EXPLORATION OF TIME RESOLVED INSTRUMENT REQUIREMENTS

DRAFT

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1. Introduction

a. Derivation of Requirements for Time Resolved Observations

This document contains examples of potential observing programs on the Thirty Meter Telescope. These observing programs require time resolved observations where the time between the start of individual integrations is of order 100s down to 0.1ms. Observing efficiencies of >80% are required[1] (i.e. dead time between separate integrations is <25% of the integration time) in order to ensure efficient observing.

The aim of this document is to provide instrument teams with information to allow them to make an initial assessment of whether a particular science program can be supported by their instrument. For each observing program, details such as spectral and temporal resolution, object type or size and wavelength region are specified.

b. Absolute timing

The observatory will provide an IEEE 1588 Precision Time Protocol (PTP) time server, allowing master-slave time accuracies on the sub-microsecond level. The PTP time server will provide a service that any observatory subsystem can utilize. Thus a very accurate method of absolute timing of science measurements will be available.

c. Issues related to temporal resolution of instruments

The largest issue regarding the implementation of efficient time resolved observing capabilities is the deadtime between science exposures. Optical detectors (CCDs) and infrared detector arrays have different issues regarding readout rates and readout noise, however readout noise is often a limitation with time resolved observations, particularly with CCDs. Below is a list of potential issues that should be considered when designing an instrument and ensuring that the capability for efficient time resolved observations is included:

i. Readout rate and noise, windowing and binning (consider frame transfer CCDs, multiple readout channels and EMCCDs (electron multiplying CCDs)).

ii. High speed data recording and other overheads.

iii. Shutter operation (consider masking areas of the detector, e.g. with a Dekker on a long slit spectrograph).

iv. Absolute timing and very well defined time stamps (some science depends on temporally correlating ground and space based observations to accuracies of a few milliseconds).

2. Examples of observing programs

a. Introduction to Observing Programs

The potential observing programs considered during the derivation of time resolved science requirements for TMT are all in the classical regime, i.e. the integration times are all considerably longer than the quantum limit of $\Delta t=1/\nu$, see Figure . For the optical to near-infrared (310nm to 5μm) this corresponds to about 10^{-14}s. Potential observing programs considered require integration times from 10^{-4}s to 96s.

Table lists a selection of potential observing programs that could be implemented on the TMT. In all but one case the sources are single unresolved point sources and the observing programs would capitalize on the large collecting area. One particular program would use

1 Observing efficiencies of >80% of time being integration time on the science target are specified in the Science-Based Requirements Document (TMT.PSC.DRD.05.001.CCR18) within the context of nodding and dithering. There is no general requirement for >80% observing efficiency.

both the large collecting area and the greater diffraction limited resolution for narrow field imaging.

