BASIC QUESTIONS ABOUT THE SOLAR SYSTEM: THE NEED FOR PROBES

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ABSTRACT

Probes are an essential element in the scientific study of planets with atmospheres. In-situ measurements provide the most accurate determination of composition, winds, temperatures, clouds, and radiative fluxes. They address fundamental NASA objectives concerning volatile compounds, climate, and the origin of life. Probes also deliver landers and aerobots that help in the study of planetary surfaces. This talk focuses on Venus, Titan, and the giant planets. I review the basic science questions and discuss the recommended missions. I stress the need for a balanced program that includes an array of missions that increase in size by factors of two. Gaps in this array lead to failures and cancellations that are harmful to the program and to scientific exploration.

1. INTRODUCTION

1.1 Relevance to NASA/OSS Objectives

- Origin and evolution of our solar system (SS)
- What our SS tells about extrasolar systems
- Distribution of volatile compounds in SS
- Differences among terrestrial planets
- SS characteristics that led to origin of life
- Sources of prebiotic compounds
- Habitable zones in the SS

These objectives are from the SSE Roadmap. I was on the Decadal Survey Committee and served as vice chair of the Giant Planets Panel. Reta Beebe was the chair of that panel, and Mike Belton was chair of the committee. I'll tell you what the Decadal Survey has recommended in the way of probes and missions to planets with atmospheres. Venus is relevant to differences among the terrestrial planets. Titan may have an ocean that has gotten mixed up with the organics on the surface, so Titan is relevant to origin of life, prebiotic compounds, and habitable zones. Giant planets are relevant to the origin of the solar system and distribution of volatiles in the solar system,

1.2 Scope of this Talk and Past Probe Missions

- Venus - Venera probes (Soviet Union) and Pioneer Venus Probes (US)
- Titan - Huygens probe (ESA) and Cassini spacecraft (US)
- Giant Planets - Galileo probe (US)

I'll be talking about Venus, Titan, and the giant planets. These are the objects with thick atmospheres, where probes are the only way to make in-situ measurements. There have been ~ 10 probes into the Venus atmosphere, one to Titan, and one to Jupiter. There were ~ 10 missions involving probes that were recommended during the Decadal Survey.

1.3 Documents and Sources

- Decadal Survey (DS) - *New Frontiers in the Solar System,* Michael J. S. Belton, chair (National Academy of Sciences, 2003)

- Community White Papers (CWP) - *The Future of Solar System Exploration, 2003-2013,* Mark V. Sykes, editor (Astronomical Society of the Pacific, 2002)

The Decadal Survey was published in 2003, although most of the work was done in 2002. The Community White Papers were published in 2002 but they were part of the whole decadal study of what does the scientific community feel is the next step in the exploration of these objects.

1.4 What Probes Measure

- Atmospheric chemical composition - major and minor constituents including noble gases and isotopes (gas chromatographs, mass spectrometers, optical spectrometers, chemical sensors)
- Atmospheric physical structure - T, P, ρ, turbulence, waves - all as functions of depth
- Clouds – particle properties (composition, size, shape, optical constants) and vertical distribution

Probes are the gold standard for measuring the composition of an atmosphere. Remote sensing gives you pieces of the composition, but there's no way you could get the isotopes and noble gases by remote sensing to the accuracy that you get by in-situ measurements. The composition is relevant to the origin of the solar system, the distribution of volatiles, and the history of surface-atmosphere interactions. Probes are also the gold standard for the physical structure of the atmosphere, which is relevant to the dynamics and sometimes the surface-atmosphere interaction. And to do sampling of clouds you need probes.

- Large-scale winds from Doppler tracking and VLBI, turbulence and waves from accelerometers and on-board wind sensors
- Radiative heating from optical and IR sensors (net flux radiometer)
- Miscellaneous – lightning, He/H2, radio opacity (NH3), exosphere composition

Probes can measure winds from accelerometers and onboard wind sensors. And again, probes are the gold standard, although you can do things from orbit on all of these objects. For Jupiter, we have a lot of cloud top winds from Voyager and Galileo and Cassini. But if you want to understand the dynamics, you need to know what the winds are doing below the clouds. You also need the radiative energy sources. And, of course, on the Galileo probe there was a lightening detector and a helium-to-hydrogen detector. The Galileo probe's radio signal passing through the atmosphere was really the best estimate of the ammonia abundance, although the mass spectrometer provided another estimate.

