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Revisiting the search for the parent body of the Tagish Lake meteorite —Case of a T/D asteroid 308 Polyxo—

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Abstract: The Tagish Lake meteorite which fell early in 2000 have turned out to be the most primitive meteorite in our collections. T. Hiroi *et al.* (Science, **293**, 2234, 2001) identified the D asteroids, especially those in the main belt, as the most probable candidate for the parent body of the meteorite. After examining more details of reflectance spectra of dark asteroids and Tagish Lake meteorite samples, we have found that the search for the parent body should be expanded beyond just the type D of the Tholen's classification used by Hiroi *et al.* (*ibid*, 2001) to include the T type. Among the D and T asteroids we examined for their possibility to be the parent body of the Tagish Lake meteorite, a T/D asteroid 308 Polyxo has turned out to be one of the best candidates because of its similarity to the Tagish Lake sample we used in reflectance spectral shape, albedo, and the presence of the 3-μm water band.

key words: Tagish Lake meteorite, carbonaceous chondrites, D-type asteroids, T-type asteroids, reflectance spectra

1. Introduction

The Tagish Lake meteorite is very special in that it may be one of the most primitive meteorites (*e.g.,* Brown *et al.,* 2000) and that it has been well preserved having fallen into ice, free from most terrestrial contaminations. The Tagish Lake meteorite is classified as a type 2 carbonaceous chondrite which has similarities to CI1 and CM chondrites but is distinct from both, having the lowest bulk density (1.67 g/cc) among all known meteorites (Zolensky *et al.,* 2002). In the above sense, it is a matter of high interest where it came from. Its final orbit entering the Earth's atmosphere observed by several artificial Earth satellites indicates it had an aphelion of about 3.3 AU (Brown *et al.,* 2000) in the outer part of the asteroid main-belt.

Hiroi *et al.* (2001) reported that the Tagish Lake meteorite likely came from a D asteroid based on comparison of their visible-NIR reflectance spectra with all spectral types of dark asteroids. The D type asteroids, together with the T type asteroids, were classified as two taxonomic types of asteroids which have the reddest visible reflectance spectra (Tholen, 1984). Meteorites which correspond to the D type asteroids have been long speculated as "supercarbonaceous" or "superprimitive" meteorites (*e.g.,* Bell *et al.,* 1989) which do not come to the earth or survive during its travel through the

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earth atmosphere.

The study by Hiroi *et al.* (2001) was focusing on deriving which spectral type of asteroid can be the parent body of the Tagish Lake meteorite. However, asteroid classification is usually based on a limited range of wavelength, and thus the asteroid classes and surface compositions may not necessarily have one-to-one correspondence. Furthermore, the D asteroids considered as the Tagish Lake parent body in their work did not have a 3-μm reflectance spectrum of a good quality which is one of key features for determining the presence of water and may be important in evaluating the probability of their genetic relationship. In addition, further study on the influence of viewing geometry on reflectance spectra of the Tagish Lake meteorite sample and its possible parent asteroid was another pending issue.

Hiroi *et al.* (2001) indicated that the spectral shape of the Tagish Lake meteorite matches not only with those of the D-type asteroids but also the T-type asteroids but did not consider the T asteroids as the candidates for the Tagish Lake meteorite parent body due to their high average albedo. However, there are some T asteroids which have low albedos similar to those of the D asteroids. Because the asteroid classification is based on their reflectance spectra in only the extended visible wavelength region and different classification schemes do not necessarily agree with one another, it is wise not to limit our investigation on their surface mineral composition to a specific spectral type. Therefore, we have expanded our search for the Tagish Lake meteorite parent body to the T-type asteroids.

In this paper, among the considered target asteroids 114 Kassandra, 233 Asterope, and 308 Polyxo we have chosen the asteroid 308 Polyxo which is classified as T type by Tholen (1984) and D type by Barucci *et al.* (1987) as the target of our investigation because its visible and near-infrared reflectance spectrum is one of the closest to that of Tagish Lake meteorite (Hiroi *et al.,* 2001) and it has a definite 3-μm water absorption band (Lebofsky *et al.,* 1990). Then, we have made some additional measurements of a Tagish Lake meteorite sample, and studied the influence of viewing geometry on both the Tagish Lake meteorite sample and Polyxo in addressing the possibility of their genetic relationship.

