Ice Giant Atmospheric Probe Design Considerations:
Galileo-Like, Staged-Probes, and Multi-Probes

2019-07-07

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Hampton University

With Thanks to SNAP Co-I's including IPPW Regulars
Robert Dillman, Tom Spilker, Dave Atkinson …

Review: Probe Scientific Objectives

Atmos. Composition - Formation and Evolution - Noble Gas - Isotopic Ratios
Thermal Structure and Energy Balance - Temperature vs. Pressure - Radiative Flux
Role of Clouds/Haze/Aerosols - Composition & Light Scattering Properties of Aerosols - Vertical Distribution of Aerosols and Vapors
Atmospheric Dynamics - Zonal Circulation - Meridional Circulation - Vertical Mixing of Disequilibrium Species

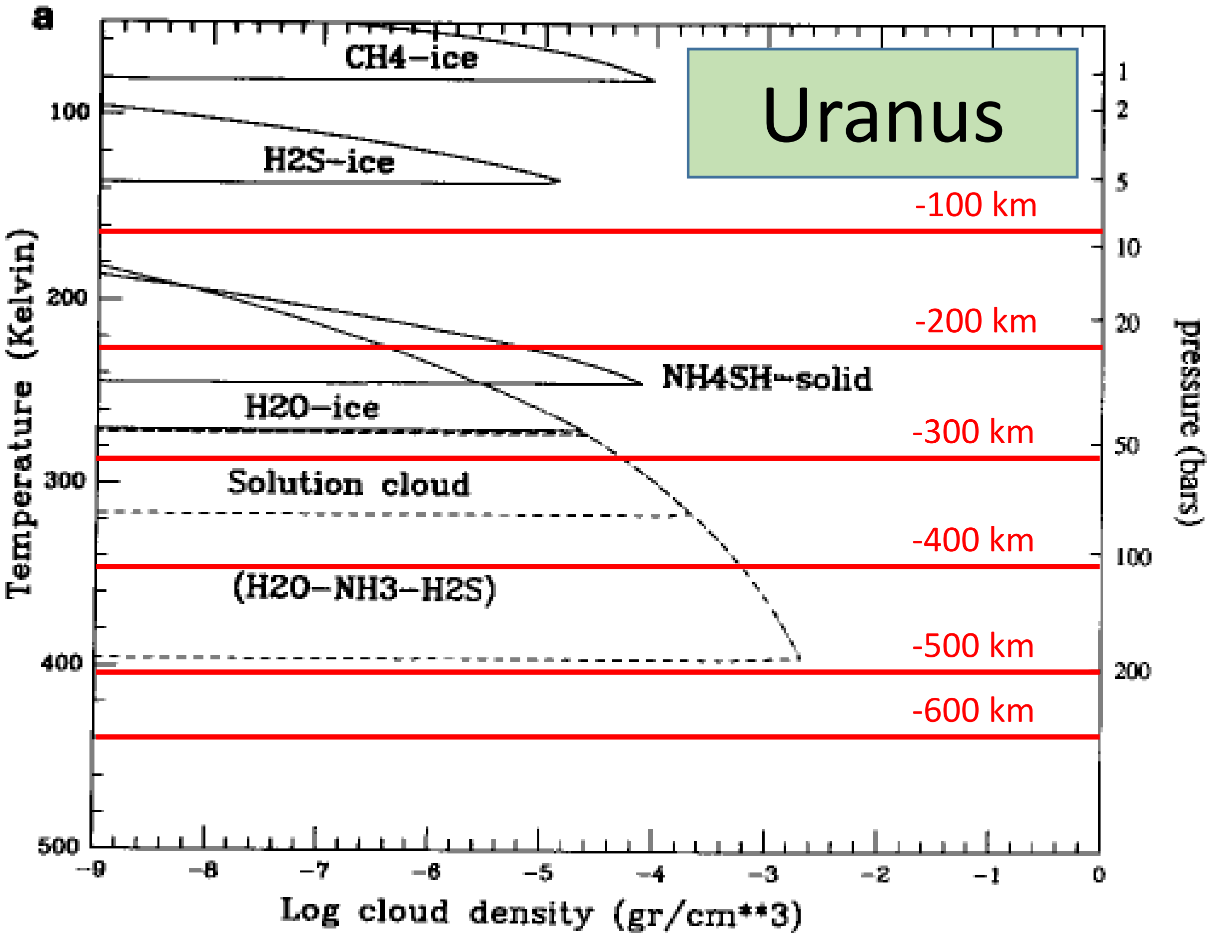
Review: Key Observables

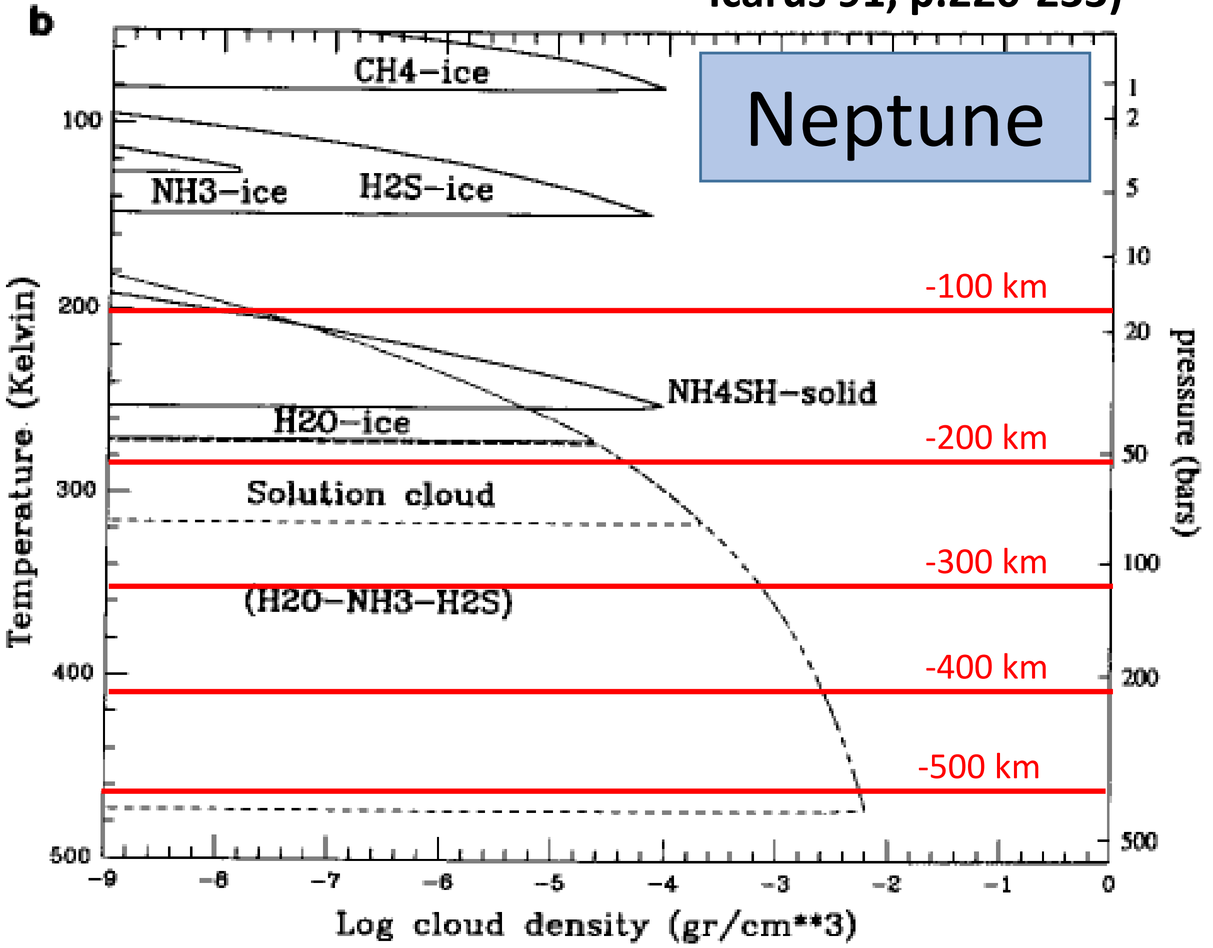
→ Science Objectives: → ↓ Observables ↓	Atmospheric Composition	Formation & Evo.	Thermal Structure + Energy Balance	Clouds	Zonal Circ.	Meridional Circ.	Vertical Mixing	Local Turbulence
Noble Gas Abundance	X	X						
Isotopic Ratios		X						
Volatile Molecule Abundance	X		X	X		X	X	
Cloud/Haze/Aerosol Properties				X		X	X	
Disequilibrium Species Concentration						X	X	
Temperature vs. Pressure/Density			X	X			X	
Radiative Flux			X	X				
Horizontal Wind Speed					X			
Probe Descent Speed+Accel.							X	X

Question #1: How deep do probe(s) need to reach?

