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The Tagish Lake Meteorite: A Possible Sample from a D-Type Asteroid

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A new type of carbonaceous chondrite, the Tagish Lake meteorite, exhibits a reflectance spectrum similar spectra observed of the D-type asteroids. The D-type asteroids are relatively abundant in the outer solar system beyond the main asteroid belt and have been inferred to be more primitive than any known meteorite. Until the Tagish Lake fall, these asteroids had no analog in the meteorite collections. The Tagish Lake meteorite is a carbon rich (4 to 5 wt.%), aqueously altered carbonaceous chondrite, and contains high concentrations of presolar grains and carbonate minerals, which is consistent with the expectation that the D-type asteroids were originally made of primitive materials and did not experience any extensive heating.

Most meteorites are believed to come from asteroids or extinct comets. The possible parent asteroid of each meteorite class may be determined through reflectance spectroscopy along with considerations of a dynamical mechanism to deliver the meteorite to Earth. However, there are several spectral types of asteroids (*1*) whose meteorite counterparts have not been found. Among them are the P and D-type asteroids which are inferred by some to be made of “supercarbonaceous” chondrites (*2, 3*); that is meteorites richer in carbon than any known carbonaceous chondrite meteorite. Here, we report on a meteorite that may be our first sample from a D-type asteroid: the Tagish Lake meteorite, a new ungrouped C2 chondrite (*4*) that fell to Earth in January 2000.

Tagish Lake is a carbon rich (4 to 5 wt.%), aqueously altered carbonaceous chondrite. It contains a high concentration of presolar grains and Ca-Fe-Mg carbonate minerals, but an unusually low amount of high-temperature nebular materials such as chondrules and calcium-aluminum rich inclusions (CAI) (*4*). These characteristics are consistent with the expected composition of P and D-type asteroids or extinct comets (*2, 3*).

Two chip samples of Tagish Lake were ground separately and passed through a 125 μm sieve. While both samples were collected months after the fall and may thus be somewhat degraded, one of them appeared to have remained relatively unaltered. Bidirectional ultraviolet-visible-nearinfrared reflectance spectra of the two samples were measured at 30° incidence and 0° emergence angles (expressed as (30, 0) below) in the wavelength range of 0.3-2.6 μm. Biconical Fourier-transform infrared (FT-IR) reflectance spectra were also measured in the wavelength range of 1-25 μm (*5*). These two samples exhibit the same properties in the 0.3-3.6 μm wavelength range where comparisons with asteroid reflectance spectra are most often made. This suggests that terrestrial weathering has had little, if any, effect on the spectra of these meteorite samples.

The spectrum of the Tagish Lake meteorite sample that visually appears least weathered has been compared with average reflectance spectra of the C, G, B, F, T, P, and D asteroids taken from the eight-color (*6*) and the 52-color (*7*) asteroid surveys, scaled to the IRAS albedos (*8*) at the 0.55 μm band (*9*). Because the reflectivity of Tagish Lake is very low (2-4%), we only compare its reflectance spectrum with low-albedo asteroid spectra. The spectrum of Tagish Lake has a characteristic red slope typical of very fine-grained carbon-containing powdered materials. If we assume the laboratory bidirectional reflectance at 0.55 μm and the asteroid albedos are comparable measures of brightness, the fact that the typical C, G, B, and F asteroids have brighter and flatter reflectance spectra than the Tagish Lake spectrum suggests that Tagish Lake has a greater content of absorbing species, consistent with its carbon-rich mineralogy (*4*). The spectral shape distinguishes many of the low-albedo asteroids. In terms of the overall spectral slope (*9*), the T, P, or D asteroids are good spectral analogues of Tagish Lake. In contrast, comparison of the reflectance spectra of Tagish Lake with all the available reflectance spectra of the C, G, B, and F asteroids did not reveal any acceptable matches.

