Planetary Decadal Study Community White Paper
The Future of Solar System Exploration (2003-2013) – First Decadal Study Contributions (Community Panel)

SUBJECT AREA: Large Satellites
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Titan

Ralph Lorenz (University of Arizona)
rlorenz@lpl.arizona.edu
t:520 621 5585
f:520 621 4933

Jacklyn R. Green (JPL)
Chuck Wood (Columbia U.)
Athena Coustenis(Paris-Meudon Obs.)
Gian G. Ori (IRSPS)
Philippe Paillou (U. Bordeaux)
Roger Yelle (NAU)
Scott Bolton (JPL)
Kevin Baines (JPL)
Rich Terrile (JPL)
Mark A. Gurwell (Harvard)
Caitlin Griffith (NAU)
Ah-San Wong (Caltech)
Kathy Rages (NASA Ames)

Executive Summary

Titan is the Mars of the Outer Solar System.

Everything that makes Mars interesting (landscape, meteorology, connections to the origin of life) applies in equal measure to Titan. As a body with a thick 'Earth-like' atmosphere, 'moon-like' gravity and the possibility of large expanses of surface liquid, Titan – already known to be a giant organic chemistry laboratory - promises to be an excellent physical laboratory for the study of terrestrial processes such as oceanography and meteorology and thus may engage a wider scientific community than has been involved in planetary science to date. Titan's importance as a scientific target may be considered in four areas:

Titan's Landscape
As yet, we have little data on Titan's surface, although both radar reflectivity and the crude maps made from groundbased telescopes and HST point to strongly heterogenous regions on the surface. The deposition of photochemical materials, including liquid ethane, suggest that Titan's surface will have widespread lakes and seas of liquid hydrocarbons, making a uniquely evocative landscape. In addition to the usual panoply of volcanic, tectonic and impact-induced landforms, Titan is likely therefore to have many exotic landforms such as tidal flats and perhaps fluvial features like river beds.

Titan's Meteorology
Methane in Titan's atmosphere behaves much as water does on Earth. It is a condensible greenhouse gas that may participate in important climate feedbacks, as well as forming clouds that form and dissipate as rainfall on short (hours) timescales. This methane weather appears more similar to – and may shed new insights on - Earth's weather than does the activity in any other solar system atmosphere. Titan study may assist important problems such as the treatment of moist convection and ocean-atmosphere fluxes. Photochemistry of methane leads to a thick organic haze which accumulates on the surface. The haze shows seasonal effects, notably a dark polar hood that builds up during polar winter and may be analogous to the polar stratospheric clouds associated with the 'ozone hole' on Earth.

Titan and the Origin of Life
The internal structure of the Galilean satellites suggests that Titan, helped with ammonia antifreeze, will have an internal water ocean like that of Europa. Unlike Europa, however, Titan has abundant organics – and in this respect *Titan may be better endowed with the ingredients for life than is Europa*. Titan, despite its distance, is energetically an easier object on which to land advanced instrumentation, since its thick atmosphere allows entry and descent via heatshield and parachute, rather than the heavy retropropulsion required for Europa. Titan also does not suffer from the challenging radiation environment at Europa. Access to the internal ocean itself is not necessary for a meaningful astrobiological investigation – surface deposits will be present where transient exposures of liquid water from cryovolcanic activity or impact melt will have interacted over thousands to millions of years with the organics deposited from the atmosphere to form a

frozen primordial soup, an experiment that cannot be adequately reproduced in terrestrial laboratories.

Titan – A Unique Icy Satellite

Titan, even stripped of its unique atmosphere, also deserves study simply as an important icy satellite. It is clearly a unique member of the Saturnian system, being considerably larger than any other saturnian satellite. It is large enough to possess significant intrinsic activity (volcanism, tectonics) and the differences in its evolution and constitution from the Galilean satellites beg to be understood. Furthermore, its orbital eccentricity presents a challenging puzzle – even without dissipation from possible oceans of surface hydrocarbon liquids, the eccentricity (unforced by resonances) points to an anomalous orbital history, perhaps indicating a recent collision or near-miss. In sum, Titan even without its atmosphere is a more important an icy satellite than any other than perhaps Europa.