Predicted Altitudes and Densities of clouds in Uranus and Neptune

de Pater et al. (1991 Icarus 91, p.220-233)



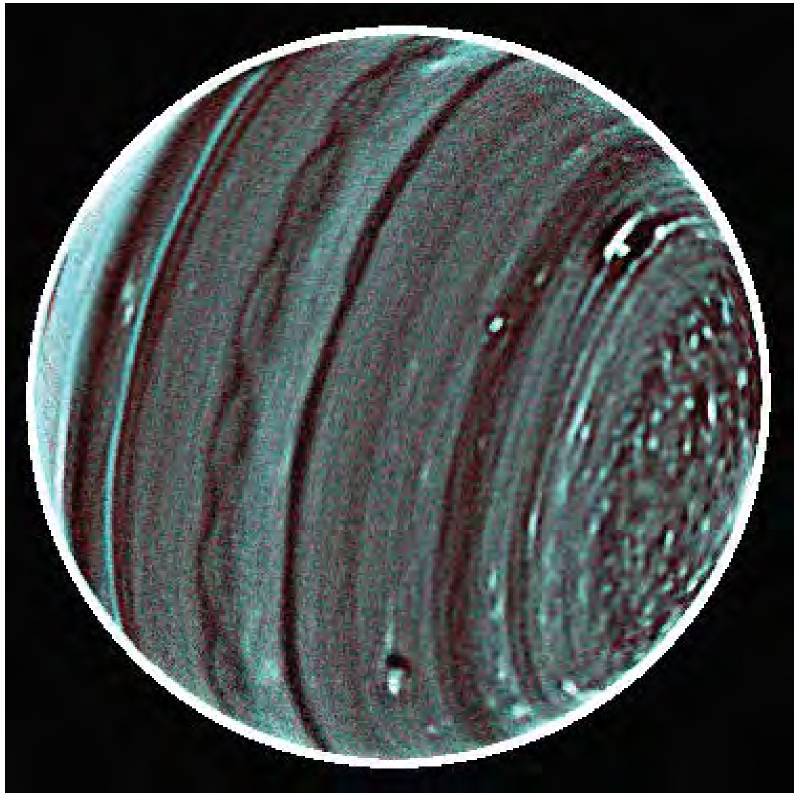


Sampling CH4-ice and H2S-ice clouds is possible with 10-bar probes, <100 km below 1-bar.
Sampling H2O-ice requires ~50-bar, 200-300 km below 1-bar.
Reaching below all clouds requires descent to 200-500 bar pressure, >500km below 1-bar.

Question #2: Which Latitude(s)? How many probes?

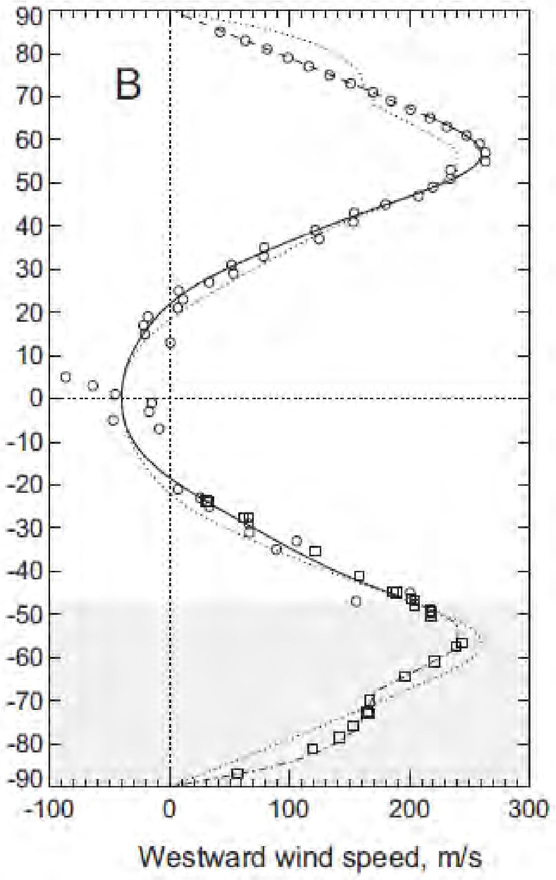
Example: Cloud bands and circulation on Uranus

Cloud Bands

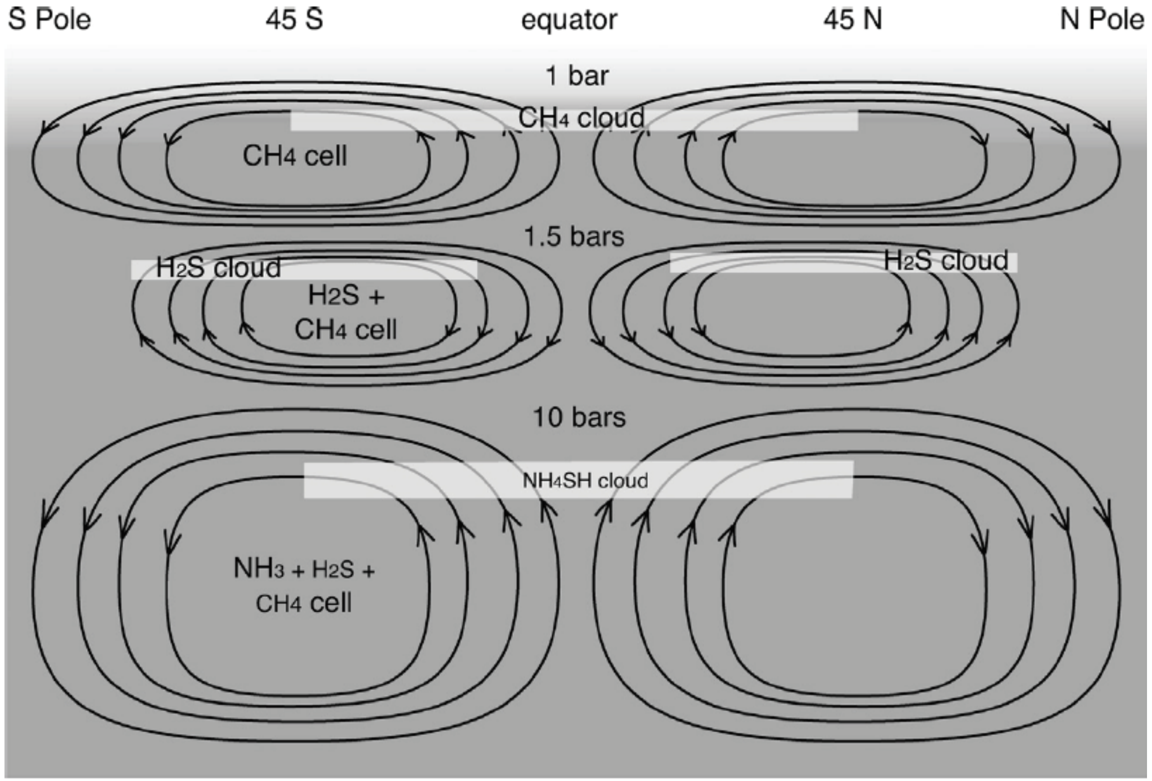


Sromovsky et al. (2015
Icarus 258, p.192–223)

Wind Bands



Meridional Circulation (Hypothesized)



Sromovsky et al. (2014
Icarus 258, p.137-155)

Which cloud band(s) should we target?
Where do we best sample the zonal wind?

How do we best test meridional circulation?
What's the effect of Seasonal forcing?

Some quantities are Homogeneous

Observable	Spatial Variation
Noble Gas Abundance	Spatially Homogeneous
Isotopic Ratios	
Volatile Molecule Abundance	Spatially Variable
Cloud/Haze/Aerosol Properties	
Disequilibrium Species Concentration	
Temperature vs. Pressure/Density	
Radiative Flux	
Horizontal Wind Speed	
Probe Descent Speed+Accel.	
Local Turbulence	

Spatially Homogeneous quantities do not need to be measured at multiple locations.