Table : List of potential time resolved observing programs

Observing program	**Resolution**	**Wavelength range**	**Observation details**[2]	**Integ time**
White dwarf surface Calcium pulsation mapping	6000	370nm to 640nm	Time resolved spectroscopy for a few hours of Mg II (4480Å) & Ca K (3933Å) to identify oscillations	12s
White dwarf and sdB star asteroseismology	4000	340nm to 610nm	Time resolved spectroscopy to get pulsation spectra of different modes	5s
	50,000	370nm to 520nm	Mode identification	5s
Pulsar non-radial oscillations and rotation	~100	340nm to 1200nm	Spin phase resolved spectroscopy with frame transfer EMCCDs	0.1m
Prompt observations of GRBs & GRB afterglow	~100	400nm to 2200nm	TOO time resolved spectroscopy with Mv of 18 to 22	1s
Supernova core collapse shock breakout	2000	525nm to 950nm	TOO time resolved spectroscopy of targets from surveys	15s
		4500nm to 5100nm	TOO time resolved spectroscopy of targets from surveys	15s
Detached WD-WD merger candidates	~5000	370nm to 450nm	Time resolved spectroscopy to get orbital radial velocities[4]	30s
Doppler tomography of Cataclysmic Variables	>4500	320nm to 2400nm	Time resolved spectroscopy of orbital changes in line profiles	15s
Cataclysmic Variables: Spectral eclipse mapping	~1000	320nm to 950nm	Rapid spectroscopy to look at line profile changes during eclipse	100m
Cataclysmic Variables: Studies of rapid variability	~3000	320nm to 950nm	Rapid spectroscopy to look at rapid continuum and line variability	50ms
LMXB echo mapping and Bowen blend secondary star measurements	1000	450 to 700nm	Correlation between X-ray and optical continuum and line emission (especially Bowen Blend 464nm and HeII 469nm)	100m
Magnetic fields and habitable zones around dwarf flare stars	4000	350nm to 700nm	Time resolved spectroscopy of emission line & continuum changes	0.1s
Exoplanet studies: Transits, secondary eclipses & surface mapping	1000	Parts of 700nm to 5000nm	Time resolved spectroscopy of ingress and egress lasting about 30 min around Mv>10 host stars	<30s
Exoplanet studies: Rossiter-McLaughlin effect	60000	550nm	Time resolved spectroscopy of 2hr transit around Mv>15 host star	96s
Asteroid morphology, binarity and composition	~1000	800nm to 2500nm	IFU observations of 0.03" sized resolved target rotating in 2 mins or unresolved objects in a binary each with 2 min light curves and a separation of 0.02"	15s
Asteroid orbits	Broadband imaging	Optical/NIR	Wide field AO assisted astrometric observations with an astrometric error of 0.03"	72s
TNO/Kuiper Belt object occultations	~1000	340nm to 5000nm	Rapid spectroscopy of background star with occultation event lasting between 1s and 200s	10ms

2 All targets are single point sources except where mentioned in the case of Asteroids and PHOs which are extended.

3 Dead time between each integration needs to be <0.25 t_{int} so the observing efficiency is >80%.

4 This does not allow eclipses to be resolved as eclipse duration is ~40s.

The potential time resolved observing programs were gathered by members of the Polarimetry and Time Resolved Science Working Group through discussions with the general community and comprise of programs covering a large range of science areas.

