Small Bodies Science with the Twinkle Space Telescope

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Abstract.

Twinkle is an upcoming 0.45m space-based telescope equipped with a visible and two near-infrared spectrometers covering the spectral range 0.4 - 4.5μm with a resolving power R $\sim$ 250 (λ<2.42μm) and R $\sim$ 60 (λ>2.42μm). Here we explore Twinkle's capabilities for small bodies science and find that, given Twinkle's sensitivity, pointing stability, and spectral range, the mission could observe a large number of small bodies. The sensitivity of Twinkle is calculated and compared to the flux from an object of a given visible magnitude. The number, and brightness, of asteroids and comets which enter Twinkle's field of regard is studied over three time periods of up to a decade. We find that, over a decade, several thousand asteroids enter Twinkle's field of regard with a brightness and non-sidereal rate which would allow Twinkle to characterise them at the instrumentation's native resolution with SNR >100. Hundreds of comets could also be observed. Therefore, Twinkle offers researchers the opportunity to contribute significantly to the field of Solar System small bodies research.

Keywords: Space telescope; visible and near-infrared spectroscopy; Solar System bodies;.

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1 Introduction

Spacecraft studies of Solar System bodies have increasingly contributed to our knowledge of these objects over recent years. While in-situ measurements provide the best means of understanding a target, dedicated lander, orbiting or fly-by missions are rare and thus remote-sensing missions offer a great chance to observe many objects of interest. Some targets can be viewed by ground-based telescopes at certain wavelengths (e.g. visible) but significant issues are encountered in other bands due to atmospheric absorption, particularly if observing at infrared (IR) or ultraviolet (UV) wavelengths. Additionally, ground-based observations can be affected by weather and atmospheric distortion. Space telescopes avoid these issues and thus are valuable for increasing our knowledge of the universe.

Potential targets for observation within our local stellar environment are diverse and each offers insight into the Solar System as a whole. Asteroids and comets are remnants of the earliest celestial bodies, providing a means of investigating the formation of the planets we know today. Studying the building blocks of the Solar System, as well as the larger bodies that have formed, enhances our understanding of planet formation and evolution. Spectroscopic observations, particularly at visible and infrared wavelengths, allow the composition of the surfaces and atmospheres of these objects to be determined and hints of their formation and evolutionary processes to be gleaned.

As these bodies are relatively unaltered since their formation nearly 4.5 Gya ago, a compositional characterisation of small bodies provides a means to identify products of the Solar nebula during the epochs of planetary formation. The implications of such a characterisation are far-reaching and, to name a few, include:

- Terrestrial and giant planet formation via understanding the protoplanetary compositions that aggregated into the planets
- Identification of the source regions for Earth's water and organics
- How and when differentiation of planetismals, protoplanets and eventual planets occurred
- The protoplanetary disk temperature, pressure, and chemical gradient structure
- The dynamics of the early Solar System via providing observational constraints to early Solar System evolution models such as the Grand Tack[112,113] and Nice Model[7,39,54,64,65,104]
- Establishing links between meteorites and asteroids to make inferences on the parent bodies of the meteorites found on Earth
- The thermal and aqueous alteration history of the small bodies
- Slow evolutionary processes such as regolith production and space weathering.

Although many small bodies have been discovered, and basic characteristics such as size and orbital parameters are known for many of them, only a small percentage have been characterised through spectroscopy. Many of the spectroscopic studies of asteroids and comets have been with ground-based telescopes such as the InfraRed Telescope Facility (IRTF). Additionally, spacecraft have increasingly contributed to our knowledge of these primordial bodies. Fly-by and rendezvous missions (e.g. Rosetta, DAWN, NEAR Shoemaker) have provided in-situ observations of a handful of small bodies in extraordinary detail while sample return missions (e.g. Stardust, Hayabusa, Hayabusa 2, OSIRIS-Rex) can offer unparalleled opportunities for studying the composition of the target bodies. For example, the NIR spectrum of comet 103P/Hartley 2 obtained by the HRI-IR[40] spectrometer during the NASA Deep Impact eXtended Investigation (DIXI) mission[2] highlighted water-ice absorption and water vapour, organics, and CO_2 emission features.[77] Such endeavours allow a few selected objects to be studied in great detail while remote-sensing missions allow for a large number of targets to be studied, albeit in less detail.

Space-based telescopes have been heavily employed for the detection and characterisation of small bodies. For example, the Wide Infrared Survey Explorer (WISE) is a medium-class space telescope launched in 2009 which acquired infrared images of the entire sky over four bands centred on the wavelengths 3.4, 4.6, 12, and 22μm.[117] During the main mission, NEOWISE (Near-Earth Object WISE), the asteroid hunting section of the project, detected and reported diameters and albedos for $>$158,000 asteroids, including $\sim$700 Near-Earth objects (NEOs,[58]). After the end of the cold mission and several years of hibernation, the spacecraft was reactivated in September 2013.[57] NEOWISE has since detected several hundred more NEOs and thousands of Main Belt Asteroids using the 3.4 and 4.6μm bands, providing albedos and diameters for these newly discovered objects.[61,70,71]

The Spitzer Space Telescope is, along with Hubble, part of NASAs Great Observatories Program. Launched in 2003, Spitzer carries an Infrared Array Camera (IRAC), an Infrared Spectrograph (IRS) and a Multiband Imaging Photometer (MIPS). The IRS was split over four sub-modules with operational wavelengths of 5.3 - 40μm[43] and has not been operational since Spitzer's helium coolant was depleted in 2009. Since the cool phase of Spitzer's mission ended, only the

IRAC has remained operational though with reduced capabilities. Thus, at the time of writing no space telescope capable of infrared spectroscopy beyond 1.7μm is operational. Spitzer has been used extensively for studying small bodies (e.g.[3,32,100,102]) including the ExploreNEOs program[103] which was a 500 hour survey to determine the albedos and diameters for nearly 600 NEOs during the warm mission phase. The CO and CO_2 emission of comets has also been observed with Spitzer.[78] Additionally, the Hubble Space Telescope (HST) has provided extraordinary data over a vast range of scientific disciplines including small bodies (e.g.[34,47]). The Hubble WFC3 camera is currently delivering spectroscopic data at wavelengths shorter than 1.7μm.

AKARI was an infrared astronomy satellite which was developed by the Japanese Aerospace eXploration Agency (JAXA) and launched in 2006.[67] Over its 6 year life, AKARI surveyed 96% of the sky and contributed to a wide range of infrared astronomy, including galaxy evolution, stellar formation and evolution, interstellar media, and Solar System objects. AKARI's infrared camera (IRC) operated from 1.8 - 26.5μm[72] and was used for several asteroid surveys. These included a catalogue of albedos and sizes for over 5000 asteroids with measurements in two mid-infrared bands (9 and 18μm) during the cryogenic phase of the mission.[106] Additionally a spectroscopic survey of tens of asteroids was conducted over 2.5 - 5μm using the grism of the near-infrared channel of the IRC.[105]

Future space telescopes will also offer opportunities for small bodies science and the most anticipated is the James Webb Space Telescope (JWST) which is due to be launched in March 2021. A Near-Infrared Spectrometer (NIRSpec) and camera (NIRCam) are included within the instrument suite[22] and thus will provide the infrared capability that is currently missing (0.6 - 5.3μm and 0.6 - 5.0μm respectively). Additionally, the Mid-Infrared Instrument (MIRI) covers the wavelength range 5 - 28μm and is capable of medium resolution spectroscopy.[118] However, a primary issue will be over-subscription and not all the science cases will necessarily need the sensitivity and accuracy of JWST. Hence, while many opportunities exist for Solar System science with this observatory (e.g.[63,68,82,99]), a smaller space telescope would offer an alternative for sources which are too bright to justify the use of JWST.

Upcoming all-sky surveys also offer potential for the characterisation of small bodies. These include Euclid, a mission to map the geometry of dark matter in the Universe, which is expected to provide spectra for $\sim$100,000 asteroids from 0.5 - 2μm.[13] Selected earlier this year, the Spectro-Photometer for the History of the Universe, Epoch of Reionization and ices Explorer (SPHEREx), is a NASA medium-class explorer mission due for launch in 2023. SPHEREx will observe the whole sky with its 20cm telescope and is expected to provide spectra of tens of thousands of asteroids over the spectral range 0.75 - 5μm at low resolution (R$\sim$35-140).[26]

Another future space-based telescope which is capable of visible and infrared spectroscopy is Ariel, the ESA M4 mission, which will study the atmospheres of $\sim$1000 transiting exoplanets.[29,101] However, Ariel's mission requirements do not include the ability to track non-sidereal targets and thus its capability for small bodies research may be limited.

Several mission concepts have been studied and submitted to calls by ESA and NASA. Medium class proposals to ESA include CASTAway which aims to explore the main asteroid belt with a telescopic survey of over 10,000 objects, targeted close encounters of 10 - 20 asteroids and serendipitous searches to constrain the distribution of smaller objects ($<$10m).[6] CASTAway's proposed payload consists of a 50cm diameter telescope with a spectrometer covering 0.6 - 5μm (R = 30 - 100), a thermal imager (6 - 16μm) for use during flybys, a visible context imager and modified star tracker cameras to detect small asteroids. Spectral features related to hydroxyl (OH), water (ice and gas), and hydrated silicates, are either partially or fully obscured in Earth-based observations due to Earth's water-rich atmosphere and the 2.5 - 3μm region is especially prohibitive. CASTAway is designed to be able to detect such features.

