Time-Domain Solar System Science

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Abstract

Time-variable phenomena with scales ranging from minutes to decades have led to a large fraction of recent advances in many aspects of solar system science. We present the scientific motivation for the **Planetary Dynamics Explorer (PDX)**—a dedicated facility to conduct repeated imaging and spectroscopic observations over a period of 5 to 10 years. PDX will execute a selection of long-term projects with interleaved scheduling, resulting in the acquisition of data sets with consistent calibration, long baselines, and optimized sampling intervals. Specific investigations will include volcanism and cryovolcanism (on targets including Io, Titan, Venus, Mars, and Enceladus); zonal flow, vortices, and storm evolution on the giant planets; seasonal cycles in planetary atmospheres; mutual events and orbit determination of multiple small solar system bodies; auroral activity and solar wind interactions; and cometary evolution. The mission will produce a wealth of data products—such as multi-year time-lapse movies of planetary atmospheres—with significant E/PO potential. A sparse aperture telescope would be an ideal configuration for the mission, trading decreased sensitivity for reduced payload mass, while preserving spatial resolution.

Existing and planned ground- and space-based facilities are not suitable for these time-domain optimized planetary dynamics studies for numerous reasons, including: oversubscription by astrophysical users, field-of-regard limitations, sensitive detector saturation limits that preclude bright planetary targets, and limited mission duration. PDX responds to the NRC Decadal Survey *New Frontiers in the Solar System*, which states, "The Survey prefers to rely on the Discovery and, where appropriate, the Explorer lines to generate appropriate candidates [for an] Earth-orbiting telescope devoted exclusively to solar system studies" (p. 166).

Requirements for PDX

The chief requirements for time-domain solar system science are angular resolution, sampling interval, and campaign duration. Although many ground- and space-based telescopes satisfy the angular resolution requirement, only a dedicated solar system mission could achieve the time domain requirements.

Angular resolution

Studies of planetary dynamics require the resolution of small distant objects such as cloud features, volcanic plumes, and fragments of small solar system bodies. With a ~3-m aperture, PDX will achieve an angular resolution of about 40 mas. This resolution is comparable to that provided by HST and the best current ground-based telescopes, which have demonstrated a wealth of time-domain science opportunities (see below). Beyond JWST, extremely high resolution will be afforded by very large ground-based telescopes, but PDX will not attempt to compete with those efforts, instead specifying a 40 mas resolution based on the minimum requirement to image dynamically relevant features in the solar system.

Sampling interval

Observing programs will be scheduled to ensure that each program acquires data at its desired sampling interval, which will typically range from hours to days. Occultation light curves will push the short-interval limits with millisecond-range sampling intervals.

Campaign duration

Campaign durations lasting from the entire mission lifetime to single visits will be accommodated, providing new opportunities as compared with semester- or cycle-based scheduling at other observatories. In particular, campaigns lasting the full mission lifetime will enable high-return high-risk science such as cryovolcanic activity searches.

Resolution / sensitivity / mass trades

For most space telescope missions, photometric sensitivity is a major requirement. For time-domain solar system astronomy, a trade can be made between sensitivity and payload mass, since relatively bright solar system targets are less demanding of sensitivity. A sparse-aperture configuration enables this trade to favor smaller payload mass, maximizing the total aperture (and thus resolving power) for a given payload mass.