The scaled reflectance spectrum of Tagish Lake is compared with each kind of spectral class of asteroid analogues (Fig. 1). While most of the P asteroids spectrally match Tagish Lake in the wavelength range longward of 0.9 μm, they are different in the shorter wavelength range. On the other hand, some of the T and D asteroids spectrally match Tagish Lake throughout the entire measured range. The visible reflectivity of the Tagish Lake powder sample prepared in this study, however, is much closer to the average albedo of the D asteroids than that of the T asteroids (*9*). The T asteroids are inferred to have compositions similar to troilite-rich iron meteorites (*10*), which is incompatible with the mineralogy of Tagish Lake.

The extended visible spectral shape and albedo of the primitive asteroids are the most decisive factors for identifying the parent body of the Tagish Lake meteorite (*9*, Fig. 1). We used a common spectral ratio to determine the spectral shape information for use with asteroid survey data. The redness is defined as R(853)/R(550) where R(λ) indicates reflectance through one of the eight-color asteroid survey (*6*) bandpass filters centering at λ nm in wavelength, and the brightness is defined as the albedo measured by the Infrared Astronomial Satellite (IRAS) (*6*) or R(550). Reflectance spectra of two additional asteroids were also taken from (*10*), from which the R(853) and R(550) values were calculated by convolving the effective transmission curves of the bandpass filters used by the Eight-Color Asteroid Survey (ECAS) with each of the asteroid spectra. Bidirectional reflectance values of the Tagish Lake sample were similarly converted (Fig. 2). In order to examine the viewing geometry dependence of brightness and redness of the Tagish Lake sample, measurements were also performed at viewing geometries of (11, 0), (6, –6), and (15, –15) because the eight-color asteroid spectral measurements were typically at small phase angles (*6*) (Fig. 2). We compared the Tagish Lake spectra with the C, G, B, F, T, P, and D asteroid spectra and found that the meteorite is closest to the D asteroids in brightness and redness, while these measurements also show that varying viewing conditions may produce properties that bridge the spectral characteristics of the D and P asteroids.

While the redness and albedo of the D asteroids are similar to those of the Tagish Lake meteorite (Fig. 2), the case linking the two would be stronger if a common characteristic absorption band could be found, such as in the case of the V asteroids and howardite, eucrite, and diogenite (HED) meteorites [e.g., (*11, 12*)]. Most spectra for low-albedo asteroids have low signal to noise and few spectral features (*9*). Perhaps the best spectral feature for comparison would be the strong hydrous (OH or H_2O) feature near 3 µm. There are four D asteroids whose 3-µm reflectance spectra (*13*) are publicly available, and they are compared with our FT-IR reflectance spectrum of the Tagish Lake meteorite sample (Fig. 3). Due to the high level of noise of the asteroid 3-µm spectra, this comparison does not give us any conclusive information other than a hint that these D asteroids may have shallower spectral bands near 3 µm than the Tagish Lake meteorite. Even if the D asteroids have shallower 3-µm bands than Tagish Lake, it may mean that the surface regoliths of the D asteroids have undergone dehydration due to space weathering processes such as micrometeorite bombardments or that minor terrestrial contamination has occurred in the Tagish Lake sample. For the former possibility, space weathering simulations (*14, 15*) on the Tagish Lake sample may be useful to evaluate band strength issues.

Based on the spectral shape and brightness discussed above, we suggest that the Tagish Lake meteorite is derived from a D asteroid. Assuming Tagish Lake came from a D asteroid, we can consider whether one of the D asteroids 368, 336, and 773 could be the parent body. Among these three, although 368 Haidea is spectrally closest to the Tagish Lake meteorite (Fig. 1), 773 Irmintraud is closest (<0.034 AU) to a chaotic zone [e.g., (*16*)] associated with one of the Kirkwood Gaps (Table 1) (*17*) due to the mean motion resonance with Jupiter. Their IRAS albedos (*8*) of 0.032 and 0.033 are both close to the reflectance of the Tagish Lake sample at 0.55 µm under a viewing geometry of (6, –6) (Fig. 2). More detailed analysis is needed to determine whether ejecta from this asteroid, or other D asteroids, can traverse the distance to the chaotic zones (*17*) when driven by impact ejection energy and the Yarkovsky effect [e.g., (*18*, *19*)]. In addition, more extensive telescopic observations are needed to determine whether the apparent spectral difference between 773 Irmintraud and the Tagish Lake meteorite is significant or whether there is a better candidate for the Tagish Lake parent body among other D asteroids. The launch efficiency from the Tagish Lake parent body may also be problematic to model because of the low density (1.7 g/cm^3) (*20*) and mechanical weakness of the Tagish Lake meteorite. The kinetic energy of impactors may be absorbed more efficiently on the Tagish Lake parent body than on stronger bodies, resulting in a smaller kinetic energy of the ejecta.

