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WHITE PAPER

Saturn Atmospheric Science in the Next Decade

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Supplemental Material Website:
http://www.atm.ox.ac.uk/user/fletcher/Site/Outer_Planet_Science_Goals.html
Contains a list of scientific investigations to answer some of the questions outlined in this document.

1. Overview

The Cassini mission to Saturn, presently in its first extended mission (ending in July 2010), has provided a wealth of new information, established new ideas and posed new questions about the Solar System's second largest planet. But even though the ringed world has been regularly observed from Earth throughout the last few decades, and despite the Pioneer 11 and Voyagers 1 and 2 flybys a full Saturnian year (nearly 30 earth years) earlier, there are many fundamental atmospheric properties and processes which remain poorly characterized. Cassini's second extended mission is expected to dominate Saturn atmospheric science in the 2013-2023 timeframe, but many questions will remain outstanding, either because (a) Cassini lacks the instrumentation to probe the necessary atmospheric levels; (b) studies of bulk and altitude-varying composition and related chemistry cannot be adequately achieved via remote sensing; or (c) Cassini's temporal or spatial coverage will be insufficient to probe the seasonal timescales or full range of latitudes necessary to understand Saturn's weather layer in full. *This white paper supports the goals of Cassini's extended mission (see white paper by Spilker et al.), and advocates continued studies of Saturn post-Cassini by the next flagship mission (TSSM or otherwise), dedicated temporal-monitoring from ground-based and space-based platforms, in addition to multiple entry probes and deep-atmosphere remote sensing.*

As the second largest gas giant planet in our Solar System, Saturn's atmospheric composition, structure and dynamics are most closely compared to those of Jupiter. Indeed, comparisons between the two gas giants, in terms of their bulk composition and their responses to differing degrees of seasonal insolation provide a wealth of information about the evolutionary processes at work on gas giants in general. Saturn's atmosphere is distinguished from Jupiter's in several important respects. The bulk rotation of the planet is poorly understood (e.g., Anderson and Schubert, 2007), a result of the close alignment of the magnetic field and planetary rotation axes, which minimizes the variable periodicity of the kilometric radiation used to assess the rotation rate. Atmospheric stability arguments, in tandem with gravitational and radio occultation data, are beginning to suggest a faster rotational period than previously thought, altering our understanding of the relationship of the cloud-top jet streams and the bulk rotational state of the interior. Saturn's temperature field, molecular composition (para-H_2, PH_3, hydrocarbons, etc.) and aerosol content exhibit strong hemispheric asymmetries driven by seasonal variations that are unique in our Solar System. The zonal organization of Saturn's weather layer apparently persists to much higher latitudes than observed on Jupiter thus far, resulting in two cyclonic hot polar vortices (irrespective of season), encircled by strong prograde jets and consistent with strong subsidence creating a polar 'eyewall' and a polar atmosphere depleted of volatiles (e.g. Fletcher et al., 2008; Dyudina et al., 2009; Baines et al., 2009).

In addition, the larger atmospheric scale height results in an atmosphere which appears more subdued than Jupiter's at visible and near-IR wavelengths, but visible and 5-μm imaging has revealed a plethora of unique dynamical phenomena (fine lanes, strings of storms or "pearls", ribbon waves, discrete lightning storms, etc.). Saturn is the only gas giant that we know which exhibits a slowly-moving hexagonal wave that is stable over many decades (from visible, thermal and near-IR imaging), and an oscillation of stratospheric temperatures with a period of half of Saturn's year (a semi-annual oscillation, Orton et al., 2008). Saturn's equatorial upwelling is apparently stronger than Jupiter's, and periodically exhibits large-scale outbursts (the Great White Storms). Slowly moving thermal waves are ephemeral in nature, unlike those in Jupiter. And, although Saturn's heavy element complement is enriched by approximately ten times solar (compared to four times solar on Jupiter), the D/H ratio and helium content of the observable atmosphere is apparently depleted (or at least the same as) that of Jupiter. Finally, because Saturn's immediate planetary environment is different from that of Jupiter, the coupling between the neutral atmosphere and the surrounding charged particle environment is likely to be unique. Specifically, Saturn differs in the magnetic field strength, the composition of magnetospheric ions (influx of neutral water from Enceladus outgassing and the extensive ring system) and the energetics of the electrons and ions funnelling into the upper atmosphere.

