SOLAR SYSTEM SCIENCE OBJECTIVES WITH THE NEXT UV/OPTICAL SPACE OBSERVATORY.

NASA Cosmic Origins Program Request for Information: Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts. White Paper to be submitted by 10 August 2012.

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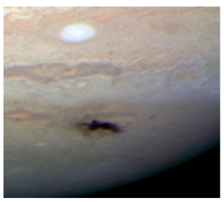 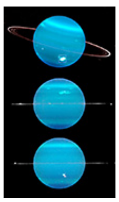 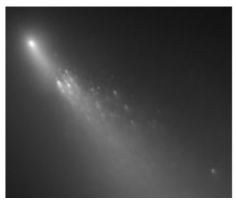 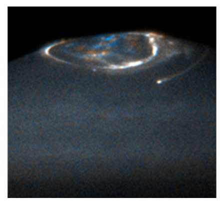  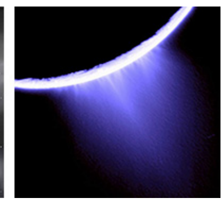

Summary

NASA's Great Observatories (and smaller space telescopes) enable a wide range of solar system science investigations, particularly in the ultraviolet, optical, and infrared ranges. These investigations are an important part of the Cosmic Origins program, providing a local reference point for the origin and evolution of stars and planetary systems. ***The next UV/optical space observatory can drive fresh insights into the origin and evolution of the solar system, if the technical requirements for planetary observations are met. These requirements are easily achieved via the groundwork that has already been done for HST and JWST.***

Some relevant research topics can be identified, although a strength of space observatories is that they can make observations to solve questions that have yet to be raised. Auroral emissions in atmospheres and magnetospheres of the giant planets can be effectively sensed only by space-based UV instruments. Observations of auroral phenomena tell us about the exchange of energy, mass, and momentum in magnetized plasmas—our closest analog for the inner portions of planet-forming disks around active protostars. These observations form a bridge between solar system planets and exoplanets. The compositional diversity of surfaces and atmospheres of planets and their satellites can also be characterized, illuminating both past and present solar system conditions. The dynamics of outer planet atmospheres can be studied by mapping jets, waves, vortices, storms, and impact debris fields at high spatial resolution. Atmospheric dynamics constrain the internal heat release and thermal evolution of gas giants, whose early analogs include glowing objects directly imaged around other host stars. One important point is that time-domain science is critically important to the rapidly changing planetary objects. Planetary observations with HST remain a vital part of the HST scientific program more than 20 years post-launch.

The proximity of solar system targets enables investigation at a high level of detail, but unique technical challenges result. The next UV/O space observatory must be able to observe bright targets, requiring a large dynamic range if faint object sensitivity is a driver for other science goals. The capability to track moving targets is also essential, although HST has shown that linear tracking (included in all 3-axis stabilized platforms) is sufficient to do great science. Although high spatial resolution is beneficial to solar system science, it cannot come at the expense of angular coverage, as solar system objects can span a field of view up to an arcminute. Placement of the observatory at a Lagrange point or in high Earth orbit eliminates limitations on temporal sampling and duration that interfere with time-domain solar system observations done from HST or the ground, and greatly decreases the geocoronal UV background emissions. When planning a future UV/O telescopic mission, a comparison with ground-based capabilities is often made. It is important to keep in mind the significance of the stable point spread function (PSF) and overall response of a telescope in space compared with ground-base AO systems. After new Plutoids are discovered, and imaged using AO on the Keck 10 m telescope, the 2.4 m HST is then employed to learn the true shape and size of the object – the justification is the stable PSF.

Scientific Investigations

In this white paper, we give a representative selection of solar system investigations that would be enabled by a UV/O space telescope, with the objective of defining common science requirements. Time domain science—either the direct study of variable phenomena, or the use of variable phenomena to understand the planets themselves—often requires the use of space telescopes due to their photometric stability and relaxed timing constraints.