- Probes deliver landers to the surface of Venus and Titan, and with difficulty, Mars
- Observe surface morphology, mineralogy, elemental composition, subsurface structure, seismology, surface-atmosphere interaction
- Probes deliver aerobots (balloons, airplanes, helicopters) that survey the surface remotely at altitudes 1/100 of orbital altitude

Probes are delivery vehicles because if you have a thick atmosphere, you really have to get to the surface by means of probes. Probes also can provide a platform for launching balloons, airplanes, and helicopters that allow you to travel around and look at many places on the surface and look at it from much closer distances and with higher resolution than you get from orbit.

2. VENUS

2.1 Venus Science Questions

- Surface history - impacts, tectonics, volcanism, erosion; global resurfacing “event” 500 Myr BP?
- History of water (loss of an ocean) and evolution of the atmosphere - noble gas composition, isotopes of O & H, outgassing, reactions with surface (C, S, O, H, Cl)
- Greenhouse effect and climate - trace gases, clouds, penetration of sunlight, IR opacity
- Super-rotation of the atmosphere

From the number of impact craters on the surface of Venus you estimate that the surface is approximately 500 million years old, which is still only one-tenth of the age of the solar system. So something's been going on, and it's not erosion. There's not a lot of evidence of degradation of surface features by erosion. The surface features are rather pristine. The other source of resurfacing is internal processes, volcanoes or something, and that whole resurfacing of Venus takes place every 500 million years. It is a principal mystery, and getting down to the surface, measuring the surface composition, is one of the principal goals for Venus.

Another important goal is what happened to the water? If Venus is the Earth's sister planet, where is the ocean? It's quite possible that there was an ocean on Venus. It might have been a steam ocean because Venus is that close to the sun, but what happened to all that water vapor, those 300 bars of water vapor? The clue may be in the isotopes of oxygen and hydrogen, which you can best measure with probes.

Venus has probably the hottest surface in the solar system. It gets hotter than Mercury. And this greenhouse effect is there because trace gases and many other things plug up the IR windows. Understanding that is very important. The atmosphere rotates 50 times faster than the solid planet, which is its own mystery.

2.2 Recommended Venus Missions

- VISE (DS) - Compositional and isotopic analysis of atmosphere, core sample of the surface lofted to balloon altitude and analyzed there, winds and radiometry during descent and at balloon station
- Noble gas and trace gas explorer (CWP) - single probe to the surface

- Dynamics explorer (CWP) - Four to eight probes
- Landers (months to year), sample return (CWP)

The Decadal Survey recommended a mission called VICE, as part of the New Frontiers line. It involves a probe, a main balloon, and a sub-balloon that drops to the surface, grabs a piece of the surface and then quickly gets back up for a rendezvous with the main balloon. The balloon carries instruments that work at room temperature but not at the surface. The balloon also does chemical analyses of the atmosphere and, of course, the little sub-balloon can do analysis on the way up and down. It's a rather ambitious concept, and there are technological hurdles that have to be overcome.

The Community White Paper said, make it simpler. Let's just have a balloon that does a good job on the isotopes and trace gases—a single probe down to the surface and no rendezvous with a main balloon.

For the dynamics, to understand the super-rotation of the atmosphere you really need a lot of probes to sample space and time, and so the Community White Paper has recommended 4 to 8 probes. And ultimately we would like to learn how to go down to the surface of Venus and operate there with instruments for a long time at temperatures of 730 K.

3. TITAN

3.1 Titan Science Questions

- Composition and extent of surface organics
- Subsurface ocean - composition, depth
- Evidence of episodic heating and exposure of organics to aqueous solutions
- Atmospheric dynamics - winds, clouds, precipitation, radiative heating, atmosphere-surface interaction

Titan doesn't have enough gravity to hold on to the lightest gases like hydrogen, so it is constantly increasing the carbon to hydrogen ratio. This means the number of multi-carbon molecules is increasing, so it's a very interesting place for organic chemistry. There's a possibility that these organics form liquid lakes or oceans. Also there's nitrogen present. Titan gives you a chance to watch an atmosphere that's evolving, as the Earth may have evolved billions of years ago.

There's also a possibility of a subsurface ocean sort of like the subsurface ocean on the Galilean satellites. And there's even the possibility that the ocean and the surface organics have gotten in contact at times, and this becomes an interesting habitability question. The atmosphere dynamics could be like Venus with a strong super-rotation. The winds appear to be large even though the amount of sunlight is small.