In this White Paper, we use the discoveries from three decades of Saturn exploration to assess the important scientific goals in the coming decade. Many are similar to the case for Jupiter science (see Fletcher et al. 2009), but several are unique to the Saturn system.

2. Scientific Goals for Saturn Exploration

I. Composition and Chemistry

As is the case for Jupiter, Saturn's bulk composition retains the chemical signatures of the primordial solar nebula from which the gas giants formed, although significantly reprocessed by accretion, thermochemistry, photochemistry and gravitational differentiation over the intervening eons. Along with comparisons to the other planets, Saturn's elemental composition provides a vital window into the past, to constrain formation and evolutionary theories of the entire solar system. Unlike Jupiter, where the Galileo probe was able to provide some estimate of bulk composition down to the 20-bar level, our knowledge of Saturn's heavy element enrichment is restricted to those accessible from infrared remote sensing (CH_4 and tentatively PH_3, NH_3). The relative enrichments of the simplest elements (C, O, N, S), along with isotopic abundances ($^{12}C/^{13}C$, D/H, $^{14}N/^{15}N$, $^{18}O/^{16}O$) and the abundances of noble gases (He, Ne, Ar, Kr, Xe, etc.) within Saturn's atmosphere are vital to constrain (a) the mass of rocky or icy material attained by Saturn during its accretion; (b) the size and composition of Saturn's core and degree of homogenization with the extended molecular atmosphere; (c) the possible sources of material (and the temperature of their formation) incorporated into Saturn for comparison to Jupiter; (d) the possible timescales for the formation of the gas giants; and (e) the thermochemical pathways and cooling history of the planet in the billions of years since its formation.

To determine the bulk composition of Saturn, we require Juno-like microwave and radio remote sensing to constrain the NH_3, H_2S and H_2O abundances beneath the cloud tops (down to 100 bar or more), in addition to multiple entry probes to determine the noble gas and isotopic ratios (e.g. the Kronos mission architecture for Saturn, Marty et al. 2008, and see white paper by Atkinson et al.). The oxygen abundance is particularly important, as current theories of planetary formation require the trapping of volatiles in ices or clathrate hydrates prior to their incorporation into the gas giants. The measurement of the helium abundance (which remains unresolved due to temporal changes in Saturn's zonal wind field) requires additional thermal, cloud-tracking and radio-occultation data from Cassini's extended mission, or deep entry probes, to determine this important parameter for evolutionary theories in our solar system. The reprocessed material intrinsic to Saturn is further modified by the influx of material (ring particles, dust, micrometeorites, satellite debris, etc.) into the high stratosphere. The rate of influx and the long-term consequences of the presence of oxygen-bearing species on the atmospheric chemistry are yet to be investigated.

In addition to bulk composition, the relation between radiative climate influences, photochemistry and the spatial and temporal distribution of Saturn's rich collection of hydrocarbons is poorly understood, requiring both an advance in mid-IR spectroscopy to constrain their distribution (horizontally and vertically), and in photochemical modelling to assess the relative influences of photochemistry, atmospheric transport, and shielding due to the uncertain properties of Saturn's haze distribution. The same is true for photochemical destruction of tropospheric compounds, particularly PH_3 and NH_3 and their relation to tropospheric haze opacity, whose latitudinal distributions indicate variability in the photochemical lifetimes at different latitudes. Of particular interest is a reconciliation of the meridional distribution of C_2H_6 and C_2H_2 as observed, and the discrepancies in modelling. Finally, higher spectral resolutions than Cassini can offer (e.g. from the IR to sub-mm range) are required to search for exotic species in the troposphere and stratosphere, and to map the distributions of disequilibrium species in the troposphere (CO, GeH_4, AsH_3, in addition to PH_3).