Main Belt Comets are objects in stable asteroid-like orbits which lie within the snow line but exhibit comet-like activity[44,90] and 18 such active bodies are currently-known. Castalia is a proposed ESA mission to rendezvous with the Main Belt Comet 133P/Elst-Pizarro to perform the first characterisation of this intriguing population, making the first in-situ measurements of the water in the asteroid belt and measuring isotope ratios as well as plasma and dust properties.[91]

Although CASTAway and Castalia were not implemented by ESA, a new small bodies mission, Comet Interceptor,[48] has been accepted for ESA's F Class call for launch with Ariel in 2028. The mission aims to encounter a dynamically new comet (i.e. one that is entering the inner Solar System for the first time) as well as making solar wind measurements. The rendezvous target is likely be a long period comet discovered by the Large Synoptic Survey Telescope (LSST) and characterisation of this pristine object will be achieved with a compact, agile set of spacecraft. Although far rarer than long-period comets, Comet Interceptor may also have the capability of encountering an interstellar object passing through our Solar System.

NEOCam is a proposed NASA Discovery class mission and is currently funded for an extend Phase A study. Launching to the Sun-Earth L1 Lagrange point, NEOCam will detect and characterise NEOs with a particular focus on those that could potentially impact Earth (i.e potential hazardous asteroids, PHAs). NEOCam's primary science objectives are: (i) Assess the present-day risk of near-Earth object (NEO) impacts, (ii) Study the origin and ultimate fate of asteroids, (iii) Find suitable NEO targets for future exploration by robots and humans. To facilitate this, NEOCam consists of a 50cm telescope operating at two photometric channels which are dominated by NEO thermal emission, 4.2 - 5.0μm and 6 - 10μm, in order to better constrain the objects' temperatures and diameters. NEOCam's field of view is significantly larger than that of WISE, allowing the mission to discover tens of thousands of new NEOs with sizes as small as 30 - 50m in diameter.[60]

Therefore, the small bodies field lacks a space-based remote-sensing mission capable of selectively characterising thousands of asteroids and comets, through visible and near-infrared spectroscopy, in the near-future. Although JWST will undoubtedly provide fantastic insights into a handful of small bodies, without a larger population study, progress in understanding these primordial objects will be slower than hoped.

2 Twinkle

The Twinkle Space Mission is a new, fast-track satellite designed for launch in 2022. It has been conceived for providing faster access to spectroscopic data from exoplanet atmospheres and Solar System bodies, but it is also capable of providing spectra of bright brown dwarfs and stars. Twinkle is equipped with a visible (0.4 - 1μm) and infrared (1.3 - 4.5μm) spectrometer (split into two channels at 2.42μm). The satellite has been designed to operate in a low Earth, Sun-synchronous orbit.[46,88]

Twinkle is a general observatory which is being managed by Blue Skies Space Ltd (BSSL). Scientists will be able to purchase telescope time and Twinkle will provide on-demand observations of a wide variety of targets within wavelength ranges that are currently not accessible using other space telescopes or accessible only to oversubscribed observatories in the short-term future.

While it has been shown that Twinkle has significant capability for characterising exoplanets,[30] the photometric and spectroscopic accuracy will also be well suited to observing Solar System objects.

Twinkle is currently entering a Phase B design review and thus the technical specifications stated here may change. Twinkle's scientific payload consists of a telescope with a 0.45m aperture, a Fine Guidance Sensor (FGS) and both a Visible and Near-Infrared (NIR) spectrometer which can be operated simultaneously. The Exoplanet Light Visible Spectrometer (ELVIS) is a visible spectrometer channel which is based upon the Ultraviolet and Visible Spectrometer (UVIS) flown on the ExoMars Trace Gas Orbiter. For the Mars application, the UVIS instrument used a dual telescope configuration: nadir (downward viewing of the surface for total atmospheric column measurements) and solar occultation observations (looking at the Sun through the atmosphere from orbit to measure vertical profiles). The telescopes were connected to a single spectrometer via a fibre optic selector link. This telescope and selector system is not required in the Twinkle application as the spectrometer is positioned in the visible beam of the main Twinkle telescope.

The main modification to the spectrometer design is the use of an alternative grating and associated coatings to optimise the spectral range to the visible to near IR range between 0.4 - 1μm with a resolving power of R$\sim$250.[88] Other planned changes include a minor electronics component change on the detector board and relocation of the main electronics board stack to improve thermal isolation and allow the detector to run at a lower temperature. Changes to the firmware code within the electronics will optimise the operations (e.g. CCD readout modes) and integration times for the Twinkle application.[88] This instrument is referred to as Channel 0 (Ch0). For the Phase A study, an e2v CCD-230-42 detector was assumed for the visible channel but this is currently under further discussion.

The design of Twinkle's near infrared (NIR) spectrometer is detailed in Wells (2016).[115] The NIR spectrometer will split the light into two channels (1.3 - 2.42μm and 2.42 - 4.5μm) to provide broadband coverage while also ensuring appreciable spectral resolution. For shorter wavelengths (λ <2.42μm), the NIR spectrometer will have a resolving power of 250 while for longer wavelengths (λ >2.42μm) this will be reduced to 60.[115] These are referred to as Channels 1 and 2 (Ch1, Ch2) respectively and the spectrometer delivers a diffraction-limited image over both channels. In the instrument design, a set of coupling lenslets are adopted to create an image of the aperture on the detectors. These lenses produce several spectra on the detector, with the spectrum from the star slit in the centre with three spectra from the background slits on either side.[115] The two channels use different halves of the same detector (assumed to be produced by Selex in the Phase A study). Due to this layout, the two IR channels (Ch1 & Ch2) must be read out simultaneously whilst the visible instrument (Ch0) can be read out independently. This current design features a spectral gap at 1 - 1.3μm. A summary of the instrument design in shown in Figure 1.

The platform has a pointing accuracy of 1 arcminute[46] and so a Fine Guidance Sensor (FGS) camera is to be used aboard Twinkle to facilitate precise pointing. The current design has a readout frequency of 1Hz and the FGS detector has a field of view of 6 x 6 arcminutes. Tip-tilt mirror (TTM) control electronics will be utilised to keep the target within the slit for the duration of an observation and the pointing precision is expected to be on the order of 100 milliarcseconds (mas). A beam splitter is used to divide light between the visible spectrometer and the FGS, reducing the usable science flux.

The satellite will be placed in a low Earth (600-700km), Sun-synchronous (dawn-dusk) polar orbit with a period of 90-100 minutes. The orientation of the satellite's orbit is constant with respect to the Sun but dictates that Twinkle's instrumentation may have to be retargeted during an orbit to

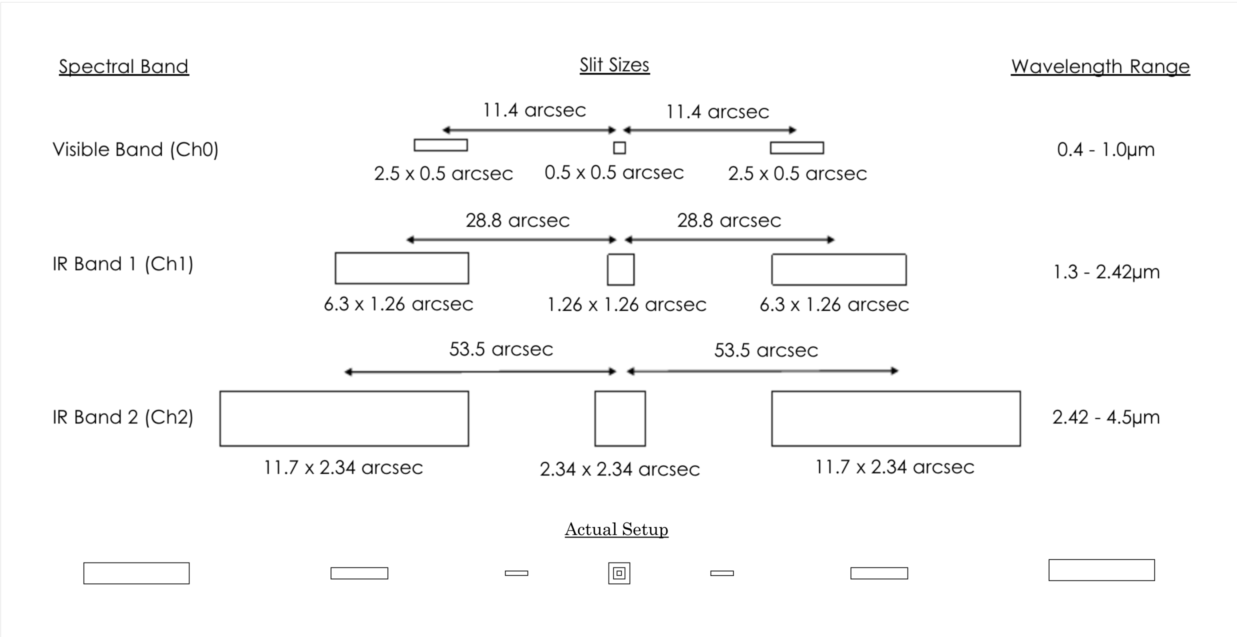

Fig 1 Top: Angular sizes of Twinkle's star and background slits (to scale). Bottom: The setup and actual separation between them shown to scale. As the star slits are overlapping, all three channels can observe the same target simultaneously.