Review: Instruments

Red Letters = Usual Suspects

Observable	Instruments
Noble Gas Abundance	Mass Spec, He Detector, Noble Gas Sensor
Isotopic Ratios	Mass Spec, TLS
Volatile Molecule Abundance	Mass Spec, TLS, Vapor Sensor
Cloud/Haze/Aerosol Properties	Nephelometer
Disequilib. Species Concentration	Ortho-Para Sensor, Vapor Sensor
Temperature vs. Pressure/Density	ASI
Radiative Flux	Net Flux Radiometer
Horizontal Wind Speed	USO/Doppler Wind Experiment
Probe Descent Speed+Accel.	ASI

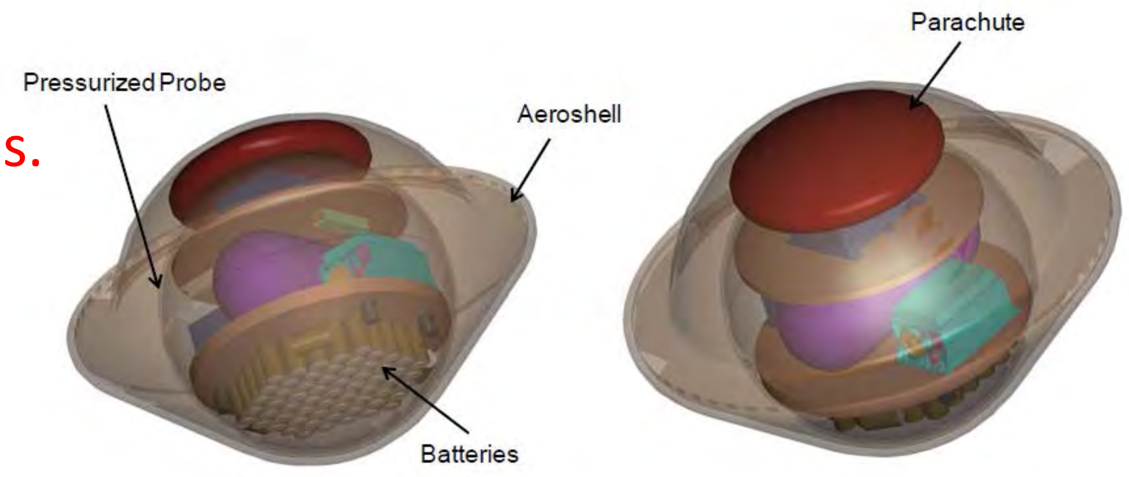
Probe Mission Architecture Considerations

- Probe must be delivered to target planet by a Carrier Spacecraft
- CRSC has to be in place to receive data from Probe
  → Direct-to-Earth comm is not realistic from Ice Giants
- Is the Probe the Primary Mission?
  - <u>Probe is Primary</u>:
    Delivery & data relay trajectory can to be optimized only for the Probe.
  - <u>Carrier is Primary</u>:
    Probe delivery & data relay must be compatible with the carrier mission.
    - Primary Mission Requirement: Orbital Tour, or using IG for Gravity Assist toward KBOs, etc.
- Probe Mission Design Choices/Constraints
  - Entry Latitude(s)
  - Target Depth (<u>limited by comm link duration</u> with CRSC)
  - Instruments

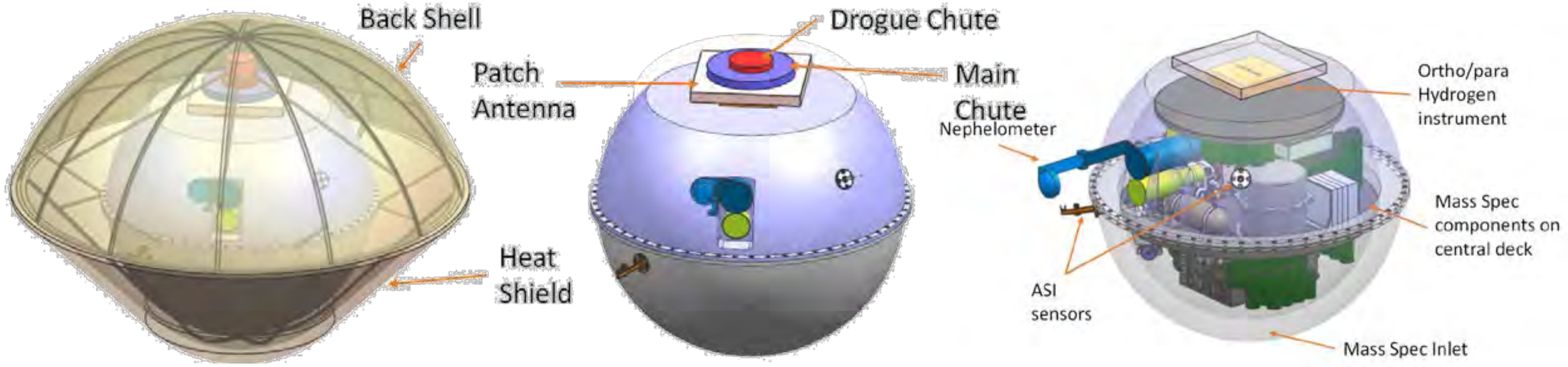
Probe Design Comparison

- Design Considerations:
  - Instruments
    - Usual Suspects: Mass Spec, ASI, USO …
    - Mass Spec has large impact on probe mass.
  - Entry Latitude & Depth
- Design Comparisons
  - Galileo Probe
  - Huygens
  - 2010 Decadal Uranus Orbiter and Probe
  - 2017 Ice Giant SDT Study
  - SNAP

2010 Decadal Uranus Orbiter and Probe



2017 Ice Giant SDT Study



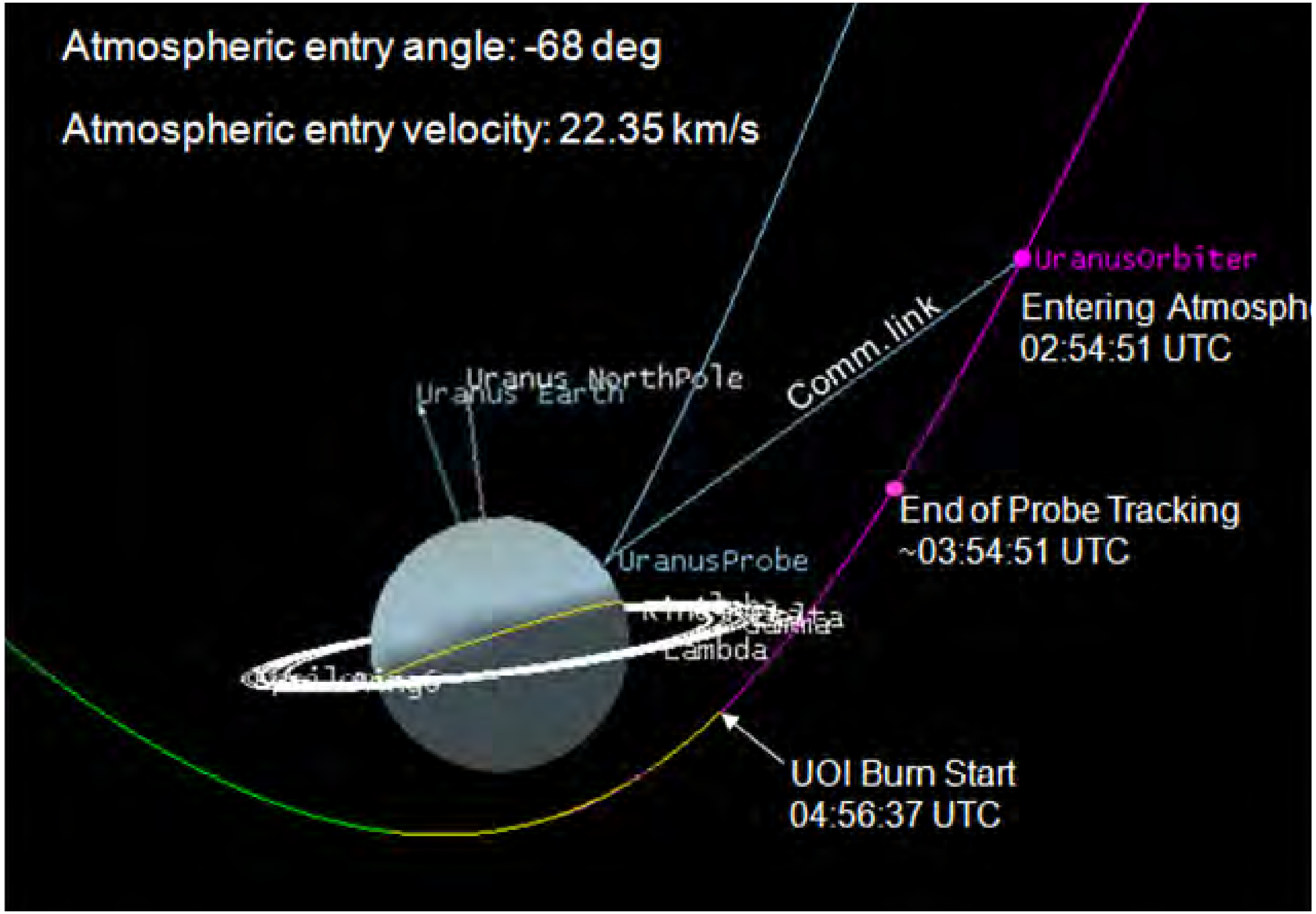
Missions	Atmos. Entry Mass	Entry Sys.	Descent Module				
	CBE +Conting. +Margin	Aeroshell + Chutes	Instruments	Inst. Mass	Mass Spec Mass	Non-MS Inst. Mass	Battery
Galileo Probe	335 kg	219 kg (65%)	MS, ASI, USO, HAD, Neph, NFR, Lightning, Energetic Particles	35 kg (10 %)	13.2 kg	21.8 kg	7.5 kg (Li-SO_2, 2.2%)
Huygens	318 kg	118 kg (37%)	GCMS, ASI, USO, DISR, Surface Sci.	48 kg (15%)	17.2 kg (+6 kg pyrolizer)	24.2 kg	13 kg ? (Li-SO_2, 4%)
2010 Uranus Study	127.1 kg	40.8 kg (46%)	MS, ASI, Neph, USO	17.1 kg (13%)	9.2 kg	7.9 kg	11.3 kg (Li-$SOCl_2$, 9%)
2017 IG SDT	320.7 kg	147.0 kg (46%)	GCMS, ASI, Neph, Ortho-Para	32.5 kg (10%)	17.4 kg	15.1 kg	17.1 kg (Li-Ion, 5.3%)
2019 SNAP	30 kg	14.8 kg (49%)	NanoChem, ASI, USO	6.6 kg (22%)	(No Mass Spec)	6.6 kg	0.34 kg (Li-CFx, 1.1 %)

Missions	Atmos. Entry Mass	Entry Sys.	Descent Module				
	CBE					Non-MS	Battery
Galileo Probe							7.5 kg (Li-SO_2, 2.2%)
Huygens							13 kg ? (Li-SO_2, 4%)
2010 Uranus Study							11.3 kg (Li-$SOCl_2$, 9%)
2017 IG SDT							17.1 kg (Li-Ion, 5.3%)
2019 SNAP	30 kg	14.8 kg (49%)	NanoChem, ASI, USO	6.6 kg (22%)	(No Mass Spec)	6.6 kg	0.34 kg (Li-CFx, 1.1 %)

Mass Spec Design Trade should be an important component of future mission studies.

