Outer Solar System Time-Domain Atmospheric Science: The Value of a Dedicated Space Observatory

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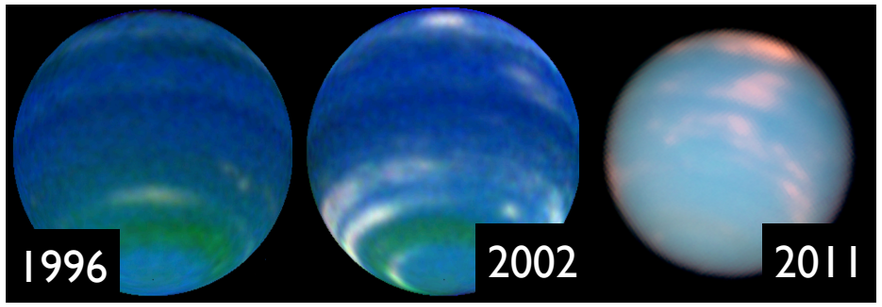
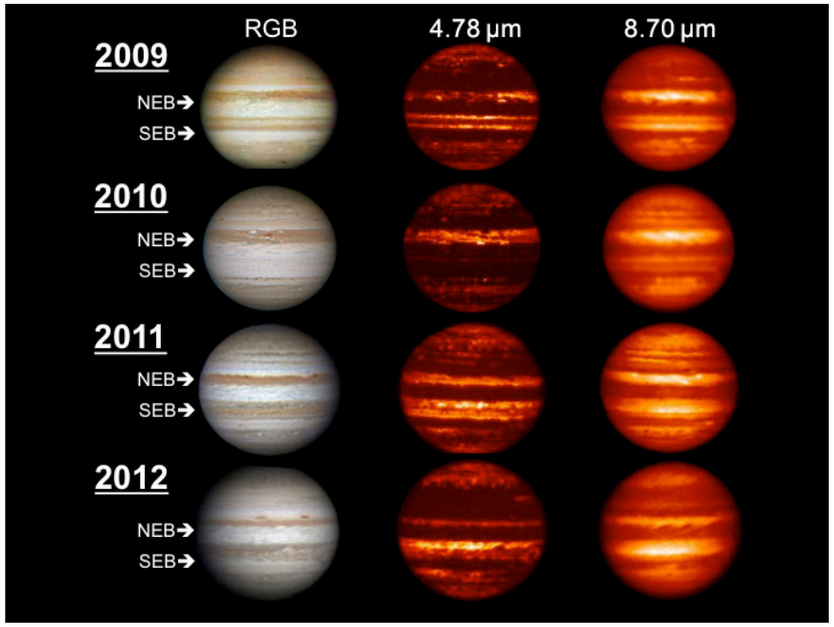
Goals

Understand planetary atmospheres and their evolution on the giant planets through imaging observations of time-variable phenomena.

Place observations of solar system and extrasolar planets in appropriate context.



Top: Seasonal Change on Neptune (NASA, L. Sromovsky, and P. Fry, ESA, Hubble Heritage)
Right: Multispectral Global Upheaval on Jupiter (NASA/IRTF/JPL-Caltech/NAOJ/A. Wesley/A. Kazemoto/C. Go)



Concept

A dedicated observatory for imaging and monitoring time-variable atmospheric phenomena in the outer Solar System provides tremendous benefit for advancing astronomy.

Key Requirements

Object Tracking - Critical for observing Solar System targets within the ecliptic.

Observation Cadence & Orbit - Hourly images of a target over weekly/monthly periods are most useful. High Earth orbits or Lagrange point placement is advantageous.

Multi-year Campaigns - Observations of seasonal changes and transformative events before, during, and after the event maximize science return.

Technical Readiness

Science objectives are met with existing and technically mature instrumentation packages (i.e. imaging cameras with standard filters, other cameras and spectrographs)

Value to NASA

Achievement of NASA SMD Goals: Addresses Solar System science objectives (e.g. evolution of the Solar System to its current state), and contributes to Astrophysics objectives through comparison with extrasolar planetary observations.

Breakthrough Science: Datasets from a dedicated space-based observatory will lead to significant advances in our understanding of outer planet meteorology.

Human Spaceflight: Provides opportunities for missions beyond low Earth orbit. Optional servicing extends data collection and strengthens science return beyond baseline.

Space Technology: Encourages development optical/laser communication between Earth relay stations and observatory, facilitating return of high data volume to Earth. Such advances benefit other human and robotic exploration missions.

Maximum Value for Minimum Risk: Returned data possess tremendous value for scientific community using fully developed instrumentation.

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Background

The atmospheres of the outer planets exhibit intriguing features that change over a variety of time scales, visible as storms, stable vortices, strong winds, and waves in the clouds. From a broad perspective, all four solar system gas giants show strong jet streams and prominent circulations steady over lengthy time scales. However, a rich, complex environment is present within each atmosphere, constituting a wide range of time-variable phenomena, such as periodic storm outbursts, and seasonal cloud activity. Understanding the differences and similarities in atmospheric dynamics between these four planets will be pivotal to interpreting such activity on extrasolar planets in the future.