Recommendations

Missions

NASA and the scientific community must be ready to respond to the explosion of public interest when Cassini arrives in 2004/5. While designs should maintain flexibility until the early Cassin/Huygens results are analyzed, early technology development efforts should be undertaken so that technology readiness is not on the critical path to a follow-on mission.

Early discussion with ESA and its member states should be undertaken to exploit the resource-sharing opportunities with these international partners who will themselves have considerable Titan scientific activities.

An extension to the nominal 4-year Cassini mission will offer significant scientific return at modest cost. At present the limiting factor on Cassini Titan science is the number of Titan flybys possible in the tour. At the end of the present nominal mission, Cassini is in a short period orbit that would permit additional Titan flybys more often than the ‘average’ for the 4-year tour and is therefore poised to add considerably to the Titan science return.

The most important element in a post-Cassini mission will be an airborne exploration platform exploiting Titan’s thick atmosphere and low gravity to give lander-like close-up investigation capability at many locations on Titan’s diverse surface. This platform could be an airship with buoyancy control or conceivably some sort of heavier-than-air vehicle. Such a platform offers tremendous scientific capability as well as unparallelled scope for public engagement. Since a Titan explorer will require a radioisotope power source in any case, its duration need not be tightly constrained – 1-2 years.

It is likely that an orbiter may be required to support the data return from such a platform ; a limited scientific payload on the orbiter should complement the capabilities of Cassini and exploit the extended period of proximity to Titan.

Critical technologies that require early development are the adaptation of a radioisotope power source to operation in an atmosphere, on-board autonomy, instrumentation and aerobraking technologies.

Laboratory Studies

The interaction of water-rich liquids with Titan organics (‘tholins’) are not well-understood, and further laboratory study should be undertaken, not only as a scientific investigation, but to anticipate and shape the design of compact instrumentation for future missions to look for prebiotic compounds such as amino acids and sugars in surface deposits.

Detailed interpretation of Cassini result will require laboratory work in other fields, such as photochemistry, haze formation, rheology of volatile-rich ices etc.

Telescope Facilities

Titan has shown itself to be a dynamic object, with meteorological changes on hourly timescales (but yet of unknown frequency) as well as a seasonal cycle. The difficulties in securing adequate observing opportunities for monitoring this activity (i.e. fractions of a night for tens to hundreds of nights a year) can be substantially mitigated by permitting more creative scheduling on groundbased telescopes via queued/service/remote observing. A program to make available modest instrumentation (1-2 micron photometers and/or CCD spectrometers) to amateurs or small colleges would provide valuable additional data and engage a wider community in Titan study.

Report

CURRENT STATE OF KNOWLEDGE

Titan is the largest satellite of Saturn, and unique in the solar system in that it is the only satellite with a substantial atmosphere. This atmosphere is particularly interesting, in that it is the only significant nitrogen atmosphere in the solar system other than that of Earth and also is host to extensive organic photochemistry.

Titan's radius is 2575km, fractionally smaller than Ganymede, and intermediate between that of Mars and the Moon. Its density has been determined at 1880 kg/m^3 – suggesting a roughly 50:50 mix of rock and ice. Titan is large enough that the energy of accretion should have softened and melted the outer layers of ice, allowing the rock component to settle into the interior forming a rocky core, although there is at present no direct measure of Titan's internal structure.

The surface gravitational acceleration is roughly 1/7 of the Earth's. The surface atmospheric pressure is 1.5 bar, and the temperature of the atmosphere just above the surface is 94K. The composition is predominantly molecular nitrogen, with a few per cent methane, an undetermined amount (less than a few per cent) of argon, and traces of many (>20 at the last count) organic compounds.