2010 Uranus Orbiter and Probe Entry and Descent

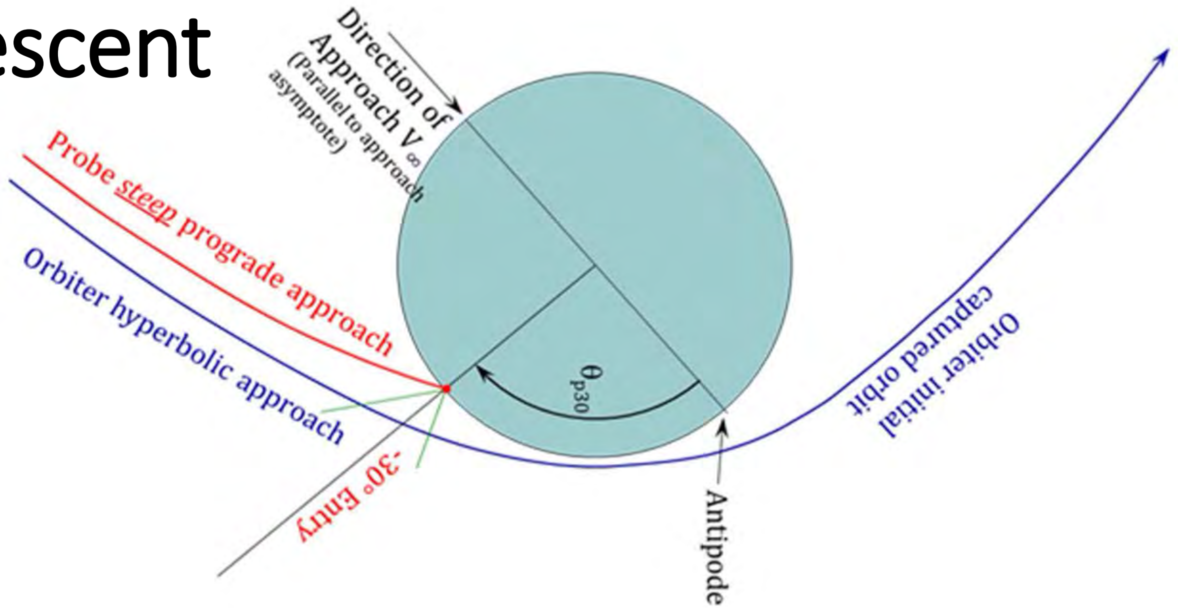
- Probe Delivery before UOI
- Probe release: 29 days before entry
- Comm. Link Duration: 60 minutes
- Target Depth: 5 bar
- Entry Flight Path Angle: -68 deg
- Peak Deceleration: 372g
- Peak Heating: 5511 W/cm^2
- Heat Load: 38.1 kJ/cm^2

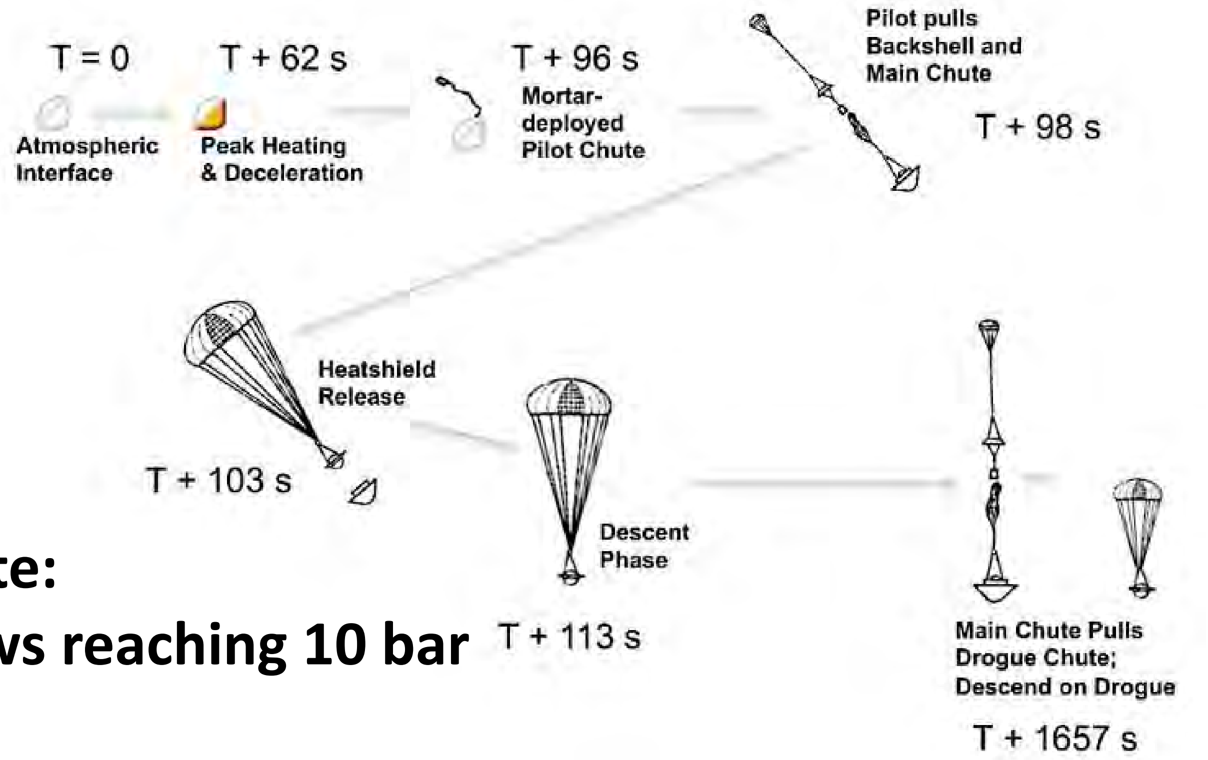


Pilot Chute + Separation/Descent Chute – reaches 5-bar.

2017 IGSDT Probe Entry and Descent

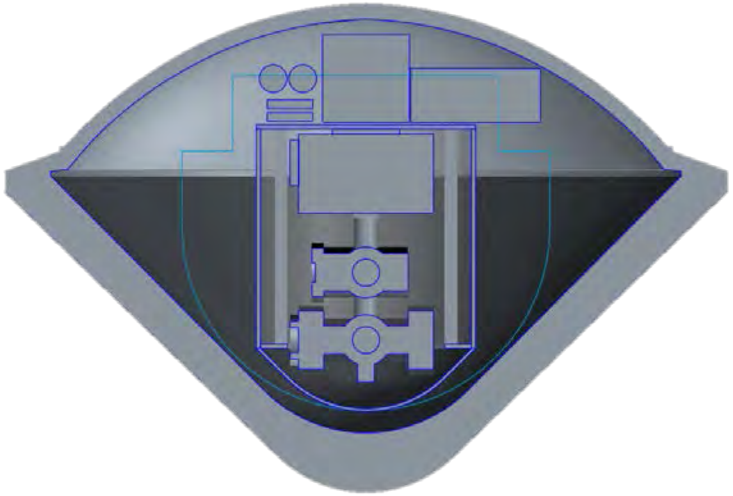
- Probe Delivery before UOI/Flyby
- Probe release: 60 days before entry
- Comm. Link Duration: 60 minutes
- Target Depth: 10 bar
- Entry Flight Path Angle: -30 deg
- Peak Deceleration: 165 g
- Peak Heating: 2498 W/cm^2
- Heat Load 41 kJ/cm^2

