# The U.S. Extremely Large Telescope Program

THIRTY METER TELESCOPE

NOAO

GIANT MAGELLAN TELESCOPE

## Key Science Program Description Document

*Date:* January 28, 2019 **Category:** Our Solar System

# Triggered High-Priority ELT Observations of Dynamic Solar System Phenomena


**Abstract of Scientific Justification**

Unexpected dynamic phenomena have surprised solar system observers in the past and have led to important discoveries about solar system workings. Observations at the initial stages of these events provide crucial information on the physical processes at work. We propose a long-term/permanent program to conduct ELT observations of high-priority dynamic phenomena, based on a predefined set of triggering conditions. The program will ensure that the best initial dataset of the triggering event are taken; separate additional observing programs will be required to study the temporal evolution of these phenomena.

**High-priority dynamic phenomena:** We select only phenomena that are rare, that cannot be anticipated, and that provide high-impact advances to our understandings of planetary processes. Examples include:

- new cryovolcanic eruptions or plumes on ocean worlds
- impacts on Jupiter, Saturn, Uranus, or Neptune
- extreme eruptions on Io
- convective superstorms on Saturn, Uranus, or Neptune
- collisions within the asteroid belt or other small-body populations
- discovery of an interstellar object passing through our solar system (*e.g.* ‘Oumuamua)
- responses of planetary atmospheres to major solar flares or coronal mass ejections

**Triggering:** Predefined high-impact events will trigger a set of pre-defined observations. Trigger conditions will be established to ensure significant science return. We also include a category for unanticipated dynamic phenomena, which will require US-ELTP or observatory leadership endorsement for activation. In many semesters, there may not be any data returned at all, so we request that there be no specific cap on the number of activations per semester.

**Data credits:** Data from this program will be immediately available to everyone, enabling rapid follow-up observations with additional DD programs at major observatories.

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**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.*

An ELT Key Science Program triggered by new and unforeseen solar system discoveries and phenomena relies on the unique capabilities of the TMT/GMT for making time-critical followup observations. The overarching goal of these observations is to use these dynamic phenomena to understand key processes that have shaped the formation and evolution of our solar system. This goal is directly aligned with the range of big questions outlined in the astrophysics and planetary science decadal surveys and the NASA science plan.

Several such opportunistic observations made over the past decade using current state-of-the-art facilities are described below. These are meant to serve as *examples* of the types of triggered solar system observations envisaged with the ELT, with the recognition that there are likely to be new serendipitous discoveries equally appropriate for triggered ELT follow-up observations.

**Impacts:** Impacts on giant planets are rare, but have provided unique insights into impactor populations, the physics of high-velocity atmospheric impacts, and giant planet stratospheric chemistry and circulation on multiple time scales. To date, we have witnessed a total of seven impact events on Jupiter: a fireball recorded by Voyager 1 in 1979 [2], the impacts of the fragments of Comet Shoemaker-Levy 9 in 1994 [14], an impact scar first detected by an amateur astronomer in 2009 and then observed with the Hubble Space Telescope [31, 5, 13, 8, 25, 30], and four subsequent impact flashes detected by amateur astronomers using high-speed imaging techniques [17, 16, 29] (Fig. 1a). Each of these events provided additional constraints on the nature of the impactors, the size distribution of small bodies in the vicinity of Jupiter, and the impact rates. An extrapolation of cratering record on the Galilean satellites suggests that Jupiter should receive $\sim$1 detectable impact (*i.e.* from a 10m-class object) every Earth year [32]. In contrast, modeling the orbital evolution of known comets and asteroids that encounter Jupiter and extrapolating the result to the 10m-class objects would result in 50 such collisions every year [22]. The discrepancy between these estimates comes from the fact that the size distribution of objects in the 10m class or smaller has not been studied in detail. As four impacts have been detected since 2009 using modest aperture telescopes, the event rate is likely to be significantly greater than one/year. Accumulating impact records is the only viable way of determining the size distribution of bodies in that class because such bodies are too small to be detected through telescopic observations.

The size distribution of small bodies is collisionally controlled; thus, determination of the small body size distribution will shed light on the evolution of the outer solar system. One scenario that has been relatively successful in explaining the orbital distribution of small bodies in the outer solar system (Trojan asteroids, Kuiper belt), the "Nice model," invokes migration and mean-motion resonance of the outer planets [24, 37, 10]. If the generalities of the Nice model are correct, substantial collisional processes must have occurred during the scattering of KBOs, leading to the production of small, 10m-class objects. An analysis of Jovian impacts enabled through ELT observations will add important constraints to these outer solar system evolution models.

