More Opportunities for Pro/Am Collaboration using Social Media / Internet (fb, skype, vnc, etc)



- Computer Software and Hardware Improving Every Year.

- Optical Quality Improving and Better Understanding of Critical Factors e.g. Telescope Thermal Behaviour.

- Better Understanding of Data Acquisition and Processing.

Camera Trends 2003 - 2016

Typical sensors in use for amateur planetary imaging:

2003

Sensor:	Sony ICX098BL
Process	CCD
QE @ 550nm	38%

2007

Sensor	Sony ICX424AL
Process	CCD
QE @ 550nm	54%

2014

Sensor	Aptina MT9M034
Process	CMOS rolling shutter
QE @ 550nm	75%

2015 - 16

Sensor	Sony IMX174
Process	CMOS global shutter
QE @ 550nm	76%

Saturn image from 2005 using the best available amateur camera :-

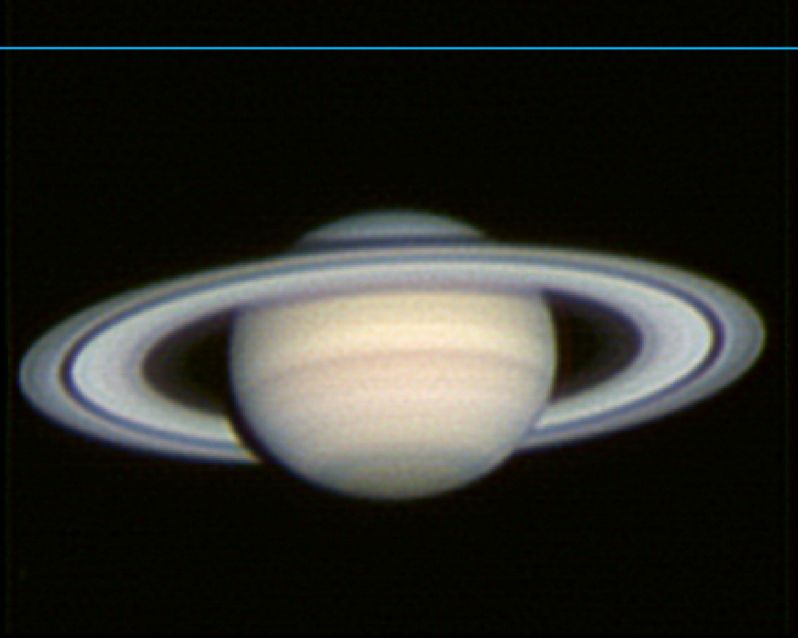
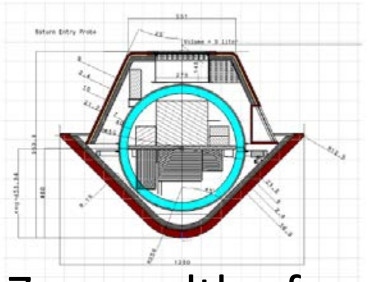


Image from 2014 using the best available amateur camera :-

The Future Exploration of Saturn

Summary



1. Until the Cassini Grand Finale concludes in late 2017, a wealth of new data and results can be expected
2. JSWT and new large paperture groundbased tel;escopes promise fundamental new data and insights Developments
3. The Amateur Community can be expected to continue to grow, both in Number of Observers and in the quality of observations
4. In-situ and orbital missions needed to ascertain elemental compositon
5. Problem: Lack of UV data