Probing the surface environment of large T-type asteroids

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ABSTRACT

Context. The thermal and radiative environments encountered by asteroids have shaped their surface features. Recent observations have focused on asteroids in the main belt and showed indications for ices and organics in the interiors of the asteroids that were likely significant on prebiotic Earth. They stand out in reflectance spectra as darker, redder colours than most collocated asteroids.

Aims. We probe the surface environment of large (>80 km in diameter) T-type asteroids. This taxonomic type is relatively ill-constrained as an independent group. We discuss their place of origin based on our probing.

Methods. We performed spectroscopic observations of two T-type asteroids, (96) Aegle and (570) Kythera, over the L band (2.8–4.0 μm) using the Subaru telescope. The spectra of other T-type asteroids are available in the literature, as are survey datasets. Based on this, we strove to find commonalities and global trends in this group. We also used the archival polarimetric data of the asteroids and meteorite spectra from laboratory experiments to constrain their surface texture and composition.

Results. Our targets exhibit red L-band continuum slopes, (0.30±0.04) μm⁻¹ for (96) Aegle and (0.31 ± 0.03) μm⁻¹ for (570) Kythera, that are similar to those of (1) Ceres and 67P/Churyumov-Gerasimenko, and have an OH-absorption feature with band centres <2 μm. For (96) Aegle, we find an indication of a shallow N–H band near 3.1 μm and a C–H band of organic materials over 3.4–3.6 μm, whereas no diagnostic bands of water ice and other volatiles exceeding the noise of the data were seen for both asteroids. The large T-type asteroids except for (570) Scheila display spectral shapes similar to those of to our targets. About 50% of large T-type asteroids contain an absorption band near 0.6–0.65 μm that is likely associated with hydrated minerals. For T-type asteroids (except for Jupiter Trojans) of all sizes, we found a weak correlation that the smaller the diameter and the closer to the Sun, the redder the visible (0.5–0.8 μm) slope.

Conclusions. The 2.9 μm band depths of large T-type asteroids suggest that they might have experienced aqueous alteration comparable to Ch-type asteroids, but that it was more intense than for most of the main-belt asteroids. The polarimetric phase curve of the T-type asteroids is well described by a particular surface structure. The 0.5–4.0 μm reflectance spectra of large T-type asteroids appear most similar to those of CI chondrites with grain sizes of ~25–35 μm. Taken as a whole, we propose that large T-type asteroids may have been dislodged roughly around 10 au in the early Solar System.

Key words. minor planets, asteroids: general – minor planets, asteroids: individual: T-type asteroids – methods: observational – techniques: spectroscopic

1. Introduction

As remains from the planet formation process, asteroids occupy distinct regions relative to the Sun as a result of perpetual gravitational scattering by planets and mutual collisions. Their wide range of surface reflectances and colours enables researchers to establish taxonomic systems by grouping asteroids showing similarities in spectral features (e.g. Tholen 1984; Bus & Binzel 2002; DeMeo et al. 2009). Asteroids in the same taxon often serve as the basis for understanding the formation and dynamical evolution of a certain region in the solar nebula (DeMeo & Carry 2014).

From dozens of spectral types, D- and T-type asteroids stand out in their spectra over 0.45–2.45 μm (VNIR), which are redder and more featureless than those of most collocated main-belt asteroids (Fig. 1). These very red (albedo <0.1) asteroids are thought to retain abundant primitive materials inside, such as organics and ice (Vernazza et al. 2015). Compared to D-type asteroids, which have been actively studied (e.g. Emery & Brown 2004; Brown 2016), there are fewer T-type asteroids1, and no consensus on their origin has yet been established. Britt et al. (1992) suggested a possible relation between T- and M-type asteroids due to their troilite-like spectra and similar semi-major axes, while the sharp OH-band shape of T-type (308) Polyxo in the so-called 3 μm region (2.8–3.2 μm), like those of B-type (2) Pallas and C-type (54) Alexandra, implies that T-type asteroids might have experienced aqueous alteration that once was prevalent throughout the mid-asteroid belt (Rivkin et al. 2002; 23 as of March 2022, labelled as T as the other asteroids at the Tholen or Bus-DeMeo taxonomies (Tholen 1984; DeMeo et al. 2009). Seven of these asteroids reside outside of the main asteroid belt.

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For instance, absorption features in the 3 \( \mu \)m at longer near-infrared wavelengths (LNIR; 2.5–4.0 \( \mu \)m) emerge in the mental bands of interest than their overtones in the VNIR emerge. In contrast, stronger fundamental features of opaque elements (e.g. amorphous carbon and magnetite) are near the local maximum of the absorption coefficients of hydrous materials (i.e. minerals including H\textsubscript{2}O or OH), so that this region has been actively investigated to shed light on the thermal history of the early Solar System (Takir & Emery 2012; Usui et al. 2019). The N–H, C–H, and C–O bands exist across the LNIR region and indicate phyllosilicates, ices, hydrocarbons, and salts. This allows us to constrain the temperature at asteroid-forming epochs and in the subsequent evolution (Rivkin et al. 2002; Clark et al. 2007; De Sanctis et al. 2018; Kurokawa et al. 2020).

We present new LNIR spectroscopic observations of the large T-type asteroids (96) Aegle and (570) Kythera obtained from the Subaru Telescope. Their large size (\( \sim 178 \) km and \( \sim 88 \) km in diameter for the former and the latter, respectively\(^2\)) has likely kept them intact after catastrophic collisions (Bottke et al. 2005; Charnoz & Morbidelli 2007). Combining our results with published LNIR spectra and survey data of other large T-type asteroids, we examine their surface texture and grain composition and discuss a plausible scenario for their formation and subsequent dynamical evolution based on our results. We here regard a T-type asteroid (T type, for short) as a body that falls in the X-complex in DeMeo et al. (2009). Of the various sub-types in this complex (e.g. Xc, Xe, and Xk), we plot the mean reflectance of X-type asteroids (X\textsubscript{Mean}) as a representative of the P-type. The shaded areas of top three curves denote the standard deviations of each taxon.

\(^2\)NASA/JPL Small Body Query Database (https://ssd.jpl.nasa.gov/tools/sbdb_query.html)

2. Observations and data analysis

In this section, we describe the observational circumstances and data analyses. The journal of observational geometry and instrument settings is summarised in Table 1.

2.1. Observations

2.8–4.2 \( \mu \)m spectroscopic observations of (96) Aegle and (570) Kythera were conducted on UT 2020 September 19 using the Infrared Camera and Spectrograph (IRCS; Kobayashi et al. 2000) mounted on the Nasmyth focus of the 8.2-m Subaru Telescope (155\(^{28}\)34\(\prime\)4W, 19\(^{49}\)32\(\prime\)N, 4139 m) at the top of Mauna Kea, Hawaii. Low-resolution (\( \Delta \lambda/\lambda \sim 150 \); pixel scale of 52 mas pixel\(^{-1}\)) grism spectroscopy mode with adaptive optics (AO188; Hayano et al. 2010) was implemented with a slit width...
of 0′.3 for the two asteroids and standard stars (solar analogues of G2V spectral type). The CFHT Sky Monitor probe showed that the night of observation was photometric, and AO188 enabled us to reach a diffraction-limited full width at half maximum down to 0′′.12.

To subtract the sky emissions and detector dark current, object spectra were taken at two positions (A and B) on the detector, separated by 4′′ along the slit direction, and nodded in the A–B–B–A dither cadence. We repeated this procedure more than four times for each asteroid to obtain a high signal-to-noise ratio for the combined spectra, achieving total integration times of 1 920 for (96) Aegle and 2 400 s for (570) Kythera. The total number of spectral images is four times the number of the A–B–B–A cadences, that is, 4N in Table 1. The telescope was tracked to follow the non-sidereal motions of the targets, during which observations of standard stars were interspersed at an airmass similar to that of the target (different by ≤0.02 on average). Observations of both targets were conducted with the same instrumental settings and exposure time per frame. The standard stars and targets were observed at the same slit position, which was set along the north-south direction (SLIT_PA = 90′). The supporting astronomer confirmed that atmospheric dispersion was negligible. Spectral flat frames were obtained at the end of observations.