One particularly intriguing aspect of Titan is that methane, known since 1944 to be present in its atmosphere, is destroyed on short ($\sim 10^7$ year) timescales by solar ultraviolet radiation. This implies that its presence in the atmosphere is buffered by resupply and/or a surface reservoir. Both methane and ethane, which is the dominant photochemical product of methane photolysis are liquids at Titan's surface conditions – making a surface at least partially covered with hydrocarbon liquids a likely scenario. Thus Titan's landscape may have been modified by marine, lacustrine or fluvial processes, like the Earth.

Some recent findings (since the development of the Cassini/Huygens mission, designed largely on the photochemistry-dominated post-Voyager view of Titan) deserve mention.

Titan has a strong seasonal cycle. Its equator is tilted to the ecliptic to a similar degree to the Earth and Mars – the haze in Titan's atmosphere is thicker in one hemisphere that the other, and 'sloshes' over to the winter hemisphere in response to the seasonal forcing. A dark hood forms over the winter pole, probably the result of accumulation and condensation of organics, and may be an important control on meteorology beneath.

Titan has weather. While methane has been long suspected to be a participant in an active hydrological cycle, observations since 1995 show evidence of transient clouds in

Titan's troposphere – including a large 'storm' event which covered 10% of Titan's disk, and events which suggest clouds come and go on timescales of hours.

Titan's surface has been imaged by near-infrared telescope cameras which can penetrate the haze. These maps show a variegated surface with some pitch-black regions suggestive of organic lakes and a large, bright (perhaps mountainous) region on Titan's leading face.

Millimeter-wave measurements suggest Titan's atmosphere is highly enriched in heavy nitrogen, suggesting that the thick atmosphere we see now (10x more mass per unit area than the Earth's) is only a weak remnant of a much (5-200x) thicker early atmosphere. Understanding the events associated with this profound atmospheric loss (which apparently did not fractionate methane – perhaps being delivered by volcanism to the surface even today) is a crucial problem.

The presence (and surprising ubiquity) of internal water oceans on icy satellites has only been realized in the past couple of years. This opens the possibility of Titan sharing characteristics of Europa in terms of being an incubator for prebiotic compounds.

KEY SCIENCE QUESTIONS

Many outstanding Titan science questions exist, and are addressed, at least in principle, by Cassini. The following set of science questions anticipates a more-or-less successful Cassini/Huygens mission and will not be addressed by it.

What is the composition and distribution of organic materials on and beneath Titan's surface?

Rationale : Cassini should determine the gas-phase atmospheric composition and its variations with latitude quite well. It will also make pyrolysis-GCMS measurements of the haze material and perhaps constrain gross surface composition at moderate spatial scales. No detailed surface composition measurements will be made, nor are there measurements of the depth of deposits to permit a good organic inventory to be determined.

Measurement : in-situ measurement of surface material from a variety of locations – requiring a mobile platform with surface sample acquisition as well as sophisticated chemical instrumentation. Sounding radar to determine depth of surface deposits.

What controls Titan's weather and how does it change with time?

Rationale : Cassini's Titan coverage during the 4-year mission will allow the identification and gross characterization of weather systems, but not detailed monitoring of their evolution. Winds will only be determined indirectly – difficult if cloud features evolve rapidly.

Measurement : in-situ meteorological measurements from a near-surface platform, augmented perhaps by global monitoring from orbit (microwave spectroscopy for winds and trace chemistry; IR spectral imaging for synoptic views)

What unique small-scale geological features does Titan possess?

Rationale : With the exception of the small region around the Huygens landing site, Cassini's optical and radar resolution is inadequate to characterize small-scale and possibly dynamic geological features (methane geysers, stream deposits, dunes etc.) To fully capture Titan's range of geology requires meter-scale or better imaging that needs to be performed from below the obscuring haze layer.

Measurement : high-resolution imaging from a near-surface platform (which will be required in any case to select appropriate sampling sites for surface chemistry)

What is Titan's Internal Structure and how does it affect the Surface?