3.2 Recommended Titan Missions

- Titan Explorer (DS) - orbiter (for relay) and probe (aerobot); use atmosphere for mobility; descend repeatedly to the surface; make high-resolution remote observations and repeated atmospheric measurements
- Airship and mobile lander (CWP) - balloons, airplane, or helicopter.
- Radioisotope power source is critical (DS)

Cassini carries the Huygens probe, which will enter Titan's atmosphere in January 2005. After the Huygens probe, there will still be the need for atmospheric mobility to descend rapidly to the surface many times and also make atmospheric measurements in many places. This would be a more ambitious device than Huygens, which just goes down in one place. So mobility is the key to the future, according to the Community White Papers and the Decadal Survey. But if the probes are to last for a long time they will need power, and solar power is not going to work. The outer solar system missions need radioisotope power, and that's an area where development is needed.

4. GIANT PLANETS

4.1 Giant Planet Science Questions

- Composition of their atmospheres and interiors - water is key (O/H ratio); major elements, noble gases, isotopes; cloud base may exist only for Jupiter and Saturn
- Liquid oceans on Uranus and Neptune?
- Deep winds, temperature structure, clouds, radiation, convection, lightning - relation to meteorology at cloud top level

Now let's talk about giant planets. The Galileo Probe did a wonderful job, but it really did not settle the issue of the oxygen to hydrogen ratio on Jupiter. That is a crucial issue because we are talking about the most abundant element and the third most abundant element, with helium in between, so water was probably the most abundant compound in the early solar system. And yet we don't know how much water is on Jupiter. To find out, we have to get down to where water is well mixed.

At least at the Galileo Probe site, we didn't do it. We need to get down to 100 bars on Jupiter and all of the giant planets. Having probes in all the giant planets makes a great deal of sense. Having deep probes to Jupiter at a number of different latitudes makes a great deal of sense too.

4.2 Recommended Giant Planet Missions

- JPOP (DS) - Polar orbiter with probes at 3 different latitudes (≤ 30°) down to 100 bars
- Neptune Orbiter with Probes (DS) - measure planet's C, S, noble gases, isotopes
- Jupiter Microwave Sounder (CWP) - Either orbiter or flyby; water & ammonia to 100 bars and below, no noble gases or isotopes
- Deep probes to all giant planets (CWP); can we detect probe signals directly at Earth?

The Decadal Survey recommended JPOP, a Jupiter Polar Orbiter with Probes, as part of the New Frontiers line. JPOP involves probes to 100 bars at three different latitudes. That can be done. What can't be done is to guarantee that we will meet an ambitious set of scientific goals and do it within a specified cost cap. There's too much uncertainty. Something's got to give.

The Community White Papers recommended something complimentary to probes—an orbiter or a fly-by that has a microwave sounder that can peer into the planet down to 100 bars. It measures the water and ammonia abundance but not as accurately as the instruments on a probe. It can't do everything probes can do, but it can get a global picture. Probes are limited in this respect, because the number of probes is limited. The microwave sounder is the Juno mission, which has Scott Bolton as PI and is working its way through the system right now. I feel these missions are complimentary, and I'd love to see both probes and a microwave sounder.

It would be nice if we could detect probes directly at Earth because communication between a probe and the fly-by or orbiter that delivered the probe is a difficult constraint on the probe. If we could cut that constraint and listen to the probe directly, it would be wonderful.

5. GENERIC RECOMMENDATIONS (DS)

- Thermal protection system for probes and aerocapture - Jupiter is the driver
- Radioisotope power sources
- Nuclear-powered electric propulsion
- Advanced telecommunications
- Balanced program - factors of 2 in cost - Discovery, New Frontiers, Flagship
- 2xFlagship, Prometheus, humans on Moon/Mars

All but the last bullet is right out of the Decadal Survey. The last bullet is my own interpretation of where we stand. The Decadal Survey said, get to work on thermal protection systems for probes. Using atmospheric drag to go into orbit is called aerocapture. The technology is similar to that of an entry probe and involves high-speed entry and thermal protection. I'm the PI on a Neptune vision mission study, which is to think about the decade after the one we are in. We are studying a mission that does not use nuclear electric propulsion—the Prometheus-type technology. We can use ordinary chemical or maybe solar electric propulsion to get out to Neptune, but then we need aerocapture to get into orbit. With aerocapture we can do a Cassini class mission for Cassini class dollars and that's what the Decadal Survey calls a Flagship mission. But, of course, the Decadal Survey also says nuclear power for propulsion is a wonderful thing and perhaps that's true. I'm concerned that it's a long way off in the future and we have to have something to keep us going in between.

