

Hubble's Legacy: Time-Domain Studies of Outer Planet Atmosphere Dynamics

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The Hubble Space Telescope is a unique asset to planetary science, allowing high spatial resolution data with absolute photometric knowledge. In this white paper, we define the outer planets as the gas/ice giant planets Jupiter, Saturn, Uranus and Neptune, and their corresponding large satellites and ring systems. Traditionally, General Observer outer-planet planetary programs have requested a few orbits for a single object within a given cycle, sometimes as SNAP or ToO programs. Because of the oversubscription rates, the low percentage of SNAP targets obtained, and absence of ToO-driven events, this has led to large temporal gaps in observing these planets. In this paper, we describe the value of regular observations for important time-domain science studies and propose that yearly monitoring for the remainder of Hubble's lifetime would provide a lasting legacy of increasingly valuable data.

Long-term atmospheric studies

Planetary climate involves a complex interplay of solar/seasonal variation, internal heat, compositional gradients, and planetary rotation—all of which affect the visible clouds. Although the basic physics of fluid flow is reasonably well understood, major advances in understanding the Earth's atmosphere came from the advent of distributed weather stations, and later from satellites that provide around the clock, near-global monitoring of the atmosphere. Yet, weather and climate prediction for the Earth remain challenging, due to the intricate balance between effects on scales as small as airborne soot particles to as large as ocean currents, or put simply, "the devil is in the details."

For the outer planets, even less is known about their atmospheric circulations and weather systems. While we do know that these planets exhibit atmospheric changes over short time periods, they also show long-term variations on timescales of many years, up to an orbital period or longer (~12, 30, 84, and 165 years for Jupiter, Saturn, Uranus, and Neptune, respectively). Seasonal changes in cloud structure and activity have been observed on Uranus and Neptune, as well as the classical "30-year Great White Storms" on Saturn and its smaller counterparts. Although the seasons are least pronounced on Jupiter, with its small (3°) axial tilt, observations over Hubble's lifetime have revealed variability of different types (monotonic, periodic, aperiodic), affecting systems like the zonal wind velocity, evolution of vortices like the Great Red Spot, and dynamical tracers like hazes and temperatures. Without a network of planetary orbiters, Hubble has been invaluable as the source

for UV/optical high-resolution coverage of these bodies, see Figure 1, supplementing the much lower resolution ground-based visible imaging data, or infrequent spacecraft missions and infrared adaptive optics imaging from the ground. The value of the Hubble data cannot be overstated in helping us develop climate models of the outer planets, a critical component in understanding the atmospheres of the ~1500 exoplanets now known.