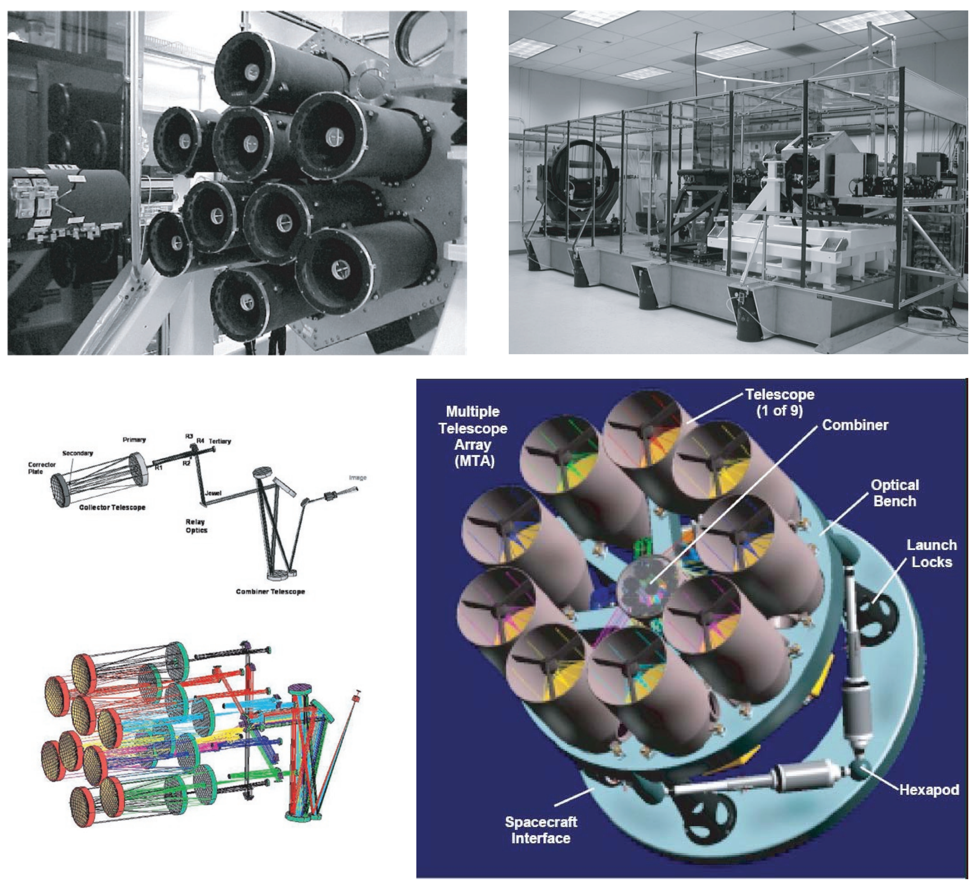


Figure 1. Sparse aperture telescope examples. *Top row:* The Star-9 prototype distributed aperture telescope on its optical testbed at Lockheed Martin (Rieboldt et al. 2005). *Bottom left:* Optical path of the Star-9 system (Rieboldt et al. 2005). *Bottom right:* Illustration of the MIDAS multiple telescope array for spaceborne remote sensing (Smith et al. 2005).

Science programs

PDX will provide an ideal platform for a range of time-domain research programs. A selection of programs will be reserved for Guaranteed Time Observers (GTOs) who are part of the mission science team, and a selection of general observer (GO) programs will be solicited from the broader solar system research community. Programs will be prioritized based on their scientific impact derived from the effective use of the resolution, sampling rate, and campaign duration opportunities uniquely provided by the PDX observatory. A set of observing programs with complementary temporal requirements will be chosen to maximize the facility duty cycle. Monitoring programs will be able to trigger shorter-interval target of opportunity observations under the appropriate conditions.

PDX will make its greatest contributions in the areas of planetary atmospheres, active geology, and small solar system bodies. A small sample of candidate investigations is given in this section; many more investigations could be persued, but these give at least a sense of the demands on sampling interval and campaign duration that are important for time-domain solar system science.

Table 1. Examples of time-domain solar system science investigations that could be explored using PDX. Note that since most investigations requiring spectroscopic data also require spatially resolved spectra, an integral field spectrometer might be an ideal spectroscopic instrument choice.

Investigation	Category	Data type (wavelength regime)	Sampling scales	Campaign duration
Giant planet zonal winds and vortices	Atmospheres	Imaging (O)	Hours, days	Years
Cloud/storm evolution and variability	Atmospheres	Imaging, spectroscopy (O, IR)	Hours, days	Days, years
Occultations	Atmospheres	Photometry, spectroscopy (UV, O, IR)	Milliseconds	Hours
Aurorae	Atmospheres/space science	Imaging, spectroscopy (UV)	Minutes, hours	Years, hours
Volcanic trace gases	Atmospheres/geology/astrobiology	Spectroscopy, imaging (IR)	Days	Years
Volcanic plumes	Geology	Imaging, spectroscopy (O, IR)	Days, hours	Years
Cryovolcanism	Geology/astrobiology	Imaging, spectroscopy (UV, O, IR)	Days	Years
Small body mutual events, lightcurves	Small bodies	Photometry (O)	Milliseconds	Hours
Cometary evolution	Small bodies	Imaging, spectroscopy (UV, O, IR)	Hours	Days

