The U.S. Extremely Large Telescope Program

THIRTY METER TELESCOPE

NOAO

GIANT MAGELLAN TELESCOPE

Key Science Program Description Document

Date: December 18, 2018 **Category:** Our Solar System

The solar system Deep Time-Survey of atmospheres, surfaces, and rings

Abstract of Scientific Justification

Spatially resolved imaging and spectroscopy reveals varying environmental conditions in our dynamic solar system. Observations conducted over the lifetime of the US-ELT system will form a long-term legacy chronicling the evolution of dynamic planetary atmospheres, surfaces, and rings, establishing a permanent resource for comparison with other observations before, during, and after the ELT era. Science investigations will use this dataset to address potential biosignatures, circulation and evolution of atmospheres from the edge of the habitable zone to the ice giants, orbital dynamics and planetary seismology with ring systems, exchange between components in the planetary system, and the migration and processing of volatiles on icy bodies, including Ocean Worlds. The common factor among these diverse investigations is the need for a very long campaign duration, and temporal sampling at an annual cadence.

(Draft version 18 December 2018)

Team Members *List the names, affiliations and e-mail addresss for all team members.*

Michael H. Wong	UC Berkeley	mikewong@astro.berkeley.edu
Richard Cartwright	SETI Institute	rcartwright@seti.org
Glenn Orton	JPL	glenn.orton@jpl.nasa.gov
Matthew Tiscareno	SETI Institute	matt@seti.org
Thomas Greathouse	SWRI	tgreathouse@swri.edu
David Trilling	Northern Arizona Univeristy	david.trilling@nau.edu
Kunio Sayanagi	Hampton University	kunio.m.sayanagi@gmail.com
Nancy Chanover	NMSU	nchanove@nmsu.edu
Al Conrad	LBTO	aconrad@lbto.org
Imke de Pater	UC Berkeley	imke@berkeley.edu
Eric Gaidos	University of Hawaii	gaidos@hawaii.edu
Michael Lucas	UT Knoxville	mlucas9@vols.utk.edu
Karen Meech	University of Hawai‘i	meech@ifa.hawaii.edu
Noemi Pinilla-Alonso	University of Central Florida	npinilla@ucf.edu
Megan E. Schwamb	Gemini Observatory	mschwamb.astro@gmail.com

Scientific Justification *Describe the scientific context for this Key Science Program, the specific research question(s) to be addressed, and the overall significance to astronomy. The Scientific Justification should be limited to 4 pages including figures.*

Background

In the realm of astronomy, new discoveries are often enabled by the opening of new domains in terms of angular resolution, sensitivity, spectral bandpass, or spectral resolution. In much of modern planetary science, an equally important dimension for new discoveries is the time domain. For example, outer-planet atmospheres evolve on timescales from minutes (impacts), days (plumes and storms), weeks to months (evolution of zonal bands), to years (seasonal changes, impact aftermaths, upper atmospheric composition and structure, and evolution of large vortices). Lake distributions may shift on Titan, cloud activity varies on the ice giants, and volatiles migrate over the surfaces of Triton and the dwarf planets.

The Outer Planet Atmospheres Legacy (OPAL) program (Simon et al. 2015) is a recent example of a major astronomical observatory (HST) committing to a solar system Deep Time-Survey, like the one proposed here. OPAL obtains consecutive pairs of global maps of the atmospheres of the giant planets on an annual basis. The long-term nature of the program has established a baseline of consistent data with yearly sampling, beginning in 2015. OPAL contains specific elements optimized for HST: consecutive global maps for wind tracking (spanning 20–40 hours of planetary rotation) and UV imaging, both of which will be impossible from the US ELTs. We propose the start of a new, long-term, annual campaign that exploits the advantages of the US ELTs: high angular resolution and resolved spectroscopy.

The scope of this program goes beyond OPAL's focus on giant planet atmospheres to encompass the atmospheres of Titan and Earth's terrestrial neighbors, and the evolution of surfaces of classical satellites and large Trans-Neptunian Objects (TNOs). For these smaller objects, the new capabilities for resolved spectroscopy will enable time-domain science that has never before been possible. Table 1 illustrates the diffraction-limited spatial resolution at the average distance of each major planet over a wavelength range relevant to first- and future-generation ELT instruments. At Titan (dia. 5149 km), spectra will be mapped across 20 resolution elements at 5 μm, or an astounding 100+ resolution elements at 1 μm. Even for Neptune's captured-TNO satellite Triton (dia. 2706 km), hemispheres will be resolved at 5 μm, and the surface will be mapped across 18 resolution elements at 1 μm.

Overview of the Deep Time-Survey

The Deep Time-Survey consists of a diverse collection of science goals, united by a common temporal requirement: regular sampling on an annual timescale, continued over a decades-long duration that is suited to the seasonal intervals in the outer solar system. In some ways, the Deep Time-Survey is like a mosaic or survey. But where a normal mosaic samples a grid of regularly-spaced points on the sky, or a normal survey samples a population of targets, the Deep Time-Survey samples a series of timesteps in the history of a small set of evolving objects.

We have constructed a traceability matrix to show the path from high-level science goals to instrument and temporal requirements. For legibility, this matrix is broken into a Science Summary (Fig. 4) and a Technical Summary (Fig. 5). We describe details of the program implementation over the desired multi-decadal campaign duration in the technical sections following this Scientific Justification.