II. Dynamics of the Deep Atmosphere and Weather Layer

Imaging in the infrared, particularly in the 5-μm region, has revealed that Saturn's atmosphere is just as dynamic as Jupiter's, despite its subdued appearance at visible wavelengths. The crucial challenge for modellers and observers in the coming decade will be to relate what we see in the weather layer to theories of the deep internal convection (i.e. linking shallow weather-layer models based on the primitive equations with flow in the deep interior). As on Jupiter, in the 'weather-layer' where the visible cloud deck resides, we must reconcile the 'classical view' of upwelling, cloudy and moist zones adjacent to subsiding, clear and dry belts with the emerging view from observations of the horizontal convergence of momentum into the jets due to eddy momentum flux (Del Genio et al., 2007) – that is, the opposite flow may be true. In particular, we must understand the mechanisms for the transport and mixing of energy, momentum and chemical species (tracers) vertically and horizontally, and how this maintains the vertical temperature and cloud structures, stable zonal jet systems, super-rotating equatorial winds and global-scale meridional circulations. Why does Saturn not exhibit the large, long-lived anticyclonic vortices of Jupiter? How deep does the zonal wind system extend into the troposphere, and what is the true rotation rate of the deep atmosphere? What is the role of moist convection, with multiple possible condensates, in setting the thermal stratification and in organizing the weather-layer into the characteristic belt/zone structure? Indeed, how is localized moist convection related to Saturn's global circulation? To what extent do thermochemistry and vertical eddy and convective mixing from the several-kilobar level influence atmospheric composition, such as the presence of the passive tracer PH_3 and other disequilibrium species at cold upper tropospheric levels? Can the distribution of these species be used as dynamical tracers of vertical transport? The vertical structure of the atmosphere could be investigated by microwave remote sensing, in situ probes, radio occultation studies, and an investigation of the shape of the gravitation field (which would be perturbed by zonal jet contrasts at great depth).

At low latitudes, we wish to know the source of the strong equatorial upwelling and its relation to the super-rotating equatorial jet. Long-term monitoring of the semi-annual oscillation (SAO) from stellar occultations, radio occultations and high-resolution spectroscopy of the planetary limb may indicate how vertically propagating waves transfer energy and momentum between different atmospheric levels, and how they modulate the spatial distribution of atmospheric species (particularly stratospheric hydrocarbons and thermospheric ions), and the resulting effect on the atmosphere's radiative heat budget. Moving to mid-latitudes, the sources of fine-scale activity such as the ribbon wave, string of pearls and discrete lightning storms in the 'storm alley' at 35°S latitude, in addition to the presence of slowly moving thermal waves, must be linked to the stability of the jet streams. Why are the zonal thermal waves ephemeral in nature, and what is their source? And towards the poles, we must understand why the zonal organization of the atmosphere persists to high latitudes, and whether the presence of the cyclonic polar hotspots at both summer and winter poles (e.g., Fletcher et al., 2008) is a natural consequence of this zonal organization, and therefore a common feature of atmospheric circulation in all gas giants. The evolution of the tropospheric hotspots with season (and the rate of atmospheric subsidence associated with them) will help answer this question. The stratospheric polar hood in the summer hemisphere, poleward of 70°S, is thought to be seasonal in nature, but the physical mechanisms responsible for the high-latitude entrainment of particles and warmth are poorly known. Observations of the onset of a stratospheric polar hood in the northern spring hemisphere in the coming years could teach us about stratospheric polar vortices on all the gas giant planets. A further challenge for modellers is the source, stability and vertical extent of the northern polar hexagon, an explanation for its permanence, and for the absence of a similar structure in the south (although Cassini has monitored ephemeral polygonal activity). A combination of numerical simulation with lab-based geophysical fluids experiments is required to resolve some of these issues.

The upper atmosphere and ionosphere of Saturn are very poorly understood at this time, with temperatures above the mbar level only measured at a few latitudes from radio occultations and limb sounding. Further Cassini measurements will provide some additional information, but will be unable to resolve some key issues, the most important of which is determination of the mechanism(s) responsible for the observed high thermospheric temperatures (similar problems exist for the other four giant planets). The two leading theories/suggestions invoke heating by gravity-wave breaking from the deeper atmosphere, or meridional transport of auroral energy by a global-scale circulation system. However, these are ad-hoc suggestions and no quantitative models are currently available or likely without further data, which Cassini will not be able to provide. Finally, although Cassini radio occultations have provided numerous electron density profiles in the ionosphere, we have no direct information on the ion composition and plasma temperatures to distinguish between different ionospheric models (Nagy et al., 2009). Cassini does not possess the necessary instrumentation to provide meaningful constraints on any present and future models, and direct measurements of ionospheric temperature and composition are required.