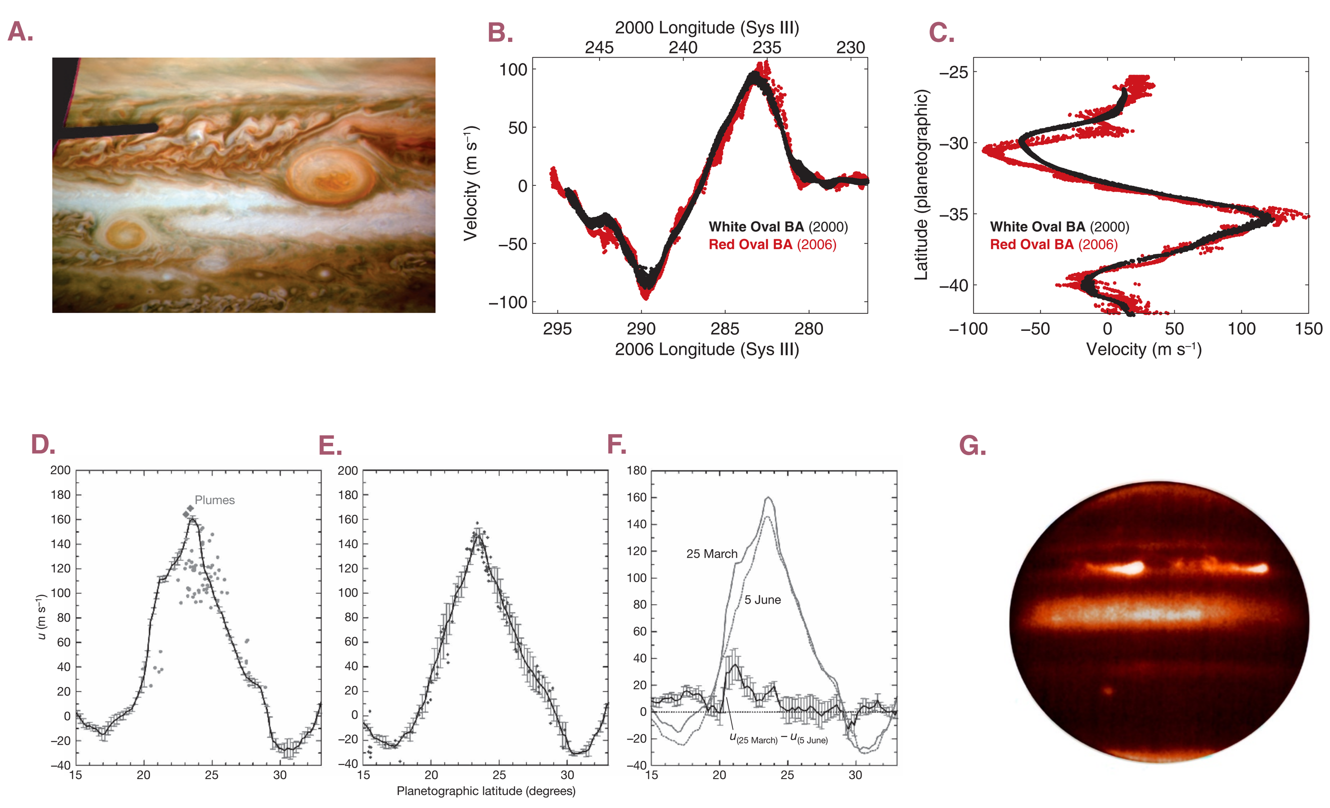


Figure 2. Examples of time-domain science at Jupiter. HST ACS/HRC images of Jupiter from 2006 at ~50 mas effective resolution *(A)* were used to provide velocity profiles along the east-west *(B)* and north-south *(C)* axes of Oval BA (Asay-Davis et al. 2009). Differences between 2000 and 2006 velocity profiles near 30° south latitude are attributed to transient interactions (of unknown timescale) between the vortex and its northward jet. Wind measurements require sampling intervals on hour timescales. Zonal wind profiles before *(D; black)*, during *(D; grey)*, and after *(E)* the eruptions of massive powerful convective plumes *(G)* revealed significant changes in the zonal winds *(F)* as derived from HST WFPC2 imaging data (Sánchez-Lavega et al. 2008).