The Decadal Survey says we need a balanced program, and that means an array of missions differing in cost by factors of 2. An example would the Discovery class, 2 times Discovery, which is the New Frontiers line, 4 times Discovery, which is a Flagship, and so on. Now here I'm going to add my own controversial thing. I think we need 2 and possibly 4 times Flagship, which is 8-16 times Discovery. Right now we don't have any Flagships to any of these objects, and we aren't even thinking about anything in the 2 times Flagship category. Prometheus is 4-8 times Flagship. We sort of leapt ahead to Prometheus and leapt even beyond that in talking about humans on Moon and Mars. I think it's a very dangerous situation when we have this gap between things that we can do and the grand things that we would like to do some day. There are wonderful things we can do in this gap and there's a danger that they won't ever get done. We're relying on this pie-in-the-sky of Prometheus and beyond, which is not a good situation to be in.

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August 23, 2004

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Relevance to NASA/OSS Objectives: SSE Roadmap

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Scope of this Talk, History

- Venus - Venera probes (Soviet Union) and Pioneer Venus Probes (US)
- Titan - Huygens probe (ESA) and Cassini spacecraft (US)
- Giant Planets - Galileo probe (US)

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What Probes Measure (1 of 3)

- Atmospheric chemical composition - major and minor constituents including noble gases and isotopes (gas chromatographs, mass spectrometers, optical spectrometers, chemical sensors)
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What Probes Measure (2 of 3)

- Large-scale winds from Doppler tracking and VLBI, turbulence and waves from accelerometers and on-board wind sensors
- Radiative heating from optical and IR sensors (net flux radiometer)
- Miscellaneous - lightning, He/H_2, radio opacity (NH_3), exosphere composition

What Probes Measure (3 of 3)

- Probes deliver landers to the surface of Venus and Titan, and with difficulty, Mars
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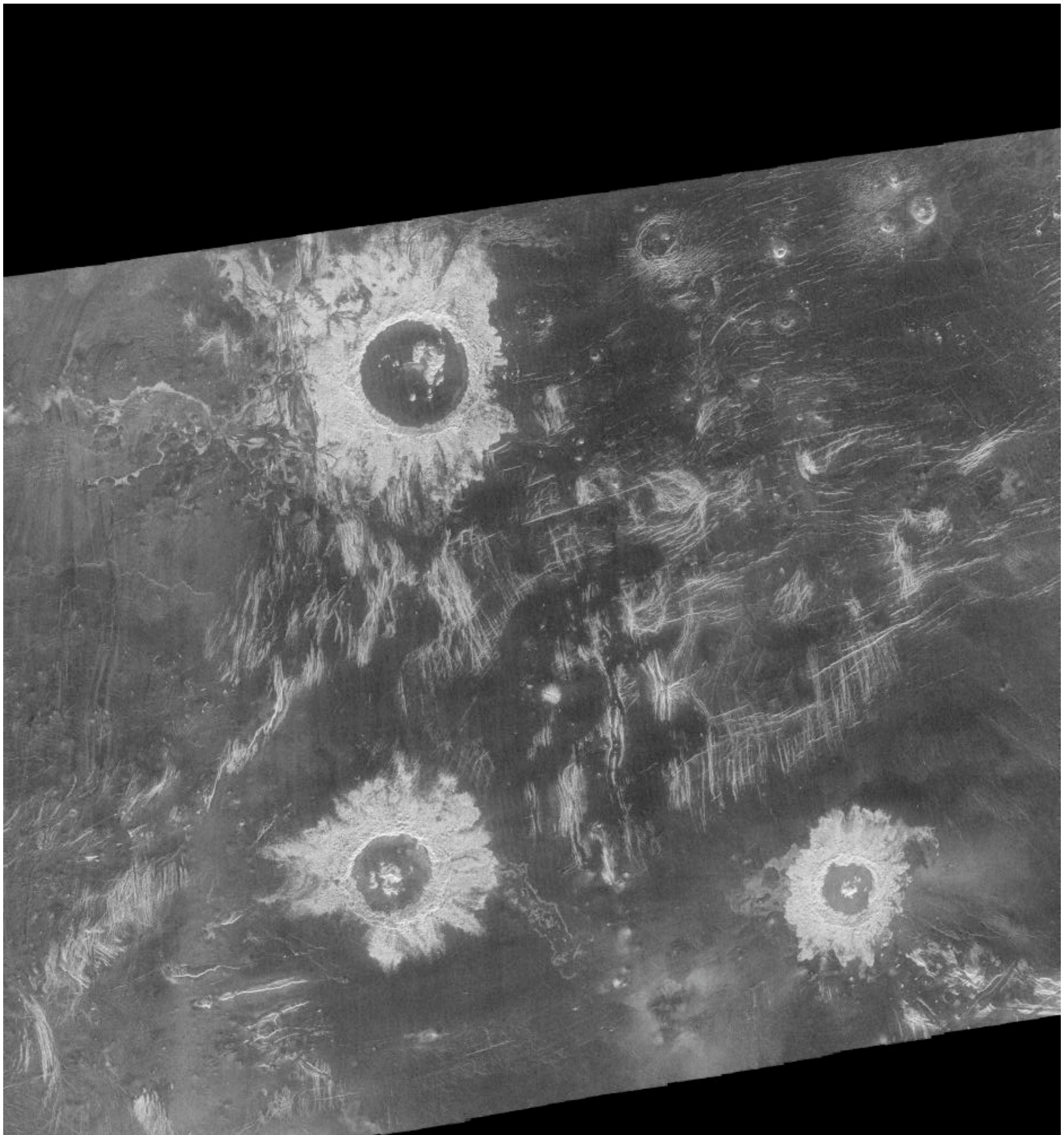