2. Experimental

A relatively fresh powder sample of Tagish Lake which had been ground and passed through a 125 μm sieve by Hiroi *et al.* (2001) was remeasured in this study. Bidirectional ultraviolet-visible-nearinfrared reflectance spectra of the sample were measured in the wavelength range of 0.3–2.6 μm at 30° incidence and 0° emergence angles (expressed as (30, 0) below) which is the same viewing geometry as in Hiroi *et al.* (2001) and at (14, 0) to check repeatability and phase-angle dependency of its reflectance spectrum.

An off-axis biconical Fourier-transform infrared (FT-IR) reflectance spectrum was also measured in the wavelength range of 2–25 μm to compare it with the on-axis spectrum measured by Hiroi *et al.* (2001). Note that, "on-axis" indicates that the central axes of the incidence and emergence light fluxes are on a plane perpendicular to the sample surface, and "off-axis" indicates that the plane is off the normal (by about

30°) to the sample surface. The latter viewing geometry is designed to minimize specular reflection from the sample surface going into the detector.

In order to obtain the absolute visible reflectivity of the Tagish Lake sample for comparison with the asteroid albedo, bidirectional reflectances of the Tagish Lake sample were measured relative to Spectralon which has a near-Lambertian (isotropic) surface at incidence angles of 30°, 14°, 11°, and 7° with a fixed emergence angle of 0° at 0.55 μm in wavelength. A phase angle of about 7° is the lower limit of mechanically possible angles for the RELAB bidirectional spectrometer utilized in this study.

Extended visible reflectance spectra of an asteroid 308 Polyxo were taken from the 24-color asteroid survey (Chapman and Gaffey, 1979), the Eight-Color Asteroid Survey (ECAS) (Zellner *et al.,* 1985), a CCD spectral dataset (Fitzsimmons *et al.,* 1994), and the Small Main-Belt Asteroid Spectroscopic Survey (SMASS) II (Bus, 1999; Bus and Binzel, 2002), its near-infrared spectrum from the 52-color survey (Bell *et al.,* 1988) and the SMASS IR (Burbine, 2000; Burbine and Binzel, 2002), and its 3-μm band spectrum from Lebofsky *et al.* (1990).

3. Results

Shown in Fig. 1 are reflectance spectra of the Tagish Lake sample and Polyxo. First of all, the same Tagish Lake powder sample shows significantly different reflectance spectra at the same viewing geometry of (30, 0) between the previous study (Hiroi *et al.,* 2001) indicated as "Old" and this study indicated as "New", most likely due to the sample heterogeneity. Compared with that difference, the difference between the new measurement at (14, 0) and the old measurement at (30, 0) is very small, suggesting that spectral variation due to phase angle change is not as significant as heterogeneity of this sample. These two spectra are very similar in shape to the SMASS II and SMASS IR. Telescopic measurements of 308 Polyxo show similar variation especially between the ECAS and SMASS IR near 1 μm. However, the overall character of 308 Polyxo spectrum which is mostly monotonous and very red is consistent among these measurements except small features near 0.7 and 0.9 μm.

The most notable feature of 308 Polyxo is the presence of a clear 3-μm band (Lebofsky *et al.,* 1990). This is very important as a candidate for the parent body of the Tagish Lake meteorite. None of the asteroids listed up as the parent body candidates by Hiroi *et al.* (2001) had any clear 3-μm band. The shape of the 3-μm band of the Tagish Lake sample depends on the viewing geometry. When the band is measured at the off-axis geometry, the continuum background of the spectrum becomes bluer than that of the on-axis measurement because of decrease of specular reflection component in the off-axis measurement. Which measurement is better for comparison with the asteroid spectrum depends on how much specular component the asteroid spectrum contains. In this case, 308 Polyxo seems to show a continuum similar to the off-axis spectrum of Tagish Lake, except for one data point of 308 Polyxo at 3.5 μm which shows such a large reflectance drop no known carbonaceous chondrite seems to show.

In order to examine the phase angle dependency of the reflectance spectrum of 308 Polyxo, its extended visible reflectance spectra whose phase angles range from 2.76 to