2.2. Data analysis

The procedure basically followed the Grism Spectroscopic Observations with IRCS (ver. 2.1.3E)⁵, which offers IRAF and the shell software⁶ to reduce the IRCS grism data. The following paragraphs spell out two topics: (i) the pre- and post-processing of the grism spectroscopic data, and (ii) intercomparison of the standard star spectra we used to estimate calibration uncertainties.

Firstly, all spectral images of 1024×1024 pixels were reduced to subtract the nod positions from each other (A–B) to eliminate OH sky emissions. The 4N images of a target were then divided into two groups (i.e. with 2N files), one group taken in the first half and the other taken in the second half of the observation. The images in each group were median combined into a single spectrum of the target, yielding two target images. The same procedures were applied to the standard stars. Next, we cropped the combined spectral images to leave 340×860 pixels in the x and y directions, respectively, with the object in the centre, and divided them by a normalised flat frame to remove pixel-to-pixel sensitivity variations on the chip. We used differential images of the lamp-on (i.e. the light from the lamp plus thermal emission of the system) and lamp-off (thermal emission only) frames to construct flat-field images. For bad pixel correction, we first co-added all flat images into a single file, divided the file by the median-combined master flat to build a bad-pixel map, and subtracted the map from the target and standard star images. It was confirmed that no bad pixels overlapped with the object positions. The resulting object images were further checked to determine whether there were any ill-behaved pixels showing ≥5σ higher or lower counts than the mean of the surrounding pixels due to a hit of cosmic rays or pixel malfunctions. If any of these were the case, the 5×5 neighbouring pixels were used to interpolate the mean value to the affected pixel.

After preprocessing, we extracted 1D source spectra (counts as a function of pixels) along the dispersion axis from the 2D spectral images. The background of each spectrum was fitted by a linear function (i.e. a second-order Chebyshev function) with a 3σ rejection cut and was subtracted from the observed signal. Third-order and second-order Legendre polynomial fitting functions were then applied to extract the spectra for the standard stars and targets, respectively, yielding root mean squares (RMS) of ∼0.03 for the stars and ∼0.15 pixels for the targets. The extracted spectra were then wavelength calibrated by matching the near-infrared sky transmission spectrum at Mauna Kea to the absorption features of the standard stars and targets. We fit the absorption features versus the x coordinate using a third-order spline (cubic spline) function. The RMS of the fits were always an order of ∼0.03 Å (pixel)⁻¹ and ∼0.20 Å (pixel)⁻¹ for standard stars and targets, respectively (which are acceptable given that the dispersion is 15.9 Å (pixel)⁻¹ in the L band). The calibrated spectra were binned three times to reduce the sampling cadence (~1200) to the spectral resolution (~150), where the data at <2.85 μm and >4.10 μm were discarded due to the nonlinearity of the detector in intensity and intrinsically small atmospheric transmission thereof (based on the recommendations in the manual). The binned spectra were then normalised, after which the two groups of the target and standard star spectra were averaged into a single spectrum. We divided the resulting spectrum of the target by the spectrum of a standard star whose airmass differed by within 0.02 on average. The standard stars we used are G2V-type solar analogues; therefore, we were able to obtain a normalised reflectance for each target.

A systematic difference in the standard stars was measured to estimate the calibration uncertainty in the spectral slope of the targets. We observed a total of three standard stars during the night (G2V-type HD 26749, in addition to the two stars in Table 1) and evaluated the consistency of their normalised counts as a function of wavelength by dividing one spectrum by another. Comparison of the stellar spectra in Fig. 2 justified our selection of standard stars (HD 12846 and HD 377) by showing that their spectral slopes are internally consistent with an accuracy of ±5% (grey areas) on unity over ∼2.9–4.0 μm. This level of uncertainty is comparable to the linear uncertainty (~3–5%) of the 0′.3 slit width in <10 000 counts, as described in the official instrument manual. Bumpy structures near 3.3 μm are due to the atmospheric CH₄ absorption (Lord 1992). Deviations larger than a ±5% uncertainty level were persistently observed at wavelengths of <2.9 and >4.0 μm; therefore, we ignore these regions in the following analysis.

In summary, we delimited the data we used for analysis from 2.9 to 4.0 μm from the original wavelength coverage sampled by the instrument from 2.8 to 4.2 μm. A slope of the target continuum has an additional ±5% error on its nominal value on account of the calibration uncertainty of the standard stars. In the following sections, the term 'L band' refers to this effective wavelength region of 2.9–4.0 μm and is interchangeably used with 'LNIR (2.5–4.0 μm).

3. Results

We examined the spectral properties of (96) Aegle and (570) Kythera. Other LNIR spectra from the literature of T types

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3 https://www.naoj.org/Observing/DataReduction/Cookbooks/IRCSsp_cookbook_2010jan05.pdf
4 https://www.naoj.org/Observing/DataReduction/index.html
5 https://www.subarutelescope.org/Observing/Instruments/IRCS/IRCSum_1.0.1.pdf
6 https://www.naoj.org/Observing/Instruments/IRCS/grism/grisms.html
Fig. 2. Ratios of the normalised counts of the standard stars. The horizontal grey shaded areas represent the ±5% uncertainty on unity. We selected HD 12846 and HD 377 for the calibration, and their normalised ratio is highlighted in red in panel b.

and the second phase of the Small Main-belt Asteroid Spectroscopic Survey (SMASSII; Bus & Binzel 2002) datasets and its extension to 2.5 μm (DeMeo et al. 2009) were also employed to explore global trends in this taxonomic group.

3.1. LNIR spectra of (96) Aegle and (570) Kythera

An intrinsic spectral shape of an asteroid can be expressed as normalised reflectance (R) by dividing the asteroid spectrum by that of a standard star. Because the data of the normalised target and standard star are represented by \( X_n \pm \sigma_{X_n} \) and \( Y_n \pm \sigma_{Y_n} \), respectively, the propagated uncertainty associated with \( R \) of \( X_n/Y_n \) is

\[
\frac{\sigma_{X_n} Y_n + X_n \sigma_{Y_n}}{X_n Y_n^2}. 
\]

The \( X_n \) and \( Y_n \) are normalised values of \( X \) and \( Y \), respectively, which are the average of the two groups’ median-combined spectra (Sect. 2.2). Figures 3 and 4 show the resulting R of (96) Aegle and (570) Kythera normalised at 3.5 μm.

The overall reflectances of both asteroids increase linearly (i.e. red spectral slopes) except for the long end of the L-band region. In general, the contribution of thermal emission to the observed flux for main-belt asteroids becomes significant beyond 3.5 μm (Lebofsky et al. 1981). We adopted simple thermal models, the equilibrium model (EM; i.e. a modified blackbody function; Delbo 2004) and the standard thermal model (STM; Lebofsky et al. 1986), to check the distribution of thermal components in our observed data. The thermal portion in the EM was calculated using a first-order blackbody function in instantaneous equilibrium with solar insolation,

\[
f_{EM}(\lambda) = \frac{\epsilon \pi B(\lambda, T_{SS}) R_e^2}{\Delta^2},
\]

where \( \epsilon \) is the wavelength-independent emissivity (0.9 used here; Lebofsky 1980), \( B(\lambda, T_{SS}) \) is the Planck radiation function at the sub-solar temperature \( T_{SS} \), \( R_e \) is the effective radius of an asteroid, and \( \Delta \) is the geocentric distance at the observing epoch. The STM requires additional steps to consider a distribution in the surface temperature over the sunlit hemisphere of the asteroid \( T(\Phi) \) and the effect of surface roughness \( \eta \) (Lebofsky 1980; Lebofsky et al. 1986),

\[
f_{STM}(\lambda) = \frac{\epsilon D_e^2}{2 \Delta^2} \int_0^{2\pi} B(\lambda, T(\Phi)) \sin \Phi \cos \Phi \, d\Phi,
\]

where

\[
T(\Phi) = \begin{cases} 
T_{max} \cos^{1/4} \Phi & \text{if } \Phi \leq \pi/2 \\
0 & \text{otherwise}
\end{cases}
\]
and the maximum temperature $T_{\text{max}}$ at the sub-solar point was obtained from

$$T_{\text{max}} = \left( \frac{1 - A}{\varepsilon \sigma r_H^4} \right)^{1/4}.$$  