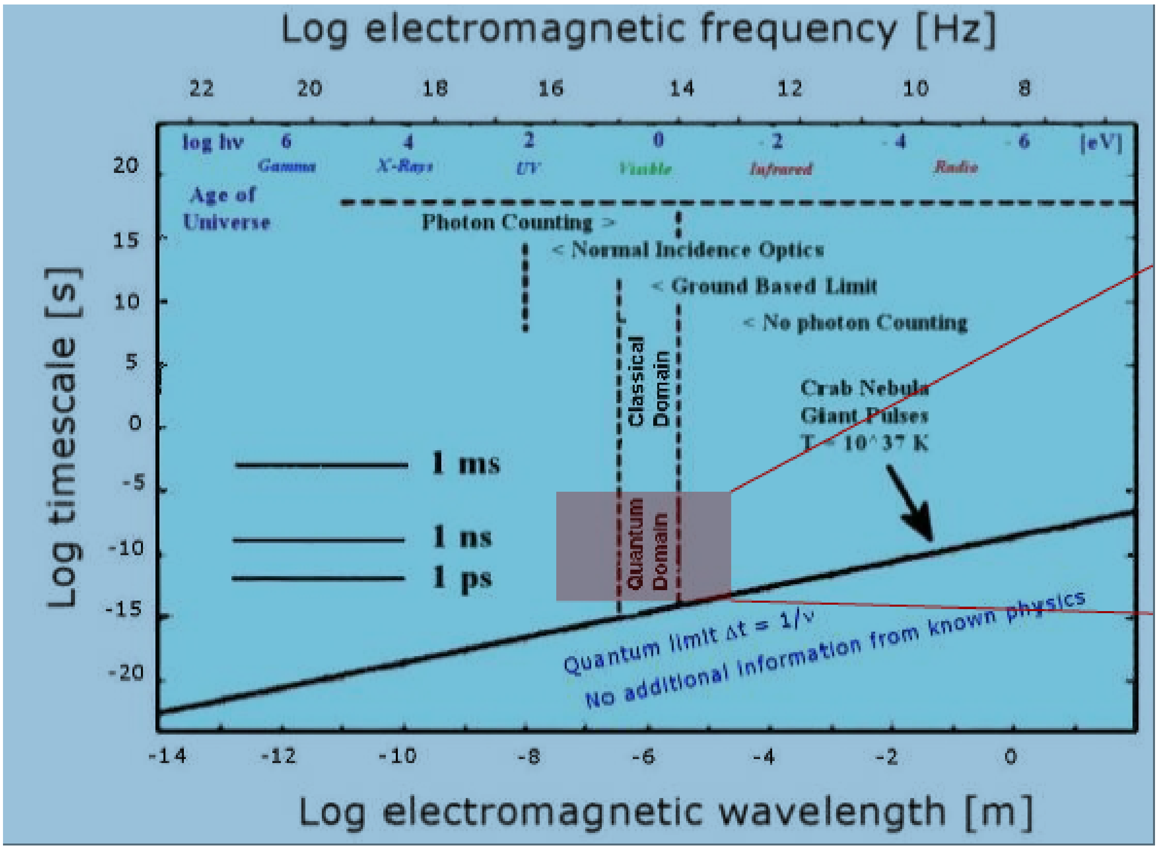

Figure : Frequency versus timescale for time domain astronomy[5].

The range of astrophysical objects that show variability is illustrated in Figure . Observing programs that are designed to characterize these objects or to study the physical process in many of these objects fall into the regime of Time Resolved observing programs discussed in this document. In this case, Time Resolved Observing Programs require integration times from between ~1ms to ~100s. To ensure efficient observing, i.e. tint>>tdead for cases where tint>100s does not generally require any particularly challenging detector readout and data handling techniques.

5 http://www.htra.ie/htra-iv/talks/05_03_Barbieri_HTRA4.pdf

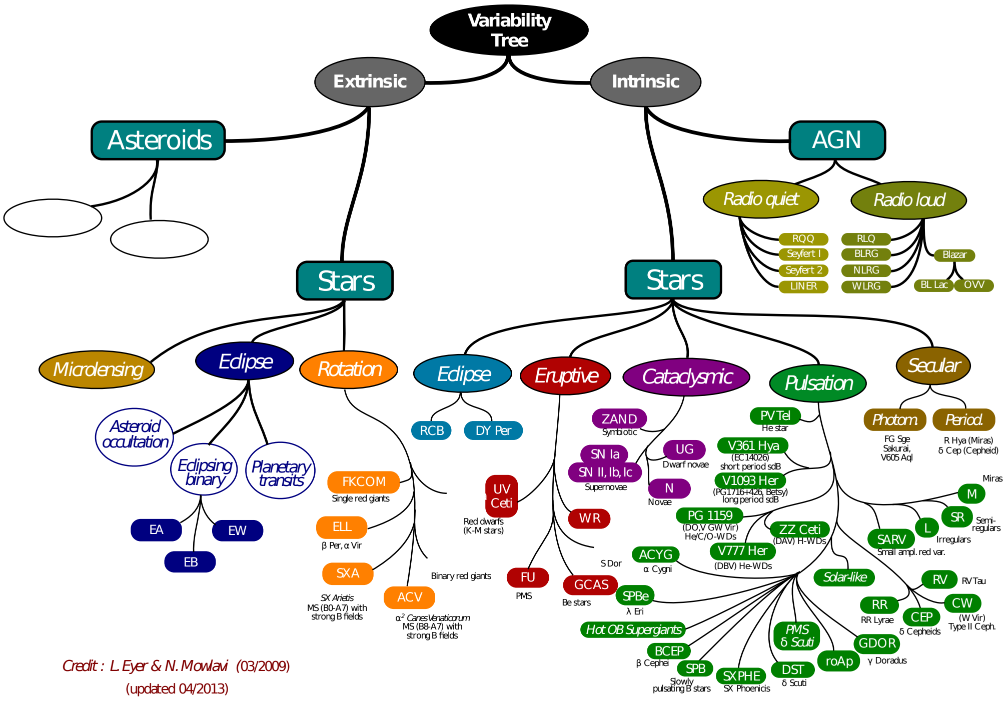

Figure : An illustration of the different types of variable astronomical objects. AGN can be further decomposed to include Blazars. Compact object rotations (e.g. pulsar spins) is also not shown.