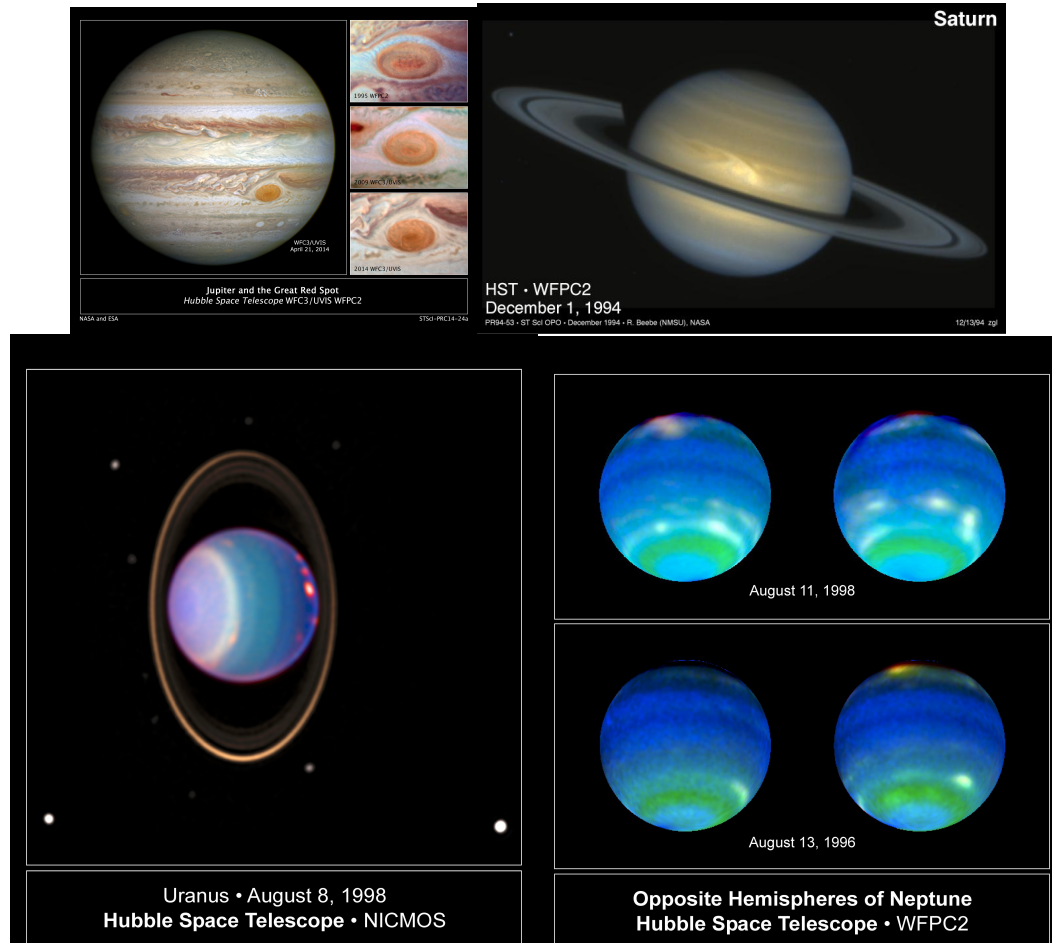


Figure 1. Montage of Hubble images of the outer planets. Jupiter time lapsed data shows the dramatic shrinking of the Great Red Spot, as well as aperiodic changes in cloud structure. Saturn's most recent Great White Storm was observed by Hubble in 1991, while 1994 images showed a smaller equatorial storm that did not progress into a global storm. Uranus exhibited signs of seasonal clouds in the late 1990s, while convective activity has also increased on Neptune.

Why a Hubble Imaging Campaign?

A long-term outer planets Hubble imaging campaign would be uniquely valuable in several ways:

- Imaging over two consecutive planetary rotations (cannot be done from the ground at a single site)
- Highest possible spatial resolution in the optical/UV range
- Consistent spectral elements, temporal sampling, and instrumental response over a multi-year campaign duration (*i.e.*, no coverage gaps)

Existing Hubble GO programs are typically limited by the current cycle, or at most a request for 3 cycles of data. When awarded, such coverage adds to the existing data, but it does not allow for the types of consistent long-term coverage needed given the long orbital periods and thus seasonal cycles of these planets. A single observation of Jupiter each cycle is equivalent to observing the Earth once a month. While that is sparse by Earth science standards, it represents a vast improvement over high-resolution spacecraft and ground-based infrared data sets, which include long time gaps of many years. For dynamical studies, the best data sets give global coverage with slight overlap to allow for studies of cloud motions.

Table 1 shows the existing visible wavelength coverage of the outer planets from WPFC2, ACS and WFC3, color coded by the time and longitudinal coverage acquired. Note for this table we did not include observations of aurora, as the focus of this study is atmospheric dynamics, nor did we assess filter coverage or spatial resolution, both of which would reduce the coverage shown. An image pair separated by a planetary rotation allows for the crude measurement of a wind profile, but can be heavily biased by longitudinal variations. A global map allows complete coverage of cloud activity at a single epoch. A pair of global maps combines full coverage with accurate wind field measurements, and ensures that wind fields can also be derived for discrete features such as the Great Red Spot on Jupiter.