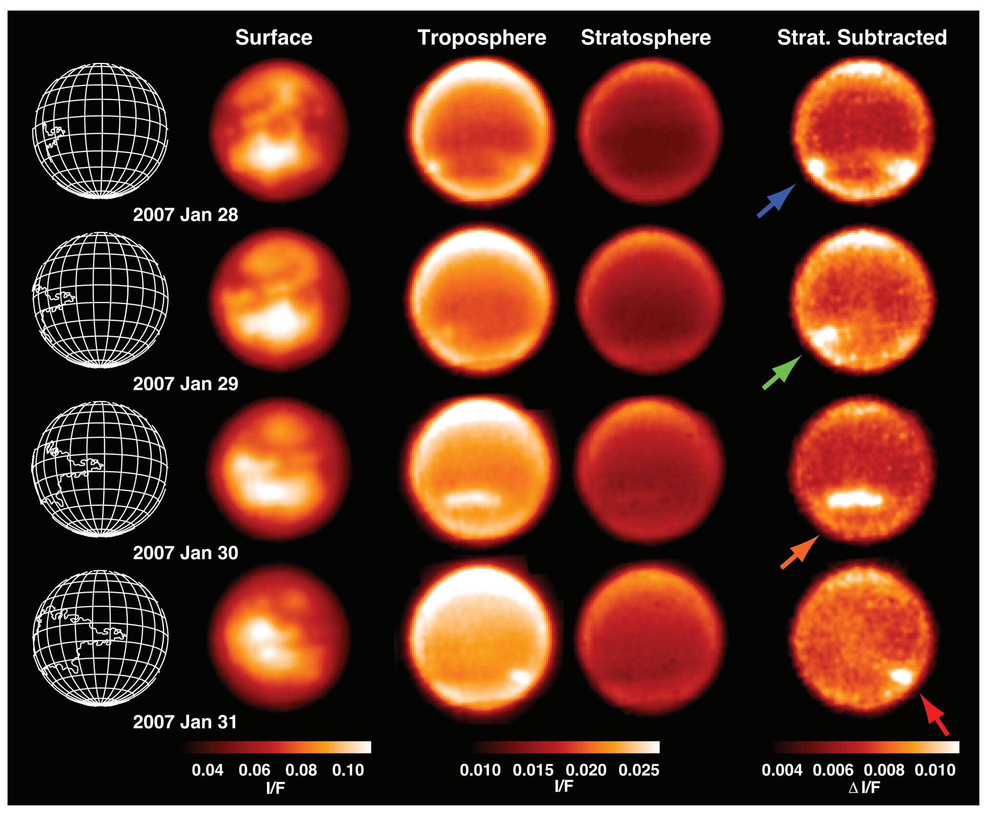
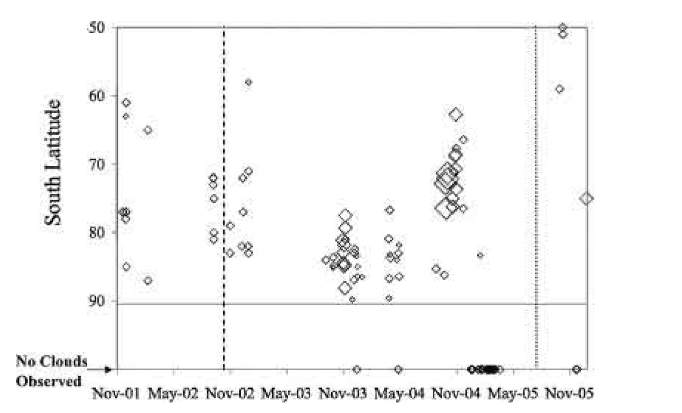


Figure 3. *Left:* Spectral imaging observations of TItan using VLT/SINFONI with ~45 mas effective resolution show that observations at 1-day intervals can reveal significant cloud variation. Much higher spatial resolution Cassini ISS data showed even more rapid change at hour timescales, but it is not clear that PDX could spatially resolve the rapid changes. *Below:* Schaller et al. (2006) used observations taken at day-scale intervals to demonstrate changes in cloud activity, which they relate to a large convective event in 2004 and to seasonal effects. The 2002 vertical line is southern solstice; the 2005 vertical line is the date when Titan's region of maximum insolation moved north from the south pole.