**Outer planet storms:** Superstorm eruptions on Saturn, Uranus, and Neptune are key to understanding the heat transport within hydrogen-dominated atmospheres, particularly the nature of moist convection and its inhibition by molecular weight stratification.

Small telescopes equipped with modern digital imaging capabilities rival the capabilities that were available with professional telescopic facilities during the 1965 equinox of Uranus. Even 1m-class telescopes now routinely resolve atmospheric features on Uranus, and these detections can be used to trigger ELT observations to study episodic atmospheric events. If a bright atmospheric feature appears and is confirmed through multiple ground-based observations sufficiently to predict its longitudinal motion, ELT observations will be triggered in order to resolve the detailed vertical and horizontal structure of such a feature. Additionally, ELT observations can reveal any secondary features such as dark spots that may be formed by a companion storm (Fig. 1b), and elucidate further details of their morphological evolution as driven by atmospheric dynamics. ELT observations of a new dark spot in the process of its formation would be especially valuable because little is known about the processes that form the dark anticyclones. To date, HST has detected only two dark spots on Uranus, and 4 on Neptune [12, 35]. Also, thermal balance of Uranus and Neptune is poorly understood; in particular, the zero thermal flux of Uranus derived by Voyager [27] may have represented a quiescent inter-storm period, while much of the heat flux may be carried by episodic storms. Thus, ELT observations of Uranus and Neptune that document transient phenomena would have implications for understanding the radiative-convective balance in their atmospheres.

**Extreme eruptions on Io:** The prodigious volcanic activity of the Jovian satellite Io is a consequence of tidal heating on an eccentric orbit maintained by the 4:2:1 Laplace orbital resonance with Europa and Ganymede [26], but the energy dissipation, melt production and transport, and the eruptions themselves are poorly understood [3]. Long-term monitoring with 8-10 m telescopes has revealed persistent yet dynamic activity, including occasional outburst eruptions that double the radiant flux from Io at 5 $\mu$m [4]. Observed near inception, these eruptions can be precisely located and eruption temperatures measured; the latter constrains the composition and degree and location of partial melting within Io's interior. Time-series observations obtain the duration, changes in location, eruption style, and effusion and eruption rates. These will help us understand the mechanism of Io's volcanism and by inference other bodies with high heat flow such as the terrestrial planets in the early Solar System and volanically active exoplanets. The greater sensitivity and resolution of TMT and GMT over current 8-10m telescopes (Io subtends only 1.2" at opposition) will provide more precise spatial and spectral information. As a demonstration, observations with the Large Binocular Telescope Interferometer [1] were able to distinguish two separate eruptions, strong evidence for a lava lake (Fig. 1c). Since the eruptions vary on timescales of minutes, hours, days, and much longer, interrupt observations with ELTs are critical to observe the site (which often cannot be observed again for several days because of Io's orbit).

**Small body collisions:** The Large Synoptic Survey Telescope (LSST) will detect large numbers of asteroids each night, including objects that exhibit activity due to escape of dust. There are two proposed mechanisms for the origin of this comet-like activity, which has been observed on several Main Belt asteroids using the Hubble Space Telescope (Fig. 1d). For some objects, the volatile escape reaches a maximum near perihelion and is repeatable, suggesting a comet-like origin for these emissions [18]. For others, the observed dust emissions are not correlated with heliocentric distance, suggesting that the dust may be a result of collisions between small bodies [21]. There are currently 18 active asteroids (those driven by volatile outgassing are referred to as Main Belt Comets) known [34], yet no single explanation for their gas and dust emissions matches all observations. If such objects are discovered through routine LSST observations, they can be used to trigger ELT observations to obtain images and spectra that together can be used to quantify the amount of ice present in these objects, and by extrapolation, in the Main Belt. This has significant astrobiology implications since these objects may represent relics of the population that delivered water to the early Earth.