avoid Earth's limb. The boresight of the telescope will be pointed within a cone with a radius of 40° which is centred on the anti-sun vector (i.e. the ecliptic). The field of regard could potentially be expanded to ±60° from the ecliptic for non-demanding targets. Further information on Twinkle, including publications describing the instrumentation, is available on the Twinkle website.[1]

Twinkle's spectrometers cover a similar wavelength range to the proposed CASTAway mission and thus will be capable of detecting many of the same features. This spectral coverage is ideal for the compositional characterisation of mafic silicates, hydration features, and organics on asteroid surfaces and within comet comae. A list of the main spectral features of some common minerals is given in Table 1. The sensitivity, pointing stability, and spectral range of the Twinkle observatory are well suited to study Near-Earth and Main Belt asteroids of all taxonomic types, as well as bright, active comets. Additionally, a space-based observatory offers several opportunities for asteroid characterisation that are not possible from the ground, allowing Twinkle to contribute unique spectral data to the small bodies community.

Hence, while Twinkle observations of asteroids of all taxonomic types would be a great benefit, the ability to obtain spectra outside the water-rich atmosphere of Earth creates a unique opportunity to further our understanding of the primitive asteroids. Currently, a full characterisation of these asteroids is strongly limited by contamination of the atmospheric water features, which prevents and complicates the identification of silicate minerals, water ice, hydroxyl, and organics contained in the C-complex asteroids.

Here we demonstrate Twinkle's ability to acquire high fidelity spectral data of many asteroids and comets within the Solar System, provide a description of which spectral features lie within Twinkle's spectral range that make it an ideal small bodies research facility, and discuss which

[1] www.twinkle-spacemission.co.uk

research areas Twinkle could contribute to most significantly.

3 Methodology

JPL's Horizons system[2] was accessed for ∼740,000 small bodies defined as NEOs, Inner, Main and Outer Belt asteroids or Trojan asteroids. Here, Near-Earth Objects (NEOs) include those that are classified by the Horizons database as Aten, Apollo and Amor. Atira asteroids are excluded as their orbits are contained entirely within the Earth's orbit and thus are not observable due to the field of regard described in Section 2. Mars-crossing asteroids are classified here as Inner Belt asteroids. Additionally, the physical characteristics of ∼1000 comets were downloaded from the Minor Planet Centre[3]. The capability of Twinkle to observe these small bodies has been analysed using the methods described in Sections 3.1 - 3.3. We note that this analysis does not include many comets (over 6000 have been discovered), due to lack of information on key orbital or physical parameters, and that future surveys (e.g. NEOCam, LSST) are expected to find additional small bodies which could be characterised by Twinkle.

3.1 Instrument Sensitivity

For many small bodies within the Solar System, such as comets and asteroids, parameters such as albedo, radius and temperature are not precisely known. Therefore, the analysis described in Edwards et al. (2019),[31] which was used for modelling Twinkle's capabilities to observe major Solar System bodies, cannot be applied. To assess Twinkle's performance when viewing such objects, the flux received has been estimated from the visible magnitude of the body and the methodology for calculating the visible magnitude of small bodies is described in Section 3.3. It is assumed that all photons received in Twinkles visible and infrared wavelengths bands are from reflected solar radiation and that a target is small enough to be viewed in its entirety in one observation. The former is valid for Ch0 and Ch1 but provides an underestimation of the flux in the spectral band 2.42 - 4.5μm while the latter assumption is true for all but the biggest, brightest objects (e.g. Ceres) which have angular diameters which are greater than the size of Twinkle's slits but are already known to be observable with Twinkle.[31] For each magnitude, the photon flux is calculated per spectral bin which can then be compared to the sensitivity and saturation limits of Twinkle for a given exposure time. The thermal emission of an asteroid can of course be significant, particularly for NEOs. By ignoring it we are underestimating the number of photons received and thus underestimating the exposure time required. When planning an actual observation with Twinkle, the thermal emission should of course be accounted for to avoid detector saturation. Here however, we attempt to classify a approximate number of potential targets rather than focusing on any individual objects. To reduce the number of assumptions in the calculation of the flux (e.g. surface temperature, diameter, albedo) we chose the simplified case of assuming just reflected solar radiation.

The minimum photon flux required to achieve SNR = 100 was calculated for various exposure times to find the sensitivity limit of Twinkle. Additionally the saturation limit was found by calculating the maximum photon flux that could be observed in each spectral bin. The noise characteristics have been calculated per spectral bin as described in.[31] In line with the Phase A design, the detector is assumed to be cooled to 70K while the telescope has been modelled at 180K. Excluding the photon noise, the dark current dominates most wavelengths although the telescope

[2]https://ssd.jpl.nasa.gov

[3]https://minorplanetcenter.net

noise is preeminent at longer wavelengths. With the current design, Channel 1 has the lowest noise levels due to the detector dark current.

3.2 Pointing and Tracking Restrictions

Twinkle's FGS operates at visible wavelengths and the detailed tracking performance of the FGS will ultimately depend on the platform pointing accuracy. However, it is expected that the wide Field of View (FOV) of the FGS camera will allow bright sidereal targets to be tracked. The ability of Twinkle to track an object varies with brightness and there exists a faintest object which Twinkle can track using the FGS. Current simulations suggest direct tracking will be possible for targets with visible magnitude of 15 or brighter. Further investigation is needed to fully ascertain the capability of the FGS and this will be performed as part of the Phase B study. For fainter targets, tracking could be simulated by scanning linear track segments. These linear track segments are linear in equatorial coordinate space; they are commanded as a vector rate in J2000 coordinates, passing through a specified RA and Dec at a specified time. The coordinates of the target can be obtained from services such as Jet Propulsion Laboratory's Horizons System. This method of tracking is by no means simple but has been employed on Spitzer (and will be for JWST). Including such a capability would be non-trivial but, given the current status of the mission, there is time to include and refine this capacity. Here we assume only on-target tracking is used.

The max tracking rate of Twinkle is also subject to further investigation. During the Explore-NEO program, Spitzer targets achieved a max rate of 543 mas/s[103] and JWST will be capable of 30 mas/s.[99] Twinkle's FGS is expected to be capable of tracking Mars (e.g. a rate of 30mas/s) though its max rate may be higher for brighter targets.

3.3 Target Availability

Twinkle has a design life of seven years but, with no expendables, has the potential to operate for far longer. A precise launch date for the mission is still under discussion: for the purpose of this work a 'first light' date of 1st January 2022 was chosen and the following analysis was completed with a mission end date of 1st January 2032. Twinkle's field of regard provides restrictions on the targets which can be observed at a given time. To assess the number of small bodies which enter Twinkle's field of regard, JPL's Horizons system was accessed and ephemeris data obtained for all small bodies over the timescale 2022 to 2032 at 1 day intervals. This was compared to Twinkle's field of regard and, when a target could be observed with Twinkle, the visible magnitude, m, of the body calculated from:

$$m = H + 2.5log_{10}\Big(\frac{d^2_{S-T} \times d^2_{O-T}}{q(\alpha) \times (1AU)^4}\Big) \tag{1}$$

where d_{S-T} is the distance between the Sun and the target, d_{O-T} is the distance between the observer and the target, q(α) is the phase integral and H is the apparent magnitude an object would have if it were at 1 AU from both the observer and the Sun. The apparent magnitude of these bodies was calculated using d_{S-T} and H from the Horizons database. For planetary bodies (with an atmosphere), the phase integral can be estimated as that for a diffuse sphere.[116] However, airless bodies (i.e. asteroids although some have tenuous exospheres such as Ceres[89]) usually reflect light more strongly in the direction of the incident light. This causes their brightness to increase rapidly as the phase angle, the angle between the Sun, the observer and the target, approaches 0°. This opposition effect is dependent upon the physical properties of the body.[49] Therefore, p(α) has been calculated from:

$$q(\alpha) = (1 - G)\phi_1(\alpha) + G\phi_2(\alpha) \tag{2}$$

where G is the slope parameter (acquired from Horizons or assumed to be 0.15) and ϕ is given by:

$$\phi_n(\alpha) = exp\Big(- A_n\Big(tan\frac{\alpha}{2}\Big)^{B_n}\Big)$$

where A_1 = 3.332, A_2 = 1.862, B_1 = 0.631, B_2 = 1.218.[28,51] This is valid for phase angles below 120°. These assumptions therefore include phase angle effects but do not account for phase angle dependent spectral effects. However, except for extreme cases at large phase angles, these effects are relatively minor.

This calculation was performed for three periods (1 year, 3 years and 10 years), each starting in 2022, to provide estimates of the number of asteroids observable with Twinkle over the mission life but also shorter time-spans. By monitoring an asteroid over time, the maximum brightness when observable with Twinkle could be obtained. The visible magnitude was utilised to calculate the number of photons received from the target in each spectral band. The rate of motion at a given time was also calculated to account for the capabilities of the FGS.