Linking asteroid types to well-studied meteorite classes is a difficult endeavor because extraterrestrial materials that fall to Earth are limited by physical conditions and form an inherently biased sample in time and space. Recovery of the Tagish Lake meteorite suggests that perhaps many more mechanically weak classes of meteorites are destroyed during atmospheric entry before they can be recovered.

References and Notes

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9. Web figure 1: Comparison of the bidirectional reflectance spectrum (*5*) at the (30, 0) viewing geometry of a Tagish Lake meteorite sample and averages of telescopic spectra of low-albedo asteroid classes (*6–8*). Asteroids to be averaged were chosen based on the completeness of the wavelength coverage and signal-to-noise ratio. They are G asteroids 1, 13, 106, and 130; B asteroids 2, 39, and 431; C asteroids 10, 31, 86, 145, 511, 521, 702, and 772; F asteroids 704 and 762; T asteroids 114, 233, and 308; P asteroids 65, 76, and 476; and D asteroids 336 and 368.
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17. Web figure 2: A plot of semimajor axes and eccentricities of numbered asteroids (*21*) where the D asteroids are indicated as filled circles along with their ID numbers.
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Fig. 1. Comparison of reflectance spectra (*5*) of Tagish Lake with individual reflectance spectra of the T, P, and D asteroids (*6, 7*). Each of the reflectance spectra of the asteroids (open squares) and Tagish Lake (solid line) are scaled for the best fit with each other for spectral shape comparison. The asteroid-meteorite spectra are then offset from one another for clarity.

Fig. 2. A plot of the redness and brightness of the low-albedo C, G, B, F, T, P, and D asteroids (*6–8*) and the Tagish Lake meteorite sample (filled squares). The redness is defined as R(853) / R(550), where R(λ) indicates reflectance through one of the eight-color asteroid survey (*6*) bandpass filters centered at λ nm in wavelength, and the brightness is defined as the IRAS albedo (*8*) or R(550). Tagish Lake viewing geometries are indicated as (incidence, emergence) angles in degrees.

Fig. 3. The 3-µm reflectance spectra (*13*) of four D asteroids compared with visible and FT-IR spectrum of the Tagish Lake meteorite sample.

Table 1. Albedo and diameter *D* (*8*), and semimajor axis *a*, eccentricity *e*, and sine inclination sin(*i*) (*21*) of the D asteroids and locations of the Kirkwood Gaps.