III. Clouds and Hazes

With the same basic mix of atmospheric constituents, Saturn's cloud decks should, to first order, be similar to those of Jupiter. However, the colder conditions place these decks at higher pressures, making remote-sensing studies more complex. The vertical distribution, composition, physical size and shape, optical properties (absorbing and scattering) and cumulative optical depth of the Saturnian clouds are all poorly constrained, and require *in situ* sampling of the atmosphere from multiple entry probes. In addition, Saturn's upper troposphere and stratosphere contain spatially and temporally variable hazes of unknown origin (although likely related to photochemical products and, perhaps, convective overshooting) and poorly constrained chemical and dynamical properties. The clouds and hazes play crucial roles in the radiative energy budget of the observable atmosphere, and are a source of large uncertainty in photochemical models (where aerosols have a shielding effect and extend photochemical lifetimes). As a result, determining the spatial distribution and composition of condensates and particulates in Saturn's atmosphere are vital goals for Saturn atmospheric science.

Several specific questions are particularly noteworthy. What is the importance of convection associated with discrete storms on replenishing the upper atmosphere with haze material, and what does this tell us about the spatial variability of vertical mixing from the deeper atmosphere? What is the relationship between the aerosols seen in the visible and thermal ranges (1 bar and above), cloud structures seen in the 5-μm region (2-3 bar), and inferred cloud distributions at deeper levels? What is the relation between observable cloud structures and lightning, and how is this related to the local atmospheric circulation? Can the small-scale cloud structures seen at depth be related to spatial variability in molecular composition (NH_3, PH_3), temperatures and the wind field? How high do the cloud structures seen at 5 μm extend into the upper troposphere? What is the altitude of cloud tracers used for wind-tracking in the upper troposphere, and can differences in wind velocities measured by Cassini and Voyager come as a result of a change in the altitudes of these tracers (e.g. in response to a Great White Storm at the equator)? At high latitudes, how does the balance between photochemistry and aurora-related chemistry influence the composition of stratospheric hazes, known to be strongly-absorbing in the UV? The properties of Saturn's clouds and hazes need to be reconciled across a wide range of wavelengths if we are to begin to understand the troposphere beneath the cloud-tops. Furthermore, *in-situ* sampling of the aerosol composition by multiple entry probes would provide a wealth of information about the vertical structure and optical properties of the condensates.

IV. Temporally Evolving Phenomena: Seasons and Rapid Change

The transport of energy, momentum and material tracers as a result of convection, eddy momentum fluxes, turbulent motion, organized jet streams, localized vortices and other physical phenomena are all *temporally evolving processes*. Individual "snapshots" of these atmospheric variables are not enough to constrain radiative, chemical and dynamical models, so new missions should focus on *long-term* monitoring of Saturn's cloud structures, temperature and wind fields and chemical composition across a wide range of wavelengths. In addition, monitoring must take place over multiple timescales, from hours to weeks (for rapidly evolving storms, lightning activity and aurora), to months and years (for quasi-periodic storm activity, long term chemical changes and wave activity), and to seasons and multiple Saturnian years (for the development of polar vortices, reversals of seasonal asymmetries and long-timescale convective regimes). What are the mechanisms responsible for the apparent changes in zonal wind between Voyager and Cassini (this has a vital effect on determinations of Saturn's helium abundance from radio-occultation observations)? Does Saturn experience quasi-periodic upheavals in the same way as Jupiter, as suggested by the episodic storms at the equator, and potentially by storms at higher latitudes? What are the physical mechanisms responsible for the onset of polar vortices? Are the tropospheric polar hotspots and north polar hexagon stable over time? What are the sources, periods and power distributions of wave activity (gravity waves, slowly-moving thermal waves) in the upper, middle and lower atmosphere, and how do they modulate the distribution of chemical species? How do these waves drive the seasonally modulated stratospheric oscillation, the Saturnian Semi-Annual Oscillation? What can the seasonal reversal of asymmetries in temperatures, hazes, para-H_2, PH_3 and hydrocarbons tell us about the response of Saturn's atmosphere to seasonal forcing? Does Saturn experience asteroidal/cometary impacts in the same way as Jupiter, and what is their frequency? And finally, is the belt/zone organization of Saturn's atmosphere constant with time, or is the atmosphere continually evolving?