The size of the asteroids which could be characterised by Twinkle is of interest and so, if not currently known (i.e. listed in the Horizons database), the diameter (in metres) has been determined from:

$$d = 10^{3.1236 - 0.5log_{10}(p_v) - 0.2H} \tag{3}$$

where p_v is the geometric albedo. For each target, three possible albedo classes are considered that represent a variety of asteroid taxonomies. The albedo classes are defined using average albedos for different taxonomic types: i) taxonomic types with low average albedos near 0.05 including the C-complex and P- and D-types (possible X-complex); ii) taxonomic types with moderate average albedos near 0.20 including the S-complex and K-, L-,(possible X-complex) and M-types (X-complex); and iii) taxonomic types with high average albedos near 0.40 including V-type (similar to S-complex) and E-type (X-complex).[25,59,98]

4 Results

4.1 Number of Observable Asteroids

By assuming a requirement of SNR = 100 and the discussed instrument characteristics, the capability of Twinkle to observe small bodies is determined by calculating the sensitivity and saturation limits of Twinkle's instrumentation for each spectrometer. These are plotted in Figure 2 and, if an object lies between these limits for a given exposure time, Twinkle can achieve spectra at the instrumentation's highest resolution with an SNR >100. At shorter wavelengths (λ<2.42μm), targets of visible magnitudes brighter than m_v ∼13.5 could be observed at Twinkle's highest spectral resolution in 300s while for longer wavelengths the magnitude limit for this exposure time is m_v ∼12. As discussed in Section 3, thermal emission has been ignored and thus the calculated flux at longer wavelengths is an underestimate for many small bodies.

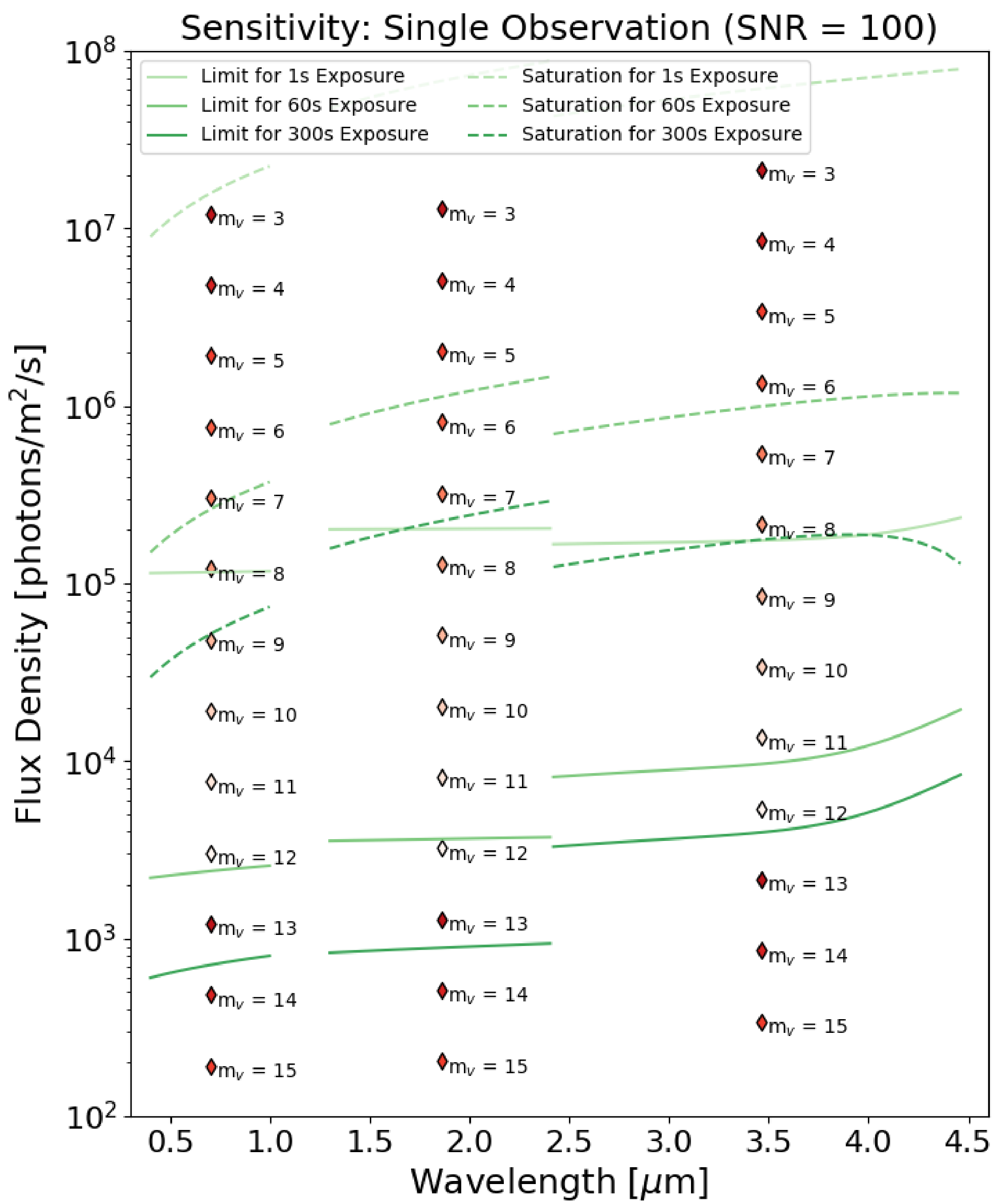

Fig 2 For a single observations of a given exposure time, the sensitivity and saturation limits of Twinkle assuming observational parameters of SNR = 100, R∼250 (λ <2.42μm) and R∼60 (λ >2.42μm). Additionally the average photon flux received per spectral band at Earth for a small body of a given visible magnitude are plotted.

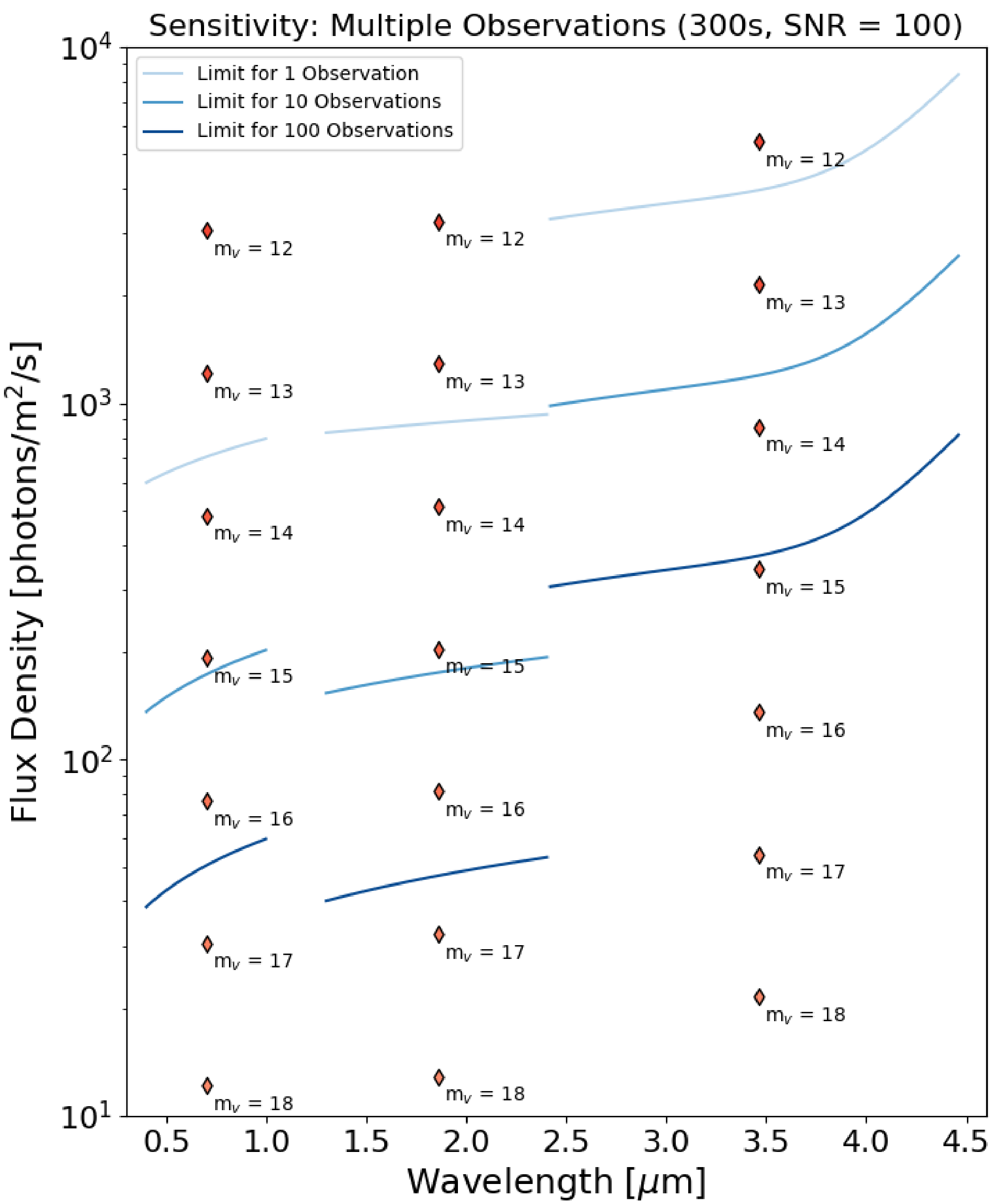

Fig 3 For multiple 300 second observations, the sensitivity and saturation limits of Twinkle assuming observational parameters of SNR = 100, R$\sim$250 (λ <2.42μm) and R$\sim$60 (λ >2.42μm). Additionally the average photon flux received per spectral band at Earth for a small body of a given visible magnitude are plotted.