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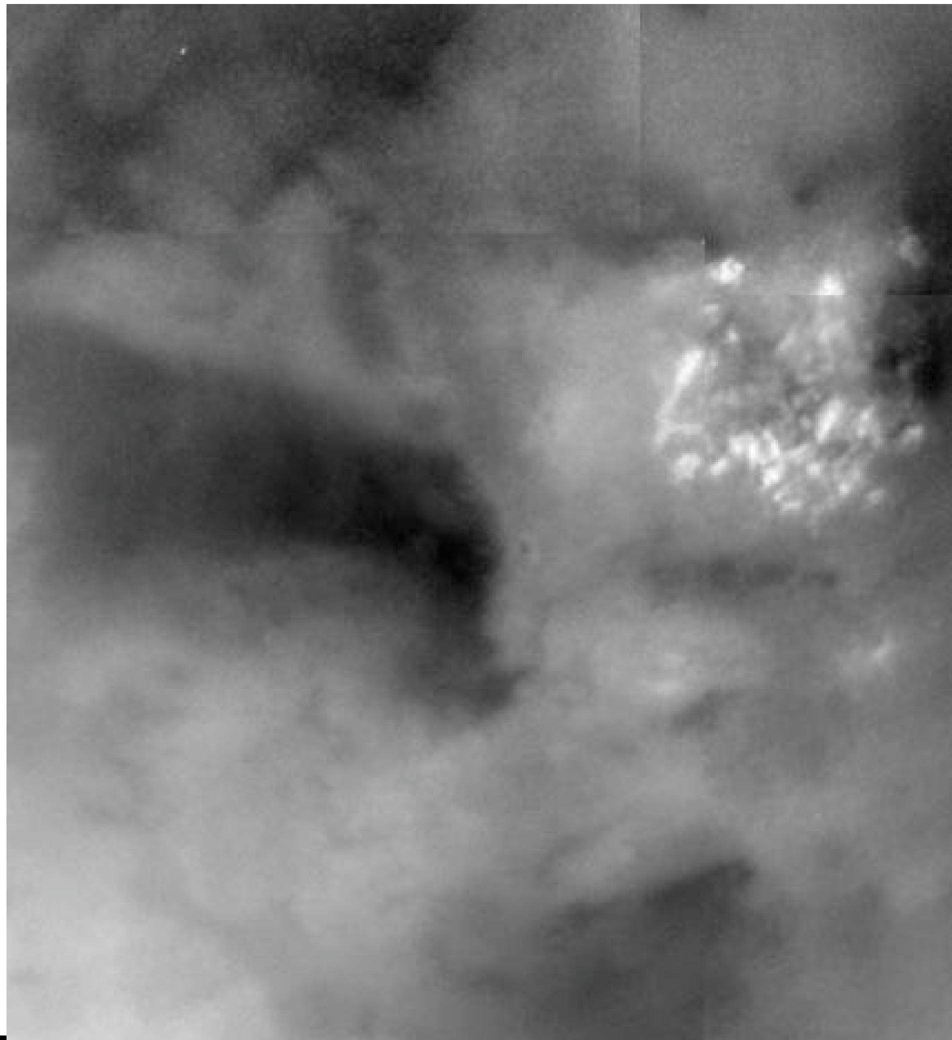