**Unexpected phenomena**: The discovery of the first interstellar object (ISO) 1I/2017 U1 ('Oumuamua) in October 2017 [23] has opened a new window on a broader perspective of planetary systems represented by the ejected building blocks and fragments that fortuitously pass through the solar system [28]. 'Oumuamua was discovered during the course of routine Near Earth Asteroid sky surveys and it was moving very quickly through the inner solar system. Within the time it took to mobilize telescope assets to conduct triggered target of opportunity observations it had faded significantly, thus reducing the quality and amount of data that could be obtained.

LSST is expected to detect more of these objects [6] and visible and infrared photometry, astrometry, adaptive optics imaging, and spectroscopy are needed to determine the orbit, shape, rotation, presence or absence of a coma, and composition of these objects (Fig. 1e). Not only has 'Oumuamua proven to be enigmatic but its investigation was limited by its small size ($\sim$ 100m), faintness ($H_V \approx 22.4$) and a hyperbolic, highly inclined trajectory though the inner Solar System ($e \sim 1.20$, $i = 123°$). If 'Oumuamua is characteristic of ISOs then effective follow-up will required very large aperture and rapid, triggered response in both geographic hemispheres to characterize these objects. The exceptional range of photometric variability of 'Oumuamua can be explained by an extreme aspect ratio [23] or binary shape [9] and the shape of ISOs are informative about their formation mechanism and tidal stress history [28]. These objects will not be spatially resolved (100m at 1 au = 0.14 mas) but the shape can be inferred by changes in the rotational light curve as the object moves along its trajectory as aspect and illumination angles change, driving the requirement for precise photometry to distances $\gg$ 1au and magnitudes to $V \sim 30$. Low-resolution optical and infrared spectroscopy of ISOs can distinguish between icy, rocky, and surfaces similar to the classic asteroid types, but current telescopes are not adequate for definitive conclusions [7]. Fainter surface brightness sensitivity will permit detection or improved upper limits on dusty outgassing [23, 19].

**Atmospheric response to solar activity**: Observing the effects on terrestrial planet atmospheres of ionizing radiation and charged particles emitted from the Sun during solar flares or coronal mass ejections provides an opportunity to study space weather on other planets. This has important implications for understanding the role of stellar activity in driving atmospheric evolution and escape. Large numbers of exoplanets have been and will be discovered around M dwarfs, many of which have levels of stellar activity higher than that of the Sun. Thus our own solar system serves as an ideal laboratory for advancing our understanding of the role of space weather in atmospheric evolution and by extension the habitability of exoplanets around active stars.

Auroral and nightglow oxygen emissions have been detected on the nightside of Venus using 3 and 10m class telescopes [33, 11], but the spatial resolution has been insufficient to characterize their spatial structure. The appearance of the oxygen green line is correlated with solar activity, and it is more closely linked to charged particle precipitation due to coronal mass ejections than enhanced EUV flux from solar flares [11]. Spatially resolved measurements of Venus' optical and NIR nightglow emissions are critical for understanding the variation of Venus' atmospheric flows with altitude, as the IR $O_2$ emissions are diagnostic of general atmospheric circulation whereas the atomic oxygen green line emission follows the subsolar to antisolar flow. These observations would be triggered by the detection of major solar eruptions during periods of high solar activity. Observations of Venus' nightglow emissions are optimal when the Earth-Venus relative velocity is maximized, *i.e.* the emissions are Doppler shifted out of the terrestrial airglow lines (Fig. 1f). Observations of Venus made with ELTs between maximum western elongation and inferior conjunction would be feasible; Venus would be observable during morning twilight with at least half of its night side visible from Earth. ELTs would offer unprecedented spatial resolution of the nightglow emissions on Venus, providing critical information about the atmospheric response to stellar activity.

**The science questions addressed by the proposed observations are diverse but all can be linked to the fundamental questions concerning the formation and evolution of our solar system. Our solar system remains an important laboratory for understanding physical processes such as migration, impacts, heat balance, and star-planet connections as we begin to develop a comprehensive understanding of the workings of planetary systems overall.**