The Discovery program's scope should be broadened to include planetary science from space based telescopes, according to the planetary science decadal survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022* (SSB, 2011). Many time-domain solar system studies require higher spatial or spectral resolution than can likely be provided by a planetary telescope within the Discovery cost cap (Wong et al. 2009a, Content 2009). However, a facility class UV/O observatory, on the other hand, would enable much of this original science (see Table 1).

Table 1. Examples of solar system science investigations that can be explored with a UV/O space observatory. Note that since most investigations requiring spectroscopic data also require spatially resolved spectra, an integral field spectrometer is a appropriate spectroscopic instrument choice. Wavelength regimes are ultraviolet (UV), optical (O), and near infrared (IR).

Investigation	Category	Data type (wavelength regime)	Sampling scales	Campaign duration	Resolution: R = spectral, θ = spatial
Giant planet zonal winds and vortices	Atmospheres	Imaging (O)	Hours, single target rotation period	Years	θ ≤ 0.05"
Cloud/storm evolution and variability	Atmospheres	Imaging, spectroscopy (O, IR)	Hours, days	Days, years	R ≥ 2500 θ ≤ 0.05"
Occultations	Atmospheres	Photometry, spectroscopy (UV, O, IR)	Milliseconds	Hours	R ≥ 100–1000

Aurorae, magnetospheres	Atmospheres/ space science	Imaging, spectroscopy (UV)	Minutes, hours	Years, hours	$R \geq 500$ $\theta \leq 0.05''$
Volcanic trace gases	Atmospheres/ geology/ astrobiology	Spectroscopy, imaging (UV, O, IR)	Days	Years	$R \geq 500$–10000
Volcanic plumes	Geology	Imaging, spectroscopy (O, IR)	Days, hours	Years	$R \geq 2500$ $\theta \leq 0.025''$
Cryovolcanism	Geology/ astrobiology	Imaging, spectroscopy (UV, O, IR)	Days	Years	$R \geq 2500$ $\theta \leq 0.025''$
Mutual events, lightcurves	Small bodies	Photometry (O)	Milliseconds, minutes	Hours, months	$R \geq 5$ $\theta > 10''$
Cometary evolution	Small bodies	Imaging, spectroscopy (UV, O, IR)	Hours	Days	$R \geq 5$ $\theta \leq 0.05''$

Wind velocities: Cloud-tracking studies illuminate the 3-dimensional wind fields in giant planet atmospheres as well as flows within coherent vortices like the Great Red Spot on Jupiter. These cloud-level velocities are the main constraints for studies in atmospheric dynamics. Sampling scales that include image pairs separated both by hours and by a single planetary rotation period provide the most accurate velocities (Asay-Davis et al. 2009). Measurements separated by one target rotation period, which for the giant planets is typically longer than a single terrestrial observing night, cannot be taken from a single ground-based observatory. Observation campaigns on the order of a decade reveal fundamental changes such as shifts in Saturn's haze distribution and equatorial wind speeds (Porco et al. 2005) and the shrinking of the potential vorticity anomaly associated with Jupiter's Great Red Spot (Asay-Davis et al. 2009). Cloud-tracked Martian winds constrain general circulation models (Kaydash et al. 2006). Existing data sets have large temporal gaps because space telescopes are based on single epoch observations constrained by observing cycles rather than by scientifically-determined campaign durations.