Cassini's second extended mission is expected to provide monitoring of Saturn through spring in the northern hemisphere, thus expanding Cassini's orbital reconnaissance to almost half of a Saturnian year. But to answer many of these questions, we require monitoring with a suite of instruments capable of providing comparable spatial resolutions across as wide a range of wavelengths as possible. Higher spectral resolutions are also necessary to investigate the vertical distributions of many species, and how these respond to seasonal forcing. Beyond Cassini, continued remote sensing observations from a dedicated space-based (or ground-based) platform, such as the Planetary Dynamics Explorer (PDX, Wong et al. 2009) or an upgraded Infrared Telescope Facility (a larger primary mirror, with novel Adaptive Optics technologies or at least tip-tilt motion compensation), should permit the characterization of Saturn's response to the changing seasons. The capability for high-resolution temporal observations of bright, extended targets such as Saturn must be maintained in the post-Hubble era (Saturn is too bright for most of the JWST instruments without special considerations/filters). In particular, if the ~30 year quasi-periodic trend of Great White Storms continues, we might expect another to appear in 2020.

V. Coupling to the Interplanetary Environment

Saturn's atmospheric phenomena cannot be considered as a closed system: we have already seen that the structure of the weather layer is likely determined by the dynamics of the deep flow, and that its composition is perturbed by the influx of exogenic material (e.g. oxygen-bearing species from ring particles, micrometeorites, etc.). In addition, interactions between the aurora and the neutral atmosphere and ionosphere might be responsible for (a) the unusual chemistry and hazes at high latitudes in the troposphere and stratosphere; and (b) the heating of the thermosphere and ionosphere to extremely high temperatures (higher than predicted from radiative energy deposition alone). On Saturn, there are significant levels of polar emission from the aurorae (the main oval is controlled by solar wind interactions of some form) which remain almost entirely unexplained. A determination of the altitude distribution of aurorae (from mapping H_3^+ emission in the near-IR or H_2 'glow' in the UV), and hence the depth to which auroral energy penetrates, would greatly aid in their modelling.

The extensive ring system also has a substantial effect on the troposphere and stratosphere because certain regions are shadowed for a large part of the Saturnian year. This shadow complicates radiative models for predictions of the seasonal atmospheric response, and it is likely that regions of the atmosphere newly emerging from ring-shadow experience some unique dynamical perturbations not found elsewhere on the planet. A more direct connection is the flux of material from the rings and the Enceladus neutral cloud towards the atmosphere, with oxygen-bearing ions channelled along magnetic-field lines into narrow latitude regions of the atmosphere; such a localized influx may be spotted in the detailed spatial distribution of stratospheric oxygen compounds.

3. Conclusion and Recommendations

This white paper strongly supports the goals of the Cassini extended mission, as it would continue to provide valuable insights into seasonally evolving atmospheric phenomena through to northern summer solstice. Furthermore, it would continue to expand the database for compositional research (e.g. helium and seasonal variations in species distributions) in the coming decades, and its approval is assumed in this white paper. Several fundamental atmospheric goals will still remain beyond its reach. *In situ* sampling of Saturn's weather layer (for meteorology, bulk composition) is a vital next step for the comparison of our Solar Systems collection of gas giants, to extend the planetary formation theories to planets around other stars. This *in situ* sampling must be supplemented by microwave, sub-millimeter and radio remote sensing observations from an orbital platform to sample altitudes within the atmosphere not previously investigated, to constrain the vertical stratification and dynamics, as well as the bulk oxygen content at the deepest levels. Finally, long-term monitoring (with multiple wavelengths) of temporally evolving phenomena over multiple timescales from a dedicated observatory (either ground-based or space-based) with high spatial resolution and capabilities for bright, extended targets is required to develop a full understanding of Saturn's dynamic atmosphere in the post-Cassini era and post-Hubble era.

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