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9969 Braille: Deep Space 1 infrared spectroscopy, geometric albedo, and classification

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Abstract

Spectra of Asteroid 9969 Braille in the 1.25–2.6 µm region returned by the Deep Space 1 (DS1) Mission show a ∼ 10% absorption band centered at 2 µm, and a reflectance peak at 1.6 µm. Analysis of these features suggest that the composition of Braille is roughly equal parts pyroxene and olivine. Its spectrum between 0.4 and 2.5 µm suggests that it is most closely related to the Q taxonomic type of asteroid. The spectrum also closely matches that of the ordinary chondrites, the most common type of terrestrial meteorite. The geometric albedo of Braille is unusually high ($p_v = 0.34$), which is also consistent with its placement within the rarer classes of stony asteroids, and which suggests it has a relatively fresh, unweathered surface, perhaps due to a recent collision.

Keywords: Asteroids; NEOs; 9969 Braille; Deep Space 1

1. Introduction

The Deep Space 1 Mission, launched on October 24, 1998 as part of NASA Jet Propulsion Laboratory's New Millennium Program, was designed as a low-cost technology validation experiment. One of the key scientific instruments carried aboard was the Miniature Integrated Camera and Imaging Spectrometer (MICAS), designed to demonstrate ultraviolet spectroscopy, short wavelength infrared spectroscopy, and high-resolution imaging capabilities in a single lightweight instrument. MICAS is a body-mounted camera that contains the two spectrometers, as well as APS (active pixel sensor) and CCD cameras. To minimize space and weight, the instrument utilized monolithic silicon-carbide (SiC) construction and a common off-axis Gregorian telescope for the two spectrometers (Soderblom et al., 2000). As part of the validation of the new technologies, the spacecraft flew by the Asteroid 9969 Braille at 15.5 km/s a few days after its perihelion, on July 29, 1999, when it was 1.33 AU from the Sun. The physical properties of Braille are summarized in Table 1. 9969 Braille is currently a Mars-crossing object, but within 4000 years it is expected to enter an Earth-crossing orbit (Hahn et al., 1999). To simplify terminology, we refer to Braille as a Near Earth Object (NEO).

Scientific observations gathered by MICAS and other instruments during the encounter provided a unique opportunity to probe an Earth-approaching object, and to advance our understanding of the connections between main-belt asteroids, Earth-approaching asteroids, and terrestrial meteorites. The encounter with Braille is unique in that it rep-

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Table 1
9969 Braille physical characteristics

Dimensions	2.1 × 1 × 1 km (Oberst et al., 2001)
Visual geometric albedo	0.34 ± 0.03 (this study)
Rotational period	226.4 ± 1.3 hr (Oberst et al., 2001)
Period	3.58 years
Orbital inclination	28.9
Semi-major axis	2.34 AU
Eccentricity	0.43

resents the first scrutiny by a spacecraft of a small asteroid (1–2 km), that is not the secondary of a larger primary, as is the case of 243 Ida and Dactyl. The possibility that Braille is a fragment of a larger parent body, coupled with its placement in an unstable orbit, means Braille may provide clues to the transport of asteroids from the main belt to the Earth through collisions or planetary perturbations, and to the evolutionary processes that affect asteroid surfaces.

During the encounter with Braille, Deep Space 1 returned two medium-resolution CCD images prior to closest approach at a phase angle of 98°, and during the outbound phase it obtained three short-wavelength infrared spectra at a phase angle of 82°. (The UV spectrometer failed during the early cruise period.) In addition, an intensive ground-based observing campaign yielded valuable auxiliary observations providing a temporal baseline and measurements in additional wavelengths. The analysis of the images, which when coupled with ground-based photometric observations, yielded estimates of the size, shape, and rotational state of Braille, is discussed in Oberst et al. (2001). The goal of this paper is to derive spectral geometric albedos for Braille and to report on the results of the short-wavelength infrared (SWIR) camera, and to draw connections between Braille, main belt asteroids, and terrestrial meteorites. Later in its mission, Deep Space 1 also obtained MICAS disk-resolved SWIR spectra of Comet 19P/ Borrelly (Soderblom et al., 2002).

2. Observations and data analysis

Discovered in 1992 by Eleanor Helin and Kenneth Lawrence of NASA's Jet Propulsion Laboratory, Asteroid 9969 (originally known as 1992 KD) was named in honor of Louis Braille, the inventor of a reading system of raised dots used widely by the blind. An intensive ground-based observing campaign prior to the DS1 encounter provided an effective reconnaissance of the asteroid that served to plan observations and augment the results from the encounter. The telescopic observations from Mount Palomar and Table Mountain (Hicks et al., 1999), Mt. Stromlo and Casleo (DiMartino et al., 1999), and by R. Meier at Mauna Kea (reported in Oberst et al., 2001) yielded a rotation period of 226.4 ± 1.3 hours (9.4 days), BVRIJHK magnitudes (see Fig. 1), and a maximum lightcurve amplitude of 2 magnitudes, corresponding to a ratio in principal axes a/b of at least 2. With a mean R magnitude (1, $\alpha = 24$ degrees) of 17.0, the mean diameter of Braille was estimated to be in the range of 1.5–2.0 km prior to encounter, with the assumption of an S-type geometric albedo in the range of 0.14 to 0.25. Braille's elongated shape is consistent with its being the product of a collision, and its long rotation period suggests it may be exhibiting non-principal axis rotation (Pravec and Harris, 2000).