Table 1. Spatial resolution for solar system targets (diffraction-limited 30-m aperture)

Target	Distance	Resolution (1 μm)	(5 μm)	(10 μm)	(25 μm)
Sky	∞	0.007″	0.035″	0.070″	0.175″
Venus	0.72 AU (1.1×10^8 km)	5 km	24 km	48 km	120 km
Mars	1.52 AU (2.3×10^8 km)	8 km	39 km	78 km	195 km
Jupiter	5.2 AU (7.8×10^8 km)	27 km	133 km	266 km	665 km
Saturn	9.6 AU (1.4×10^9 km)	48 km	238 km	476 km	1190 km
Uranus	19.2 AU (2.9×10^9 km)	99 km	493 km	986 km	2465 km
Neptune	30.1 AU (4.5×10^9 km)	153 km	765 km	1530 km	3825 km

Science Goals

Science goals of this program are closely tied to Priority Questions from the last decadal survey (Visions and Voyages), as indicated by numbers in column 1 of the Science Summary (Fig. 4). We briefly describe the individual science goals here:

Search for life on Mars: Methane in the atmosphere of Mars has been detected from ground-based telescopes and orbiting and landed spacecraft; it could have exogenic, geologic, or even astrobiological origins. The observed concentration of CH_4 is highly variable with space and time, with transient pulses and hemispheric differences (Formisano et al. 2004, Mumma et al. 2009, Krasnopolsky et al. 2004, Webster et al. 2015). The sinks for methane (OH radicals and possible surface chemistry on dust grains) are also seasonally variable, thus monitoring on timescales of Earth months to a year will help us understand the dynamics (Webster et al. 2018).

Circulation and evolution of atmospheres on the edge of the habitable zone: Non-LTE emission from CO and CO_2 in the atmospheres of Mars and Venus constrains circulation in the mesosphere (Lellouch et al. 2000, Drossart et al. 2007), contributing to our understanding of the evolution of atmospheres toward states too hot or too cold for liquid surface water.

Understand volatile cycles and seasonal variation on Titan, and similar processes in the solar system: A resolved spectroscopic campaign would increase our understanding of variable cloud activity (e.g. Roe et al. 2008), as well as the CH_4 "hydrological" cycle (e.g. Teanby et al. 2008, Adamkovics et al. 2016), which includes effects such as evaporation from lakes (e.g., Brown et al., 2009; Turtle et al., 2009). Cloud activity patterns and trends in tropospheric CH_4 concentrations provide valuable tests for circulation models (Tokano 2014, Mitchell 2012), none of which match all the observations. A long-term campaign of Titan observations sensitive to atmospheric composition and clouds would extend the legacy of extensive observations of Titan by NASA's Cassini mission, which covered only two full seasons.

Understand the heat transport, circulation, climate, and space weather of giant planets, and the relation to exoplanets and Earth: Changes in coloration and reflectivity have been observed on regional and global scales in all the giant planets (Hammel and Lockwood 2007, Karkoschka 2011, Fletcher 2017), but the drivers for this evolution are not well understood, particularly since timescales are variable on Jupiter, and seasonal timescales extend for decades on the ice giants. Long-term observations will constrain the relevant timescales and periodicities, and

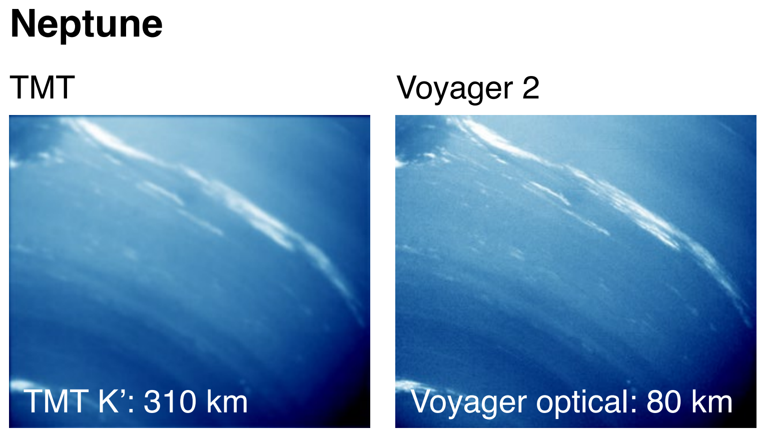

Figure 1 - ELTs will achieve spatial resolution at the ice giants approaching what was achieved by the only spacecraft mission to visit them (Voyager 2). The optical image at right has been blurred to TMT resolution (at K band) to show that fine scale clouds will still be detected; methane clouds such as the white features seen by Voyager are even more prominent in the IR. Figure from Otarola et al. (2015).