b. Brief Description of Observing Programs

b.i. White dwarf surface Calcium pulsation mapping

Studies of polluted white dwarfs (i.e. those with high metal content) is a powerful means to explore the composition of extra-solar planetesimals, comets and asteroids. The white dwarfs accrete from a dusty disk and up to 25% of pulsating DAV white dwarfs show calcium in their spectrum[6], indicating active accretion. There has been limited investigation of the accretion geometry onto pulsating DAV white dwarfs,[7] further studies are limited due the source brightness. Because gravitational settling is much more rapid than turbulent mixing the distribution of accreted material on the white dwarf surface indicates the location of the accretion, i.e. equatorial accretion, uniform accretion or, if white dwarf magnetic fields are important, polar accretion. The pattern of pulsations for different g-modes corresponds to different patterns of temperature fluctuations, with periods of ≥100s. Temperature fluctuations cause changes in the equivalent width of emission lines. Thus the distribution of material over the white dwarf surface can be mapped by comparing the equivalent width variations for separable pulsation modes.

This type of measurement requires several hours of observations for each target of optical (370nm to 640nm) time resolved (t_{samp}~15s from t_{int}~12s and t_{dead}~3s) spectroscopy (R~6000) on targets with M_v>15. In addition, optical time resolved photometry over many nights from networks such as the Whole Earth Telescope is needed contemporaneously to identify the particular pulsation mode or modes present during the time resolved spectroscopic observations.

b.ii. White dwarf and sdB star asteroseismology

6 Mike Jura, UCLA, private conversation

7 http://adsabs.harvard.edu/abs/2010ApJ...714..296T

At a late stage of the evolution of low mass stars (M<2.3M☉), after removal of their envelope via several possible mechanisms, some stars become sdB stars, Helium burning cores with a shell too thin to support Hydrogen burning, i.e. Extreme Horizontal Branch stars. p-mode pulsations (‘Pressure’ with t_{pres} >60s) and g-mode pulsations (‘Gravitational’ with t_{grav} >100s) can be present simultaneously, pulsation amplitudes are about 1%. Studies of p-mode pulsations allow shell structure to be investigated, whilst g-mode pulsation studies allow the internal stellar structure to be determined. Time resolved spectroscopic asteroseismological studies of sdB stars[8] allow different harmonic modes that have the same frequency to be discerned. Limb darkening is a function of wavelength, so different modes and similar modes with different eigen values yield different pulsation patterns and can have very different pulsation spectra (amplitude versus wavelength).

Studies of the pulsation spectrum of sdB star p and g-mode pulsation modes require time resolved (t_{samp}~6s, t_{int}~5s, t_{dead}~1s) optical (340nm to 610nm) spectroscopy (R~4000). To identify the particular modes, high spectral resolution (R~50,000) time resolved optical (370nm to 520nm) spectroscopy is needed to follow wavelength dependent features related to individual modes in the many narrow lines that are present in sdB star spectra.

b.iii. Pulsar non-radial oscillations and rotation[9]

Pulsars have spin periods ranging upwards from a few milliseconds. Forms of cyclotron emission accounts for much of the emission over a large wavelength range (X-ray to radio)[10]. The optical pulse shape and spin resolved polarimetry provide information about the geometry of the emission region and magnetic field around the neutron star. This type of study is greatly enhanced when combined with simultaneous X-ray, γ-ray and/or radio observations where combined studies help us to determine the effects of inclination against the line of sight and allow the most appropriate model for the emission mechanism to be established. This type of multi-wavelength study is particularly appropriate for magnetars. For pulsars discovered from X-ray and γ-ray observations but with low radio fluxes, optical observations are particularly useful for studying the thermal emission of the pulsar, giving strong constraints on their radii[11].