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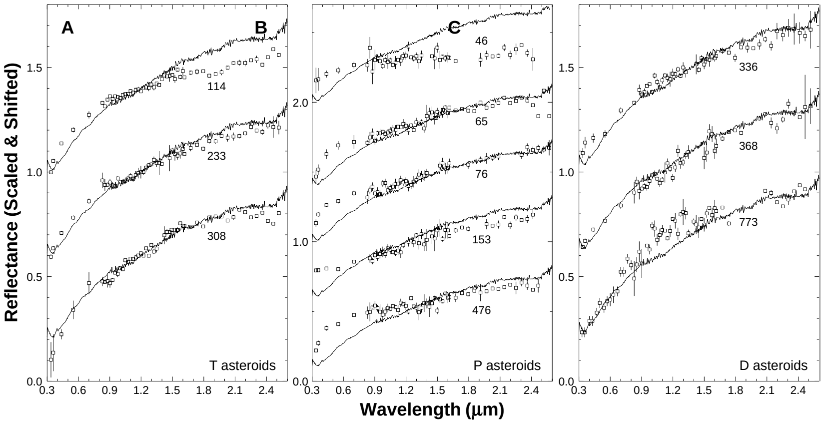
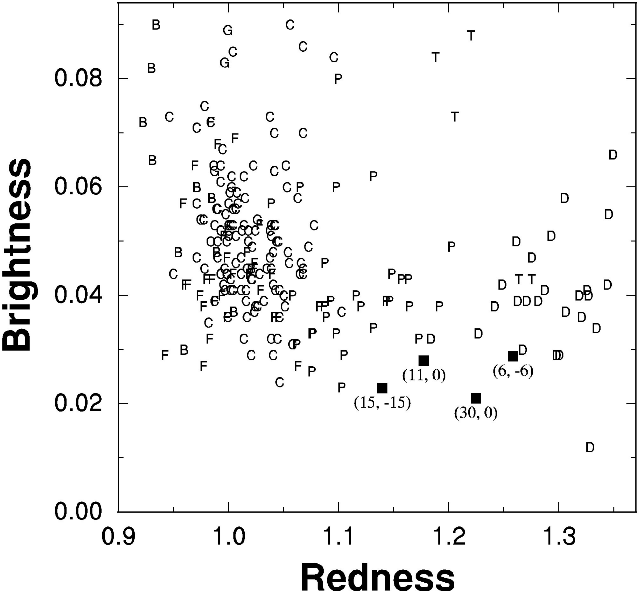
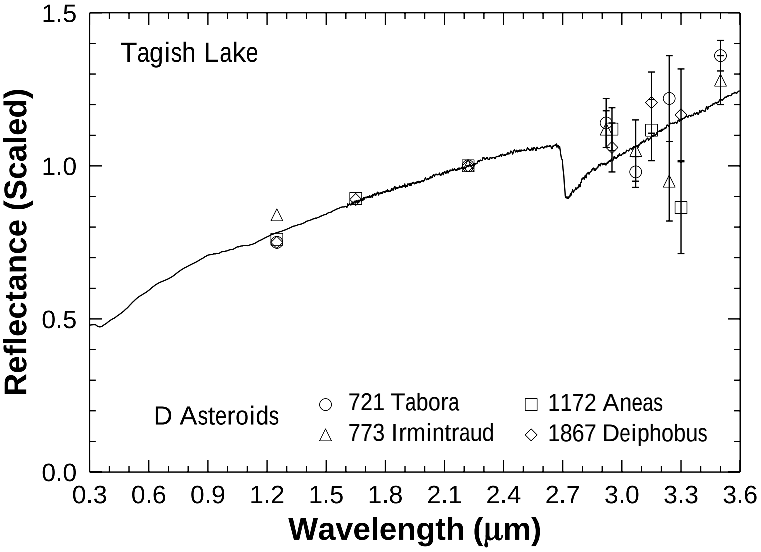
Table 1.

Albedo	***D*** **(km)**	***a*** **(AU)**	***e***	**sin(*i*)**	**No.**	**Name**
0.042	72.0	2.252	0.091	0.110	336	Lacadiera
		2.500				***Gap 3:1***
		2.824				***Gap 5:2***
0.033	99.1	2.858	0.047	0.301	773	Irmintraud
		2.956				***Gap 7:3***
0.032	74.5	3.070	0.170	0.163	368	Haidea
		3.276				***Gap 2:1***


A
B
C
114
233
308
T asteroids
46
65
76
153
476
P asteroids
336
368
773
D asteroids
Reflectance (Scaled & Shifted)
Wavelength (µm)
0.0
0.5
1.0
1.5
2.0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4


Brightness
0.00
0.02
0.04
0.06
0.08
Redness
0.9
1.0
1.1
1.2
1.3
B
G
C
F
P
T
D
(15, -15)
(11, 0)
(30, 0)
(6, -6)


Tagish Lake
D Asteroids
○ 721 Tabora
△ 773 Irmintraud
□ 1172 Aneas
◇ 1867 Deiphobus
Reflectance (Scaled)
Wavelength (μm)
0.0
0.5
1.0
1.5
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3.0
3.3
3.6