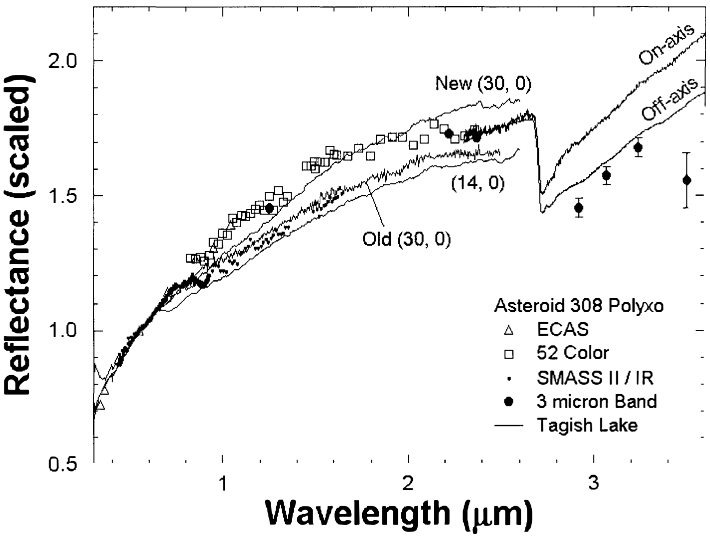

Fig. 1. Comparison of reflectance spectra of a T/D-type asteroid 308 Polyxo taken from the ECAS (Zellner et al., 1985), 52-color asteroid survey (Bell et al., 1988), SMASS II (Bus, 1999; Bus and Binzel, 2002), SMASS IR (Burbine, 2000; Burbine and Binzel, 2002), and 3-μm band measurements (Lebofsky et al., 1990) and a Tagish Lake meteorite powder sample (Hiroi et al., 2001). Three visible and near-infrared spectra of the Tagish Lake sample are, from top down, new and old (Hiroi et al., 2001) measurements at (incidence, emergence) angles of (30, 0) degrees and a new measurement at (14, 0). Two 3-μm spectra of the Tagish Lake sample are an on-axis (Hiroi et al., 2001) and off-axis measurements. The ECAS, SMASS II, and laboratory Visible-NIR spectra are scaled to 1.0 at 0.55 μm, the 52-color spectrum is scaled to connect consistently with the ECAS spectrum, the SMASS IR spectrum with the SMASS II spectrum, and the telescopic and laboratory 3-μm spectra with the 52-color spectrum.

19.1 degrees are plotted in Fig. 2. Although the 24-color and ECAS spectra are noisy and SMASS II shows a clear feature around 0.9 μm, their spectral shapes seem consistent with one another in the range of 0.55–0.75 μm. In order to see this situation more clearly, the reflectance ratio between 0.55 and 0.71 μm is plotted against phase angle in Fig. 3 for these five spectra. Considering the error bars of the reflectance ratios, there is no significant deviation from the ratio of about 1.15 due to the phase angle variation.

Shown in Fig. 4 is a plot of phase angle *vs.* reflectance at 0.55 μm of the Tagish Lake sample relative to Spectralon. The IRAS albedo (Tedesco, 1989) of 308 Polyxo is also plotted at 0° phase angle. The reflectance starts to rise nonlinearly around 12°.

4. Discussion

4.1. Optical properties of the Tagish Lake meteorite and the asteroid 308 Polyxo

Similarity in reflectance spectrum between the Tagish Lake meteorite and the asteroid 308 Polyxo shown in Fig. 1 is remarkable. They show almost identical visible spectra, undistinguishable near-infrared spectra within the variation due to the hetero-

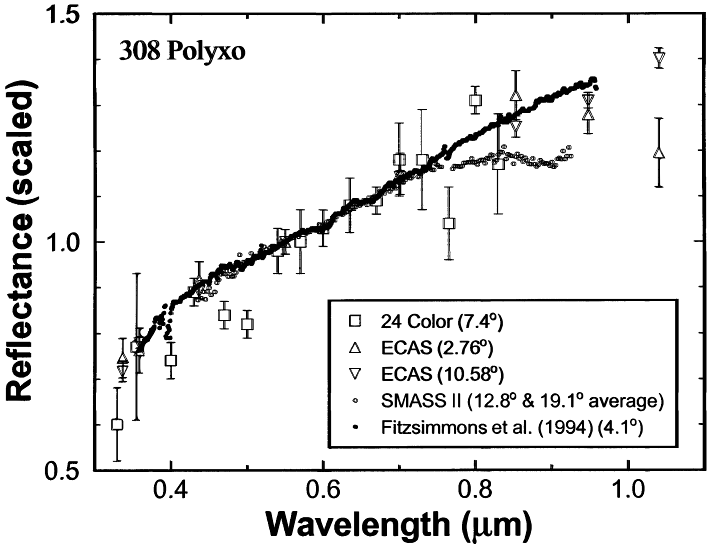

Fig. 2. Comparison of extended-visible reflectance spectra of the asteroid 308 Polyxo at various phase angles taken from the 24-color asteroid survey (Chapman and Gaffey, 1979), ECAS (Zellner et al., 1985), SMASS II (Bus, 1999; Bus and Binzel, 2002), and Fitzsimmons et al. (1994).