Rationale : Cassini will determine the gross structure of Titan from gravity measurements. Variations in crustal thickness and the presence of small-scale geothermal anomalies like near-surface melt may not be detectable from Cassini remote measurements. Titan is excited tidally and thus seismic measurements will be easy.

Measurement : sounding radar from a near-surface platform. Seismic measurements during extended surface contact periods of the platform mission.

RECOMMENDATIONS

Mission

An extension to the nominal 4-year Cassini mission will offer significant scientific return at modest cost. At present the limiting factor on Cassini Titan science is the number of Titan flybys possible in the tour. At the end of the present nominal mission, Cassini is in a short period orbit that would permit additional Titan flybys more often than the 'average' for the 4-year tour. Funding and DSN support capability for an extended mission of at least 2 years should be factored into NASA planning.

The post-Cassini mission that satisfies the broadest range of anticipated post-Cassini objectives and promises the greatest scope for public engagment will be an airborne exploration platform exploiting Titan's thick atmosphere and low gravity to give lander-like close-up investigation capability at many locations on Titan's diverse surface. This platform could be an airship with buoyancy control or conceivably some sort of helicopter. Early studies have been made of these concepts, and while significant development effort is required, there are no obvious technological barriers. Since a Titan explorer will require a radioisotope power source in any case, its duration need not be tightly constrained – 1-2 years.

It is likely that an orbiter may be required to support the data return from such a platform ; a limited scientific payload on the orbiter should complement the capabilities of Cassini and exploit the extended period of proximity to Titan.

Critical technologies that require early development are the adaptation of a radioisotope power source to operation in an atmosphere, on-board autonomy, instrumentation and aerobraking/capture technologies. Solar-electric propulsion opens up mission delivery opportunities, albeit at higher cost than conventional propulsion.

It is clear that such a mission will not fall under a Discovery budget : An early JPL study has already been performed of a mission with an airship and heavy orbiter, together costing about $1 billion: further studies may identify significant cost-saving options. There are no significant technological barriers. Furthermore, development of autonomous airborne vehicles may attract investment from other US agencies, and the participation of experienced international partners offers considerable scope for cost-sharing.

Laboratory Studies

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Detailed interpretation of Cassini result will require laboratory work in other fields, such as photochemistry, haze formation, rheology of volatile-rich ices etc.

Telescope Facilities

Titan has shown itself to be a dynamic object, with meteorological changes on hourly timescales (but yet of unknown frequency) as well as a seasonal cycle. The difficulties in securing adequate observing opportunities for monitoring this activity (i.e. fractions of a night for tens to hundreds of nights a year) can be substantially mitigated by permitting more creative scheduling on groundbased telescopes via queued/service/remote observing.

Targeted studies of particular questions can be largely addressed by existing and anticipated ground- and space-based capabilities.

An additional augmentation to such a monitoring program would be the provision, perhaps via the Planetary Astronomy program, of suitable near-IR instrumentation since the crudest (photometry, spectroscopy) measurements can be performed with modest telescopes available to amateurs or small colleges . 1-2 micron photometers and CCD spectrometers are becoming available off the shelf for only a few $K). The former instrumentation would be also useful for Io monitoring.

CLOSING REMARKS

It is vital that the prospects for a future Titan mission be sufficiently advanced that the expertise gained from the Cassini/Huygens development and recent groundbased observations not be lost. The long lead times associated with outer solar system exploration make this a particular problem.

Although Titan is unlikely to play a significant role as a target for human space activities in the near term, various space environments may be useful in studying Titan (as an example, haze particle formation and coagulation could be usefully studied in microgravity since settling and wall effects are a significant perturbation to terrestrial laboratory experiments.)

As a scientific target, Titan promises to reach a more diverse range of disciplines than perhaps any other target. Not only conventional planetary geology, atmospheres and space physics topics, but also hydrology, oceanography, protein chemistry, meteorology and so on may adopt Titan as a case study.

Titan – and in-situ exploration by airborne platform - can capture the imagination in ways few places can) and thus offers tremendous outreach opportunities.