By combining multiple observations, the faintest object which could be observed by Twinkle can be improved. We find that by stacking fewer than 100 observations, each with exposure times of 300s, Twinkle could probe to visible magnitudes of $m_v \sim$15-16.5 (Figure 3). The sensitivity limit of Twinkle could be further increased by binning down the spectra, reducing the resolution but increasing the number of photons per spectral bin.

The number of asteroids which Twinkle could characterise depends upon the brightness of targets when entering the field of regard, which dictates the possibility of tracking it with the FGS (without the need for linear tracking segments) and the data quality achievable. The cumulative number of asteroids of a given visible magnitude that enter Twinkle's field of regard with non-sidereal rates of $<$30 mas/s is shown in Figure 4. We find that several thousand Main Belt asteroids with a visible magnitude $<$15 enter Twinkle's field of regard over the time periods considered. Around a hundred Outer Belt asteroids are bright enough for on target tracking with the current FGS design, as are a handful of Trojans and tens of asteroids in the Inner Belt. Additionally tens of NEOs could be studied, some of which may be potential Earth impactors, allowing Twinkle to contribute to planetary defence by characterising bodies in close proximity to the Earth. We note that the $\sim$70 asteroids studied spectroscopically by AKARI are likely to be included within these potential targets for Twinkle.

4.2 Size of Potential Observable Asteroids

For each asteroid which enters Twinkle's field of regard over the period 2022 - 2032, the maximum visible magnitude has been calculated as described. Additionally, the diameter, if not already known, has been determined assuming 3 different albedos (0.05, 0.2 and 0.4). Figure 5 shows the sizes of asteroid that Twinkle could characterise. The plotted value for the diameter is that calculated assuming an albedo of 0.2 while the error bars show the change in the diameter if the albedo is between 0.05 and 0.4. We find that the majority of potentially observable asteroids are large ($>$1km) but there are also some possible targets with sizes of 100's of metres or less. If tracking via bright stars is employed and data resolution or quality can be sacrificed (i.e. spectral binning of spectra or SNR $<$100) then objects fainter than M_v = 15 could be observed with Twinkle which would allow for many asteroids with smaller diameters to be characterised.

4.3 Comets

The visible magnitude of $\sim$1000 comets has been monitored over the period 2022 - 2032 and Figure 4 shows the maximoum brightness achieved. Over a decade, $\sim$200 comets are found to be brighter than the current tracking limit of Twinkle's FGS and thus spectra with SNR $>$100 could be obtained for these over multiple observations at Twinkle's highest resolution. However this is likely an underestimate as many known comets have not been included in the analysis, due to lack of a database which provides access to their key orbital and physical parameters, and surveys, such as LSST, which are expected to find many more in the coming years.

5 Discussion

With its wavelength coverage, position outside of Earth's atmosphere, instrument performance and stability, Twinkle is ideally suited to acquire high fidelity visible and near-infrared (VNIR) data for the small bodies of the Solar System. The short exposure times required for many objects mean that Twinkle could observe thousands of small bodies, multiple times, in only a small fraction of the

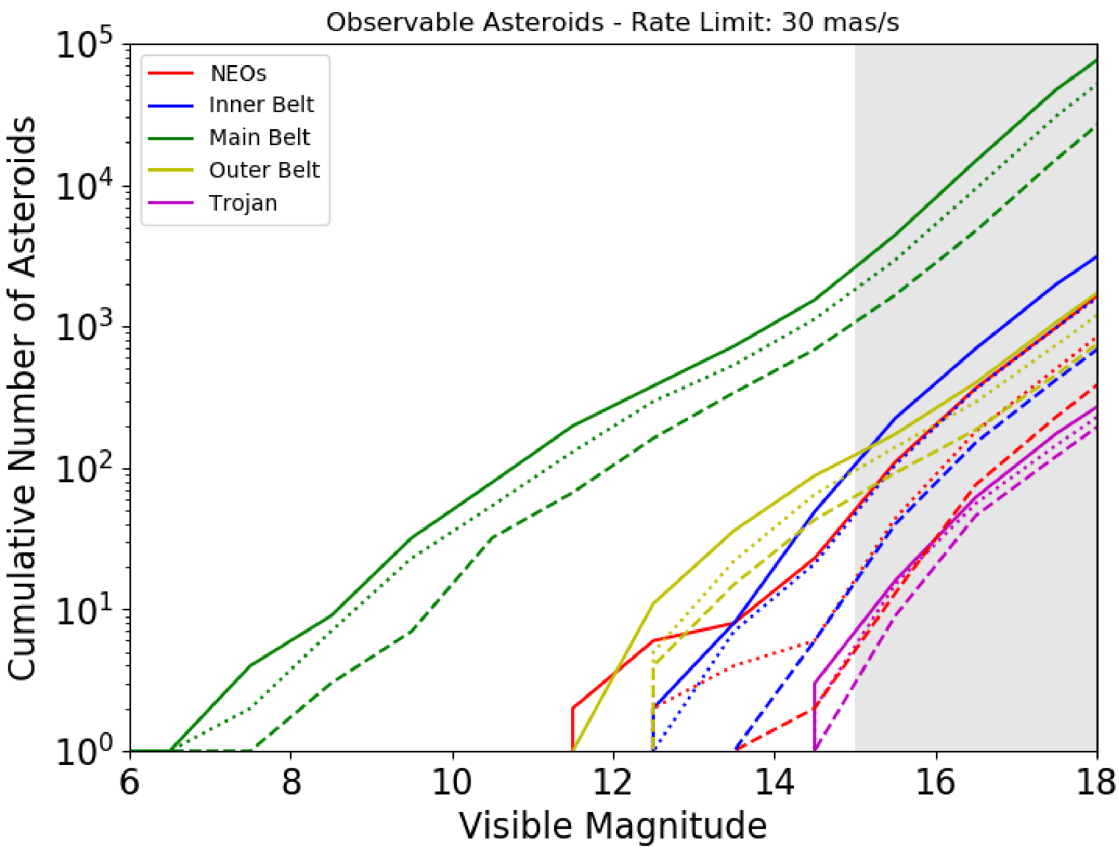

Fig 4 Cumulative number of asteroids of a given visible magnitude and type that enter Twinkle's field of regard over several time periods (dashed: 2022 - 2023, dotted: 2022 - 2025, solid: 2022 - 2032) with non-sidereal rates of <30 mas/s. The grey area indicates the cut-off due to the tracking capability of the current FGS design.

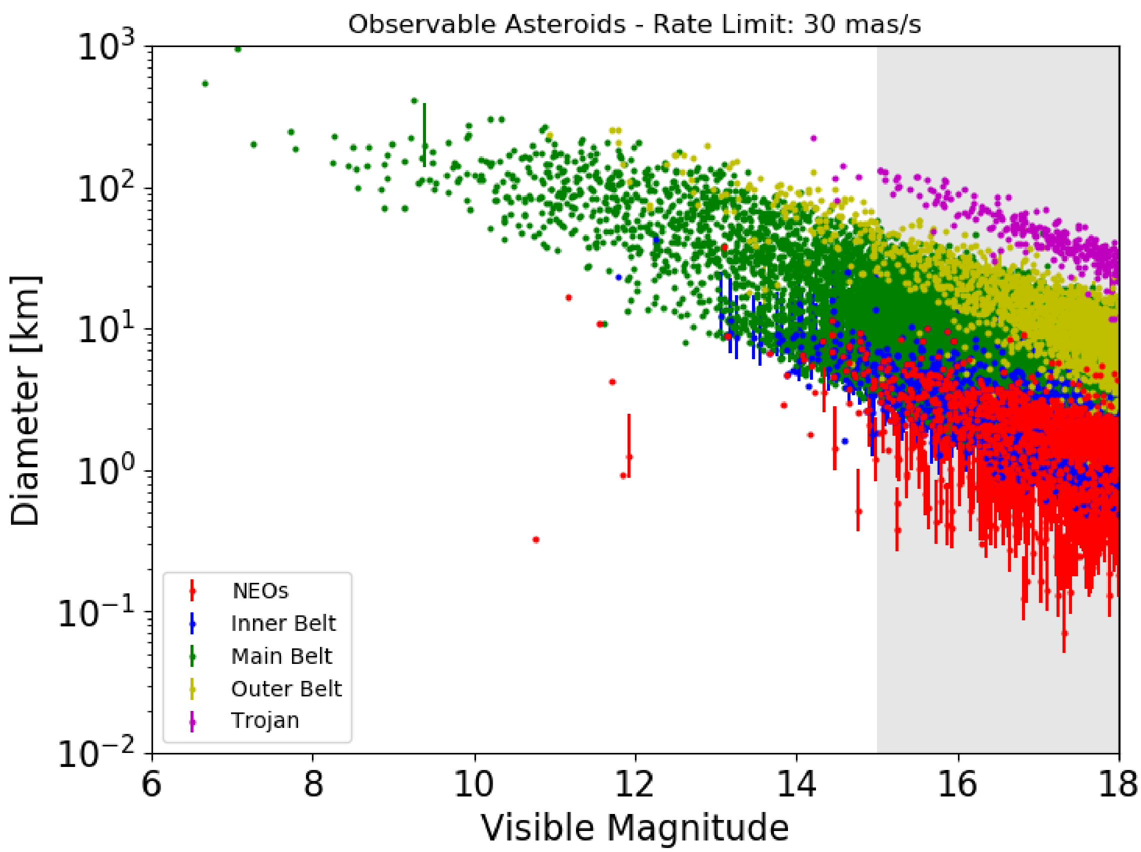

Fig 5 The diameters of asteroids which enter Twinkle's field of regard and the max visible magnitude they are observable at with non-sidereal rates of <30 mas/s. The grey area indicates the cut-off due to the tracking capability of the current FGS design.