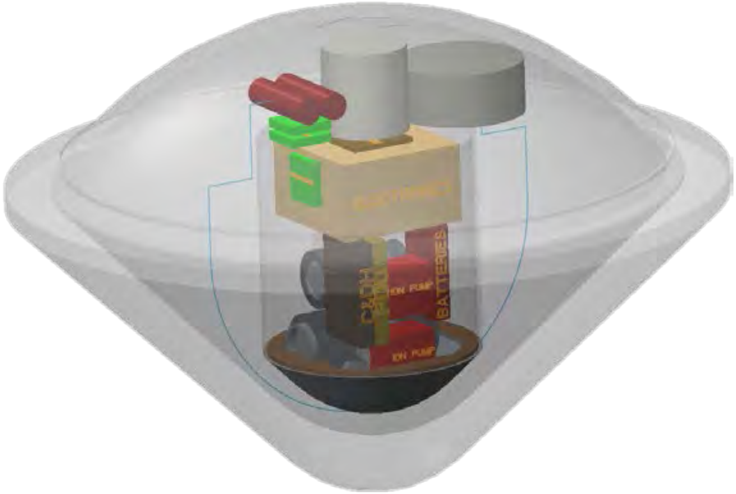


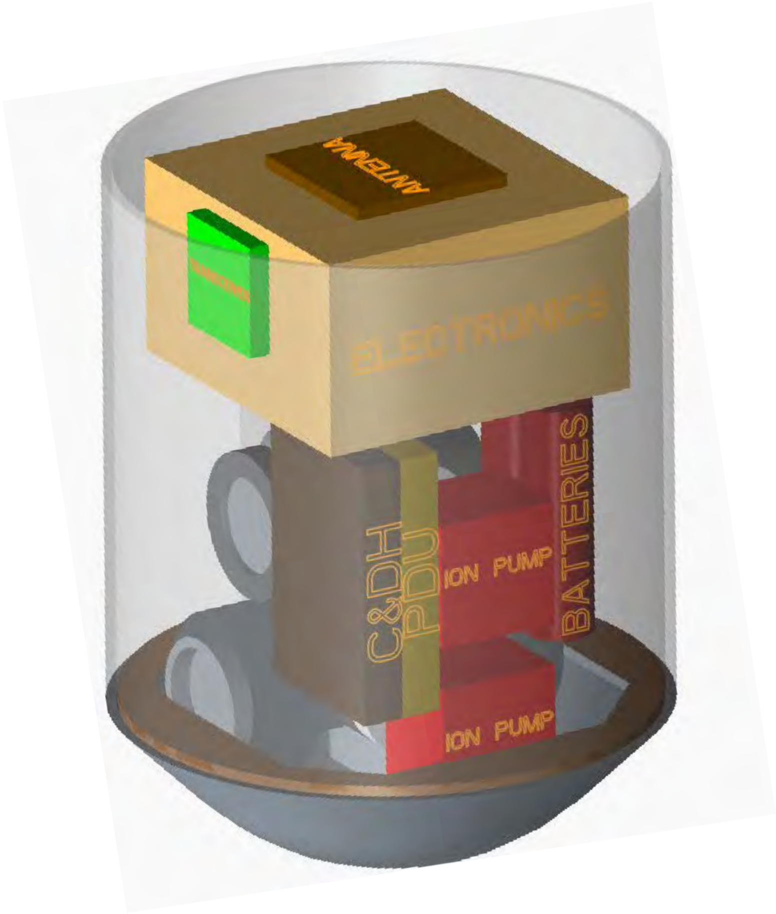


Pilot Chute + Separation Chute + Drogue Chute:
Descending under a small Drogue Chute allows reaching 10 bar

Going Deeper: Two-Stage Saturn Probe Design



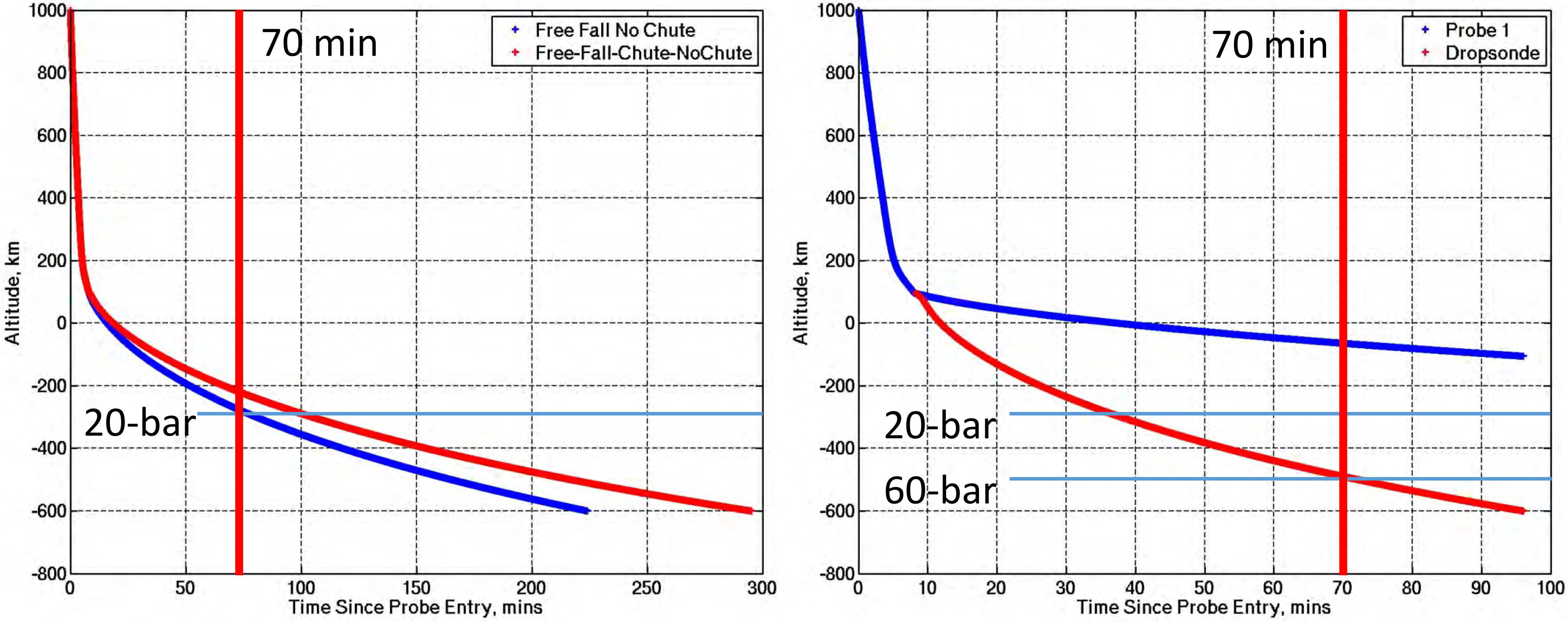




- Presented by Sayanagi et al. 2017 at IPPW-2017)
- Re-Design of 2010 Saturn Probe Study
- Incorporated 2010 study's aeroshell,
  re-packaged a releasable mass-spec + ASI.
- Deep-stage sends data to shallow stage, which relays to CRSC
- Benefits for Uranus/Neptune – yet to be studied.
- Reaching 50-bar on Uranus/Neptune would sample Water-ice Cloud Base.

Reaching Deeper requires Staged Probes

Two-Stage Saturn Probe Study (Presented by Sayanagi et al. 2017 at IPPW-2017)
Concept to reach Saturn's Water Cloud-base at 20-bar – **Comm. Window is 70 min**



At Saturn, single-stage probe can reach 20 bar at most in 60 min
Releasing a MS-Package allows reaching in 60+ bar in 70 min.

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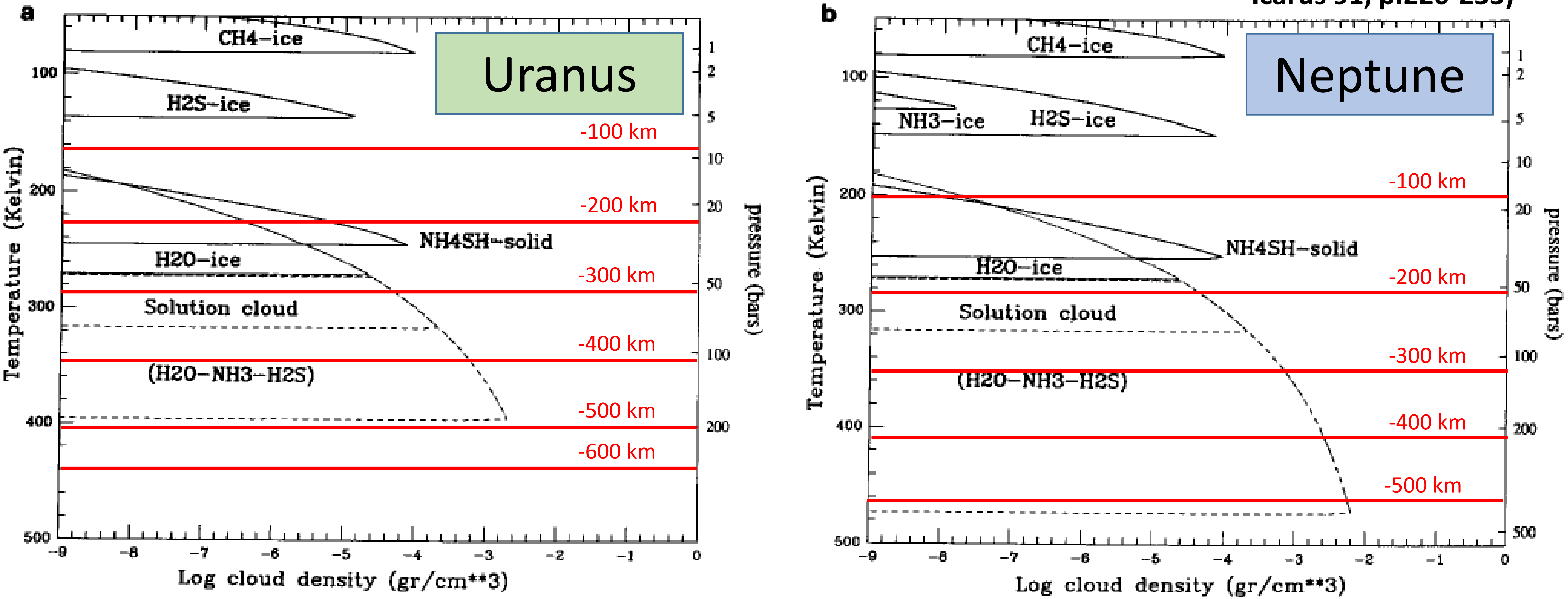