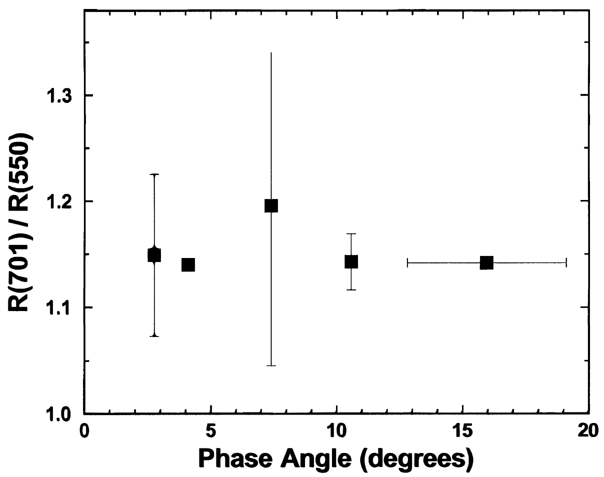

Fig. 3. A plot of phase angle vs. reflectance ratio (701 nm/550 nm) extracted from the spectra of the asteroid 308 Polyxo plotted in Fig. 2 (Chapman and Gaffey, 1979; Zellner et al., 1985; Bus, 1999; Bus and Binzel, 2002; Fitzsimmons et al., 1994). The vertical bars indicate error estimates, and the horizontal bar a range of phase angles of averaged spectral measurements (for SMASS II).

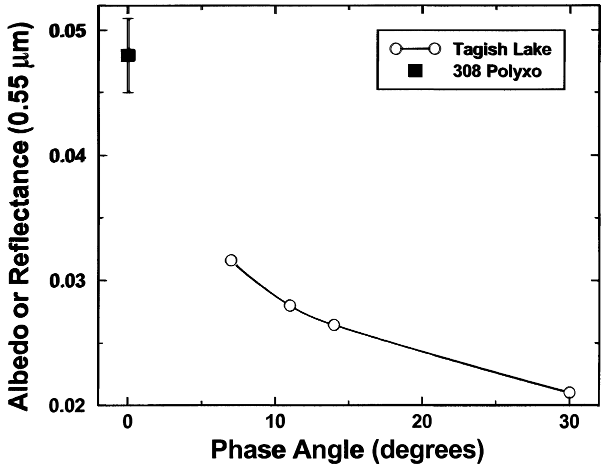

Fig. 4. A plot of phase angle vs. reflectance at 0.55 μm of the Tagish Lake sample (open circles) and the IRAS albedo (Tedesco, 1989) of the asteroid 308 Polyxo (filled square).

geneity of the Tagish Lake meteorite, and similar absorption band strengths in the 3-μm region although their band shapes may be different. The apparent insensitivity of the spectrum of 308 Polyxo to the phase angle shown in Figs. 2 and 3 seems to justify its comparison with the Tagish Lake spectrum measured at different viewing geometries. Similarly detailed phase angle dependency study on the Tagish Lake meteorite sample would have to wait for another occasion because the two examples of viewing geometries shown in this paper (30, 0) and (14, 0) have already shown enough complexity of such a study due to an unknown cause such as heterogeneity of the sample. The trend of the absolute brightness variation of the Tagish Lake sample due to the phase angle shown in Fig. 4 seems to indicate the possibility that it may become comparable to the IRAS albedo (Tedesco, 1989) of 308 Polyxo at 0° phase angle. All these evidences support that the surface of 308 Polyxo may be made of a material similar to the Tagish Lake meteorite.

Many researchers tend to have a misconception that the identification of two materials using their optical properties requires the presence of a prominent absorption band such as those seen in the case of the HED meteorites and the asteroid 4 Vesta. However, even in the absence of any clear absorption band, the spectral slope and curvature and the brightness are as important clues as prominent absorption bands to identify the material. It is even more true because we are only comparing two very narrowly defined groups: meteorite materials and asteroid surface materials, instead of regarding all the possible geologic/chemical materials as the target. The presence of the 3-μm band in both Polyxo and Tagish Lake spectra is remarkable, considering the absence of the band in most D asteroids (*e.g.,* Cruikshank *et al.,* 2001). It confirms that both contain hydrated minerals although possibility of their shape difference requires us to investigate this point with better observation and understanding of the asteroid surface alteration processes such as heating and space weathering.