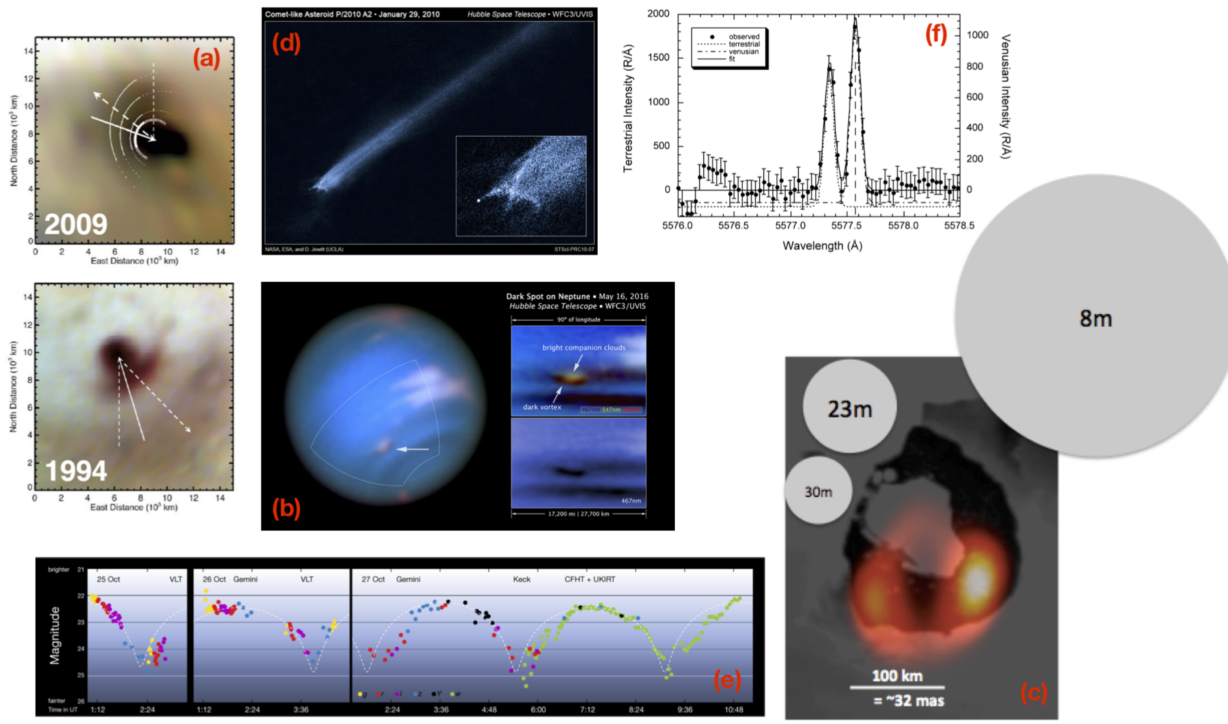


Figure 1: Examples of time-critical solar system phenomena that could be observed through triggered ELT observations. (a) Map projections of Jupiter impact debris acquired after the 2009 impact event (top) and the Shoemaker-Levy 9 impacts in 1994 (bottom) [31]. (b) Dark vortex on Neptune discovered using the Hubble Space Telesocpe [38]. (c) Voyager spacecraft image with emission measured by 23m LBTI overlaid in orange color and smoothed for better visualization. The resolution disks for that 23m aperture, along with disks for 8 and 30m apertures, are also shown for comparison. (d) HST observation of main belt comet P/2010 A2 revealing an extended dust tail [20]. (e) Light curve of ‘Oumuamua obtained over three days in October 2017 showing a brightness range of 2.5 magnitudes (from https://www.eso.org/public/images/eso1737f/). (f) Oxygen green line emission detected on Venus’ night side with the Keck 10m telescope shortly after a solar flare and coronal mass ejection [33, 11].

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**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.*

The primary requirement for ELT triggered solar system observations is rapid response, which places operational constraints on the proposed observations (discussed further below). Each trigger will likely require both an imaging and spectroscopic response, and will make use of AO imaging and visible/near-IR/mid-IR spectroscopic instrumentation. Specific instrument choices include IRIS+NFIRAOS, MIRES, NIRES, and WFOS on the TMT, and G-CLEF, TIGER, GMTIFS, and GMTNIRS on the GMT.

Use of GMT or TMT (or both) will depend on the target location. Solar system objects that travel along the ecliptic will be visible from both hemispheres and can take advantage of using complementary instrumentation on the two telescopes nearly simultaneously to maximize the science return. Objects with highly inclined orbits may only be accessible with one of the two telescopes, and will be restricted to the available instruments.

**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.*

The targets for this program cannot be selected *a priori* and must be identified on a case-by-case basis. Example targets are described above in the Science Justification section; that list provides representative examples of the types of targets that could be observed through this kind of program.