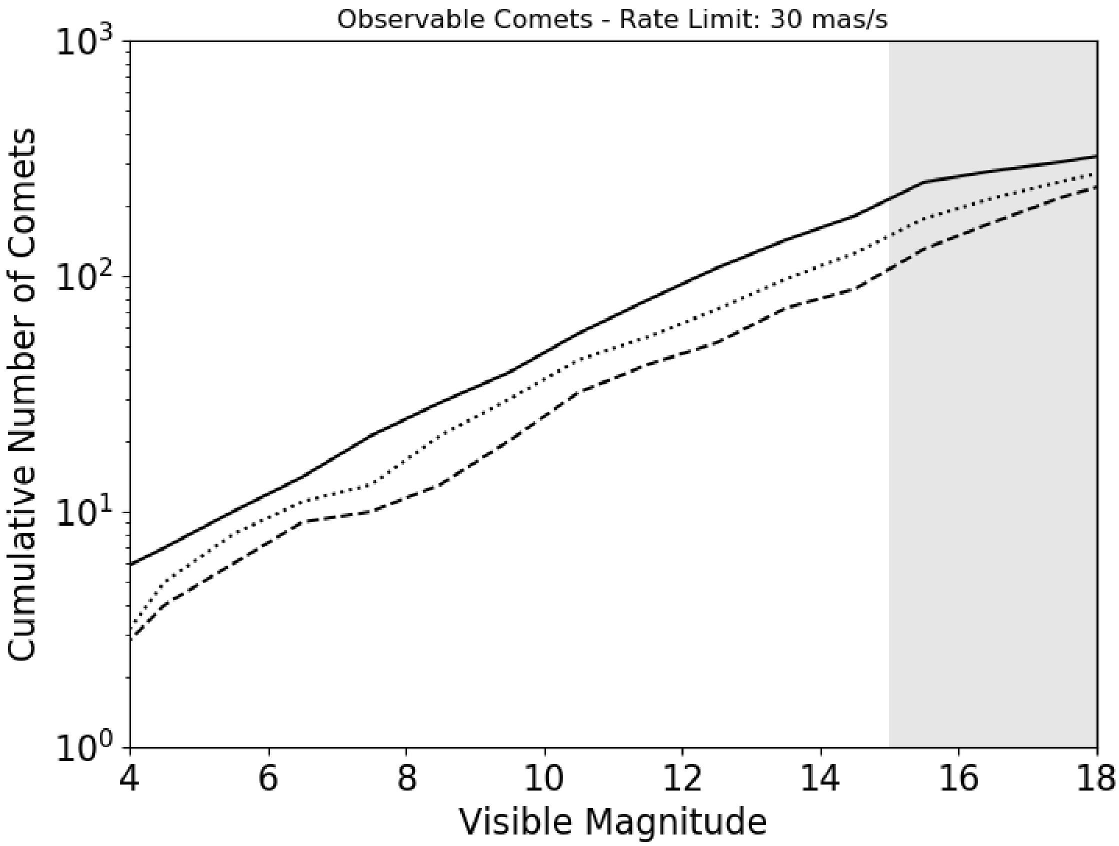

Fig 6 Cumulative number of comets of a given visible magnitude that enter Twinkle's field of regard over several time periods (dashed: 2022 - 2023, dotted: 2022 - 2025, solid: 2022 - 2032) with non-sidereal rates of $<$30 mas/s. The grey area indicates the cut-off due to the tracking capability of the current FGS design.

mission life. While Twinkle is well-suited to investigate asteroids of all types, the most promising contribution is the characterisation of primitive asteroids. Twinkle's ability to fully resolve spectral features related to hydroxyl (OH), water (ice and gas), and hydrated silicates, which are either partially or fully obscured in Earth-based observations due to Earth's water-rich atmosphere, offers the opportunity to collect the best primitive asteroid VNIR data set to date. Currently, telluric (atmospheric) water features in the spectral data prevents a full characterisation of the primitive asteroids and comet comae. Such a characterisation is required to determine the composition and mineralogy of these objects and Table 1 (see Appendix) contains various minerals with absorption features within Twinkle's spectral range. Without a large database of VNIR spectra free of atmospheric water contamination, our understanding of the composition of the most primitive bodies of the Solar System has been stunted. This has strongly limited the scientific pursuits enumerated in Section 1. Here we discuss some of the open questions within the small bodies field and the potential impact Twinkle data could have on these avenues of research.

5.1 Characterising composition and mineralogy of primitive asteroids

A characterisation of the composition and mineralogy of the primitive asteroids (C-complex, some X-complex, D-type, and potentially L-/K-type) remains unconstrained. This is in part due to the fact that the surfaces of these asteroids contain abundant opaques (e.g. amorphous carbon), which lead to the spectra of these asteroids types being, for the most part, featureless. However, the primary problem with characterising the composition and mineralogy of primitive asteroids using VNIR spectroscopy is that almost all VNIR spectroscopic studies to date have been limited to ground-based observations. The few absorption features observed in primitive asteroids are associated with water and/or hydration (either chemically or physically absorbed), which are contaminated by atmospheric water in ground-based observing campaigns.

5.1.1 0.7 and 3μm features

Two notable absorption features associated with primitive asteroids are the 0.7μm and 3.0μm features which are commonly observed in CM chondrites as well as C-complex and M-type asteroids.[18,81,84,110,111] The 0.7μm feature is not obscured by atmospheric water, but what compositional information it constrains is still an open question. This feature is often associated with phyllosilicates and attributed to Fe^{2+} - Fe^{3+} intervalence charge transfer.[110,111] Regardless of its association with phyllosilicates, the 0.7μm feature is not currently a diagnostic of phyllosilicate mineralogy or composition.

The 3μm feature is, in many cases, a complex blend of several different features. The 3μm band is associated with hydration and is due to a combination of possibilities: hydroxyl (OH), water ice, and water/hydroxyl associated with phyllosilicates.[5,12,16,42,62,74,81,87,97] The shape of this feature is dependent on the composition. For example, OH has band positions between 2.7 - 2.8μm that vary based on the associated composition (i.e., OH in hydrated minerals).[16] An OH-only 3μm feature will have a sharp absorption drop off near 2.7μm that transitions to a near-linear return to the continuum level for wavelengths long-ward of the feature minimum. Some studies have shown that the location of the OH band minimum in carbonaceous chondrites is an indicator of phyllosilicates and of the degree of aqueous alteration experienced.[5,42,74,96] A 3μm feature due entirely to water ice, on the other hand, will have a broader, more bowl-shaped minimum region.[62,97] The water ice 3μm feature is a composite of three absorption bands due to molecular vibrations located at near 3.0, 3.1, and 3.2μm that shift slightly in wavelength location depending on whether the ice is crystalline or amorphous and as a function of temperature.[62] In addition to the contributions from water and hydroxyl, hydrated minerals, such as the phyllosilicates, also have spectral absorption features near 3μm with band positions that vary based on mineral species and composition.

The large diversity of 3μm band shapes and centres is used to divide the NIR spectra of asteroids with a 3μm feature into four spectral groups (the sharp, or 'Pallas'-like, rounded or 'Themis'-like, 'Ceres'-like, and 'Europa'-like),[96] and divide the spectra of CM and CI chondrites into three spectral groups, with band positions tenuously associated with degree of alteration and composition of the phyllosilicate serpentine.[97] The relationship between these two groups is still not understood, and there have been no meteorite spectral matches to the 'Ceres'-like, 'Pallas'-like, or 'Europa'-like asteroid spectral groups.[96,97] Efforts to resolve this problem would greatly benefit from spectral data sets of primitive asteroids obtained by a space-based telescope, such as Twinkle, coupled with further laboratory measurements of hydrated minerals and carbonaceous chondrites.