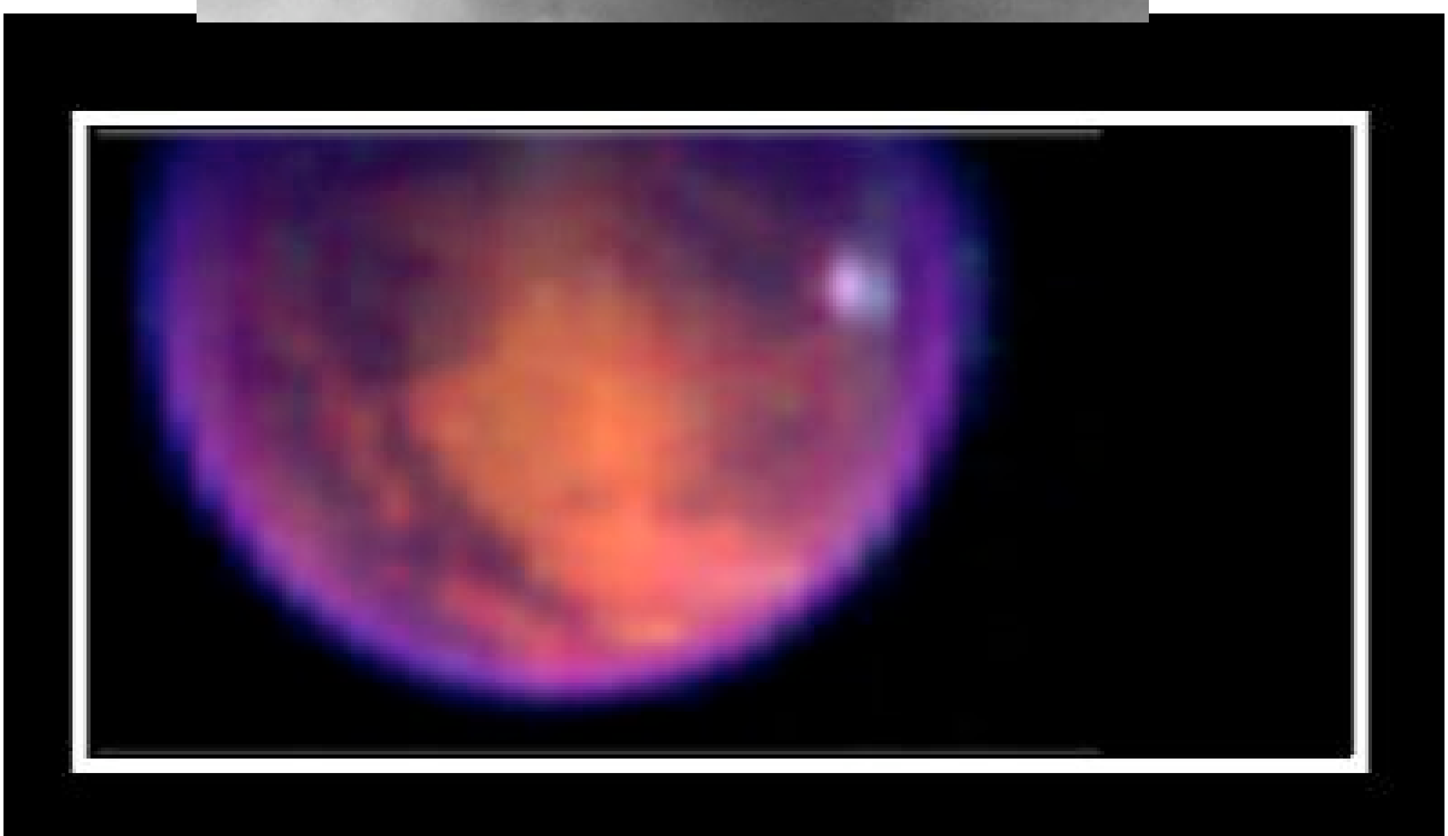

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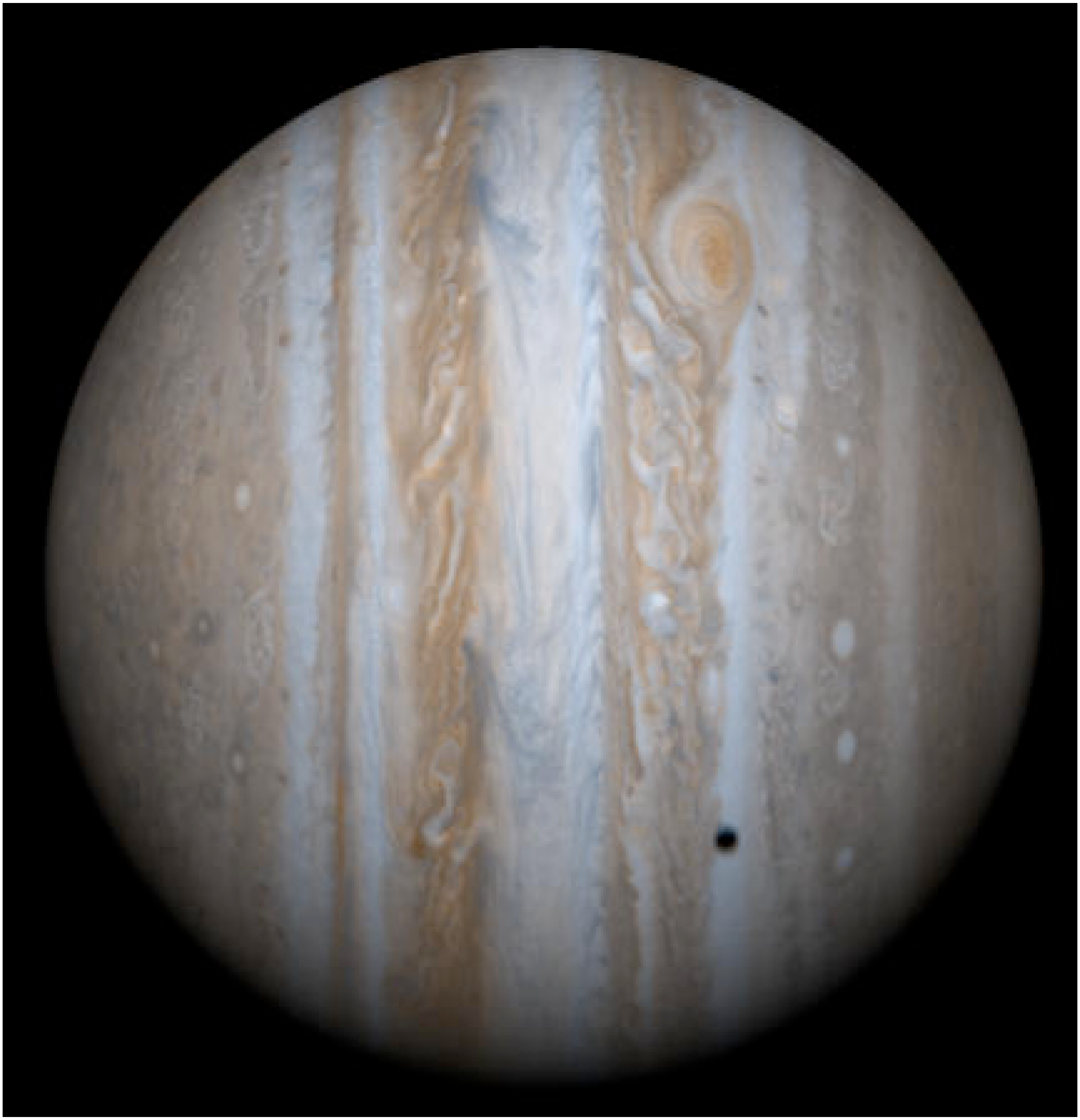

Giant Planet Science Questions

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Generic Recommendations (DS)