Analysis of the combined ground-based measurements and MICAS CCD images yielded a size of 2.1 × 1 × 1 km (Oberst et al., 2001). Using the telescopic observations of Hicks et al. (1999) and Meier (Oberst et al., 2001) and assuming an S-type phase coefficient of 0.033 mag/deg (Helfenstein and Veverka, 1989) we find the spectral geometric albedos listed in Table 2. A visual geometric albedo of 0.34 ± 0.04 is remarkably high. As virtually no S-type asteroids have geometric albedos greater than 0.30 (Tedesco et al., 1989), this high value suggests that Braille is a member of one of the rarer classes of stony asteroids: The A-type (olivine rich), the Q-type (olivine and pyroxene-rich), V-type (Vesta-like), or the R-type, a class intermediate between A and V (Gaffey et al., 1989).

In addition to the CCD images, MICAS obtained three SWIR spectra about 15 minutes after closest approach, when the spacecraft was approximately 13,000 km from the target, at a solar phase angle of 82 degrees. The MICAS SWIR camera covers the wavelength region 1.25 to 2.6 microns with an average spectral resolution of 12 nm. A target consisting of 256 54-μrad fields-of-view arranged along the spectrometer slit is mapped onto four square detectors.

Each of the four detector-arrays was processed with the following three steps: bias-subtraction, flatfielding, and scattered light subtraction. Radiometric calibration was accomplished through inflight observations of the K-type standard star α-Bootes (Arcturus). Refinements to the calibration were done by comparing the results with photometric ground-based observations of Braille, which when combined with the dimensions of the asteroid determined from the MICAS CCD images yield absolute fluxes. The spectrum was dispersed in three rows, which were coadded. Finally, all three spectra were coadded to increase the signal-to-noise. The results are shown in the top of Fig. 1, along with the ground-based observations of the MICAS Science Team obtained from Table Mountain Observatory (Hicks et al., 1999) and from Mauna Kea Observatory (Oberst et al., 2001, Ta-

Table 2
Spectral geometric albedos of 9969 Braille

Wavelength	Geometric albedo
0.44	0.25 ± 0.02
0.54	0.34 ± 0.03
0.63	0.34 ± 0.03
0.82	0.23 ± 0.04
1.2	0.35 ± 0.01
1.6	0.40 ± 0.01
2.2	0.34 ± 0.07

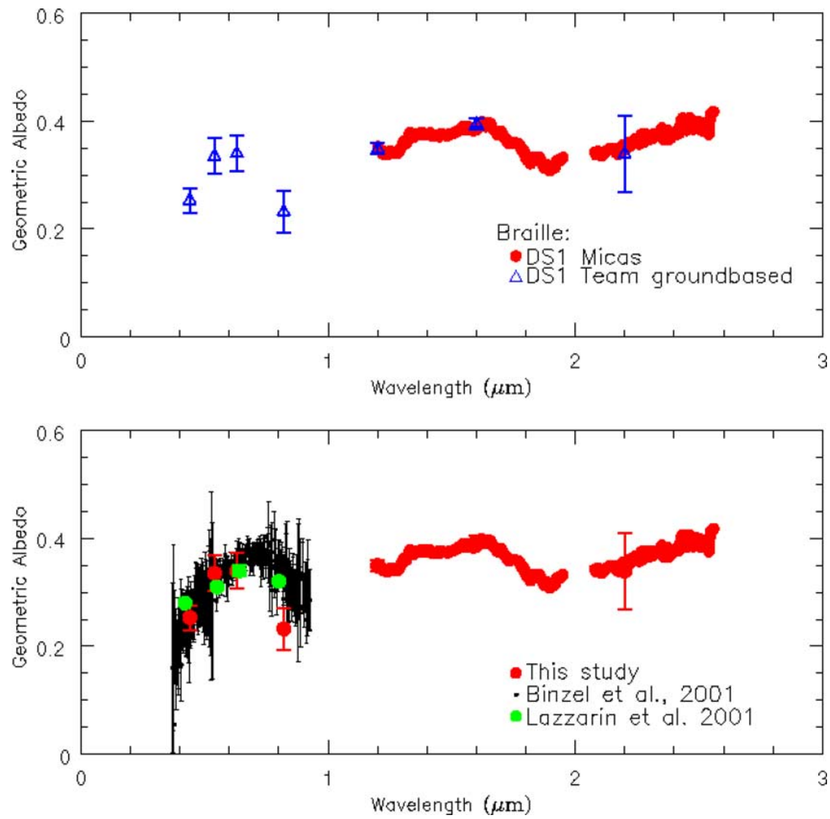

Fig. 1. The top figure shows the MICAS spectrum with the ground-based observations of Meier (1999) and Hicks et al. (1999). The geometric albedos of the ground-based observations are based on the sizes for Braille derived in Oberst et al. (2001). The error bars for the DS1 observations are approximately equal to the size of the data points. The lower figure compares our results (from both ground-based and DS1 observations) with previously published measurements of Braille. The observations from Binzel et al. (2001) and Lazzarin et al. (2001), which were reported as normalized spectra, are normalized to our physical units at 0.63 μm.