Table 1: Years w/ Planet Coverage by Hubble UV/Visible camera

Planet	'94	'95	'96	'97	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14
Jupiter																					
Saturn																					
Uranus																					
Neptune																					

Color code: white = no data, blue = imaging only, green = wind pairs, red=high res. global maps

In the ideal scenario, there would be at multiple global maps per year per object and the entire table would be red. Ground-based coverage can fill in the temporal gap, but sacrifices longitude coverage, spatial resolution, and spectral range (*i.e.*, without UV capability). From a spatial resolution stand point, the ability of ground-based optical facilities does not match that of Hubble, even under the best seeing conditions and image-stacking techniques. High-resolution imaging can be achieved from the ground using adaptive optics at infrared wavelengths, but this technique can be used only rarely due to the availability of natural guide stars. Even under the best conditions, the mismatch between Earth and outer planet rotation rates means that it is not possible to achieve coverage of the same areas on successive rotations from a single ground-based facility. The best time coverage comes from a large cadre of highly motivated amateur observers, but their image-enhancement techniques remove any photometric information from the data, such that they are completely unsuitable for spectral studies, and the lower resolution and cadence still do not allow wind studies.

Insufficient temporal coverage makes studies of the highest-speed wind motions and waves difficult, if not impossible, while insufficient spatial and spectral coverage limits the ability to understand cloud structure. Hubble's advantages in temporal and spectral coverage, combined with high spatial resolution, make it ideal for constraining circulation models and understanding the roles of seasonal forcing and internal heat driven convection. For the data we have in hand, we already know that simplistic models cannot simulate the observed jovian weather, such that applying similar models to the even sparser exoplanet data is highly unlikely to produce realistic atmospheric circulations.

Jupiter

Although a number of missions have provided observations of Jupiter, almost all were in brief flyby encounters. The Galileo mission offered the longest time coverage (1995-2003), but was substantially limited in its data return due to a dysfunctional high-gain antenna and global approach imaging was lost due to a stuck tape recorder. Thus, no global view of the planet was obtained, and only limited “snapshots” were returned for any region of the planet, and those were limited in their spectral sampling. The Juno mission, due to arrive in 2016, is focused on the deep interior of the planet, and has only a limited public outreach camera in the near-UV to near-IR spectrum. In terms of instrumentation and orbital design, Juno is not capable of acquiring global Jupiter maps in the optical/UV, so Hubble data would be highly complementary.

Long-term studies include analysis of variations in the zonal wind field (Simon-Miller et al. 2010, Asay-Davis et al. 2011). Jupiter has a known stratospheric oscillation in temperature with a 4-5 year period, but no corresponding change has been found in the wind field (Orton et al. 1991, Simon-Miller et al. 2010). On the Earth a similar stratospheric oscillation occurs on a 2-year time scale, the QuasiBiennial Oscillation (QBO), and its effects are seen in winds, temperatures and stratospheric composition (Dunkerton and Delisi 1985). While the QBO is known to be driven by large planetary-scale atmospheric waves, they alone cannot account for its magnitude. Studying similar phenomena in other atmospheres may provide significant new insight to this currently unsolved problem.

Thus, further studies of the winds (visible wavelength imaging), stratospheric haze (UV wavelengths), auroral features (UV wavelengths), large vortex activity, waves, and color changes (UV + visible wavelengths) will help to constrain the mechanisms that govern wind and storm generation and maintenance, as well as planetary wave activity that may drive wind jets and atmospheric oscillations. Advancements in the studies of waves and cloud variation frequency require yearly coverage. In particular, Hubble imaging in the next few years may be crucial in understanding Jupiter's ever-shrinking Great Red Spot, and will also place small-footprint Juno observations into regional and global context (Wong et al. 2011).