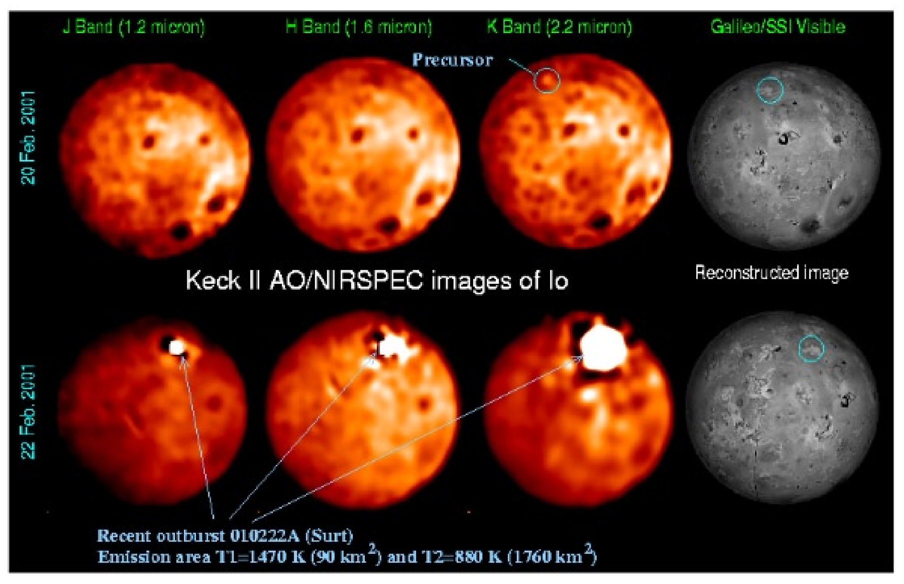


Figure 4. Images of Io at ~50 mas resolution demonstrate that a sampling interval of no greater than 1 day is probably required to catch the development of volcanic eruptions (here, the volcano Surt; see Marchis et al. 2002). However, eruption durations last for days to months, so sampling intervals could be tuned depending on specific science goals.

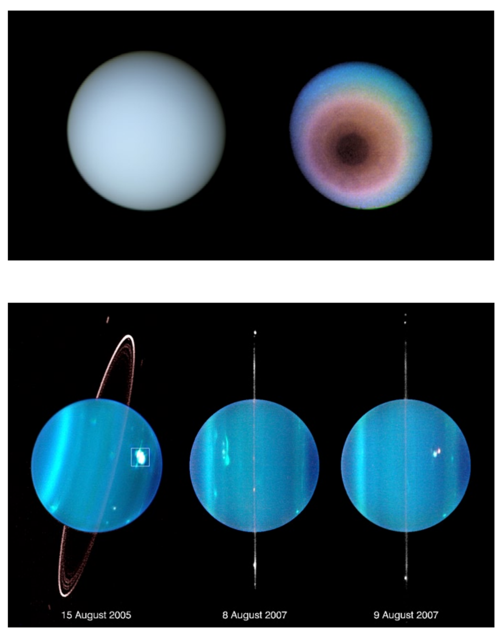


Figure 5. Although taken at different wavelengths, these 1986 Voyager *(top)* and 2005–2007 Keck *(bottom)* images of Uranus demonstrate the variability of cloud activity over long timescales. The bright cloud complex (bottom left) has been tracked for several years and changes in altitude, area, latitude, and longitude (Sromovsky et al. 2007). Observations spanning many years—including data from HST/WFPC2—show evidence of significant decade-scale changes on both Uranus and Neptune that is only partially explicable as effects of changing subsolar latitude (Rages et al. 2004, Hammel and Lockwood 2007).

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