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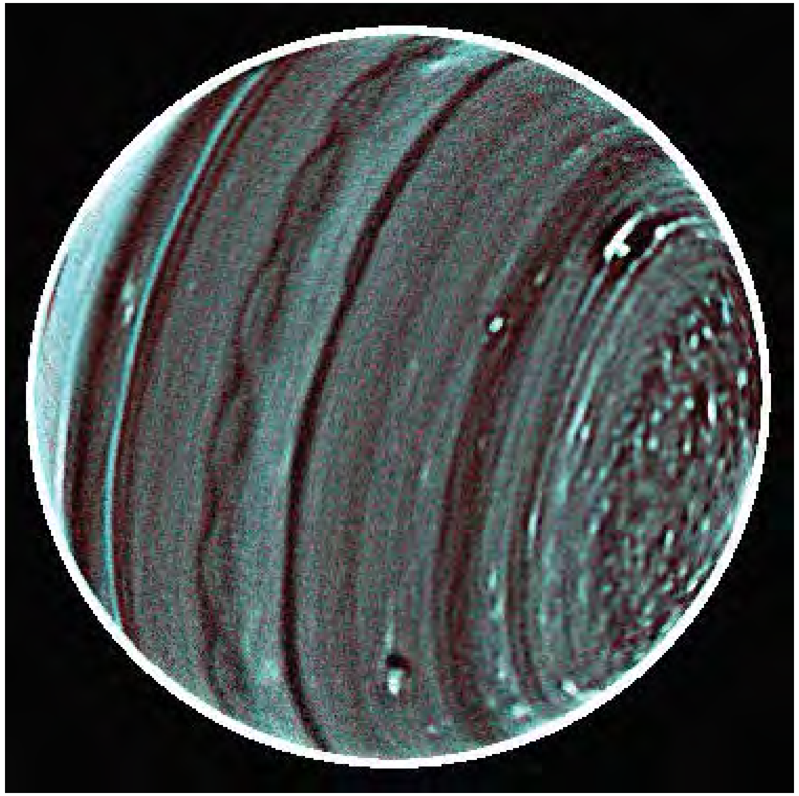

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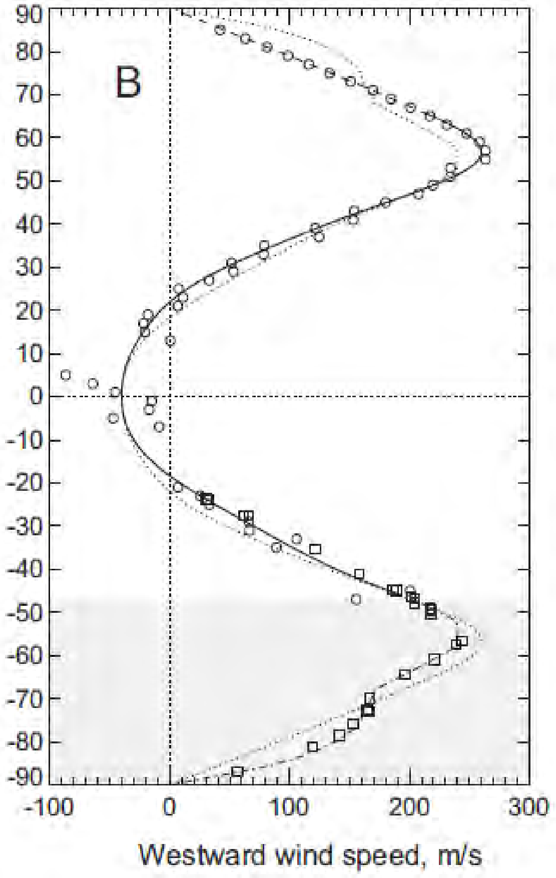

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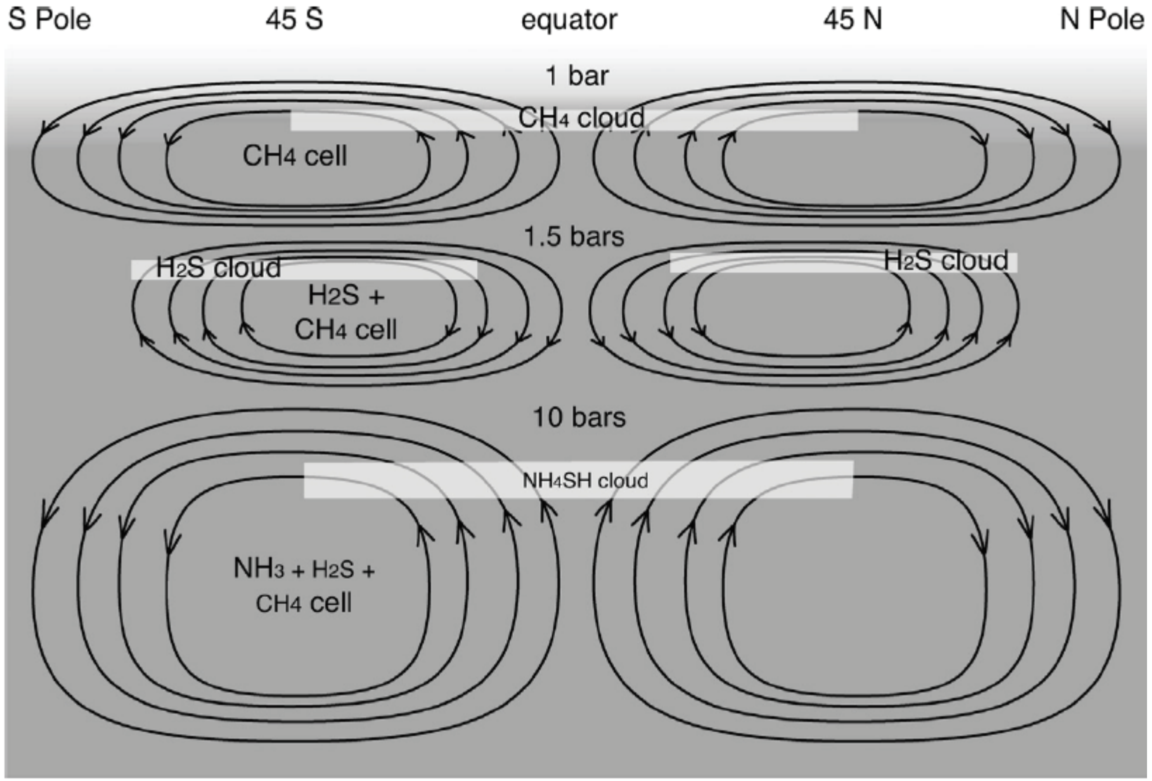

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Multi-Probe Planetary Missions:

- Advocated by Decadal Surveys
- Provide data on spatially varying atmospheric phenomena.
- **2003 Survey**: Advocated for a Jupiter Multi-Probe mission
- **2013 Survey:** Emphasized that a second probe can significantly enhance the scientific value of a probe mission
- Never realized due to perceived high-cost.