4.2. Qualification to be the parent body of the Tagish Lake meteorite

Even if we believe 308 Polyxo is made of mineralogically identical material with the Tagish Lake meteorite, it does not guarantee that the Tagish Lake meteorite came from 308 Polyxo. Another point to be addressed is the possibility that the Tagish Lake meteorite could dynamically travel from the asteroid to the Earth. The fall of the Tagish Lake meteorite was observed by several satellites and its orbit is well estimated: Semimajor axis $a=2.1\pm0.2$ AU, eccentricity $e=0.57\pm0.05$, and inclination $i=1.4\pm0.9°$. Its aphelion distance is 3.3 ± 0.4 AU (Brown *et al.,* 2000). This suggests that the Tagish Lake meteorite left its parent body within about 3.3 AU from the Sun if any orbital evolution after it left its parent body can be disregarded. If it is truly the case, the parent body must have an orbit which comes to the distance of about 3.3 AU or less from the Sun during its orbital period. Shown in Fig. 5 is a plot of semimajor axis *vs.* eccentricity of the main-belt asteroids with the D-type asteroids and 308 Polyxo highlighted. Majority of the D asteroids including 308 Polyxo in Fig. 5 come within 3.3 AU from the Sun.

Also indicated in Fig. 5 are the Kirkwood Gaps which are believed to be windows of delivering meteorites to the Earth due to the mean motion resonance with Jupiter. Asteroid 308 Polyxo has an orbit which stays well within 3.3 AU and is about 0.07 AU away from the nearest Kirkwood Gap (5:2). If the Tagish Lake meteorite came from

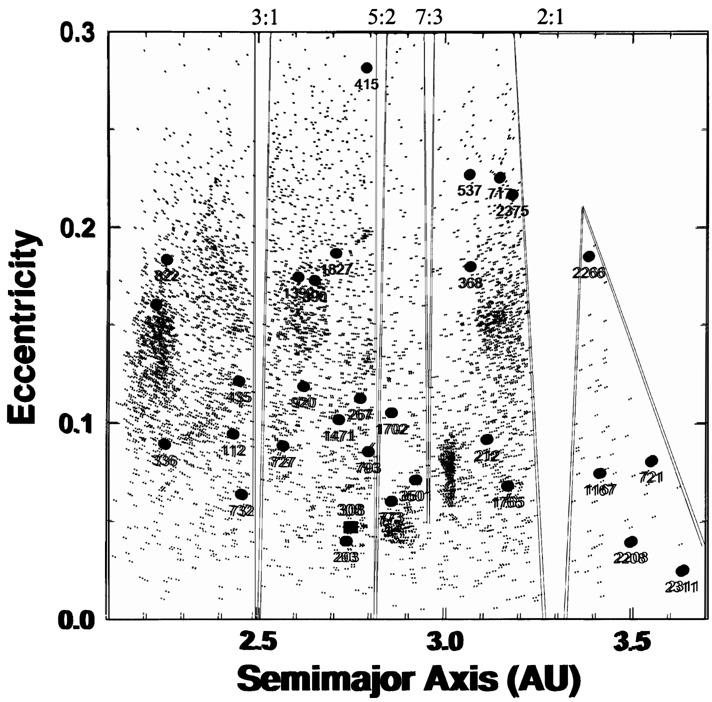

Fig. 5. A plot of semimajor axis vs. eccentricity of asteroids including D-type asteroids (large filled circles) and 308 Polyxo (filled square) with the mean-motion resonance zones with Jupiter indicated.

Polyxo, in order to take its final orbit, the Tagish Lake meteorite would have had to gain some energy through an impact when it was ejected from Polyxo or gradually after its departure before reaching the Earth by some other mechanism such as the Yarkovsky effect (*e.g.,* Farinella *et al.,* 1998). Whether the distance of 0.07 AU is small enough for the meteorite to travel by the Yarkovsky drift is not clear. There are several other D asteroid which are located closer (about 0.03 AU) to one of the Kirkwood Gaps than 308 Polyxo as can be seen in Fig. 5. More spectral measurements of those D asteroids would be necessary for narrowing down the candidates for the parent body of the Tagish Lake meteorite.

5. Conclusions

1) The Tagish Lake meteorite sample and the surface material of the asteroid 308 Polyxo show very similar visible and near-infrared reflectance spectra, which seem to be mostly free from the viewing geometry variations.

2) Both the Tagish Lake meteorite and the surface of 308 Polyxo contain hydrated minerals indicated by the presence of the 3-μm band from both spectra.

3) Although there is no denying that the Tagish Lake meteorite could come from 308 Polyxo, there are other D-type asteroids located closer to one of the meteorite delivery windows than 308 Polyxo is.

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