Here, $D$ is the effective diameter of the asteroid, $\Phi$ is the solar colatitude, $S$ is the solar constant (1360.8 W m$^{-2}$), $\sigma$ is the Stefan-Boltzmann constant (5.67 $\times$ 10$^{-8}$ W m$^{-2}$ K$^{-4}$), $\eta$ is the beaming parameter (0.756 for large low-albedo asteroids; Lebofsky et al. 1986), and $r_H$ is the heliocentric distance. $A$ is the bolometric Bond albedo and approximated to that in the $V$ band as $A = A_V = q \times p_V$, where $p_V$ is the geometric albedo (0.048 for (96) Aegle$^7$ and 0.044 for (570) Kythera; Masiero et al. 2011). $q$ is the phase integral that equates 0.290 + 0.684$G$ in the standard $H$–$G$ magnitude system (Bowell et al. 1989), where $G$ is the slope parameter (0.15 used here). In Figs. 3a and 4a, we overplot the modelled thermal fluxes assuming that their contribution at 2.9$\mu$m is negligible. The modelled curves were used to compare the spectral shapes with the observed spectrum to diagnose the influence of thermal contamination. The steep rise of thermal components appears to occur along with the observed reflectances at $\geq 4.0$ $\mu$m for (96) Aegle and $\geq 3.8$ $\mu$m for (570) Kythera. The shorter wavelength data show a linear increase and match the published result of Fraeman et al. (2014) well (background grey symbols in Fig. 3a), justifying the negligible slit loss of our data that the implementation of AO188 could achieve. The thermal inerts of (96) Aegle at 178 km and (570) Kythera at 87 km do not differ much within the measurement errors (Hung et al. 2022); therefore, the observed slight difference in the thermal emission of the two asteroids is probably caused by their different heliocentric distances at the time of observation.

We made a least-squares linear fitting over the 2.90–3.75 $\mu$m and measured the spectral slopes of the targets:

$$(0.30 \pm 0.04) \mu m^{-1} \text{ for (96) Aegle and (0.31 \pm 0.03) \mu m^{-1} for (570) Kythera.}$$

The continuum was then removed from the observed reflectance of each asteroid (panel b in Figs. 3 and 4), and the result was compared with the atmospheric transmission curve modelled by ATRAN (Lord 1992) in the same airmass as the asteroids to search for plausible absorption features. Most of the data points across the $L$-band fluctuate near the guidelines of the $\pm 5\%$ calibration uncertainty (Sect. 2.2), whereas points of (96) Aegle and (570) Kythera that are contaminated by the thermal excess deviate more than the average. There is a broad, shallow local minimum over 3.4–3.6 $\mu$m on the spectrum of (96) Aegle, which would be compatible with the C–H absorption bands of organic materials (Khare et al. 1990). Its band depth is comparable to but slightly exceeds the $\pm 5\%$ uncertainty level. The asteroid also seems to contain absorption around 3.14 $\mu$m, whose band centre could be associated with the N–H stretch of ammonium ions at $\sim 3.1–3.2$ $\mu$m (Lodders 2003). In contrast, the bumpy structures clustered shortward of $\sim 3.2$ $\mu$m for (570) Kythera follow similar trends with atmospheric transmittance, primarily attenuated by H$_2$O sky absorptions. A local minimum of $\Delta R$ around 3.25 $\mu$m may be a meaningful feature. However, considering that the feature position is in between the local maxima of atmospheric absorptions and that its neighbouring data points have significant errors due to the CH$_4$ sky absorption at $\sim 3.3$ $\mu$m, we suspect that the data points in this region might be affected by the residuals of atmospheric calibration. We thus defer the discussion of this figure to future observations with better data quality. Overall, the reflectance spectra of the two $T$ types exhibit red and linear continuum slopes in the $L$ band, indicating the N–H band near 3.1 $\mu$m and the C–H band near $\sim 3.5$ $\mu$m for (96) Aegle.

3.2. Large $T$-type asteroids in the VNIR–LNIR region

Featureless $L$-band spectra are less informative of the surface conditions of the asteroids. We thus extended the wavelength coverage to the VNIR region using the SMASISSI datasets (DeMeo et al. 2009). Because strong telluric lines and thermal background noise often degrade the data quality for LNIR ground-based observations (Cruikshank et al. 2001; Emery & Brown 2003), only a handful of large $T$ types have been observed in the $L$-band region: (308) Polyxo (Takir & Emery 2012), (596) Scheila (Yang & Hsieh 2011), (773) Irmtraud (Kanno et al. 2003), (96) Aegle (this study and Fraeman et al. 2014), and (570) Kythera from this study. We digitised their LNIR spectra from the published figures. The 2.2–3.4 $\mu$m spectrum of (96) Aegle in Fraeman et al. (2014) nicely fits our $L$-band data, the composite spectrum of which was then scaled to the SMASISSI spectra. In the case of (570) Kythera, we found no available data concurrently covering the $L$ band and shorter wavelengths to refer to giving an offset. Instead, we employed its near-infrared albedo ($p_{IR}$) information measured by the NASA Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010). A $p_{IR}$ over the W1 (3.4 $\mu$m) and W2 (4.6 $\mu$m) bands contains a sufficient fraction of reflected sunlight, such that the ratio of $p_{IR}/p_V$ can be used as a measure of their reflectances (Masiero et al. 2011; Harris & Drude 2014). We thus scaled the observed reflectance of (570) Kythera at 3.4 $\mu$m to 0.0653 ($p_{IR}$) so as to make $p_{IR}/p_V = 0.0653/0.0440 \approx 1.48$ (Masiero et al. 2011). Previous observations for the other three asteroids covered wavelengths in the $K$ (1.8–2.5 $\mu$m) and $L$ bands simultaneously.

Figure 5 reveals that the large $T$ types we considered particularly have the slope difference and a reflectance drop-off between the $K$ and $L$ bands in common. Their VNIR shapes are concaving...
down, whereas those in the L band are nearly linear. These discontinuities on either side of the region that is made opaque by water vapour in Earth’s atmosphere indicate the presence of an absorption band. Their linear increase in reflectance over 2.9–3.2 μm is a characteristic feature of the so-called ‘sharp’ or ‘Pallas’ 3 μm spectral group of asteroids with an OH-band of phyllosilicates as a product of aqueous alteration (Vilas & Gaffey 1989). The band centre depends on the mineralogy, specifically, on cations gluing silica layers of phyllosilicates. For instance, the 0.7 μm band shifts to shorter wavelengths as the composition becomes more Mg rich (Cloutis et al. 2011b). Serpentine and smectite group (saponite) phyllosilicates yield a band centre near 0.7 μm (Vilas et al. 2001a) and have linear slopes, (3) their spectral shape and brightness change discontinuously between the K and L bands, and (4) all large T types we used for the comparison except for (596) Scheila are consistent with having an OH-absorption band. This means that they belong to the sharp 3 μm group defined by Takir & Emery (2012).

### 3.3. Search for correlations

We enlarged the scope of consideration to T types of all sizes by exploiting the SMASII data of 21 T types (~0.9–177.8 km in diameter for T types constrained their size) except for Jupiter Trojans. We strove to find global trends in the T types and correlations between their spectral characteristics (reflectance, spectral slope, and spectral curvature) with sizes and orbital elements implying any universal physical processes acting on their surfaces.