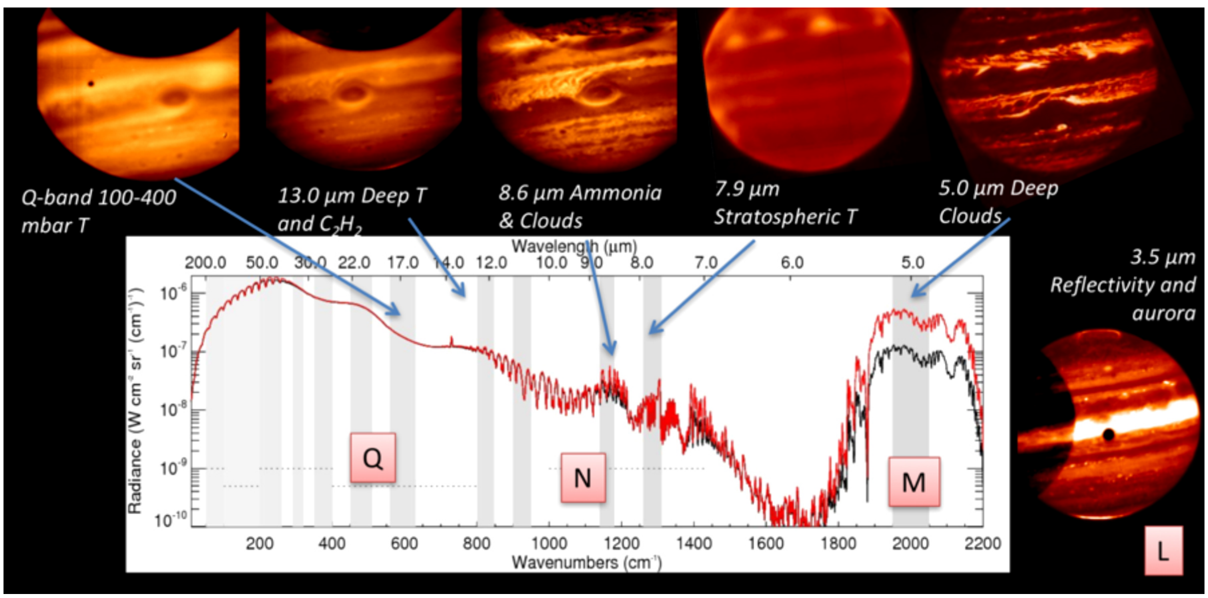

Figure 2 - Jupiter’s thermal infrared emission reveals spatial variation in atmospheric properties that trace chemical and dynamical processes.

GMT first-generation visible light NGAO imaging will even enable cloud color measurements to characterize changes in aerosol properties at high angular resolution (Simon et al. 2006, Wong et al. 2011). Imaging sequences will also be able to measure 2D flow on short timescales, thanks to the high precision available from exceptional spatial resolution (Fig. 1), while compositional variation is diagnostic of vertical flow. Second generation and later instruments will open up the thermal infrared wavelength regime, adding studies of long term variation in composition and temperature to the timeline (Fig. 2). At higher altitudes, giant planet atmospheres interact with magnetospheric charged particles, ring rain, interplanetary dust, and impacting comets/asteroids, producing compositional spectral signatures that evolve over many years, as well as H_3^+ auroral emission on Jupiter and Saturn that vary over the shortest resolvable timescales. Do auroral spots vary with volcanic activity, as expected from Io, or water plumes, such as those emanating from Europa or Enceladus? H_3^+ is hard to detect in Uranus, but long-term upper-atmospheric temperatures have decreased over time. Its emission has not been detected in Neptune, despite model predictions (Melin et al. 2011).

Understand the structure and evolution of planetary rings, derive insights to planet formation processes, and constrain the interior state of giant planets: Planetary rings serve as accessible natural laboratories for disk processes, as clues to the origin and evolution of planetary systems, and as shapers and detectors of their planetary environments (e.g., Tiscareno and Murray 2018). Long-term or seasonal phenomena within the rings and small moons of the outer planets require time-domain observations (a cadence of one year would be ideal) for characterization. These include the the ring arcs of Neptune, the apparently Myr-unstable inner moons of Uranus, the μ ring and Mab, spokes and propellers in Saturn's rings, arcs in the rings of Jupiter, and moons with poorly understood orbital variations such as Daphnis and Prometheus. Wave structures within planetary rings, potentially resolvable with ELTs, have been used to constrain unobserved impacts in the Jupiter (REF) and Saturn (Hedman et al. 2015) systems, as well as internal oscillations that constrain the deep structure of gas giants (REF).

Understand the evolution of surface volatiles on icy bodies, including Ocean Worlds: The large and tidally-locked satellites of the giant planets and the large dwarf planets in the Kuiper Belt experience continual modification of their surface and atmospheric compositions. Modification is driven by a suite of processes, including: (1) bombardment by UV photons and energetic charged particles, (2) bombardment by heliocentric and planetocentric micrometeorites, (3) seasonal migration of volatiles, and (4) geologic activity (i.e. cryovolcanism, impact events, mass wasting, etc). Outer planet satellites and small bodies exhibit a dazzling array of processes relevant to the origin and evolution of the solar system, as well as the potential for extraterrestrial life. For example, magnetospheric irradiation produces disequilibrium chemistry (REF) that could provide energy for life if exchange with subsurface oceans is active in the jovian system; E-ring material from cyrovolcanic Enceladus accumulates on the surface of the Saturnian moons Mimas, Enceladus, Tethys, Dione, and Rhea (Hendrix et al. 2018); in the uranian system, CO_2 ice migrates due to varying insolation and solar heating (Grundy et al. 2006, Sori et al. 2017), allowing the surface distribution of dark, potentially carbonaceous material to be studied (Cartwritght et al. 2018); the variation of frosts on Triton and KBOs may be related to transitions between global and local atmospheric states (Fig. 3, Holler et al. 2016, Cruikshank et al. 1993); there may be recent geologic activity, including possible glaciation and cryovolcanic structures on Pluto (Umurham et al., 2017; Moore et al., 2016, 2017); and aerosols generated via UV photolysis "rain out" onto Pluto's surface, incorporating into existing geologic provinces like Chulthu Macula (Gao et al. 2017, Grundy et al. 2018).

Synergy between TMT, GMT, and Other Facilities

- Observatories in both hemispheres enable better coverage of bodies whose orbital inclinations take them above/below the ecliptic.
- Varying instrumental capabilities at TMT/GMT will enable observations in different spectral/imaging modes that contribute new insights to long-term processes.
- In every instance, NASA missions have benefited tremendously from supporting ground-based observations. The ELTs additionally will profoundly influence mission designs because these advanced facilities will enable very high spectral- and angular-resolution observations from the ground, allowing spacecraft to focus on complementary investigations.
- The main benefit of this program would be the establishment of a long-term baseline of time-resolved observations, that extends the temporal coverage of spacecraft missions like Cassini and observatory programs like OPAL. The legacy data generated by this program would serve