5.1.2 The 3.2 - 3.6μm organics feature

The spectrum of C-complex asteroid 24 Themis exhibits a feature spanning 3.2-3.6μm that has been associated with organic material on the surface.[12,81] This feature is blended with the strong 3μm absorption. By fitting a spectral model to the 3μm feature which includes water ice coated pyroxene grains intimately mixed with amorphous carbon, the residual 3.2 - 3.6μm feature has been extracted.[81] The shape and position of the residual feature was used to suggest the presence of organic material with CH_2 and CH_3 functional groups. However, an additional feature centred near 3.3μm, indicative of aromatic hydrocarbons, may be required to provide a decent spectral match.

Currently, 24 Themis and 65 Cybele[55] are the only asteroids with spectroscopically confirmed detections of organics. Asteroid 24 Themis is the largest fragment in a dynamical family of over 1600 asteroids located near 3.2 AU from the Sun.[121] There are indications that a significant percentage of them have the 0.7μm feature implying aqueous alteration.[36] Several other studies also suggest that the Themis family has a variety of compositions, based on a large spectral diversity in NIR (1 - 2.5μm[11,24]) and mid-infrared (5 - 14μm[55]) observations. This makes the Themis family a likely candidate to search for organics via an absorption feature near 3.3 - 3.6μm. The largest (diameters 50 - 100km) Themis family members are observable with high SNR for relatively short exposure times, making this group of asteroids targets of interest for Twinkle that could extend the number of detections of organics and our knowledge of organics in the asteroid belt. Additionally, the Themis family contains three of the newly discovered Main-Belt Comets (e.g.[10,69,90]), where a full 0.4 - 4.5μm spectrum uncontaminated by atmospheric water would significantly benefit small bodies science.

5.1.3 Additional hydration features

The 1.4 and 1.9μm features often used in terrestrial studies, but are yet to be detected in asteroids due to the presence of opaques or contamination by atmospheric water.[16] The 1.4μm feature is the first overtone of the OH-band at 2.7 - 2.8μm discussed previously. The 1.9μm feature is a combination of water ice bending and OH stretching modes. While these features have yet to be observed in the NIR spectra of asteroids, they are expected to be present in asteroid spectra that exhibit a strong 3.0μm feature. Twinkle's position as a space-based telescope offers the opportunity to provide the first detections of these features.

The 2.2 and 2.4μm features are OH combination bands that generally appear in pairs,[45] and so they are considered together here. These features are commonly used in Earth and Mars spectral studies to identify phyllosilicates, and they have band centre positions that are diagnostic of Al and/or Mg composition.[76] They have been tenuously identified in some CM chondrites and as weak features in a few CI chondrites, but thus far there have only been tentative detections in asteroid spectra.[18,19,83] Twinkle has the potential to identify these compositionally diagnostic features for C- and X-complex asteroids.

5.2 Composition of Comet Nuclei and Comae

Comets are considered to be reservoirs of some of the most primitive material in the Solar System. They formed out beyond the H_2O frost-line where ices can condense and become incorporated into growing planetesimals. As such, they contain a plethora of volatile ices, organics, and silicate material that has remained relatively unaltered since the comet forming epoch. This 'pristine' quality makes comets an ideal object to study to understand the origin and evolution of our Solar System.

Detecting the solar light reflected by cometary nuclei is a powerful and efficient method for determining their size and for studying their properties. However, this technique requires knowledge of the albedo and the contributions from the comet coma can be difficult to disentangle. Hubble's high spatial resolution has been used to solve this issue (e.g.[52,53]). However, Twinkle's instrumentation does not provide high spatial resolution and, to characterise the nucleus, will generally have to observe comets near aphelion. This presents an issue as the large separation causes the comet nucleus to be extremely faint. There is also no guaranteed cut-off boundary for cometary activity with many comets know to be active beyond 5 AU (e.g.[95]) and 2P/Encke has been anomalously bright when observed at aphelion.[35]

Hence, Twinkle's capability for determining the size of comet nuclei and detecting water-ice, or other compounds, will require analysis on a case-by-case basis. However, Twinkle will be able to observe the comae of many comets to search for water-ice, water-vapour, CO_2, and organics, all of which will add to our understanding of comets and the origins of water and organics in our Solar System.

As a comet nucleus approaches the Sun, the ices near the surface begin to sublimate, liberating material from the surface to form a temporary thin atmosphere of gases and dust (i.e., a comet coma). NIR observations of comet comae frequently reveal the gaseous phase of cometary volatiles: primarily H_2O vapour, but also as CO_2 and CO gas (e.g.[2,33,85,94]). However, over the past decade, there has been a growing number of detections of water-ice (at 2.0 and 3.0μm) in the comae of comets made by in-situ spacecraft or ground-based telescopes.[2,21,33,50,77,93,94,120] Characterising the composition, size, and structure of these ice grains is a newly-emerging field in cometary science. This could be accessible with Twinkle and it offers the ability to increase our understanding of the initial stages of planet formation, the structure of the early solid grains in the Solar System formation, and the outer disk environmental conditions of the pre-protoplanetary disk of gas and dust.

In addition to the water-ice features, Twinkle has the opportunity to detect water vapour (2.7μm), organics (3.3 - 3.6μm), and CO_2 (4.3μm) as emission features in the comae of comets.[20,114,119]

Measurements of the 4.3μm CO_2 feature can be used to derive CO_2 abundances in comets. In turn, the abundance of CO_2 in comets constrains cometary formation and is the driver of activity on comets, especially at large heliocentric distances that are external to the frost-line. As atmospheric CO_2 heavily obscures the 4.3μm feature, ground-based studies are unable to observe this feature. A large number of comets were studied as part of the WISE/NEOWISE mission, providing constraints on dust, nucleus size, and the CO/CO_2 abundance.[4] Additionally 23 comets were studied by Spitzer allowing them to be classified as CO/CO_2 'rich' or 'poor'.[78] However, in both cases these were broadband measurements making disentangling CO and CO_2 emission difficult. AKARI observed 18 comets, constraining the CO_2 production, with respect to H_2O production, for 17 of them.[73] Therefore the total number of comets with observed CO_2 features and derived abundances is small. Hence, Twinkle, as a space-based observatory with NIR spectral coverage capable of observing this feature, can potentially provide a highly valuable resource to the cometary science community. Additionally, the Large Synoptic Survey Telescope (LSST) is expected to discover ~10,000 comets,[92] some of which will be entering the inner Solar System for the first time. Characterising these pristine objects, as well as short period comets which have undergone surfaces changes, would allow for a deeper study of comet evolution.

5.3 Composition and Mineralogy of S-complex and V-type asteroids

VNIR spectroscopy spanning 0.4 - 2.5μm of the stony type asteroids (S-complex and V-type) with mafic mineral compositions primarily of pyroxene and/or olivine are not strongly impeded by atmospheric water, and therefore there have been numerous spectroscopic studies of these types of bodies. The majority of these studies are performed using the SpeX instrument on the IRTF, a well-subscribed ground-based telescope. Twinkle offers an additional resource to the small bodies community to acquire VNIR spectra of stony asteroid surfaces and provide complimentary data. However, Twinkle's current design may limit the characterisation of these stony asteroids as discussed in Section 5.3.1.

5.3.1 The 1.0 - 1.3μm spectral gap

Twinkle's current design has a spectral gap between the visible and infrared spectrometers at 1.0 - 1.3μm. Twinkle is currently in a Phase B design review and thus the instrument characteristics are being reassessed. If a channel that covers the 1.0 - 1.3μm region were included, the following types of studies would become possible with Twinkle:

- **Characterisation of S-type asteroids to establish links to meteorite analogues.** A major goal of VNIR spectroscopic studies of asteroids is to establish meteorite analogue connections. This requires both high quality remote-sensing data of asteroids, from a platform such as Twinkle, and several laboratory measurements of meteorites including reflectance spectra and a mineralogical analysis of the meteorites via methods such as electron microprobe or x-ray diffraction. Previous investigations have been successful in establishing such connections.

- **Identification of ordinary chondrite parent bodies.** Another key objective of spectral studies of asteroids is to identify a meteorite analogue, and, in cases where a strong link exists between meteorite type and asteroid type, to leverage that information to identify asteroid families that could represent the parent bodies of those meteorites. Identification of such parent bodies extends our knowledge of the thermal structure of our protoplanetary disk, and of how each of the different OC meteorite groups formed. Hence, using Twinkle to obtain spectra of S-type asteroids in an effort to identify ordinary chondrite parent bodies would add significantly to our understanding of planetary formation, thermal history and evolution of protoplanets, and the dynamical evolution of the Solar System during the protoplanetary disk epochs.

- **Characterisation of Stony Asteroids** is limited by the spectral gap. Asteroids with mafic silicates, olivine and pyroxene on their surfaces have two prominent absorption features near 1 and 2μm (Figure 7) that are diagnostic of silicate mineralogy and composition.[1,9,17,27,38,86] These two features, often referred to as Band I and Band II for the 1 and 2μm bands, respectively, are commonly used to determine mineralogy (olivine-to-pyroxene ratio) and composition (molar percent of Fe in olivine and pyroxene) of S-complex and V-type asteroids via band parameter analysis studies (e.g.[8,23,38,41,56,66,79,86,100]).