One of the widely used proxies for the hydration status of the surfaces is the so-called 0.7 μm band (0.6–0.75 μm), which can likely be attributed to iron oxides in phyllosilicates, a product of aqueous alteration (Vilas & Gaffey 1989). The band centre depends on the mineralogy, specifically, on cations gluing silica layers of phyllosilicates. For instance, the 0.7 μm band shifts to shorter wavelengths as the composition becomes more Mg rich (Cloutis et al. 2011b). Serpentine and smectite group (saponite) phyllosilicates yield a band centre near 0.7 μm (Vilas et al. 1994) and ~0.6–0.65 μm (Cloutis et al. 2011a), respectively. Intrigued by (570) Kythera showing this absorption band near 0.65 μm (Vilas & Gaffey 1989), we took a closer look at this spectral region of other large T types (a total of eight with >80 km in diameter), adding (595) Polyxena, which was not initially observed by Bus & Binzel (2002), but was observed later by Lazzaro et al. (2004) because it shows a visible slope that is compatible with T types in the Bus-DeMeo taxonomy. Figure 6 shows their continuum-removed spectra (AR). A continuum was defined as a linear function fitting the data points over ~0.44–0.55 μm and ~0.72–0.76 μm, the exact start and end wavelength points of which were slightly adjusted for each asteroid due to their different spectral curvature.

Of the eight large T types, a weak absorption feature appears for (96) Aegle, (308) Polyxo, (570) Kythera, and (595) Polyxena between ~0.60 and 0.65 μm (highlighted in purple). The SMASII spectrum (grey line) indicates no feature for (570) Kythera, whereas that from the NASA/PDS Vilas Asteroid Spectra (Vilas et al. 2020, initially observed by Vilas & Gaffey 1989) has an absorption band (black line), as reported by the authors. When they are detected, the band centres of the large T types appear at shorter wavelengths than those of most hydrous...
Fig. 6. Continuum-removed spectra of all currently known large T types (Table A1). The continuum was fitted by a linear function using data points at ~0.44–0.55 and ~0.72–0.76 μm (exact start and end points of the wavelengths were adjusted depending on the spectral curvature of the asteroids). Each was normalised at 0.55 μm and offset for clarity. Positive and negative detections of the 0.7 feature were coloured in purple and grey, respectively.

main-belt asteroids (e.g. Ch type) near ~0.7 μm (Rivkin et al. 2002). Shallow band depths (~3% of the ambient continuum levels at most) agree with previous observations that the 0.7 μm band intensity is typically ~1–6% of the continuum (Vilas & Gaffey 1989; Vilas et al. 1994; Fornasier et al. 1999, 2014). We were unable to find an equivalent spectral feature for the other four large asteroids ((114) Kassandra, (233) Asterope, (596) Scheila, and (773) Irmtraud), either due to the absence of the materials on the observed surfaces and/or because their content is not strong enough to be detected. For smaller (<50 km in diameter) T types, the fluctuation of the spectra is too large to investigate these subtleties.

Finally, we studied the distribution of the reflectance ratios (corresponding to the spectral slope) in the VNIC and LNIC regions as a function of semi-major axes. The ratio of the reflectances measured at 0.8 and 0.5 μm (R_{0.8}/R_{0.5}) represents the VNIC slope, while that measured at 3.2 and 2.9 μm (R_{3.2}/R_{2.9}) represents the LNIC slope. Figure 7 illustrates the results, and all information of the T types used in this figure is summarised in Table A1.

Firstly, for large T types compared in Fig. 5, the VNIC and LNIC slopes show no apparent relations with their sizes, albedos, and orbital elements. (We also tested relations with their eccentricity, inclination, and perihelion distance, but do not plot them here.) However, when T-types in all size ranges are considered, NEOs tend to have the reddest VNIR slope of the T types (R_{0.8}/R_{0.5} ~1.326 on average), followed by intermediate-size (~1.223 on average) and larger (>80 km) asteroids for the shallowest (~1.215 on average). T-type NEOs inside 2 au exhibit redder slopes than the NEOs with main-belt semi-major axes. This apparent relation may be caused by a difference in phase angles during observation. The spectral slopes of D-like red asteroids and comet nuclei have been found to change with phase angle, where they generally become redder with increasing phase angle (Fornasier et al. 2016; Lantz et al. 2018). To determine whether this phase reddening shapes the colour distribution, we considered the phase angle of each data point and confirmed that phase angles of the asteroids are distributed randomly, spanning from 0° to 23.4° except for one NEO (2001 UU92) observed at a phase angle of 59.8° (Binzel et al. 2004). The phase angles of the other NEOs are in the range of the main-belt T-type phase angles. Given (1) the negligible correlation between the phase angles and R_{0.8}/R_{0.5} values (Spearman’s correlation r = –0.029 for the asteroids analysed here), and (2) the reddening in this phase angle range for dark main-belt asteroids, which is usually less significant than the observational uncertainties (Marsset et al. 2020; Beck et al. 2021a), the result might not be associated with the phase angle conditions of the asteroids.

Except for the moderate connection between the spectral slope and diameter of the asteroids, we found no further correlations between the T-type properties and their dynamical characteristics, and none between the slope and albedo of the asteroids (r = 0.002), within the limited number of T-type data currently available. This absence of global correlations seems in
A spectroscopic study of 16 Jupiter Trojans finds \(~3.1\) \(\mu\)m N–H stretch and \(~3.4\) \(\mu\)m organic features for a subpopulation with a less-red colour (Brown 2016). The nucleus of comet 67P/C-G from the Rosetta mission also reveals a prominent N–H band at \(3.1–3.2\) \(\mu\)m (Poch et al. 2020) and a broad C–H absorption complex of organics between 3.3 and 3.6 \(\mu\)m (Quirico et al. 2016). The corresponding features may exist on our T type (96) Aegle spectrum, but to a lesser degree at \(~3.1\) \(\mu\)m and \(~3.5\) \(\mu\)m (Figs. 3 and 8). This is quite surprising because these \(3.1\) \(\mu\)m N–H bands require the availability of NH\(_3\) and/or N\(_2\) ices in the accretion stage (Lodders 2003). That is, the presence of the volatile bands requires parent bodies (or their constituents) to be originated from the outer Solar System (\(\geq 5–10\) au; Lodders 2004; Kurokawa et al. 2020), far away from the current positions of large T types in the mid-asteroidal belt. The spectrum of C-type (1) Ceres from the Dawn mission contains a well-developed 2.7 \(\mu\)m band of Mg-rich phyllosilicates as large T types due to the extensive aqueous alteration (McSween et al. 2018). However, its \(3.1\) \(\mu\)m band of NH\(_3\) salts and the organics and carbonate bands at \(3.3–3.6\) \(\mu\)m and \(3.9–4.0\) \(\mu\)m (De Sanctis et al. 2018) implies that the early materials of (1) Ceres probably contained abundant CO\(_2\)/CO and NH\(_3\) ices (Carrozzo et al. 2018; Kurokawa et al. 2020) and again signals its connection to the outer region (\(>20\) au; Fujiiya et al. 2019).

The LNIR continuum slope (\(~0.3\) \(\mu\)m\(^{-1}\)) of T types is shallower than that of Jupiter Trojans (\(~0.9\) \(\mu\)m\(^{-1}\)), but comparable to the nucleus of 67P/C-G (\(~0.2\) \(\mu\)m\(^{-1}\)) and (1) Ceres (\(~0.3\) \(\mu\)m\(^{-1}\)). This similarity in slope may have implications for the close affinity of anhydrous (i.e. early) components of T types to those in the primitive Ceres and comet 67P/C-G, which is again not feasible if large T types were formed and have been stored at their current warmer locations. An OH-absorption band present on the T types but not on the other low-albedo bodies (Fig. 8) suggests that the T types had abundant water ice at their birth and experienced higher temperatures than the others for melting ice for some time (McSween et al. 2002). It is unclear whether the lack of C–O bands on the T-type spectra arises because their formation distance is closer than the CO\(_2\) condensation front, the outgassing during the aqueous alteration, or the current orbital positions of the asteroids in the mid-asteroidal belt sublimating CO\(_2\) ices from the near-surface layers (Kurokawa et al. 2020). However, given the similarities observed in the N–H and C–H bands and the background refractory materials, it is most likely that the large T-types originated outside of the main asteroid belt.