Non-radial pulsations of neutron stars give valuable information about the equation of state[12] of cold ultra-dense material. Low Mass X-ray Binaries (LMXBS) are known to exhibit rapid oscillations during flaring events caused by non-radial neutron star pulsations excited by the unstable nuclear burning occurring on the neutron star surface. Near infrared LMXB flux has been seen to increase by a factor 2 during the X-ray flares. Known LMXBs can be as faint as 24th magnitude and the non-radial modes can have frequencies around 1 kHz. Hence a large telescope is needed to study these phenomena.

Low resolution (R≥100) optical and NIR (to 1.2 μm) time resolved (t_{samp}~0.1ms) spectroscopy and spectropolarimetry would allow the phase resolved pulsation or spin spectrum (amplitude versus wavelength) to be measured.

b.iv. Prompt observations of GRBs & GRB afterglow

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8 http://adsabs.harvard.edu/abs/2000MNRAS.314..209V

9 non-radial oscillations of SGRs have not been included as there are no clear studies in the optical or predictions of optical signatures.

10 http://adsabs.harvard.edu/abs/2009arXiv0908.1349A

11 http://www.nature.com/nature/journal/v389/n6649/pdf/389358a0.pdf

12 Thorne K. & Campolattaro A., 1967, ApJ.,Vol. 149, P. 591

Prompt Gamma Ray Burst observations, beginning within a few hundred seconds of the trigger detection, allow the GRB fireball to be studied. Studies so far rule out a standard fireball model as the emission model in the prompt phase[13] and suggest an inhomgenous relativistic outward flow with inverse Compton or synchrotron emission, velocity variations causing gamma-ray emission, mild internal shocks at larger radii cause optical emission.

To study the prompt phase of GRB outbursts, telescope response time needs to be less than about 10 minutes and flux variations of a factor 10 over 1 minute need to be sampled. Low resolution spectroscopy (R~100) with 1s sampling is required in passbands in the optical to NIR (400nm to 2.2µm) range.

b.v. Supernova core collapse shock breakout

When the core of a massive star collapses a shock propagates outwards at a few percent of the speed of light and leads to the ejection of the envelope. The shock heats the envelope and dissipates at the stellar surface at shock breakout. There is no external indication of the initial core collapse and subsequent shock propagation until the shock approaches the surface, at which time radiation diffuses far enough ahead of the shock to raise the temperature of the stellar photosphere to about 10^5K before the final envelope expansion. The rise in flux during the rise to breakout is about 6 orders of magnitude over timescales of 1 to 15 minutes depending on the progenitor type, giving opportunity for detection by an appropriate optical survey and possible early follow up by TMT. The flux then drops by about a factor 2 over the subsequent 5 hours during which optical follow up would yield information about the conditions in the expanding envelope.

Moderate resolution spectroscopy (R~2000) in bands 525nm to 950nm and 4.5µm to 5.1µm with tsamp~18s (tint~15s) for the first few hours after detection will show the evolution of the temperature and dilution factor and give information about the progenitor characteristics.

b.vi. Detached WD-WD merger candidates

White dwarf binary systems consisting of a He and a C/O white dwarf with orbital periods less than 10 hours are quite numerous (24 identified as of 2012) and will merge within 1 Gyr[14]. The system with the shortest orbital period (12.75 minutes) will merge in less than 1 Myr. Some systems show pulsations, eclipses and other variability. These mergers are important to understand due to their relation to metal enrichment and type Ia SN progenitors.

Time resolved spectroscopy (R~5000, t_{samp}~35s, t_{int}~30s) in the U and B bands (370nm to 450nm) with TMT will give information on the white dwarf core structure, the Hydrogen envelopes, tidal effects, differential rotation and spin rates.

b.vii. Doppler tomography of Cataclysmic Variables

Cataclysmic variables, consisting of a primary compact stellar mass object with a second lower mass stellar body (either a main sequence star or a white dwarf) in a Roche lobe filling orbit, provide a very convenient laboratory to study the process of accretion. With orbital periods ranging upwards of 10 minutes, a broad range of accretion rates, cyclic accretion disk behavior, degrees of magnetism and radiation environments the mechanism(s) controlling the accretion process can be explored.