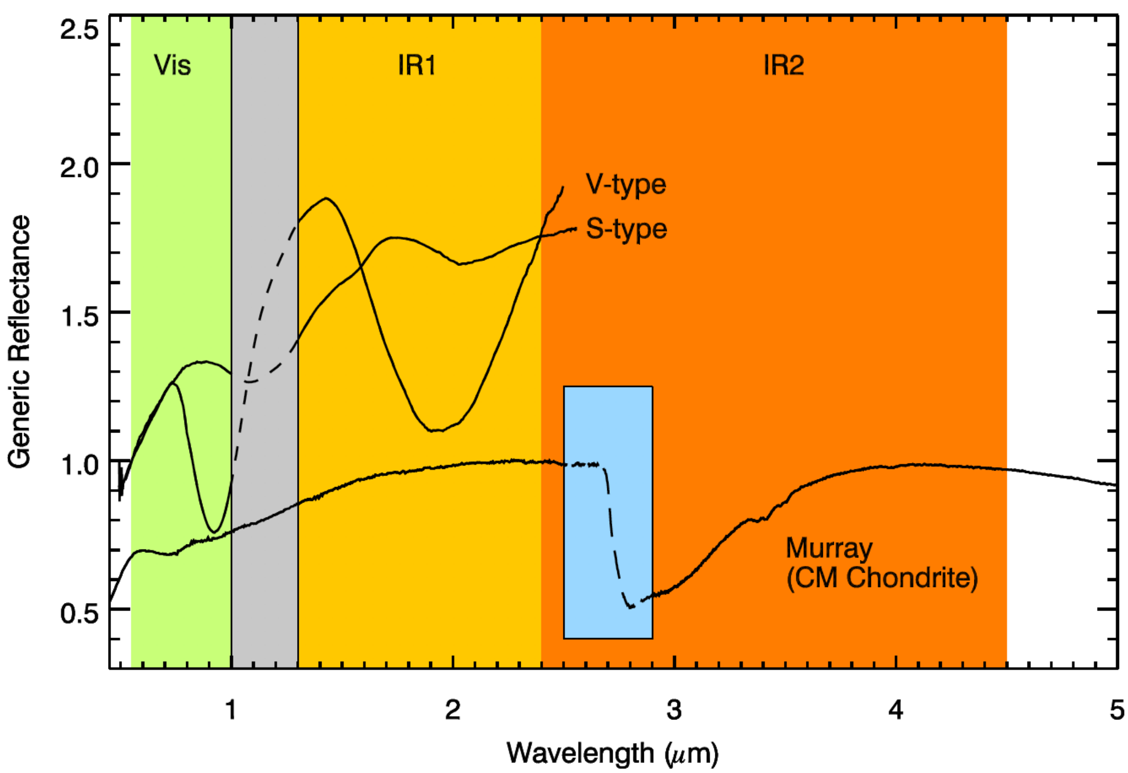

Fig 7 Example spectra of potential targets plotted over the visible (Vis) and two near-infrared (IR1, IR2) channels of Twinkle. The CM Chondrite, Murray, is representative of primitive, hydrous asteroids. The 0.7μm and 3.0μm features associated with hydrated primitive asteroids (see Section 5.1) are apparent in the spectrum of Murray. The small blue inset window represents the 3μm portion of the spectrum obscured by Earth's atmosphere. The Earth's atmosphere can also obscure the spectrum near 1.4 and 1.9μm (not shown). The generic S- and V-type asteroid spectra (from[56]) exhibit the 1 and 2μm bands used to determine mafic mineralogy and compositions (see Section 5.3). The vertical grey bar highlights the spectral gap from 1.0 - 1.3μm in the current Twinkle design. The spectrum for Murray was acquired from the RELAB database.[75]

5.4 *Rotationally Resolved Spectral Data Sets*

Based on the exposure time estimates from Figure 2 and asteroid brightness from Figure 4, Twinkle will be able to obtain rotationally resolved spectra for a large number of Main Belt asteroids and some NEOs. Spectral variability is expected for asteroids due to a number of effects, including space weathering, composition and grain size heterogeneity, thermal effects, and viewing aspect (i.e. phase angle of observation). Constraining any of these as the cause of spectral variability offers a tremendous opportunity to further our knowledge on the processes governing the formation and evolution of asteroids. For example, S-type asteroids are susceptible to changes in VNIR spectral slope and Band I parameters (depth, centre, and area) due to space weathering by irradiation and micrometeorite impacts.[14,15] If subsurface material is brought to the surface via an impact event or rotational fission event (i.e., mass-shedding), this 'fresher' material, that has not been processed by space weathering, will have different spectral characteristics than the rest of the regolith on the surface, which would lead to spectral variations as a function of rotation. If detected, this would provide a valuable dataset to understand the rotational evolution and potential disruption of asteroids as well as how space weathering proceeds in different parts of the Solar System.

To date, rotational variability in VNIR spectra of asteroids has been observed from in-situ spacecraft measurements for 951 Gaspra, Ida and Dactyl by Galileo,[107,108] 433 Eros by NEAR,[109] 4 Vesta from the Dawn spacecraft[80] and ground-based observations,[37] as well as for a handful of NEOs. There have also been suggestions of spectral variability due to surface heterogeneity for other asteroids, but it is likely that these variations are caused by observational effects, such as viewing aspect or poor observing conditions, or different data reduction methods.[56,86] However, as mentioned previously, there are many reasons to expect spectral variability on the surfaces of asteroids. Therefore, it is likely the dearth of confirmed spectral variations due to surface heterogeneity is a result of the reliance on ground-based facilities for VNIR spectroscopy of a large population of asteroids. Considering the relatively short exposure times needed to acquire high signal to noise spectra with Twinkle, and its position as a space-based observatory, Twinkle could be an ideal telescope to conduct rotationally resolved spectral studies.

6 Conclusions

Here we explore Twinkle's capabilities for small bodies science and find that the observatory will have the capability to acquire high SNR spectra for a large variety of asteroid types including a vast number within the Main Belt. Spectra at Twinkle's highest resolution and with SNR>100 could be obtained for asteroids brighter than M_v = 12 in <300 seconds. Combining multiple observations, or reducing the observational requirements, will allow many fainter objects to be characterised.

With respect to potential impact, Twinkle's strongest contribution to small bodies science could be the opportunity to investigate the composition of the primitive asteroids that exhibit features associated with hydration (water ice, hydroxyl, and phyllosilicates), which to date, is an area that has been severely limited due to atmospheric water contamination in ground-based observations. Twinkle also offers the opportunity to study of stony (S-complex and V-type) asteroids. Finally, with respect to asteroid science, Twinkle offers the potential to be the best resource to study rotational variation in spectra of asteroids, which is difficult to do with ground-based telescopes due to Earth's atmosphere generating spectral variations similar to what is expected for asteroids.

Additionally to asteroid science, Twinkle will have the capability of investigating the comae of bright comets, providing valuable data sets on CO_2 production and the presence of water-ice and organics in the comae. Therefore, Twinkle potentially provides a resource that would push our understanding of asteroids and comets, and hence the formation and evolution of the Solar System, well beyond its current state.

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7 Appendix

Table 1: Main spectral features of some common minerals within the 0.4 - 4.5μm spectral region

Minerals	Main Spectral Features [μm]		Comments
Carbonates			
Calcite/Dolomite		1.85 - 1.87	
		1.97 - 2.0	
		2.12 - 2.16	
		2.30 - 2.35	
		2.50 - 2.55	
		3.40	
		4.00	
Oxides			
Chromite		0.49	
		0.59	
		1.3	At the edge of Channel 1
		2.0	
Spinel		0.46	
		0.93	
		2.80	
Organics			
e.g. n-alkanes,	numerous	1.7	
amino acids	including:	2.3	
		2.4	
Phosphates			
Apatite	OH - apatite	1.4	
		1.9	
		2.8	
		3.0	
	F - Cl apatite	2.80	

		3.47	
		4.00	
		4.20	
Silicates			
Olivine		0.86 - 0.92	
		1.05 - 1.07	Not currently covered
		1.23 - 1.29	Not currently covered
Pyroxene	Mg - Fe	0.91 - 0.94	
		1.14 - 1.23	Not currently covered
		1.80 - 2.07	
	Ca - Mg - Fe	1.2	Not currently covered
		2.0	
Feldspar	Na - Ca	1.1 - 1.29	Not currently covered
Phyllosilicate	e.g. saponite	1.35	
		1.8	
		2.3	
		2.8	
	e.g. serpentine	1.4	
		1.9	
		2.2	
		2.9	
		0.7	
		0.9	
		1.1	Not currently covered

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Dr Neil Bowles is an Associate Professor at the University of Oxford. His main research interests are in laboratory measurements that help analyse and interpret data returned from space-based remote sensing and in-situ instruments for landers. He also works on developing new space-based instrumentation. Neil is a co-investigator and science team member on numerous ESA and NASA missions including Ariel and Mars Insight.

Dr Marcell Tessenyi is the CEO of Blue Skies Space Ltd and Project Manager for the Twinkle mission. He is responsible for the day-to-day programmatic activities of the Twinkle project. Marcell has a PhD in astrophysics from University College London in exoplanet spectroscopy. His contributions to space instruments include the European Space Agencys M3 candidate mission EChO and the M4 mission Ariel.