The \(0.7\) \(\mu\)m band is attributable to (but not definitive for) hydrated minerals harbouring iron oxides in phyllosilicates (Vilas & Gaffey 1989; Vilas et al. 1994), which together with much lower thermal background levels than in the LNIR makes the \(0.7\) \(\mu\)m feature a tool for assessing the aqueous alteration history of asteroids (Rivkin et al. 2015b and references therein). Rivkin et al. (2002) found that the observed frequencies of the \(0.7\) \(\mu\)m and \(3.0\) \(\mu\)m bands for low-albedo asteroids (the C, B, G, F, and P classes) seem proportional. Rivkin (2012) reported from the distribution of the \(0.7\) \(\mu\)m band that roughly 60% of the C-complex asteroids in the Sloan Digital Sky Survey Moving Object Catalogue might have experienced hydration. Fornasier et al. (2014) suggested that the difference in the detection rate of the \(0.7\) \(\mu\)m band for different taxonomic types likely reflects the range of their permittivity. However, asteroids with sufficient signals of OH-absorption bands do not always accompany the \(0.7\) \(\mu\)m band (Fornasier et al. 2014; Rivkin et al. 2015b; Usui et al. 2019), which is often explained on account of the weak \(0.7\) \(\mu\)m band intensity (typically \(~1–6\)%; Vilas & Gaffey 1989;
4.2. Surface texture of large T-type asteroids

The environments asteroids have been exposed to shape their present-day compositional and physical surface properties (Clark et al. 2002). When it is scattered by the surface, sunlight becomes partially linearly polarised. The resulting degree of linear polarisation $P$ draws a bell-shaped dependence on the phase angle $\alpha$ (angle of Sun–asteroid–observer), often fitted by an empirical trigonometric function (Cellino et al. 2015 for a review). This phase curve can be characterised by six parameters, among which those depicting the curve around the backscattering region (i.e. small $\alpha$) are well known to be sensitive to the texture and optical properties of the surfaces (Wolff 1975; Dollfus & Geake 1975; Geake & Dollfus 1986; Geake & Geake 1990; Dollfus 1998).

From the Asteroid Polarimetric Data (APD) provided by the NASA Planetary Data System (PDS) Small Bodies Node (Lupishko 2022), we adopted $V$-band (the effective wavelength of 0.55 $\mu$m) data because it contains the most observations, where five large T types, (96) Aegle, (114) Kassandra, (233) Astarte, (308) Polynyo, and (773) Irmtraud, are available. The polarimetric phase curve, $P(\alpha)$, of the selected data was then obtained using the trigonometric function of Lumme & Muinonen (1993),

$$P(\alpha) = b \sin^{c_1}(\alpha) \cos^{c_2}\left(\frac{\alpha}{2}\right) \sin(\alpha - \alpha_0),$$

where $b$, $c_1$, $c_2$, and $\alpha_0$ are free parameters shaping the curve. $\alpha_0$ is the inversion angle where $P$ equals 0% and thus has different signs on its either side, that is, $P$ is negative at $\alpha < \alpha_0$ and positive at $\alpha > \alpha_0$. Figure 10 shows the average trend of the T-type asteroids. The fitting parameters are $b = 0.39 \pm 0.03$, $c_1 = 0.93 \pm 0.03$, $c_2 = (2.47 \pm 0.10) \times 10^{-11}$, and $\alpha_0 = 20.18 \pm 0.29$. The minimum polarisation degree ($P_{\text{min}}$) and its phase angle ($\alpha_{\text{min}}$) were retrieved by differentiating the above equation and leaving it equal to zero: $P_{\text{min}} = -1.35 \pm 0.02\%$ and $\alpha_{\text{min}} = 9.75 \pm 0.10$.

The retrieved polarimetric parameters of the T types were then compared with those of low-albedo asteroids in different taxonomic types (Table 3 in Beltskaya et al. 2017) in the plot of the absolute value of $P_{\text{min}}$ ($|P_{\text{min}}|$) versus $\alpha_0$ (Fig. 11). Two dashed lines (2.0% and 1.2%) encase the $|P_{\text{min}}|$ range of carbonaceous chondrites measured by Zellner et al. (1977). Asterisks are the measurements of dark (albedo <0.10) pulverised rocks and meteorites (Geake & Dollfus 1986). Thick solid curves partition the territories of rocky–particulate surfaces (left curve) and particulate–fine-grained surfaces (right curve) derived from the measurements of lunar regoliths (Geake & Dollfus 1986). Numbers in parentheses show the average geometric albedos of the asteroids used here. We found no one-to-one relation between the albedo and polarimetric parameters, as Zellner & Gradie (1976) reported that the polarimetric–albedo relation saturates for very dark (albedo $\leq 0.06$) asteroids. Within the error limits, the $|P_{\text{min}}|$ values of all taxonomic types broadly overlap the range of carbonaceous chondrites, though the three darkest (F/D/P) types are located more on the borderline of the lower limit.
We can therefore interpret the fact that the polarimetric parameters of large T types are well in the region of dusty rocks to mean that their surfaces are covered by particulate media, not by rocks or large fragments or fine-grained fluffy dust (Geake & Dollfus 1986). This is well aligned with a general tendency of asteroidal surfaces: kilometer-sized bodies as rubble piles of collisional fragments are covered by coarse surface grains with typical sizes in the millimeter to centimeter range, whereas larger objects likely possess fine on-surface grains with sizes of about 10–100 µm (Gundlach & Blum 2013; Beck & Poch 2021). The T, Ch, C, P, and B types in the particulate surface region have more or less similar diameters of ∼120–170 km (the abnormally large (1) Ceres of 939.4 km, (2) Pallas of 513 km, and (10) Hygiea of 407.12 km in diameter were excluded from the count). The average size of the D types used here is about half of this (∼68 km), which might result in their observed α0 position near the coarser-grained territory. However, this trend appears not to be applicable to the point of F types that are located in the rocky surface region, even though their average size is ∼130 km. It is uncertain at the moment whether surface processes vastly different from most low-albedo asteroids have prevailed on the F types or if the interpretation of α0 is not a simple function of the grain size, especially for the dark asteroids of interest (Belskaya et al. 2017). Therefore, we only take the most straightforward message from Fig. 11 that a similar location of the large T types with low-albedo dusty rocks, meteorites, and other large-diameter asteroids in the polarimetric parameter plot would mean that their particulate surfaces are covered by ∼10–100 µm grains (Gundlach & Blum 2013).

4.3. Comparison with carbonaceous chondrites

Asteroids are expected to be a major source of meteorites (Lipschutz et al. 1989). Dark asteroids devoid of strong diagnostic absorption bands in the VNIR have been associated with carbonaceous chondrites (CCs), a group of meteorites relatively rich in C, H, N, and O (Miyamoto & Zolensky 1994; Burbine et al. 2002) that could have been relevant to habitability (Kwok 2016). Among CCs, CI (Ivuna type) and CM (Mighei type) chondrites are of particular interest because they contain a prominent 3 µm OH absorption band, indicating aqueous alteration on their parent bodies (Lebofsky et al. 1981; Beck et al. 2010, 2021b; Cloutis et al. 2011a,b; Takir et al. 2013; McAdam et al. 2015). It is hard to directly compare asteroids and meteorites primarily due to the possible difference in sampling regions (i.e. observed asteroidal surfaces are susceptible to space weathering, in contrast to meteorites originating from any parts of the parent bodies) and observing geometry (Hiroi et al. 2001; Jedicke et al. 2004). Nonetheless, when large T types can be connected with CCs, particularly their LNIR reflectance spectra, the composition of the bodies and the nature of thermal processes that occurred in the early Solar System become clearer.