Doppler Tomography uses orbital phase resolved spectroscopy of emission and absorption lines to isolate the location of line emission or absorption in velocity space. Integrations times of 15s and resolution of R>4500 over bands within the range 320nm to 2.4µm are needed for the shortest orbital period systems.

b.viii. Cataclysmic Variables: Spectral eclipse mapping and studies of rapid variability

13 Guidorzi C., et al., Mon. Not. R. Astron. Soc. 417, 2124–2143 (2011)

14 http://adsabs.harvard.edu/abs/2012ApJ...751..141K

A subset of Cataclysmic Variable systems are eclipsing, providing a means using time resolved observations to spatially isolate the emission from the accretion disk and stream/disk impact region within the system. With rapid (~100ms) relatively low resolution (R~1000) optical (320nm to 950nm) the continuum and line emission can be mapped in real space.

Some accretion disk systems show rapid variability that may be evidence of flares arising in the accretion disk itself[15]. This could be important evidence of the mechanism underlying the viscosity process within the disk. Slightly higher temporal and spectral resolution over the same wavelengths as for eclipse mapping allows disk flaring events to be studied, t_{samp}~50ms and R~3000.

b.ix. LMXB echo mapping and Bowen blend secondary star measurements

Low Mass X-ray Binaries are a subclass of Cataclysmic Variables where the primary component is a neutron star or black hole. X-ray emission from the vicinity of the compact primary is processed and re-emitted in the optical by structures in the system such as the accretion disk and the secondary star[16]. Orbitally phased simultaneous X-ray and rapid optical observations allow the structures in the system to be mapped based on the delay between the reprocessed optical emission and the X-ray radiation. Average time delay between the X-ray and optical is about 2 seconds[17].

R~1000, t_{samp}~100ms, BVR (450nm to 700nm) time resolved spectroscopy with TMT is cross correlated with contemporaneous X-ray measurements.

b.x. Magnetic fields and habitable zones around dwarf flare stars

Young M dwarf stars are often very active with high rates of very energetic flares, producing little high energy radiation except during flares. Flares typically have timescales or durations of 15 minutes[18] with some very rapid emission line and continuum changes during the course of a flare. M dwarf stars are both common hosts for exoplanets and are favored in planet search surveys due to the high planet to star flux and mass ratios. However, the presence of flares significantly affects any planets orbiting these stars, intermittently bathing the planets with high energy radiation, altering the planetary atmospheric composition and temperature characteristics, ultimately affecting the habitable zone and prospects for life around the stars. The effects of flare emission on the detection and characterization of exo-planets is poorly understood. M-dwarf flare stars are the next step in the evolutionary track after TTauri stars but the physical flare process is essentially the same in both cases and the flares seen in T Tauri stars occur in systems at the end of the T Tauri stage[19].

Areas where significant debate remains includes:

i). The early evolution of M dwarf stars after the T Tauri phase

ii). The dependence of flaring activity on height from the galactic plane[20]

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15 http://adsabs.harvard.edu/abs/2004RMxAC..20..155S

16 http://adsabs.harvard.edu/abs/2002MNRAS.334..426O

17 http://adsabs.harvard.edu/abs/2009MNRAS.399..281H

18 http://adsabs.harvard.edu/abs/2012AJ....143...12T

19 N. D. Melikian, et al., Astrophysics, Vol. 49, No. 4, 2006

iii). The relation of flaring stars to magnetically active and inactive stars

Exploration of both the line and continuum emission gives important details about the flare mechanism. The main shape of the flare is caused by continuum radiation, the emission lines peaking well after the peak. Time resolved (t_{samp}~0.1s) optical UBVR (350nm to 700nm) spectroscopy with R~4000 is required to study the most rapid continuum and emission line changes.

b.xi. Exoplanet studies: Transits, secondary eclipses & surface mapping

There are a number of questions, for example:

1) What are the compositions of extra-solar planetary atmospheres?