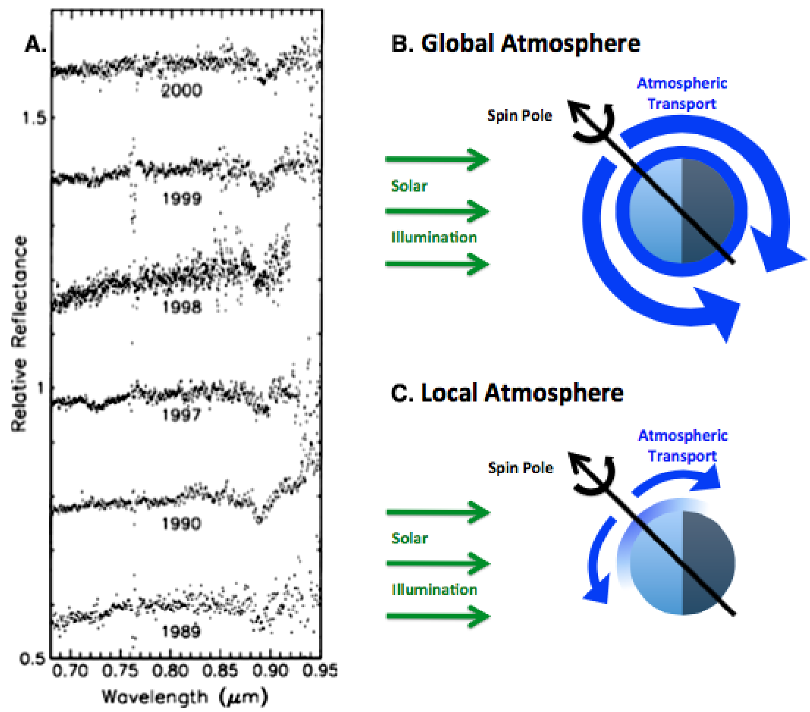

Figure 3 - A. Short-timescale spectral changes in Triton's reflectance suggest non-seasonal transport of N_2/CO/CO_2 frosts, which act to suppress spectral signatures of reddish material or CH_4 ice. Figure from Hicks and Burratti (2004). B. and C. The atmosphere of Eris may transition between a global state that can transport volatiles over the entire surface, and a local state where transport is limited to regions close to the warmest surface areas. Figure from Hofgartner et al. (2018).

as a resource of ever-increasing value for understanding periodic and stochastic processes in the solar system.

Conclusion

A long-baseline campaign of solar system observations will enable a wide range of science, unified by a common need for annual/semiannual/biannual observations. The overarching motivation for these diverse studies fully spans the range of Decadal Survey topics of planetary origins, planetary evolution, interacting systems, and the search for life.[1]

References

[2]

Drossart et al. 2007. A dynamic upper atmosphere of Venus as revealed by VIRTIS on Venus Express. Nature 450, 641.

Encrenaz et al. 2004a. Detectability of minor constituents in the Martian atmosphere by infrared and submillimeter spectroscopy. Planet. & Space Sci. 52, 1023.

Encrenaz et al. 2004b. Hydrogen peroxide on Mars: Evidence for spatial and seasonal variations. Icarus 170, 424.

Encrenaz et al. 2004c. First detection of CO in Uranus. Astron. & Astrophys. 413, L5.

[1] Although this KSP exceeds four pages, if it were a real proposal, it would have been broken into multiple focused components (e.g., outer planet atmospheres, inner planet atmospheres, small bodies, and rings). Thus, we are actually saving the KSP "TAC" a large amount of reading.

[2] Draft version: references have not been checked for completeness.

Science Goals	Science Objectives	Observables
Search for life on Mars. [5,6]	Quantify CH4 on Mars: spatial and temporal variability	High resolution, spatially-resolved, synoptic spectra of Mars
Circulation and evolution of atmospheres on the edge of the habitable zone. [5,6,9,10]	Trace mesosphere circulation	Spatially-resolved NIR and MIR spectra of Venus nightside and Mars dayside
Understand volatile cycles and seasonal variation on Titan, and similar processes in the solar system. [4,10]	Determine the spatial and temporal variation of haze layers, clouds, CH4 humidity, and surface moisture	Imaging and spatially-resolved spectroscopy of clouds and hazes on Titan
Understand the heat transport, circulation, climate, and space weather of giant planets, and the relation to exoplanets and Earth. [7,9,10]	Determine the spatial distribution and vertical structure of cloud features on Uranus/Neptune	Spatially-resolved spectroscopy of clouds and hazes
	Measure 3D wind flow in all four giant planets	High-resolution image sequences for cloud tracking at multiple pressure-levels
	Understand temporal variation of particle properties, composition, and temperature in zonal bands in all four giant planets	High-resolution images with global coverage
	Understand interactions with magnetospheres, plasma torii, solar wind, ring rain, interplanetary dust	NIR/MIR resolved spectroscopy: Jupiter/Saturn polar regions, Uranus/Neptune globally.
Understand the structure and evolution of planetary rings, derive insights to planet formation processes, and constrain the interior state of giant planets [1,2,4,7,8,10]	Measure evolution of dynamical properties of rings and moons, and radial/asimuthal particle properties	High-resolution images of ring systems, covering 180°+ of ring orbital longitude
Understand the evolution of surface volatiles on icy bodies, including Ocean Worlds. [4,6,10]	Understand changes in H2O ice state, and in the abundance/spatial distribution of irradiation-produced volatiles	Spatially-resolved NIR spectroscopy of icy Galilean and saturnian satellites
	Measure seasonal changes in volatile CO2	Unresolved NIR spectroscopy of uranian satellites
	Measure migration of hypervolatiles like CO, N2, CH4, including surface/atmosphere interactions	Spatially-resolved NIR spectroscopy of Triton, Pluto/Charon, TNO dwarf planets

Figure 4 Traceability of science goals to observables. Numbers in first column refer to Table S.1 in *Vision and Voyages for Planetary Science in the Decade 2013-2022* (p.19). Team members wishing to edit the matrix should use the online google sheet for this by typing in this URL to your browser: https://goo.gl/5uqwy9 (make sure to use the correct worksheet tab for this cadence proposal).