Cloud and storm evolution: The formation and evolution of clouds and storms is central to the topic of energy transport in planetary atmospheres. For example, Mars Global Surveyor observed dust storm 2001a with high temporal resolution, providing new insights into the origin and evolution of dust storms and new constraints on global circulation models for Mars (Smith et al. 2002, Strausberg et al. 2005). In the outer solar system, New Horizons spectroscopic imaging data spanning five Jovian rotations charted the evolution of an ammonia cloud system, providing a crucial piece of the puzzle of the scarcity of such signatures in a cloud layer that is supposedly dominated by ammonia ice (Reuter et al. 2007). Similar studies with a baseline long enough to determine statistical trends would inform questions such as the transport of internal heat through convective storms (Ingersoll et al. 2000) and the pattern of belt-zone transport and wave dynamics (Showman and de Pater 2005, Simon-Miller et al. 2012). Serendipity, rather than desired temporal sampling, allowed Sánchez-Lavega et al. (2008) to observe the genesis of powerful convective plumes at 23° N in Jupiter's atmosphere; these plumes were part of a poorly understood global upheaval and are associated with long-term changes in the upper tropospheric haze distribution (Wong et al. 2009b). Clouds on Titan show intriguing variability (Schaller et al. 2006) but high-resolution observations have been available for only a fraction of a Titanian season; a facility UV/O observatory would enable a long campaign duration optimized to capture seasonal variation and link it to a methane cycle analogous to the Earth's hydrologic cycle. Aerosol distributions on Uranus and Neptune vary on diurnal to seasonal timescales, tracing the causes and effects of very different solar forcing and internal heat release on these otherwise similar planets (Sromovsky et al. 2003, Rages et al. 2004, Hammel and Lockwood 2007, Sromovsky et al. 2007).

Occultations: The density, thermal, and compositional profiles of planetary atmospheres are probed with high vertical resolution using optical and ultraviolet stellar occultations (Atreya 1986, Smith and Hunten 1990). Tenuous atmospheres can be discovered using this technique; this was how Pluto's atmosphere was unambiguously identified (Elliot et al. 1989). With vertical resolution tied directly to sampling rate, occultations drive high-frequency sampling requirements. Space-based occultation experiments have the advantages of photometric stability and access to the ultraviolet region of the spectrum, where spectroscopic occultation observations return compositional profiles.

Aurorae and magnetospheres: Auroral and airglow emission has been observed on Jupiter, Saturn, Uranus, Io, Europa, and Ganymede. The dynamics of auroral spectral and brightness distributions reveals magnetospheric interactions with the solar wind and with planetary satellites. Observations from space can track the emission, which is variable on time scales of less than an hour and can vary with seasonal timescales that are decades long for the outer planets (e.g., Clarke et al. 2009). Exoplanets may emit cyclotron radiation that can be detected in the near future (Vidotto et al. 2010), and validating models of these distant systems requires testing against observations of magnetospheres in our solar system.

Volcanism and cryovolcanism: Volcanic processes are either known or plausible on several rocky and icy solar system bodies. Active volcanism on Io was discovered when Voyager imaged a plume over the volcano Pele (Morabito et al. 1979), a structure that easily could be resolved by a 4-m class UV/O space telescope with a 400-nm diffraction-limited resolution of about 80 km at a typical geocentric distance. Ultraviolet stellar occultations confirmed the spatially-confined cryovolcanic plumes in the south polar region of Enceladus (Hansen et al. 2006) and would be enabled by stellar UV occultations of other icy bodies. A search could be conducted for new cryovolcanic sources in the outer solar system on satellites and Kuiper belt objects, with a high-risk long term monitoring program. On Venus, a variable concentration of SO_2 at the cloud tops measured via ultraviolet spectroscopy hints at potential volcanic activity, and a space observatory could continue with both this technique as well as with searches for corresponding variation in the deep atmospheric SO_2 concentration, and for direct detection of thermal radiation from lava flows (Esposito 1984, Bézard et al. 1993, Hashimoto and Imamura 2001). Spatial and temporal variation of Martian CH_4 has recently been claimed, requiring either a geochemical or astrobiological origin to replenish the gas against photochemical destruction (Formisano et al. 2004, Krasnopolsky et al. 2004, Mumma et al. 2009). The variability of Martian methane has not been well constrained and will help to determine the source of the gas.