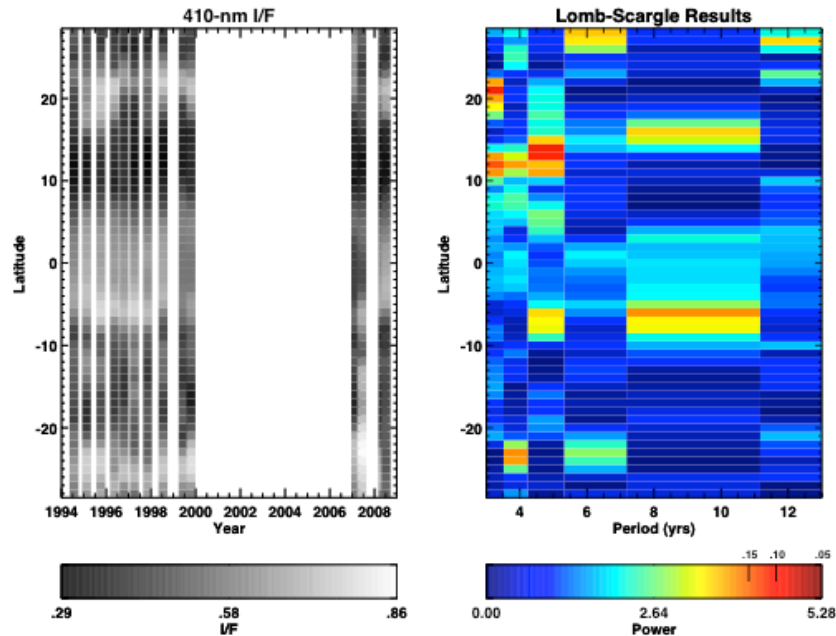


Figure 2. An example of the type of long-term studies that can be done with Hubble data. This particular study was hampered by the long data gap from 2000-2007 (Simon-Miller et al. 2010)

Saturn

Saturn was visited by the Voyager 1 and 2 spacecraft in 1981, with limited temporal coverage. The Cassini mission entered orbit in 2004 and is expected to continue operations until 2017. Having covered nearly a half of a Saturn year by the end of mission, and with much of the data yet to be analyzed, we are not requesting more Hubble coverage until after end of mission in 2017. Data acquired after that time will contribute to studies of hemispheric asymmetry, as convective activity and cloud changes appear to have both seasonal and non-seasonal periodicities.

In addition, Saturn is thought to have an atmospheric oscillation, based first on comparison of Cassini wind profiles with those from Voyager, showing a large change in equatorial wind speed (Sanchez-Lavega et al. 2003, Flasar et al. 2005). Since then, thermal retrievals from IR spectra have shown that a stratospheric oscillation is present (Fouchet et al. 2008, Orton et al. 2008). Continued long term observations of cloud/haze height and wind velocity are needed to understand if Saturn's oscillation is purely seasonal, is wave driven, as it is on Earth and Jupiter, or if it is an entirely different phenomenon.

Uranus and Neptune

Uranus and Neptune have only been visited by the Voyager 2 spacecraft, which provided partial coverage of the satellites and atmospheres. From the Voyager 2 perspective, Uranus was a very bland planet, while Neptune showed a single dark storm (Stone and Miner 1986, 1991). Hubble data showed that that storm has disappeared in 1994, and a new one likely formed in 1995 (Hammel et al. 1995). Since then, both planets have shown increased cloud activity, not entirely related to

seasons, and no consistent long-term vortices have been observed (*e.g.*, Sromovsky et al. 2012).

This raises several questions about variability in weather and convective cloud formation on these worlds under conditions of much lower solar insolation than at Jupiter and Saturn. Only sustained time coverage will determine whether the ice giants experience variable activity analogous to tropical storm season on Earth, or to global upheavals on Jupiter. There are big differences in the systems of east-west jets on the ice giants, as compared to the jets on Jupiter and Saturn, possibly explaining the lack of long-lived vortices. The zonal jets are highly variable spatially and temporally, on short and long timescales. A consistent long-term temporal study with Hubble would constrain variability on multi-year timescales.