We set the spectrum of (96) Aegle as a representative of large T types in our limited sample, as its spectral shape over the entire VNIR–LNIR range is almost identical to the much-observed (308) Polyxo, but has less noise in the spectrum (Fig. 8). The whole spectrum was scaled to its visible geometric albedo (0.048; Mainzer et al. 2019) and compared with hydrated CM and CI chondrites. Because sample texture (e.g. powder and pellet) can significantly affect the spectral slope and depth of absorption features (Ross et al. 1969; Johnson & Fanale 1973; 

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8 All size information is quoted from the NASA/JPL Small Body Query Database (https://ssd.jpl.nasa.gov/tools/shdb_query.html).
Table 2. Information for the meteorite spectra used in Fig. 12.

| Panel in Fig. 12 | Spectrum ID     | Type                    | $\lambda_{min}\ (\mu\text{m})$ | $\lambda_{max}\ (\mu\text{m})$ | $a\ (\mu\text{m})$ | Reference        |
|------------------|-----------------|-------------------------|-------------------------------|-------------------------------|-------------------|-----------------|
| a                | bmr1mt0186      | Cold Bukkeveld (CM2)    | 1.4                           | 25.1                          |                   | RELAB (4)       |
|                  | bmr1mt0187      | Nogoya (CM2)            | 1.4                           | 25.1                          |                   |                 |
|                  | bmr1mt0188      | Mighei (CM2)            | 1.4                           | 25.1                          |                   |                 |
|                  | bmr1mt0190      | Murchison (CM2)         | 1.4                           | 25.1                          | <35               | RELAB (4)       |
|                  | bir1mt218       | MET 01070 (CM1)         | 0.8                           | 28.6                          |                   |                 |
|                  | bir1mt220       | QUE 93005 (CM2)         | 0.8                           | 28.6                          |                   |                 |
|                  | bir1mt221       | Y-791198 (CM2)          | 0.8                           | 28.6                          |                   |                 |
| b                | bir1mb064d1     | Murchison (CM2)         | 0.8                           | 99.7                          | <25               | RELAB           |
|                  | bir1mb064d2     |                         | 0.8                           | 99.7                          | 25–45             |                 |
|                  | bir1mb064d3     |                         | 0.8                           | 99.7                          | 45–75             |                 |
|                  | bir1mb064d4     |                         | 0.8                           | 99.7                          | 75–125            |                 |
| c                | bir1mt025a      | Tagish Lake (C2-ung)    | 0.8                           | 99.7                          | <25               | RELAB           |
|                  | bir1mt025b      | Tagish Lake (C2-ung)    | 0.8                           | 99.7                          | 25–125            |                 |
|                  | bir1mt264       | Alias (CI1)             | 0.8                           | 99.7                          | <35               | RELAB           |
|                  | bir1mt191       | Orgueil (CI1)           | 1.4                           | 25.1                          | <35               | RELAB           |
|                  | bir2mx064p      | Orgueil+Ivuna (CI1)     | 0.8                           | 25.1                          | <125              |                 |
|                  | 2478-7413 (5)   | Ivuna (CI)              | 0.3                           | 25.1                          | fine powders (6)  | Takir et al. (2013) |

Notes. (1) Starting wavelength for the spectrum in $\mu$m; (2) ending wavelength for the spectrum in $\mu$m; (3) the particle size in $\mu$m; (4) RELAB database (https://pds-geosciences.wustl.edu/spectrallibrary/default.htm); (5) section number from the Smithsonian Institution, as described in Takir et al. (2013); (6) Ground, but not measured exactly.

Cloutis et al. (2018), we selected meteorite spectra only in a particular or ground state in line with what the polarimetric properties of T types imply for their surface structure (Fig. 11). The detailed information about the meteorite samples we used for the comparison is listed in Table 2.

Figure 12a plots the T-type spectrum with CM chondrites that account for the dominant number of hydrous CCs (Zolensky et al. 1997) and have been nominated as a meteorite analogue for Ch types (Rivkin et al. 2015a; DeMeo et al. 2022). The petrologic variations of the CM chondrites correspond to a range of the intensity of aqueous alteration on their parent bodies (Wood 2005; Cloutis et al. 2011a). The abundance of phyllosilicates in the CM chondrites is higher than in CM chondrites due to the advanced aqueous alteration, based on which they can be classified into several subgroups (e.g. Browning et al. 1996; Rubin et al. 2007). We selected CM samples at different hydration levels: MET subgroups (e.g. Browning et al. 1996; Rubin et al. 2007). For consistency, the particle size of the samples was unified as <35 $\mu$m (Rubin et al. 2007). For consistency, the particle size of the samples was unified as <35 $\mu$m. In Fig. 12a, strongly altered CM samples explain neither the continuum slope nor the absorption band shape of the T-type spectrum.Positing that spectra of dark asteroids often have bluer slopes than their meteorite analogues (Beck & Poch 2021), likely due to the space weathering (change in surface properties by solar wind or micrometeoroid bombardments) on the asteroid surfaces (Lantz et al. 2017, 2018). CM samples that show far flatter slopes than the T type would not be good analogue candidates. Murchison (black curve) matches the overall T-type spectrum relatively better than the other CM samples. However, its reflectance seems too low (~2.83 $\mu$m to ~2.72 $\mu$m) and its band shape becomes deeper, narrower, and more asymmetric (Takir et al. 2013). Tagish Lake meteorites have been suggested as one of the best meteorites for D-, T-, and P-type red asteroids because their slopes are similar (Hiroi et al. 2001; DeMeo et al. 2022). Our comparison shows that Tagish Lake spectra in small (<25 $\mu$m, the solid black line) and larger (25–125 $\mu$m, the dashed black line) particle sizes are both much darker than the T-type spectrum. They also display either a much steeper VNIR slope (the smaller one) or shallower VNIR slope (the larger one) than the T types, but they match the OH-band shape better than CM chondrites. The VNIR slopes and overall reflectance of three CI spectra from the RELAB database are consistent with the T-type spectrum (the smaller the grain size, the better the match). We noted that their broad troughs around 3 $\mu$m denote the contamination of adsorbed terrestrial water molecules (Gounelle et al. 2008; Beck et al. 2010; Takir et al. 2013) and instead referred to another fine-grained CI Ivuna spectrum from Takir et al. (2013). Without requiring any...
Bidirectional reflectance of hydrated CO3 chondrites is unable to describe the OH absorption band properties. Samples of smaller particles of the meteorite spectra: CO3 ALH-77307 (Dotto et al. 2004; Emery et al. 2006); therefore, the observed emissivity in the MIR could be more sensitive to the physical properties of small grains on the surfaces, such as the grain size and porosity (Kwon et al. 2021; Kimura et al. 2022). In comparison, the reflectance around the OH-absorption band might be more determined by the mineralogy of hydrous silicates (Takir et al. 2013; Prince & Loeffler 2022).

To summarise, CI1 chondrites appear to match our representative spectra for large T types best in terms of the overall VNIR–LNIR spectral shape, reflectance, and absorption band properties. Samples of smaller particles of <35 μm (but not smaller than 25 μm) regardless of chondritic types always explain the T-type spectrum better, whereas the reflectance and spectral slopes of coarser samples of >45 μm is too low and are too shallow compared with the asteroid data. Among the meteorite spectra compared here, the reflectance spectrum of large T types appears most similar to CI chondrites with grain sizes of ~25–35 μm, which appears to be consistent with the indications of the surface conditions derived from the polarisation parameters.

4.4. Implications for the origin of T-type asteroids

The large T types probed in this study have featureless red spectra that are similar to those of D and P types in the VNIR region and L-band continuum slopes comparable to (1) Ceres and comet 67P/C-G. This spectral context of T types means that they have a stronger affinity to dark small red bodies originating from the outer part of the solar nebula than to collocated main-belt asteroids.