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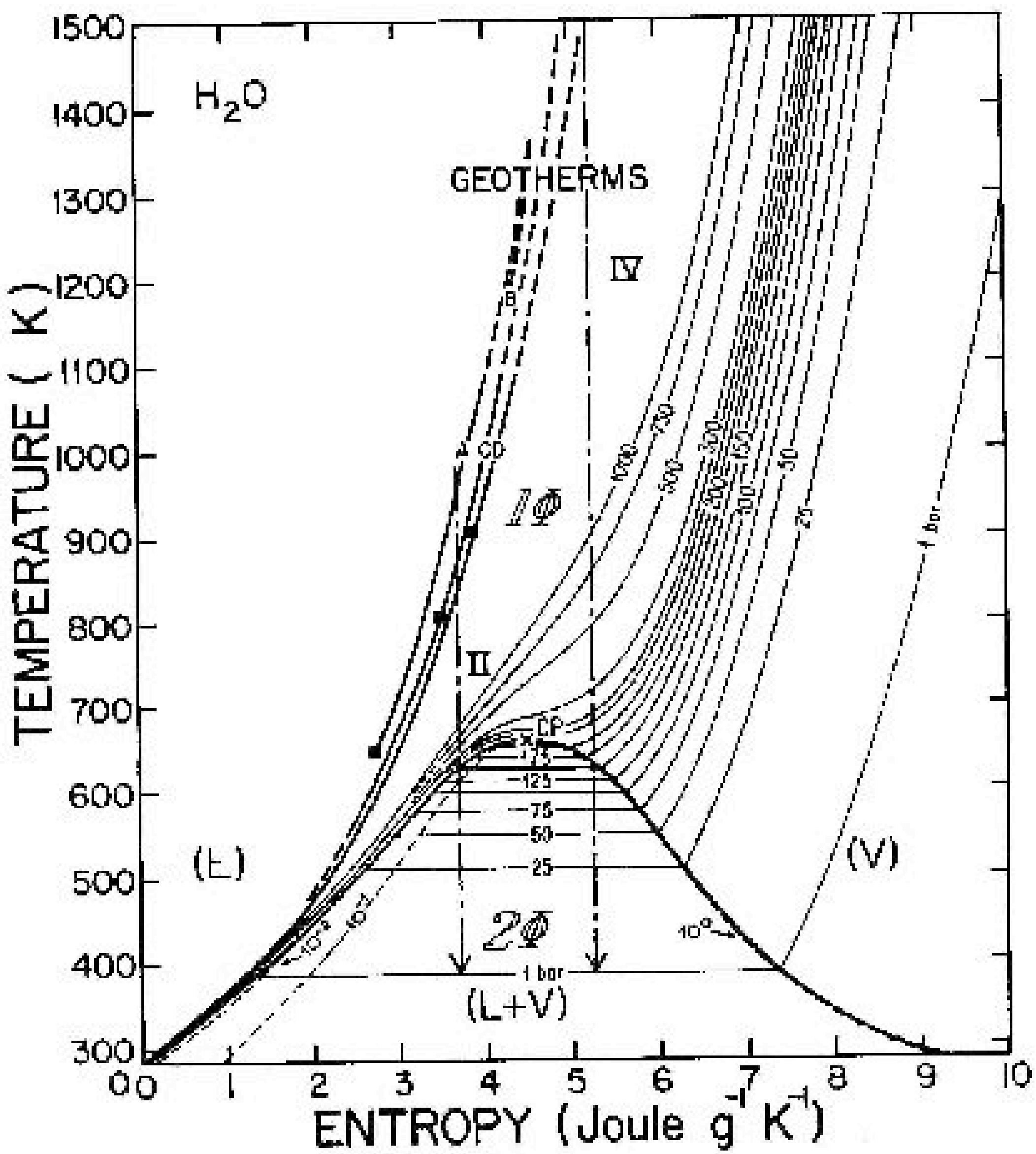
Oceans on Uranus and Neptune

- Bulk density and cosmic O abundance imply planet is 15% H_2 , 85% H_2O by mole
- Internal heat implies convection, which implies moist adiabatic structure
- Must pass through $T = 63$ K, $P = 1$ bar
- Need a liquid water interface at $T \sim 560$ K, $P(H_2) \sim 1.5$ kbar, $P(H_2O) \sim 75$ bar



H2O
GEOTHERMS
(L)
(V)
(L+V)
1Φ
2Φ
II
IV
CP
1 bar
TEMPERATURE (K)
ENTROPY (Joule g-1 K-1)