As Table 1 shows, there has been reasonable coverage of Uranus and Neptune until recent years. However, given their very long orbital periods, continued coverage is still required, as we have only seen a fraction of their seasonal cycle. These types of data will be crucial to planning a future Ice Giant Flagship mission (the next highest priority in the 2013-2022 Planetary Science Decadal Survey, after Mars 2020 and Europa).

Required Coverage and Science Return

We discuss three imaging cadences, and the corresponding science return for each. One of the key merits of this type of program is consistency in coverage, both temporally and spectrally. This can best be achieved using a consistent set of WFC3/UVIS filters at each epoch. All data would be immediately publicly available. Table 2 summarizes the orbital allocation for each case.

Case 1) Wind Snapshot

Requires: 6 orbits/yr, 8 orbits/yr beginning 2018

- Single views of each planet, two orbits each, separated by one rotation period
- Image pairs enable crude assessment of zonal wind profiles and their stability
- Spectral variation as a function of latitude



Figure 3. Four orbits, with proper time spacing, allow for full longitude coverage on Neptune.

Case 2) Global Map

Requires: 15 orbits/yr, 21 orbits/yr beginning 2018

- Full longitudinal coverage, minimum wind fields
- Uranus/Neptune require fewer orbits each map than Jupiter/Saturn because of their slower rotation rates and reduced overlying haze and better cloud feature isolation allow maps to be created at longitudes farther from disk center (see Fig. 3)
- Determines full spatial variation of distinct cloud features, banded features, and vortices
- Spatially periodic albedo or latitude variations reveal planetary scale waves

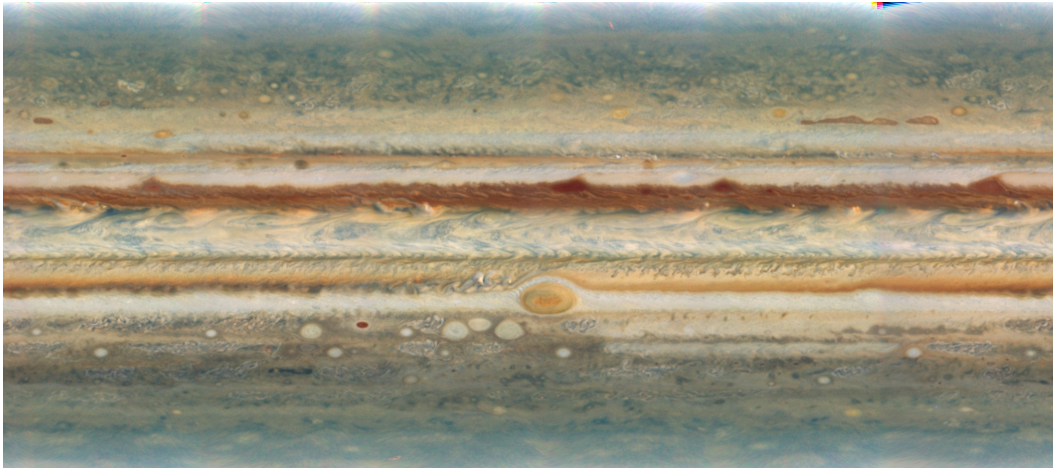


Figure 4. Seven contiguous orbits allow for full longitude coverage on Jupiter.

Case 3) Global Map Pair (maximum science value case)

Requires: 29 orbits/yr, 41 orbits/yr beginning 2018

- Full longitudinal coverage plus global wind field measurement
- Higher accuracy wind field measurement than Case 1 because longitudinal variability is measured
- Allows full discrimination between spatial and temporal wind dispersion
- Cases 2 and 3 could be employed on alternating years and maintain much of the return of maximum science Case 3

Table 2: Orbit allocations for three imaging cases

Case	Orbits/Yr					
	Jupiter	Saturn*	Uranus	Neptune	Total w/o Saturn	Total w/ Saturn*
1. Wind Snapshot	2	2	2	2	6	8
2. Global Map	7	6	4	4	15	21
3. Global Map Pairs	13	12	8	8	29	41

*Saturn imaging campaign to begin 2018, after completion of Cassini Proximal Mission

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