The apparent concordance with CI chondrites (Fig. 12), along with the possible detection of the 3.1 μm N–H band on (96) Aegle (Fig. 8) that requires NH2 and/or N2 ices at the formation epoch (Lodders 2003), favours the inward migration of large T types into the current orbits. CI chondrites are exceptional in almost every aspect: they retain the highest abundances of volatile elements (materials made of C, H, O, and N; Bland et al. 2005; Vollstaedt et al. 2020), deuterium in organics (Wood 2005; Alexander et al. 2007; Gourier et al. 2008; Remusat et al. 2010), and water-to-rock ratios (Brearley 2006; Alexander 2019; McDonough & Yoshizaki 2021) relative to any other CCs. All the chemical information indicates that CCs except for CI chondrites originated from a narrow radial distance from the Sun (2.7–3.4 au, thus experiencing similar peak temperatures), whereas CI-like materials migrated from farther distances in the protoplanetary disk (Alexander et al. 2007; Vollstaedt et al. 2020). During aqueous alteration on the parent bodies, the formation of saponite over serpentine was favoured by higher water-to-rock ratios (Zolensky et al. 1989; Kurokawa et al. 2020). Saponite group phyllosilicates naturally became enriched in CI...
chondrites instead of serpentine groups dominating in CM chondrites (Brearley 2006). These two products of aqueous alteration have a different band centre in the 0.7 μm region: serpentines at ≥0.7 μm, and saponites at 0.6–0.65 μm (Cloutis et al. 2011a,b). When we consider that the 0.7 μm serpentine band of CM chondrites matches the spectra of hydrous (e.g. Ch, C, and B types) main-belt asteroids well (Rivkin et al. 2015a; DeMeo et al. 2020), the CI-like large T-type band centres at 0.6–0.65 μm (Fig. 6) may support the idea that they would have undergone alteration processes different from that operating at main-belt distances.

When we assume that large T types were initially composed of D-type-like redder, darker materials (the most abundant taxonomic types beyond the main asteroid belt; DeMeo & Carry 2014), aqueous alteration and enhanced space weathering on their way to the current orbital positions would entail a systematic change in the physical and compositional properties of the observed surfaces. The formation of opaque minerals (e.g. magnetite) as products of aqueous alteration would flatten the continuum slope (Loeffler & Prince 2022). An extensive aqueous alteration may also cause grain growth (Jones & Brearley 2004), and for low-reflectance materials, the spectral slope becomes flattened with increasing particle size (Milliken & Mustard 2007; Vernazza et al. 2016). The plausible size range of the regolith of large T types constrained in this study (~25–35 μm) is larger than that of D type Jupiter Trojans, for which previous studies reported that their spectra appear to be explained by fine grains of <25 μm (Emery & Brown 2004; Emery et al. 2006).

The larger on-surface grains of T types might also demonstrate a similar band shape but weaker 10-μm silicate intensity of T type (308) Polyxo than D type (624) Hektor (Dotto et al. 2004; Emery et al. 2006). Space weathering in the inner Solar System is apparently also capable of turning the red slopes of D types to C- and P-like shallower slopes (Vernazza et al. 2013; Lantz et al. 2017, 2018; Gartrelle et al. 2021). Hasegawa et al. (2022) recently reported a change in the continuum slope of (596) Scheila since its impact in 2010 from the T type before the event to the D-type-like redder slope and suggested based on this that the D-type slope represents a less-evolved sub-surface layer of the weathered T type. The weak correlation of the slope redness that is favourable for smaller T types at a closer distance to the Sun (i.e. asteroids likely having experienced collisions in more recent times; Bottke et al. 2005) may also support this D–T connection.

Consequently, we propose that the current location of large T types is not representative of where they originally formed. Figure 13 illustrates the current orbital distribution of dark, red asteroids, with arrows showing the possible emplacements. The inward arrow pointing to Jupiter Trojans indicates the possibility that some of them were captured trans-Neptunian objects (Levison et al. 2020 and references therein). The dominant spectral types of each group are listed in decreasing order from top to bottom (DeMeo & Carry 2014). D types, which tend to dominate in the outer part of the main belt and beyond, are generally thought to have a spectral appearance similar to that of cometary nuclei (e.g. DeMeo & Binzel 2008; Poch et al. 2020; Kareta et al. 2021). In the absence of C–O bands for the large T types, we are unable to constrain their original location relative to the CO and CO₂ condensation front (≥10 au; Fayolle et al. 2011; Fujiyama et al. 2019) solely based on their reflectance spectra because the observed dearth of volatiles could be either intrinsic (due to their formation distance at <10 au) or extrinsic (thermal conditions in their present orbits are too hot for such primitive materials to survive; Kurokawa et al. 2020). We thus inferred their place of origin from the high spectral compatibility of T types with CI chondrites.

It has been suggested that CI-like materials most likely originated outside of a pressure trap near the proto-Jupiter at ~3–5 au in the solar nebula (van Kooten et al. 2019, 2021; Larsen et al. 2020; Brasser & Mojzsis 2020). CI chondrites typically contain lower volatile contents (Vollstaedt et al. 2020) and higher water-to-rock ratios (Wood 2005; Brearley 2006) than most comets. However, recent dynamical studies have shown that comets could form over a wide range of semi-major axes in their early phases (Brasser & Morbidelli 2013). There are also differences in the deuterium-to-hydrogen (D/H) ratios of comets in water ranging from low ratios like the terrestrial values to values that are several times higher (Lis et al. 2019 and references therein), where the D/H ratios of CI chondrites are consistent with those of comets with terrestrial ratios (Gounelle et al. 2008; Alexander 2017). Because the D/H ratio is a proxy for the temperature at the formation site (Meier & Owen 1999) and tends to increase with increasing distance from the Sun (Drouart et al. 1999), this consistency implies that the formation region of CI chondrites could overlap with the warmer (i.e. inner) part of the comet formation range.

Taken as a whole, we tentatively conclude that large T types may have been dislodged from the outside of the proto-Jupiter (~3–5 au), but not as far as the cryogenic Kuiper Belt (~35 au), where D type Jupiter Trojans (Brown 2016) and parent bodies of short-period comets likely formed (Dones et al. 2015). Hence, we propose that large T types might originate somewhere between these two regions, near the very rough central point of comet formation distance (~10 au; A’Hearn et al. 2012).

5. Summary

We presented new L-band spectroscopic observations of two large T types, (96) Aegle and (570) Kythera, from the Subaru telescope in September 2020. Combining reflectance spectra of
other T types that are publicly available, we examined the surface characteristics to constrain their place of origin. The main results of the analysis are listed below.

1. Our targets exhibit red L-band slopes: $(0.30 \pm 0.04) \, \mu m^{-1}$ for (96) Aegle and $(0.31 \pm 0.03) \, \mu m^{-1}$ for (570) Kythera. The contribution of thermal excess to the observed reflectance was negligible for both targets, except at the long ends of the L-band region $(\geq 3.8 \, \mu m)$. We found a discontinuity of the spectral curvature between the $K$-band (concaving down) and $L$-band (linear increase) for both asteroids, indicating the presence of an OH absorption band. We also found a possible N–H stretch band at $\sim 3.14 \, \mu m$ and a C–H band of organic materials over $3.3–3.6 \, \mu m$ for (96) Aegle, but no further absorption features stronger than the $\pm 5\%$ calibration uncertainty.

2. We compared the VNIR–LNIR reflectance spectra of the targets with three other large T types whose L-band reflectance was measured: (308) Polyxo, (596) Scheila, and (773) Irmtraud. An OH-absorption band appears on their spectra except for (596) Scheila. The linear increase of the reflectance over 2.9–3.2 $\mu m$ means that the large T types belong to the sharp 3 $\mu m$ group (Takir & Emery 2012) whose surface is dominated by phyllosilicates. (96) Aegle and (308) Polyxo possess a nearly identical spectral shape across the VNIR and LNIR regions. The slope of (596) Scheila has changed from T to D type since its 2010 impact event, but the OH-band signal is lacking.