The specifics of the required observations will depend on the nature of the target to be observed. The triggered observations will likely require an imaging and spectroscopic response, and will likely make use of some combination of AO imaging and visible/near-IR/mid-IR spectroscopic instrumentation. Specific instrument choices include IRIS+NFIRAOS, MIRES, NIRES, and WFOS on the TMT, and G-CLEF, TIGER, GMTIFS, and GMTNIRS on the GMT. A matrix of possible triggers and their required instruments (along with potential backup instruments) would be developed for a full observing proposal so that a rapid response can be executed under any conditions.

The timing constraints also will be a function of the nature of the target being observed. Based on past experience with triggered solar system observations we expect the schedule interrupt time to range between 0.5 – several hours to several days.

**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.*

An ELT program to observe dynamic solar system phenomena could be triggered by any member of the proposing team. A proposal would be submitted, reviewed, and if approved on scientific and technical merits, would be held in reserve for activation when and if appropriate. Different triggers have different probabilities, as discussed in the Science Justification. These probabilities depend on a wide range of factors, for example the nature of an impacting population, the thermal balance in the deep atmospheres of the ice giants, or the level of solar activity. A proposal for triggered solar system observations would take these different probabilities into account to ensure that rare events would always trigger, while more common events would trigger only once per interval (*e.g.* semester or year).

The total amount of observing time requested would likely sum to $\leq 1$ night per year, but this is envisaged as a long-term program.

**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.*

The data obtained through this program would provide unique and valuable insight into time variable phenomena in the solar system. As a result of the rapid response time, these initial time steps will form the basis of evolution studies enabled through subsequent observations made with US-ELTs and other facilities. By virtue of their large apertures and superior instrumentation suite, the ELT observations will provide unique observations at unprecedented spatial resolution.

The ancillary science that can be enabled by these data is extensive. These first-response observations will produce a rich dataset that can be mined for additional science. In this way the US-ELT program can broaden active participation in its overall effort. Contributing monitors will have a personal stake in the publicly-available ELT data resulting from the overall program. For example, if an impact event on Jupiter triggers follow-up ELT observations, which will likely consist of imaging and spectroscopy, those data can be used to address additional science objectives outside the scope of the triggering science. Jupiter's zonal (east-west) wind profile is known to vary at certain latitudes, likely as a result of the interaction between zonal jets and vortices [36], but a detailed understanding of these interactions is lacking. ELT observations of Jupiter acquired during the aftermath of an impact even will allow measurements of jetstream speeds and vortex drift rates, which will enable the study of the long-term interaction between the jetstreams and the vortices.

**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.*

Currently most rapid-response observations of solar system phenomena are acquired at the discretion of telescope directors, who decide if and when to interrupt the normal schedule for these unanticipated observations. The data are sometimes proprietary for a period of time after the observations (*e.g.* 6 months). Having a Key Science Program designated for ELT time-critical solar system observations increases the likelihood of obtaining data during those early, critical time steps, but the details of the data reduction and dissemination would need to be determined. An initial set of high-level science products would be needed as soon after the event as possible, thus some formal support structure needs to be implemented to identify individuals (perhaps members of a Triggered Solar System Events Team) with those responsibilities.

**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.*

This proposed program covers only an initial look at transient solar system events. Studying the evolution of high-priority phenomena would require additional resources such as Director's Discretionary time or fast-turnaround time requests at the ELTs. Other facilities such as space observatories or ALMA may participate in follow-up observations as well, but they would typically have much slower response times.

This Key Science Program will rely heavily on preparatory or ancillary datasets in order to identify trigger-worthy events. For the space weather effects on the atmospheres of terrestrial planets, space weather monitoring services will be used for notifications of solar flares or coronal mass ejections. For some of the small bodies phenomena, the alert streams from LSST can be used to identify potential trigger events. For the giant planets studies, there is a substantial network of amateur astronomers who regularly observe the giant planets at high spatial resolution. Their observations are submitted, stored, and hosted by the International Outer Planets Watch (IOPW) [15], which maintains a searchable database. Images collected by IOPW/PVOL have led to numerous peer-reviewed publications and demonstrate the power of networked planetary observations. This network of planetary observers will play a critical role in identifying new impact events that should be studied in detail using the ELT capabilities.