Multi-Probe Mission Considerations

Science Objectives can be re-organized

Multi-Probe Shared Objectives:

Determine spatial variability in atmospheric properties:

- Vertical distribution of cloud-forming molecules
- Thermal stratification and static stability
- Atmospheric dynamics as a function of depth

Proposal: Probe Summer and Winter Hemispheres

Main Probe-only Objectives:

Determine Bulk Composition:

- Measure abundances of the noble gases (He, Ne, Ar)
- Measure isotopic ratios of H, C, N, and S

SNAP

Small Next-generation Atmospheric Probe

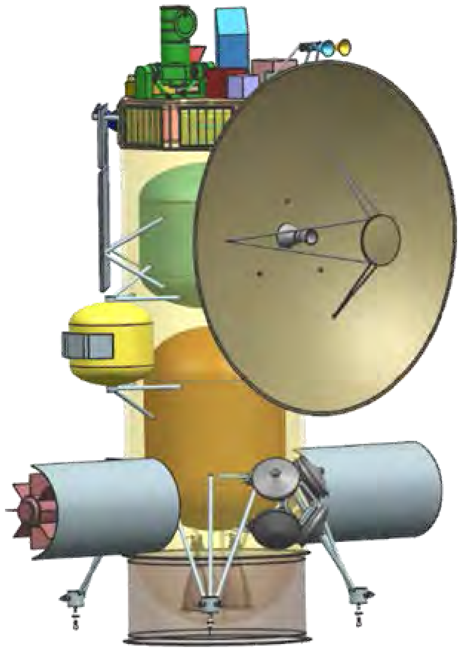
To Enable Future Multi-Probe Missions

Dillman et al. 2018 IPPW

Sayanagi et al. 2019 IG In-Situ Exploration Workshop

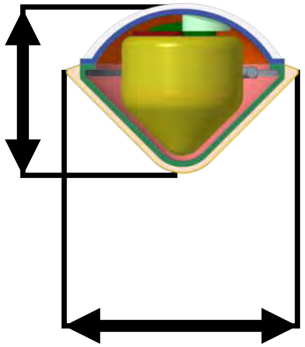
Add SNAP as a Second Probe to the 2017 SDT Design

From Ice Giant SDT Study



SNAP

Not to scale with Orbiter



Orbiter
• Mass in orbit: 1913 kg • Payload Mass: 50 kg • UOI r_p: 1.05 R_U • Orbital Period: ~142 days

Primary Atm. Probe (PP)
• Mass: 321 kg • Diameter: 1.2 m, 45° sphere-cone • 10-bar* pressure altitude • Probe release: ~60 days • EPFA: -20° to -50°

Baseline Orbiter and Probe: Ice Giant SDT Architecture #5

SNAP
• Mass: 30 kg • Diameter: 0.5 m, 45° sphere-cone • 10-bar* pressure altitude • Probe release: 30–60 days • EPFA: -20° to -50°

SNAP Science Instruments

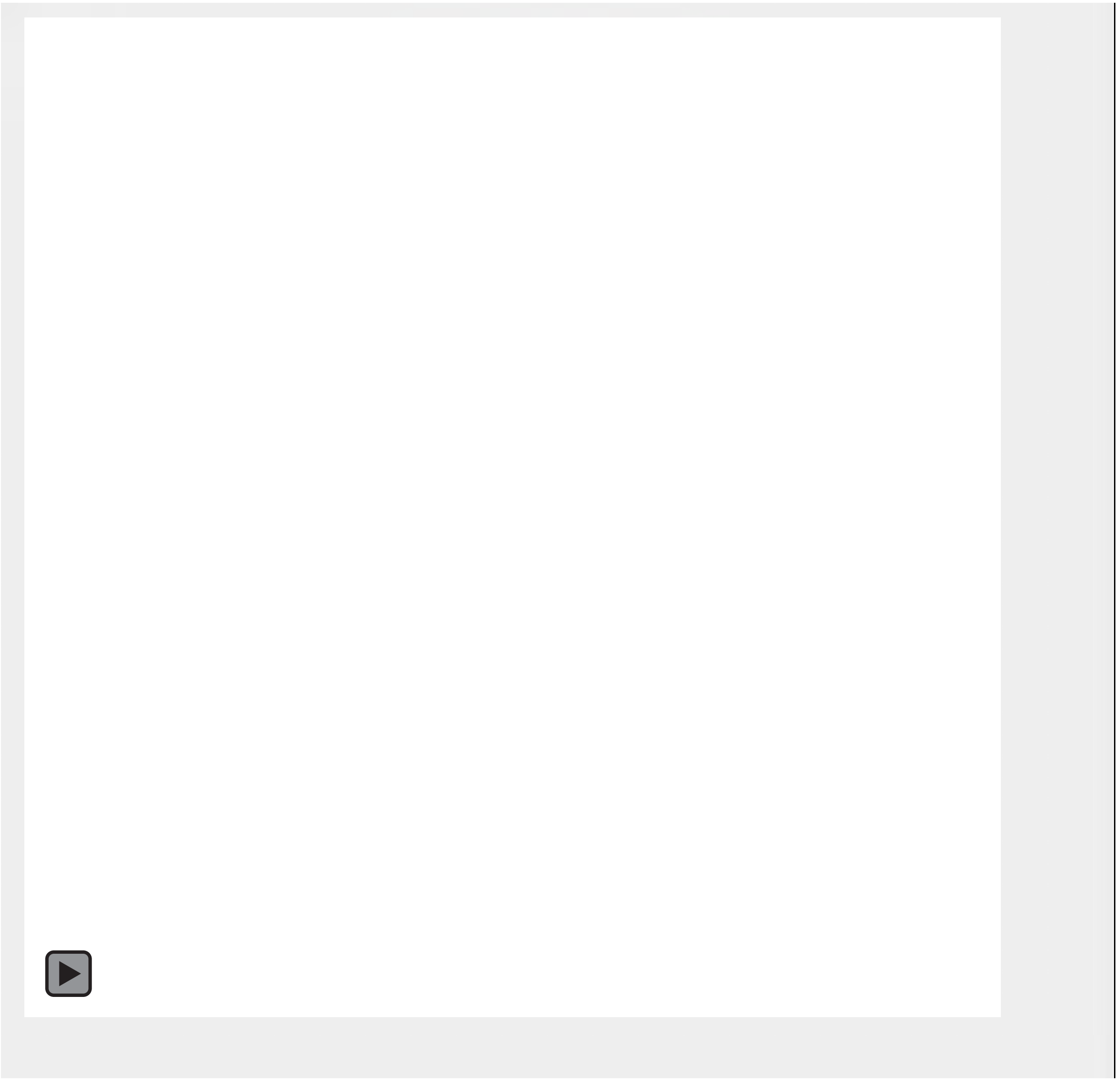
Instrument	Measurement	Mass	Power	SNAP Data Return
NanoChem	Vapor Pressure	1.0 kg	1 W	0.6 Mbit
Atmospheric Structure Instrument	Pressure Temperature Acceleration	1.3 kg	5 W	4.5 Mbit
Ultra-Stable Oscillator	Doppler Wind Experiment	1.7 kg	3 W	0.03 Mbit (Housekeeping Only)
Total		**4 kg**	**9 W**	**5.1 Mbit**

SNAP Mass Summary

SNAP Components	CBE Mass +Contingency +30% Margin
Aeroshell	**14.8 kg**
Backshell	3.1 kg
Forward Heatshield	8.6 kg
Separation Mechanisms	1.2 kg
Separation Parachute + Mortar	1.9 kg
Descent Module	**15.2 kg**
Structure	2.1 kg
Instruments	6.6 kg
Engineering Subsystems	5.9 kg
Descent Parachute	0.6 kg
Total Mass	**30.0 kg**

Dual-Probe Delivery Trajectory w/ SNAP

- Deliver PP and SNAP at two significantly different locations
- During each probe’s atmospheric descent:
  - Orbiter used as Data Relay
  - Orbiter must be within 30 degree comm. cone around zenith.
  - Each probe must reach at >5-bar while Orbiter is in 30-deg cone.
- Solution:
  - Deliver Primary Probe during Orbit Insertion
  - Deliver SNAP at the end of 1st Orbit.



Take Home Messages

- Mass Spectrometer design drives the probe mass
  - Gas Chromatograph or Neutral Mass Spec?
  - Consider Non-Mass Spec Options
    - Helium Abundance Detector, Noble Gas Detectors, etc.
    - Alternate Sensors are not sensitive to Isotopic Ratios
- Staged Probes enable exploring deep layers
  - Benefits for Ice Giants need to be studied
- Multi-Probe Missions
  - Secondary Probe(s) do not need to carry a Mass Spec
  - Multi-Probe Delivery Trajectory – need more studies
- Trajectory Studies
  - Dual-Probe Delivery during Orbit Insertion?
  - (Dual?) Probe Delivery during GA Flyby?
  - See Tom Spilker’s Talk next!