Science Objectives	Instrument requirements	Cadence Visits per year	Mosaic span	Mosaic step duration (hr)	Mosaic steps (N)
Quantify CH4 on Mars: spatial and temporal variability	NIR spectra at R~100,000. AO spatial resolution.	2	25 hr	0.5	6
Trace mesosphere circulation	TBD	TBD	TBD	TBD	TBD
Determine the spatial and temporal variation of haze layers, clouds, CH4 humidity, and surface moisture	Diffraction limited imaging. Spectroscopy in 0.8–2.5 µm range at R~2000.	1	16 d	0.5	4
Determine the spatial distribution and vertical structure of cloud features on Uranus/Neptune	Diffraction limited spectroscopy in 0.8–2.5 µm range at R~2000.	2	15 h	1	4
Measure 3D wind flow in all four giant planets	Diffraction-limited imaging in NIR, range of ~5 narrow-band filters sampling different gas opacities.	4	20-30 h	0.5	16
Understand temporal variation of particle properties, composition, and temperature in zonal bands in all four giant planets	Diffraction-limited imaging in visible, NIR, and MIR.	4	10-15 h	0.5	6
Understand interactions with magnetospheres, plasma torii, solar wind, ring rain, interplanetary dust	Diffraction-limited NIR imaging for short-term context, spatially-resolved spectroscopy for temperatures and abundances.	4	5 h	5	1
Measure evolution of dynamical properties of rings and moons, and radial/asimuthal particle properties	Diffraction-limited NIR imaging within CH4 absorption bands	4	10 h	0.5	1-4
Understand changes in H2O ice state, and in the abundance/spatial distribution of irradiation-produced volatiles	Diffraction limited spectroscopy in 0.7-2.4 µm range at R~4000	12	2-80 d	0.5	4
Measure seasonal changes in volatile CO2	Point-source spectroscopy in K at R~4000	5	1-10 d	0.5	4
Measure migration of hypervolatiles like CO, N2, CH4, including surface/atmosphere interactions	Diffraction limited spectroscopy in 0.7-2.4 µm range at R~4000	10	0-5 d	0.5	4

Figure 5 Traceability of objectives to instrument and cadence requirements. See technical sections for detailed discussion of cadence parameters. Briefly, mosaics are arrays of regularly-spaced pointings in time (not regularly-spaced pointings on the sky as is usually the case). Each pointing has a specific observation duration, and pointings are spaced over a span ranging from < 1 hr to many days. Because there are multiple targets, mosaic visits are repeated several times per year with similar temporal layouts each instance, but different targets. Team members wishing to edit the matrix should use the online google sheet for this by typing in this URL to your browser: https://goo.gl/5uqwy9 (make sure to use the correct worksheet tab for this cadence proposal).

Encrenaz et al. 2013. HDO and SO2 thermal mapping on Venus. II. The SO2 spatial distribution above and within the clouds. Astron. & Astrophys. 559, 65.

Fletcher et al. 2010. Neptune's atmospheric composition from AKARI infrared spectroscopy. Astron. & Astrophys. 514, 17.

Formisano et al. 2006. Observations of non-LTE emission at 4.5 microns with the planetary Fourier spectrometer aboard the Mars Express mission. Icarus 182, 51.

Fouchet et al. 2008. An equatorial oscillation in Saturn's middle atmosphere. Nature 453, 200.

Howard et al. 2010. The occurrence and mass distributions of close-in super-earths, Neptunes, and Jupiters. Science 330, 653.

Lellouch et al. 2000. The 2.4-45 μm spectrum of Mars observed with the Infrared Space Observatory. Planet. & Space Sci. 48, 1393.

Lellouch et al. 2002. The origin of water vapor and carbon dioxide in Jupiter's stratosphere. Icarus. 159, 112.

Lellouch et al. 2003. Titan's 5-μm window: Observations with the Very Large Telescope. Icarus 162, 125.

Melin et al. 2011. New limits on the H3+ abundance on Neptune using Keck NIRSPEC. Monthly Not. Roy. Astron. Soc. 410, 641.

Orton et al. 2014. Mid-infrared spectroscopy of Uranus from the Spitzer infrared spectrometer: 2. Determination of the mean composition of the upper troposphere and stratosphere. Icarus 243, 471.

Roe et al. 2008. A rough guide to Titan. Nature 453, 453.

Rymer et al. 2018. Solar system ice giants: Exoplanets in our backyard. Solar system exoplanets white paper 2018arXiv180403573R.

Teanby et al. 2008. Titan's winter polar vortex structure revealed by chemical tracers. J. Geophys. Res. 113, E12003.

Yelle and Griffith. 2003. HCN fluorescence in Titan. Icarus 166, 107.

Zasova et al. 2004. Infrared spectrometer of Venus: IR Fourier spectrometer on Venera 15 as a precursor of PFS for Venus express. Adv. in Space Res. 34, 1655.

Bennett, C.J., Pirim, C. and Orlando, T.M., 2013. Space-weathering of solar system bodies: A laboratory perspective. Chemical reviews, 113 (12), p. 9086-9150.

Brown, R.H. and Cruikshank, D.P., 1983. The Uranian satellites: Surface compositions and opposition brightness surges. Icarus, 55 (1), p. 83-92.

Brown, M.E., Schaller, E.L. and Fraser, W.C., 2012. Water ice in the Kuiper Belt. The Astronomical Journal, 143 (6), p. 146.

Cartwright, R.J., Emery, J.P., Rivkin, A.S., Trilling, D.E. and Pinilla-Alonso, N., 2015. Distribution of CO2 ice on the large moons of Uranus and evidence for compositional stratification of their near-surfaces. Icarus, 257, p. 428-456.

Cartwright, R.J., Emery, J.P., Pinilla-Alonso, N., Lucas, M.P., Rivkin, A.S., and Trilling, D.E., 2018. Red material on the large moons of Uranus: Dust from the irregular satellites? Icarus, 314, p. 210-231.