3. Four out of eight large T types appear to contain an absorption feature near 0.6–0.65 $\mu m$ that is likely associated with iron oxides in phyllosilicates. For 21 T types in all sizes (except for Jupiter Trojans), we found that T type NEOs tend to have the reddest VNIR slope of the asteroids we considered, followed by intermediate-sized and larger ($>80 \, km$ in diameter) asteroids for the shallowest. We infer that the phase reddening effect of dark asteroid surfaces may not be responsible for this colour distribution because the asteroid phase angles at the observing epochs and their slopes are apparently uncorrelated (Spearman’s correlation $r = -0.029$). The slopes of T type NEOs inside 2 $au$ are redder than those of their counterparts with main-belt semi-major axes. No other trends are statistically significant in the current observations of T types.

4. The large T types retain an overall LNIR slope comparable to (1) Ceres and comet 67P/Churyumov-Gerasimenko, but it is less red than the slopes of Jupiter Trojans. Except for the possible absorption features of (96) Aegle, the large T types are overall devoid of the diagnostic 3.1 $\mu m$–H band of ammonium or of the 3.9 $\mu m$ C–O band of carbonates that are otherwise seen on these dark small bodies.

5. For large asteroids belonging to the sharp 3 $\mu m$ group, we found a positive relation between the average 2.9 $\mu m$ band depth of a taxonomic type and the detection rate of the 0.7 $\mu m$ band therein, which means that the 0.7 $\mu m$ band can be used to diagnose the intensity of aqueous alteration. In this context, the T type might have experienced aqueous alteration roughly comparable to the Ch type, but more extensively than most hydrated main-belt asteroids.

6. We derived the minimum polarisation degree ($P_{\text{min}} = 1.35^{+0.02}_{-0.03}$) and the inversion angle $(\theta_0 = 20.18^{\pm 0.29})$ of large T types from their polarimetric dependence on phase angle. Their polarimetric parameters are in the ranges of dark (albedo $< 0.1$) pulverised rocks and dusty carbonaceous meteorites, indicating the particular surface texture of T types.

7. The reflectance spectra of large T types show the best match with CI chondrites with grain sizes of $\sim 25–35 \, \mu m$ in terms of the overall spectral slope, band shape and centre, and reflectance. CM chondrites are able to explain hydrous C-complex main-belt asteroids appear to be less consistent with these spectral characteristics than CI chondrites. Meteorite spectra in small grains always describe the asteroid data better than coarser grains.

8. Compiling all currently available results relevant for T types, we tentatively conclude that the current orbital positions of large T types do not reflect their place of origin. They may have been dislodged from about 10 $au$.

Substantial mixing in the early Solar System might have left its mark in the transitional natures of T types connecting D and C types. Our study adds additional observational evidence supporting the implantation from outward of the main asteroid belt (Levison et al. 2009; DeMeo & Carry 2014). We expect that systematic spectral observations of T types in a wide range of sizes and orbital distances using the James Webb Space Telescope will provide intriguing insights into the structural evolution of the Solar System.

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### Appendix A: Summary of the asteroid properties and their references

#### Table A.1. Profiles of T-type asteroids used in Figure 7 and references of the original spectra

| Ast. Name | Tholen | SMASSII | $D_{v}^{(1)}$ | $b_{v}^{(2)}$ | $a^{(3)}$ | $e^{(4)}$ | $m^{(5)}$ | $R_{03}/R_{05}$ | $R_{32}/R_{29}$ | Reference |
|-----------|--------|---------|--------------|--------------|----------|----------|----------|----------------|----------------|------------|
| (96) Aegle | T      | T       | 177.7 0.048  | 3.049 0.141  | 15.982   | 1.203±0.001 | 1.092±0.010 | (1), this study |
| (114) Kassandra | T      | Xk      | 94.2 0.088  | 2.676 0.138  | 4.945    | 1.185±0.001 |          | (1)            |
| (233) Asterope | T      | K       | 99.7 0.093  | 2.660 0.100  | 7.691    | 1.196±0.001 |          | (1)            |
| (308) Polyxo | T      | T       | 128.578 0.046 | 2.749 0.040  | 4.362    | 1.244±0.001 | 1.161±0.028 | (1), (2)       |
| (570) Kythera | ST     | T       | 87.486 0.044  | 3.420 0.119  | 1.816    | 1.235±0.001 | 1.099±0.013 | (1), this study |
| (595) Polyxena | –      | T(1)     | 90.647 0.096  | 3.206 0.064  | 17.831   | 1.250±0.001 |          | (3)            |
| (596) Scheila | PCD    | T       | 159.726 0.037  | 2.929 0.163  | 14.658   | 1.191±0.001 | 1.063±0.003 | (1), (4)       |
| (773) Irmtraud | D      | T       | 91.672 0.048  | 2.859 0.079  | 16.667   | 1.225±0.001 | 1.028±0.004 | (1), (5)       |
| (1471) Tornio | –      | T       | 28.719 0.085  | 2.716 0.119  | 13.607   | 1.241±0.002 |          | (1)            |
| (2271) Kiso | –      | T       | 31.229 0.055  | 2.762 0.061  | 3.389    | 1.231±0.002 |          |                |
| (2813) Zappala | –      | T       | 32.040 0.062  | 3.136 0.154  | 14.760   | 1.279±0.002 |          |                |
| (2857) NOT | –      | T       | 9.313 0.169  | 2.401 0.095  | 5.733    | 1.223±0.001 |          |                |
| (2929) Harris | –      | T       | 16.176 0.155  | 3.120 0.067  | 14.891   | 1.230±0.002 |          |                |
| (3254) Bus | –      | T       | 31.104 0.073  | 3.970 0.155  | 4.412    | 1.243±0.001 |          |                |
| (3311) Podobed | –      | T       | 17.336 0.071  | 2.787 0.040  | 0.931    | 1.208±0.003 |          |                |
| (3443) Leetsungdao | –     | T       | 8.852 0.132  | 2.394 0.306  | 12.709   | 1.225±0.001 |          |                |
| (85490) 1997 SE5(6) | –    | T       | –      | –      | 3.762 0.661  | 2.575    | 1.232±0.001 |          |                |
| (138911) 2001 AE2(6) | –   | T       | –      | –      | 1.350 0.081  | 1.662    | 1.296±0.004 |          |                |
| (162998) 2001 SK162(6) | –   | T       | 0.875 0.161  | 1.925 0.475  | 1.681    | 1.286±0.004 |          |                |
| (2001) UI92(6) | –      | T       | –      | –      | 3.174 0.666  | 5.359    | 1.231±0.006 |          |                |
| (2001) YE1(6) | –      | T       | –      | –      | 1.914 0.501  | 4.456    | 1.304±0.002 |          |                |

**Notes.** (1)Effective body diameter in km; (2)Geometric albedo; (3)Semi-major axis in au; (4)Eccentricity; (5)Inclination in degree; (6)Near-Earth Objects (NEOs); (7)Initially not observed by Bus & Binzel (2002), but classified as T type in this taxonomic system. The physical and dynamical properties are quoted from the NASA/JPL Small-Body Database Lookup (a and WISE database (Masiero et al. 2011)). Numbered references indicate (1) DeMeo et al. (2009); (2) Takir & Emery (2012); (3) Lazzaro et al. (2004); (4) Yang & Hsieh (2011); (5) Kanno et al. (2003).

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#### Table A.2. Profiles of sharp 3-μm group asteroids used in Figure 9 and reference of the 2.9-μm band depth ($BD_{2.9}$)

| Taxonomy | Ast. Name | $D_{v}^{(1)}$ | $BD_{2.9}$ | Measurement |
|----------|-----------|---------------|------------|-------------|
| Ch       | (48) Doris | 216.473       | 23.50±3.65 | Takir & Emery (2012) |
|          | (91) Aegina | 103.402       | 27.48±26.99 |                      |
|          | (104) Klymena | 136.553      | 11.82±10.18 |                      |
|          | (121) Hermione | 209.000     | 24.02±7.7  |                      |
|          | (130) Elektra | 180.652      | 36.90±9.57 |                      |
|          | (187) Lambert | 147.294     | 18.56±10.18 |                      |

**Notes.** The $D$ values stand for the effective body diameter in km, which were quoted from the NASA/JPL Small-Body Database Lookup.*

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*A https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html# A173, page 16 of 16