On the giant planets, this activity occasionally manifests as planetary-scale transformations, such as the recent global upheaval on Jupiter in 2007-2012 [1]. These events are marked by a sequence of Jupiter's normally dark atmospheric belts generating increased convection and clouding over, and white zones temporarily clearing of clouds before returning to normal. Similar upheavals on Jupiter occurred quasi-periodically throughout the last several decades [2], leading some to speculate of a cycle driven by internal heat transfer, though the cause is as of yet unknown. These upheavals typically last for many months to years, before the planet's external appearance restores to its pre-upheaval state.

The remaining outer planets also experience similar transformative changes, some of which may be seasonally driven. Saturn's atmosphere produces episodic storms of planetary scale [3], and other changes to its atmospheric activity may be driven by the seasonally variable insolation from its Earth-like inclination and the complications added by its ring shadow [4]. Uranus, with its severe axial tilt, exhibited outbreaks of cloud activity during its recent equinox [5]. Neptune's Great Dark Spot is a large storm first observed during the Voyager 2 flyby in 1989, but has since disappeared in observations. Other vortices and storms have appeared, and recent Hubble images show many high methane clouds [6], demonstrating that although Neptune receives little solar energy, activity continues to flourish within its atmosphere.

Long-term imaging campaigns and observations have increased our understanding of temporally variable atmospheric phenomena, as well as leading to new discoveries. Time-lapse movies showing the evolution of Jupiter's equatorial atmosphere during the approach of Cassini led to the discovery of a new planetary-scale Rossby wave on Jupiter [7], as latitudinal perturbations of cloud features were only apparent from continuous monitoring of the atmosphere. Similar monitoring of highly variable hot spot

features illustrate the complex dynamics and interactions that these features have with the surrounding latitudes [8]. Other observational studies reported mergers and the darkening of mid-latitude vortices [9], as well as continual changes to the aspect ratio of the Great Red Spot [10], and the occasional high altitude circulation tracing after impact events leave behind stratospheric debris fields [11].

Interesting time-domain planetary atmospheric science is not limited to the planets of the outer solar system. Titan, Saturn's largest satellite, has a substantial nitrogen atmosphere and methane cycle, producing cloud outbursts and abatements linked to seasonal cycles of solar insolation [12]. Precipitation from these outbursts likely plays a pivotal role in shaping the surface landscape of the satellite [13].

Science Drivers and Open Questions

Examination of these features through imaging observations is crucial for addressing key questions regarding the evolution of the atmosphere and the planet's internal energy balance. Because atmospheric features can have a prominent effect on observations of planetary targets, whether they are within the solar system or extrasolar, understanding planetary atmospheres is essential for placing (temporally or spatially) unresolved observations in appropriate context.

Other open questions include, but are not limited to, the following:

What drives the long-term stability of jet streams in giant planet atmospheres, and what is their altitude profile?

How do seasonal processes affect atmospheric dynamics and chemistry in the outer planets (and satellites)?

How do prominent meteorological features (vortices, storms, waves) on the outer planets evolve on short and long timescales?

Enabling Mission Drivers

Object Tracking: The fundamental capability of a space-based observatory for monitoring outer planet atmospheres is the ability to track moving objects, particularly within the ecliptic plane. Ideal observations of a planetary target would be when the object is at opposition; placements of any solar arrays or sun shields must be arranged to optimize observational opportunities in light of engineering constraints. . Pointing and tracking require attitude control via reaction wheels and thrusters (with expendable propellant). The attitude control system's lifetime could be extended by a manned servicing mission.

Instrumentation: Monitoring of planetary atmospheres primarily requires only optical imaging. Near-infrared and ultraviolet filters would greatly extend the science return by increasing vertical resolution and discriminating between cloud components with different compositions.

Spatial Resolution: At least 0.05” is sufficient for resolving features of interest.

Long-Term Campaigns: Regular, periodic observations made throughout the operational lifetime of the space observatory enable advances in our understanding of outer planet atmospheres. Transformative and seasonal events can occur over several years; ideal temporal coverage of such an event encompasses the event itself as well as the state of the atmosphere before and after. Campaigns encompassing the entire mission lifetime (5-10+ years) maximize science return.

Orbits and Imaging Cadence: General monitoring utilizes hourly images over a target’s rotation period. These images lead to full-longitudinal maps, which when collected throughout an observation campaign, lead to progress in addressing science questions. Ideally these should be continued over days to months to allow detailed atmospheric motions to be studied on timescales that allow for sufficient coverage of waves and interactions. However, other, less strenuous cadences may be useful, depending on the target and science goal. A low Earth orbit similar to Hubble is least conducive because the target is visible for only half of the 90-minute orbit. Higher orbits offer improved target visibility, whereas orbits around a Lagrange point are optimal for avoiding thermal fluctuations (telescope breathing). Planetary observations are flexible enough to fit almost any observing platform, with small optimizations.

Value and Relevance to NASA

Beyond the delivery of substantial advancements in NASA’s solar system science objectives, a space-based observatory provides extraordinary benefits and opportunities for progress in both Human Exploration and Space Technology. Low Earth Orbit (LEO) is not ideal for our science objectives; however, placement of the telescope beyond low Earth orbit is an enabling opportunity for human spaceflight missions in the long-term.

Opportunities for servicing missions also add tremendous value to human spaceflight and exploration and the overall science return, though achievement of the science objectives outlined above are not critically dependent on servicing.

The rapid observation cadence necessary for science generates high data volumes, enhancing NASA’s Space Technology resources by encouraging the development of rapid optical/laser communication with the space observatory. Such advances will also benefit other human and robotic exploration missions.

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