Cassidy, T., Coll, P., Raulin, F., Carlson, R.W., Johnson, R.E., Loeffler, M.J., Hand, K.P. and

Baragiola, R.A., 2010. Radiolysis and photolysis of icy satellite surfaces: experiments and theory. Space science reviews, 153 (1-4), p.299-315.

Clark, R.N. and Lucey, P.G., 1984. Spectral properties of ice-particulate mixtures and implications for remote sensing: 1. Intimate mixtures. Journal of Geophysical Research: Solid Earth, 89 (B7), p. 6341-6348.

Cruikshank, D.P., Roush, T.L., Owen, T.C., Geballe, T.R., De Bergh, C., Schmitt, B., Brown, R.H. and Bartholomew, M.J., 1993. Ices on the surface of Triton. Science, 261 (5122), p. 742-745.

Earle, A.M., Binzel, R.P., Young, L.A., Stern, S.A., Ennico, K., Grundy, W., Olkin, C.B. and Weaver, H.A., 2017. Long-term surface temperature modeling of Pluto. Icarus, 287, p. 37-46.

Gao, P., Fan, S., Wong, M.L., Liang, M.C., Shia, R.L., Kammer, J.A., Yung, Y.L., Summers, M.E., Gladstone, G.R., Young, L.A. and Olkin, C.B., 2017. Constraints on the microphysics of Pluto's photochemical haze from New Horizons observations. Icarus, 287, p. 116-123.

Grundy, W.M., Young, L.A. and Young, E.F., 2003. Discovery of CO2 ice and leading–trailing spectral asymmetry on the uranian satellite Ariel. Icarus, 162 (1), p. 222-229.

Grundy, W.M., Young, L.A., Spencer, J.R., Johnson, R.E., Young, E.F. and Buie, M.W., 2006. Distributions of H2O and CO2 ices on Ariel, Umbriel, Titania, and Oberon from IRTF/SpeX observations. Icarus, 184 (2), p. 543-555.

Grundy, W.M., Young, L.A., Stansberry, J.A., Buie, M.W., Olkin, C.B. and Young, E.F., 2010. Near-infrared spectral monitoring of Triton with IRTF/SpeX II: Spatial distribution and evolution of ices. Icarus, 205 (2), p. 594-604.

Grundy, W.M., Bertrand, T., Binzel, R.P., Buie, M.W., Buratti, B.J., Cheng, A.F., Cook, J.C., Cruikshank, D.P., Devins, S.L., Dalle Ore, C.M. and Earle, A.M., 2018. Pluto's Haze as a Surface Material. Icarus, 314, p. 232-245.

Hendrix, A.R., Buratti, B.J., Cruikshank, D.P., Clark, R.N., Scipioni, F. and Howett, C.J., 2018. Surface Composition of Saturn's Icy Moons. Enceladus and the Icy Moons of Saturn, p.307.

Hicks, M.D. and Buratti, B.J., 2004. The spectral variability of Triton from 1997–2000. Icarus, 171 (1), p. 210-218.

Hofgartner, J.D., Buratti, B.J., Hayne, P.O. and Young, L.A., 2018. Ongoing Resurfacing of KBO Eris by Volatile Transport in Local, Collisional, Sublimation Atmosphere Regime. Icarus. https://doi.org/10.1016/j.icarus.2018.10.028

Holler, B.J., Young, L.A., Grundy, W.M. and Olkin, C.B., 2016. On the surface composition of Triton's southern latitudes. Icarus, 267, p.255-266.

Johnson, R.E. and Jesser, W.A., 1997. O2/O3 microatmospheres in the surface of Ganymede. The Astrophysical Journal Letters, 480 (1), p. L79.

Moore, J.M., McKinnon, W.B., Spencer, J.R., Howard, A.D., Schenk, P.M., Beyer, R.A., Nimmo, F., Singer, K.N., Umurhan, O.M., White, O.L. and Stern, S.A., 2016. The geology of Pluto and Charon through the eyes of New Horizons. Science, 351 (6279), p. 1284-1293.

Moore, J.M., Howard, A.D., Umurhan, O.M., White, O.L., Schenk, P.M., Beyer, R.A., McKinnon, W.B., Spencer, J.R., Grundy, W.M., Lauer, T.R. and Nimmo, F., 2017. Sublimation as a landform-shaping process on Pluto. Icarus, 287, p. 320-333.

Noll, K.S., Roush, T.L., Cruikshank, D.P., Johnson, R.E. and Pendleton, Y.J., 1997. Detection of ozone on Saturn's satellites Rhea and Dione. Nature, 388 (6637), p. 45.

Owen, T.C., Roush, T.L., Cruikshank, D.P., Elliot, J.L., Young, L.A., De Bergh, C., Schmitt, B., Geballe, T.R., Brown, R.H. and Bartholomew, M.J., 1993. Surface ices and the atmospheric composition of Pluto. Science, 261 (5122), p. 745-748.

Schaller, E.L., 2010. Atmospheres and surfaces of small bodies and dwarf planets in the Kuiper Belt. EPJ Web Conferences 9, 267-276.

Sori, M.M., Bapst, J., Bramson, A.M., Byrne, S. and Landis, M.E., 2017. A Wunda-full world? Carbon dioxide ice deposits on Umbriel and other Uranian moons. Icarus, 290, p.1-13.

Spencer, J.R. and Calvin, W.M., 2002. Condensed O2 on Europa and Callisto. The Astronomical Journal, 124 (6), p. 3400.

Tiscareno, M.S. and Murray, C.D., 2018. *Planetary Ring Systems: Properties, Structure, and Evolution.* Cambridge University Press, 598pp.