2) Can a planetary atmosphere distribute heat from the dayside of a planet to the night side? This is important for tidally locked hot-Jupiter type planets.

3) Does UV radiation modify the species present in some planet atmospheres, leading to the presence, or absence, of stratospheric inversion layers?

Secondary eclipses allow the emission from the daytime side of the planet to be examined, giving information on the temperature, bulk atmospheric composition and albedo. The transmission spectrum through the upper layers of planetary atmosphere can be measured for transiting systems, allowing the atmospheric structure, composition, cloudiness and equilibrium state to be explored. Cyclic variations in the planetary brightness around the orbit let us create temperature maps of the planet surface and explore the efficiency of energy transport by the planetary atmosphere.[21]

Transits and secondary eclipses have ingress and egress timescales of about 10 minutes and that can contain much shorter features, necessitating sampling periods of about 30 seconds. Due to the surface temperatures peaking at around 3000K (peak emission around 1μm) they are best studied from the ground in regions of the wavelength range 700nm to 5000nm at relatively low resolution of about R~1000.

b.xii. Exoplanet studies: Rossiter-McLaughlin effect

As a transiting planet passes in front of a star it sequentially blocks off light along a path over the rotating stellar surface causing an asymmetric distortion of the line profiles resulting in radial velocity modulations. The form of this distortion depends on the angle between the planet's orbital axis and star's rotation axis, the impact parameter, whether the planet's orbit is prograde or retrograde, stellar limb darkening and many other parameters.

A planetary transit lasts about 3 hours, with large changes in the radial velocity occurring rapidly in about 20 minutes for certain combinations of system parameters[22]. Thus a sampling time of about 2 minutes is required to gather radial velocity measurements using high resolution (R~60,000) optical spectroscopy (λ~550nm)[23].

b.xiii. Asteroid morphology, binarity and composition

The primary components of near earth binary asteroids appear to have a characteristic spinning top shape[24] with an equatorial ridge. Some isolated asteroids also have a similar

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20 Hilton, E., et al., 2010, arXiv:1009.1158v1

21 https://openaccess.leidenuniv.nl/handle/1887/17878 (PhD. 2011, de Mooij)

22 http://iopscience.iop.org/0004-637X/622/2/1118/pdf/61460.web.pdf

23 http://iopscience.iop.org/0004-637X/724/2/1108/pdf/apj_724_2_1108.pdf

shape[25]. The explanation for the spinning top shape is believed to be linked to binarity. The shaping mechanism is affected by the YORP effect (re-radiated solar flux that alters the asteroid rotation). The rubble pile spin limit is about 2 hours with many examples occurring close to the break up rotation rate. Some monolithic asteroids spin in less than 2 minutes. Sizes of the primary component of asteroids are in the range of a few km with binary orbital radii only slightly larger and the orbits through the solar system can bring them within a few hundred thousand km of Earth. Time resolved (t_{samp}~18s) optical and near IR spatially resolved (<0.006 arc seconds per pixel) IFU spectroscopy (800nm to 2500nm) with R~1000 and FOV ~1.5" will allow variations in the amounts of pyroxene, olivine, iron, anorthite, etc. to be mapped. The very low albedo of many asteroids puts NIR and optical studies beyond the reach of existing 8m to 10m class facilities.