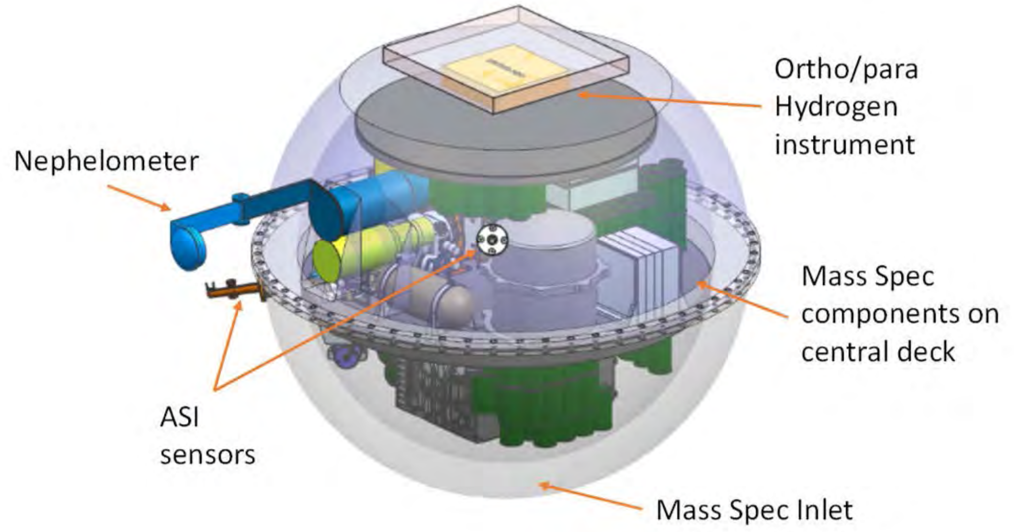
Backup Slides

2010 Uranus Orbiter and Probe Decadal Study

- APL Technical Design Team led by Zibi Turtle
- Total Atmospheric Entry Mass:
  - Current Best Estimate (CBE): 88.87 kg
  - With Contingency: 103.40 kg
  - With Contingency + 30% margin: 127.08 kg
- Instrument CBE + Contingency Mass: 17.13 kg
  - 17% instrument mass fraction
  - Mass Spec + ASI + Nephelometer + USO
  - Mass Spec = INMS CBE+Contingency Mass = 9 kg.
  - Non-MassSpec Inst Mass CBE+Contingency = 8 kg.
- Entry System (Aero/back-shell + TPS + Parachute) CBE Mass: 35.5 kg

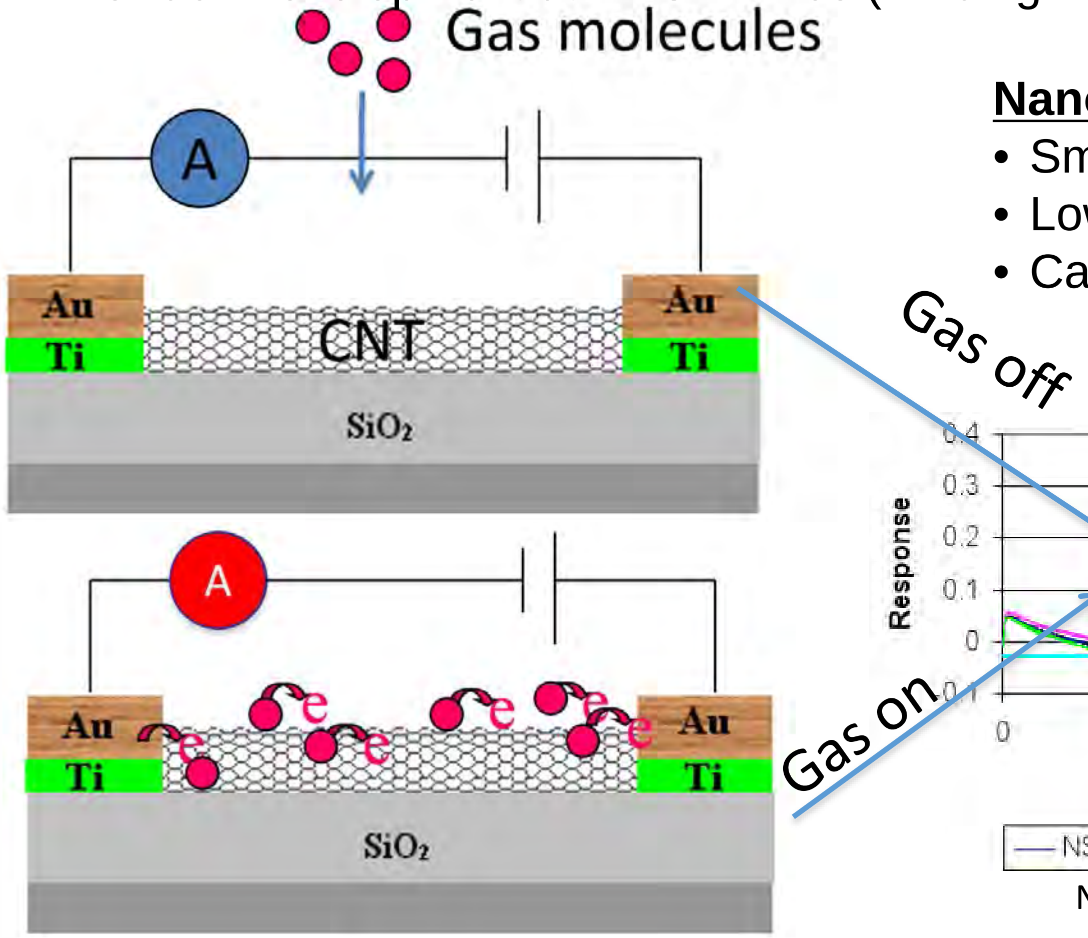
2017 Ice Giant Flagship SDT Study

- SDT Chairs: Amy Simon and Mark Hofstadter
- Total Atmospheric Entry Mass:
  - Current Best Estimate (CBE): 224.3 kg
  - With Contingency + Margin: 320.7 kg
- Instrument CBE + Contingency Mass: 32.5 kg
  - 10% instrument mass fraction
  - Mass Spec + ASI + Nephelometer + Ortho/Para : (No USO)
  - Mass Spec = Gas Chromatograph Mass Spec w/ CBE Mass = 17.4 kg
  - Non-MassSpec Inst Mass = 7.9 kg
- Entry System CBE Mass: 102.8 kg



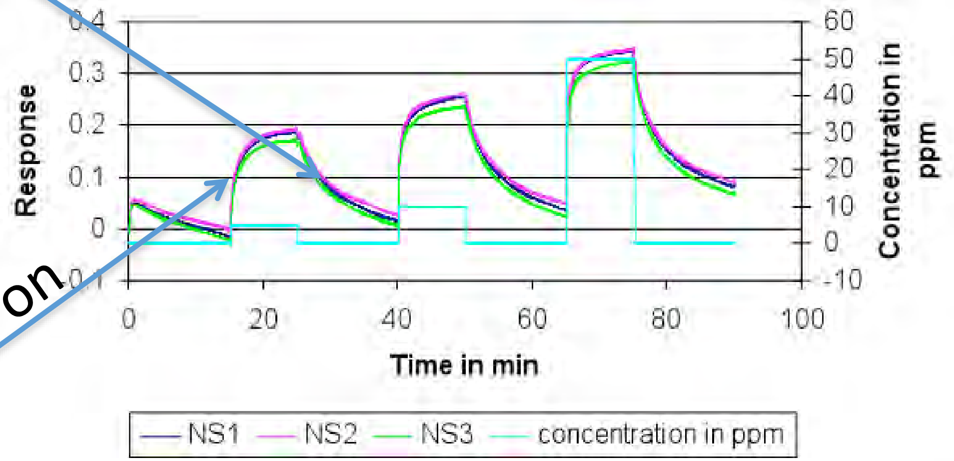
NanoChem: How it works

- Measures <u>Changes in Resistivity</u> in response to vapor concentration
- Sensor Heads can be arrayed up to 16 x16 grid on a single chip
- Under Development at NASA Ames (PI: Jing Li)



<u>NanoChem Advantages:</u>

- Small Sensor Package
- Low Mass, Lowe Power
- Can operate without Vacuum Pump



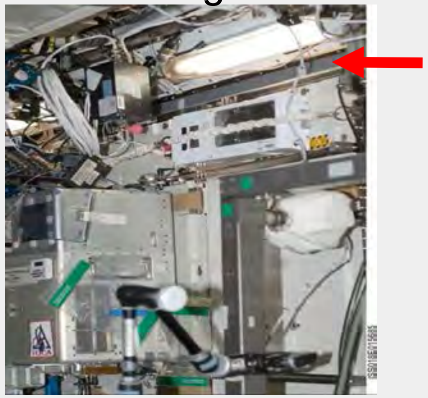
NanoChem response to ammonia

NanoChem: TRL = 4 Today

Launched and Operated in Space

Navy MidSTAR-1 satellite in 2007

Environmental Monitoring on ISS



Sensitivity demonstrated for:

… CH_4, H_2O, and NH_3, among others

… in Mars and Earth conditions

Need to

…develop sensitivities for H_2S

… demo in Giant Planet Conditions

Analyte	Sensitivity/Detection Limit
CH_4	1 ppm in air
Hydrazine	10 ppb tested
NO_2	4.6 ppb in air
NH_3	0.5 ppm in air
SO_2	25 ppm in air
HCl	5 ppm in air
Formaldehyde	10 ppb in air
Acetone	10 ppm in air
Benzene	20 ppm in air
Cl_2	0.5 ppm in N_2
HCN	10 ppm in N_2
Malathion	Open bottle in air
Diazinon	Open bottle in air
Toluene	1 ppm in air
Nitrotoluene	256 ppb in N_2
H_2O_2	3.7 ppm in air

NanoChem Commercialization

- Development at NASA Ames
  PI: Jing Li
- A/D on NanoChem Attachment
- Power from Phone (~mW)
- Processing on the Phone
- High sensitivity – ppb to ppm
- Data Transmission through Cellular Network