Trafton, L., 1984. Large seasonal variations in Triton's atmosphere. Icarus, 58 (2), p. 312-324.

Umurhan, O.M., Howard, A.D., Moore, J.M., Earle, A.M., White, O.L., Schenk, P.M., Binzel, R.P., Stern, S.A., Beyer, R.A., Nimmo, F. and McKinnon, W.B., 2017. Modeling glacial flow on and onto Pluto's Sputnik Planitia. Icarus, 287, p. 301-319.

Verbiscer, A.J., Helfenstein, P., Buratti, B.J. and Royer, E., 2018. Surface Properties of Saturn's Icy Moons from Optical Remote Sensing. Enceladus and the Icy Moons of Saturn, p.323.

Telescopes and Instruments *Discuss the program requirements for the telescope(s) (GMT and/or TMT), instrumentation, and adaptive optics systems. Use of both TMT and GMT in an integrative fashion merits particular attention. If the program can be carried out using instruments planned for the GMT/TMT early-light suites, discuss what particular capabilities (e.g., spectral resolution, angular resolution, AO performance, etc.) are required. If new capabilities beyond the defined early-light instruments are needed, describe the requirements in a suitable level of detail.*

Operational requirements: The most important consideration for this program is the temporal requirements. We discuss this in the following section (Experimental Design). Queue scheduling is particularly important for efficient operations, and lessons learned from Gemini Observatory's scheduling and operational procedures may be helpful for development of GMT and TMT operational concepts (REF DPS).

Instrument requirements: Due to the large number of targets, instruments, and observing modes desired, detailed exposure time and other technical requirements are beyond the scope of this KSP. Helpful capabilities for solar system observations would be the ability to provide AO corrections with differential tracking rates between guide stars and targets, extended sources as AO guide stars, good AO corrections over FOVs in the several tens of arcsec for imaging of extended sources, access to mid-IR wavelengths for imaging and spectroscopy, saturation limits that accommodate bright object observations, long (20-60") spectroscopic slit lengths to enable spectroscopy on extended sources, and large (60") chop/nod offsets for extended object sky frames.

First- and future-light instruments: For visible light imaging at high angular resolution, we would use the GMT commissioning camera, GMT GMagAOx, and TMT PSI. For NIR imaging and spectrscopy at high angular resolution, we would use GMT IFS and TMT IRIS with NFIRAOS. For mid-IR spectroscopy and imaging, we would use TIGER and MIRES/MICHI.

Experimental Design *Describe the details of the observational program, including: • Target/sample selection. This may be a description of a target selection strategy that would be appropriate in the future when the project would be executed. Specific targets may be specified, particularly if they demonstrate the value of a 2-telescope, 2-hemisphere system. • A description of the required observations. • Signal-to-noise requirements and exposure time estimates. Because the detailed parameters of future instruments may not be precisely known now, this section should discuss the assumptions adopted. • Special requirements for observing conditions (if appropriate), in particular with regard to image quality and adaptive optics, precipitable water vapor, or other special conditions. • Scheduling requirements (as appropriate), including lunar phase, observing cadence, and/or timing constraints.*

Target list: Targets in this program include Venus, Mars, Jupiter, Saturn, Uranus, and Neptune; the rings of the outer planets; over a dozen moons across the giant planets; and resolvable TNOs including centaurs, Pluto/Charon, and several dwarf planets. The number of dwarf planets with potential surface/atmospheric evolution is still increasing, with new objects expected to be discovered prior to the start of this program. Target sizes range from the arcminute scale (Venus, Jupiter, and the main rings of Saturn) to less than an arcsec (TNOs and satellites).

AO scenarios: A range of scenarios can be anticipated. For the largets objects, faint AO guide stars would remain fixed while the bright target drifts at a non-sidereal rate; Gemini observation tools provide good heritage for identifying guide stars in this use case. For many objects with diameters up to the size of Uranus (4″), it would be advantageous to be able to perform wavefront sensing on the target itself, as can be done with the Keck and Gemini AO systems. NFIRAOS is not expected to enable wavefront sensing with extended sources.

Timing requirements: The Technical Summary matrix (Fig. 5) lists temporal requirements for each science objective. We first define each column of the table, and then give an example of how each element affects the design of an observing program.

Visits per year - the number of times per year that an individual target needs to be observed to characterize long term change on multiple timescales. In some cases, the number of visits per year is much greater than one, indicating that the science objective calls for observations of multiple targets on an annual basis.

Mosaic parameters - these collectively describe the temporal sampling in an individual target visit. In this case a mosaic consists of several discrete observations of a rotating body in order to create a longitudinal mosaic that spans the full observable globe. In the case of cloud-tracked winds on giant planets, the full mosaic spans two full rotations. On a given rotation, not all longitudes will be sampled due to limited visibility in a single night; this limitation can be partially overcome in some favorable cases by combining observations from both TMT and GMT at different longitudes on Earth. At each "mosaic step" in the global coverage, we assign a minimum observation duration of 0.5 hr for straightforward imaging or spectroscopic observations of bright targets, and longer durations in cases where short-timescale variation can be observed. The number of mosaic steps is determined by the number of samples needed to provide good longitudinal coverage for a particular objective.

As an example, consider the observations of planetary rings to measure the evolution of dynamical properties of rings and moons, and radial/azimuthal particle properties. There are 4 visits/year, because each giant planet hosts a ring system that is observed annually. The science requirement is that at least 180° of longitude are observed. For ring systems viewed at large ring opening angles, this can be done all at once (mosaic steps = 1), but for more edge-on systems, up to 4 mosaic steps are required over a span of 10 hours as the rings rotate.

NRM Imaging of Io: High resolution imaging with non-redundant masking (NRM) of Io (and the Jovian system in general) requires a zenith distance (ZD) within 20 degrees or so for rotational coverage. Depending on where it is in its cycle, Jupiter will be nearer to the zenith of TMT or GMT. A coordinated campaign could therefore take advantage of having a telescope in both the south and the north to always observe at a time when Jupiter is transiting near zenith.