Investigation of the physical properties of near Earth asteroids is important for the planning of future NASA and ESA missions to asteroids.

b.xiv. Asteroid orbits

Complimentary to asteroid morphology, binarity and composition studies, accurate asteroid orbital determination using astrometry is limited by object brightness and proximity to earth, faint objects require long exposures that cause the images to trail by an amount dependent on the earth-asteroid distance. Short exposure (t_{int}~72s) broad band Optical/NIR images with reduced trailing of more distant targets obtained with higher astrometric precision will enhance the ability to determine the orbital parameters. Most notably, the AO corrected NIR astrometric error could be better than 0.001 arc sec for a target at more than 7 times the distance compared to 0.3 arc sec obtained for an M_v~19 target using optical seeing limited imaging with small ground based telescopes[26]. Radio astrometry is limited to objects closer to earth than 0.24 AU (if observed with Arecibo), small ground based optical telescopes make measurements out to several AU.

i. TNO/Kuiper Belt object occultations

Sizes of known Kuiper belt objects range from 1200 km (Eris) down to 1km with possible detections of smaller (500m) objects being reported[27]. They are generally between 30 to 55 AU from the sun. Models for the formation of the Kuiper Belt Objects and the solar system as a whole are in disagreement with observationally based estimates of the KB total mass and mass/size distributions. Measurements of the sizes constrain the formation models. The search for and possible study of any atmosphere around a KBO has implications for the origins and thermal & compositional evolution of the KBO bodies.

KBO stellar occultation durations range from about 100s down to ~0.1s second based largely on object size and chord location. For larger objects, to adequately sample the effects of limb darkening of the occulted star and probe for the presence of and characterize the composition of any atmosphere, moderate resolution (R~1000) optical and infrared (~340 nm to ~5μm) time resolved (t_{samp}~10ms) spectroscopy is required. Similar observational requirements exist for occultations of small (~500m sized) objects as the wavelength dependent Fresnel diffraction pattern creates rapid fluctuations in the flux of order a few percent at a few Hz.

3. Examples of Detector Readout Schemes

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24 http://echo.jpl.nasa.gov/asteroids/1999KW4/1999kw4.html

25 http://www.rssd.esa.int/Staff/sbesse/REPRINTS/Jorda_steins_2012.pdf

26 Assuming brightness limit of M=27 and error α 1/distance

27 nature08608.pdf H. Schlichting, et al., 2009, Nature Vol. 462, P. 895

a. Windowing and binning

Windowing allows just a subsection of a CCD to be readout rather than the whole image. Binning allows groups of pixels to be readout as a though they were a single pixel, thus reducing the readout time. Binning is particularly effective at reducing read noise which is often the dominant noise term in time resolved observations. Binning of the detector in a spectrograph in the spatial direction reduces the effect of read noise and read time whilst binning in the dispersion reduces the spectral resolution characteristics, however many time resolved science programs require relatively low spectral resolution.

b. Low Smear Drift Mode

Low smear drift mode (LSDM) has been implemented on several spectrometer systems, the best documented is that for the ISIS Spectrograph on the WHT[28] which has served as the model for later implementations (e.g. at the AAO[29]).

LSDM requires that the slit be masked in the spatial direction so that only a narrow region of sky (plus target) is exposed on the detector. The narrow region and a small border around is sequentially shifted down the detector until finally being read out.

The result of LSDM is a series of spectroscopic frames, each one narrow in the spatial direction with effectively unexposed borders on either side. In the case of the WHT system, all of LSDM frames are part of one larger fits file image.

c. High Smear Drift Mode

High smear drift mode (HSDM) requires that the slit be masked in the spatial direction. The masking will be such that sky flux is minimized. HSDM has been implemented on the ISIS spectrograph on the WHT (see above) and has been utilized with LRIS at Keck[30] as well as other systems at other observatories (e.g. SAAO).

Operationally in HSDM, the target is observed for periods and the readout continues while the telescope is offset for sky measurements. This is a scheme akin to that used historically with single channel photometers.

d. Other examples

Palomar DBSP has a fast mode and cyclic charge shuffling capability on the blue arm CCD.

28 http://www.ing.iac.es/astronomy/observing/manuals/html_manuals/wht_instr/drift_mode_man/ccd_drift_mode_manual.html

29 http://star.arm.ac.uk/~csj/papers/conference/2003ehb_csj_sdbvs.ps

30 http://adsabs.harvard.edu/abs/2001MNRAS.323..484S and http://adsabs.harvard.edu/abs/2001MNRAS.326.1067O