Small body time-domain photometry and astrometry: Dwarf planets and small solar system bodies reveal basic physical characteristics both in photometric light curves that are modulated by rotation and by changing viewing geometry, and in astrometric image sequences of multiple systems. Mutual events such as eclipses and occultations also contribute. Basic information gained from these studies will include sizes, shapes, albedos and albedo patterns, and masses and densities of multiple systems. Ground-based programs using moderate aperture telescopes have contributed greatly to this area, but fainter targets require larger telescope apertures that are limited by oversubscription. Resolving multiple systems requires them again to be bright enough to enable adaptive optics observations from the ground, whereas a UV/O space observatory would be able to resolve fainter and smaller targets, enhancing statistics on binarity rate and other properties in the populations of small bodies in orbit around the Sun.

Small body population studies: Small solar system body populations clearly provide clues to the formation and evolution of our planetary system. But they also serve as parent bodies for debris disks similar to those around other stars, where parent bodies are far too small to be directly observed. UV/O space observatories like Hubble and its successor play important roles in the studies of these populations. The UV colors of populations with different collisional histories (and thus surface ages) reveal the effects of space weathering, and only high-resolution space imaging can reveal faint binaries and companions, since adaptive optics are limited to targets bright enough to enable wavefront sensing.

Cometary evolution: Shoemaker-Levy 9 and subsequent disrupting comets provided spectacular opportunities for sequential imaging to reconstruct the comet's fragmentation history, density, and internal structure, and to study the diversity of internal structure, surface layering, and chemistry among cometary nuclei (Asphaug and Benz 1994, Solem 1994, Sekanina et al. 1998, Boehnhardt 2002, Kidger 2002). These comet properties also control atmospheric entry fragmentation, a key consideration for the determination of surface ages by crater-counting (Korycansky and Zahnle 2005). Accurate fragment trajectories allow measurements of competing influences such as rotation, solar radiation pressure, outgassing, and clumping. Identifying fragments and their trajectories requires sampling frequencies on the order of hours and campaign durations of at least several days. Gas production can increase dramatically during fragmentation (Crovisier et al. 1996), allowing infrared spectroscopic observations to constrain compositional heterogeneity in the parent bodies (DiSanti and Mumma 2008).

Scienctific Requirements

Moving target tracking: Solar system targets are not fixed with respect to the stars. Linear tracking approximations to the target motion have worked well for HST, and the software system to support this is in place and working. All 3-axis stabilized spacecraft are designed with linear tracking capability to move from place to place on the sky, so the inclusion of moving target tracking is neither expensive nor a new development effort.

Bright objects: High sensitivity drives the requirements for faint object investigations, but many solar system investigations require the capability to observe bright targets.

Angular resolution: Studies of planetary dynamics require the resolution of small distant objects such as cloud features, volcanic plumes, and binary objects with small separations. With a nominal 4-m aperture, the new UV/O facility would achieve an angular resolution of about 25 mas at 400 nm. 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. In the coming decades, extremely high resolution will be afforded by large ground-based telescopes with adaptive optics, but solar system observations with these facilities can only be done at rare intervals and for short durations. The stable PSF, sensitivity, and spectral response achieved in space have all proven to be invaluable on HST, and a smaller aperture in space has great merit compared with the new generation of large ground-based systems.

Sampling interval: Critical sampling intervals for various programs typically range from hours to days. Occultation light curves will push the short-interval limits with millisecond-range sampling intervals. The full range of optimal sampling intervals will be enabled by an observatory located in high Earth orbit, at an Earth-Moon or Earth-Sun Lagrange point, or in a Spitzer-esque breakaway orbit, rather than in low Earth orbit, where observations would be interrupted by frequent and/or long Earth occultations.

Campaign duration: Campaigns lasting the full mission lifetime will enable both high-return/high-risk science such as cryovolcanic activity surveys, as well as studies of seasonal variations on objects in the outer solar system.

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