Observing Program Summary *Summarize the overall observing program. This should include: • A high-level review of the program as it would be executed, potentially over several years, including the sequence of observations if relevant. • The total observing time required for each telescope, instrument, and instrument mode used, based on the detailed information from the Experimental Design.*

Total time: The overall program proposed here would require about 130 hours per year, and would continue for the lifetime of the ELT observatories. We have not prepared a breakdown of time per instrument or observatory, but the instrument requirements in Fig. 5 suggest that the majority of the observations would be done in NIR imaging and spectroscopic modes, with instruments like TMT IRIS and GMT IFS. Within an overall program that continues for decades, we envision multi-year campaigns, where uniform observations are obtained with a particular target/instrument combination throughout the campaign. If 130 hours/year is not a feasible time allocation, a reduced set of objectives could be investigated in each campaign. A committee of experts could convene regularly to decide the balance of objectives receiving time during a campaign, and the instruments used for each objective.

Opposition: The timing of outer solar system observations should be within about 40 days of solar opposition, yielding maximal spatial resolution due to reduced geocentric distance, and minimum target airmass.

Duty cycle: Throughtout the year, individual observation visits to all the targets would be scheduled in a queue mode to ensure observatory efficiency. For example, Fig. 5 lists the objective, "Understand temporal variation of particle properties, composition, and temperature in zonal bands in all four giant planets." For this objective, a visit consists of 6 evenly-spaced mosaic steps, each 0.5-hours long, spanning 10-15 hours total duration per target (corresponding to the target's rotation rate). For the fastest rotating target then, it is 1.7 hours between mosaic pointing start times, but a single pointing only takes 0.5 hours of observing time. Queue scheduling would enable other programs (or other visits in this program) to occupy the unused 1.2 hours of time between mosaic pointings. For planetary satellites, orbital periods can be long (up to 80 days for Iapetus), so a single visit might consist of four mosaic pointings spread over several months to obtain the required longitudinal coverage.

Legacy Value *Discuss the legacy value of these observations and the data they would generate for the broader scientific community, including a description of potential data products and the ancillary science that might be enabled by this dataset.*

Long-term baseline: The true value of this program is its contribution to a long-term baseline of observations of dynamic processes. The overall effort extends beyond the ELTs, extending the results of prior spacecraft missions like Cassini, and prior long-term observing campaigns like the Outer Planet Atmospheres Legacy program with HST. Likewise, future efforts focused on time variation will build upon the legacy of the US-ELTs Deep Time-Survey. Although discoveries will be made with individual Deep Time-Survey observations, the true objective is to achieve discoveries using the long campaign of observations obtained after many years of operation.

Data processing and distribution: To realize the full potential of the data, curators will be needed to process the data beyond standard instrument pipeline levels. To enable users to pick up the data and immediately conduct science investigations, the data will need to be processed so as to be mapped in each target's latitude/longitude frame, and calibrated in terms of physical units such as reflectivity (in the visible and NIR ranges) or brightness temperatueres (in the mid-IR). At this point, it is not clear what mechanism would exist to ensure that the data curation takes place, in a uniform and reliable way, for the duration of the program.

Operational differences from traditional PI-led programs: The major difference between the proposed program, and traditional PI-led programs, is the uniform time coverage and long term program duration. PI-led programs result in gaps in the temporal coverage and/or inconsistencies in the types of data obtained (interfering with the measurement of dynamic processes). On the other hand, PI-led programs have a clear director to ensure publication of results. This type of program would be new, and would need careful thought as to how data would be curated and results published.

Analysis Plan *Describe the program requirements for data analysis and interpretation. This may include: • Data management and software needed for data reduction and analysis. • Simulations needed to interpret the data. • Other resources (e.g., computational, user support) that may be necessary.*

Mission model: One option for processing and analysis could be the NASA spacecraft mission model. NASA requires spacecraft mission science teams to process data up to specific levels, and to archive the data in permanent repositories. This of course requires a science team, so there would need to be a mechanism for establishing a science team for the US-ELTs Deep Time-Survey effort. In the NASA mission model, the science team would publish initial results, but the entire science community would also join in the analysis of the archived data.

Minimal model: A more minimal model would still rely on an observer or team of observers to define useful observations, but analysis of the data would be done by community members based on raw data from the observatory archive. This approach might lead to reduced science yield, or it could result in a type of open-source community without any central organization. The outcomes of such a minimal analysis model would be less predictable.

Synergy with Other Facilities or Resources *If relevant, describe how the proposed TMT/GMT observations complement data from other facilities. This may include: • Required coordination between the proposed GMT/TMT program and observations or data resources from other facilities in space or on the ground. • Preparatory or ancillary datasets that will be required to carry out this Key Science Program.*

Temporal synergy: Observations as part of this program would primarily be synergistic with past and future observations of the dynamic solar system. The US-ELT program's establishment of a long-term baseline of observations of time-domain processes in the solar system would be a lasting legacy of similar value to the Hubble archive, which is polled whenever researchers study time-domain processes. Future studies in the post-ELT era are difficult to conceptualize at this point in time, but they will rely on the US-ELT's Deep Time-Survey for comparison because it will represent the state of the art in planetary astronomy. Likewise, data from this program will reveal causes and effects of dynamic processes that could not fully be understood from past data due to limitations in spatial resolution, temporal coverage, or sensitivity.

Spacecraft mission synergy: Clearly, US-ELT observations will provide temporal context for any spacecraft missions of the past or future. But they will also supplement simultaneous solar system missions. For example, many recent missions have lacked mid-IR instruments in their payloads, enabling ground-based observations to fill in the gaps in this crucial wavelength range (Orton et al. 2017).