ble 1). Figure 1 (bottom) shows our results compared with previous ground-based observations (Binzel et al., 2001; Lazzarin et al., 2001). Unfortunately, scattered light from the solar panels corrupted the data between 1.95 and 2.08 μm. The estimated equilibrium temperature of Braille at the time of the encounter was 238°, if one assumes a phase integral of 0.4 to yield a Bond albedo of 0.14, and unit emissivity. The thermal contribution shortward of 2.6 μm is negligible for this temperature (Kraus, 1966).

3. Results and discussion

The MICAS spectrum combined with ground-based measurements in the visible region offers a wide spectral range with diagnostic absorption bands suitable for determining Braille's taxonomic type and mineralogy, and for constraining its connection to terrestrial meteorites. Based on its spectrum between 0.45 and 0.9 μm, Binzel et al. (2001) suggest the asteroid is a Q-type, while Lazzarin et al. (2001), suggest it is a Q-type or V-type. The broad absorption band centered near 2 μm, which has a depth of $\sim$ 10% of the continuum for Braille and is characteristic of low-calcium pyroxene, is a major component of four major classes of asteroids: The classical S-type; the V-type (for 4 Vesta and its kin, often called Vestoids) with a strong absorption; and the transitional Q and R types. The fifth type of stony asteroid, the A-type, consists of essentially pure olivine with little evidence of an absorption band at 2 μm. Rarer categories of asteroids with one or two members, such as the K, L, and O types have also been identified (Tedesco et al., 1989; Binzel et al., 2001). The characteristics of these taxonomic classes of stony asteroids indicate gradual changes in composition that yield clues on the bodies' conditions of formation and provenance. Table 3 is a simplified summary of the characteristics of the major types of stony asteroids.

Figure 2 shows our combined spectrum of Braille with typical representatives of the five major types of stony asteroids and the rare O-type. Braille is most similar to the Q taxonomic type. The typical S asteroid has far weaker absorption bands (as well as lower albedos), while the A-type has no 2 μm absorption band, and a far higher albedo, particularly in the infrared. The O-type appears to be a possibility, but the diagnostic feature of this type is the "bowl-shaped" spectral feature between 0.75 and 1.3 μm, which Braille lacks (see especially the bottom of Fig. 1). Perhaps the most diagnostic connection between Braille and 1862 Apollo is the reflectance peak at 1.6 μm, indicating olivine (Wagner et al., 1987; Gaffey et al., 1989); the V-type and R-type, which exhibit peaks at 1.3–1.4 µm, are less likely analogues than the Q-type. Spectra of objects that are primarily pyroxene tend to have reflectance peaks at these much shorter wavelengths, as do their associated meteorites (HED basaltic achondrites). Braille's peak at 1.6 µm, and the depth of its broad 2.0 µm absorption band, suggest a composition of roughly equal parts of olivine and pyroxene. More specifically, the ratio of the integrated area of the band between 0.75 and 1.4 µm to the area of the band between 1.6 and 2.6 µm is 1.0 ± 0.1, which implies equal abundances of the two minerals (Cloutis et al., 1986; Gaffey et al., 1993).

Table 3
Attributes of stony asteroids

Type	Mineralogy, connection to meteorites, and visual albedo (p_v)
A-type	Olivine; reflectance peak at 1.6 µm
	Pallasites or olivine achondrites
	$P_v = 0.44$ (Asporina)
Q-type	Olivine and pyroxene, plus metal
	Ordinary chondrites
	$P_v = 0.25$ (1862 Apollo)
R-type	Pyroxene and olivine
	Pyroxene-olivine achondrites
	$P_v = 0.34$ (439 Dembowska)
S-type	Pyroxene; one and two µm features, with metal
	No simple meteorite analog
	$P_v = 0.10$–0.30
V-type	Pyroxene and feldspar
	Basaltic achondrites
	$P_v = 0.38$ (4 Vesta)

Based on Gaffey et al., 1989; Tholen and Barucci, 1989; Tedesco et al., 1989; and Chapman et al., 1994.

The identification of Braille with the Q-type is not entirely solid, however. The visual geometric albedo of 1862 Apollo, the only one measured in the Q-class, is 0.25 (Chapman et al., 1994), far lower than Braille's albedo of 0.34. Since asteroid classes have substantial ranges in albedo, and the error on the measurement of Apollo's albedo may have the typical error of 15–20%, the mismatch is not a serious flaw in Braille's identity as a Q-type. The lack of spectral information between 0.95 and 1.2 µm for Braille and the lack of any published spectral information for other Q-type asteroids longward of 1.6 µm are other weak points in

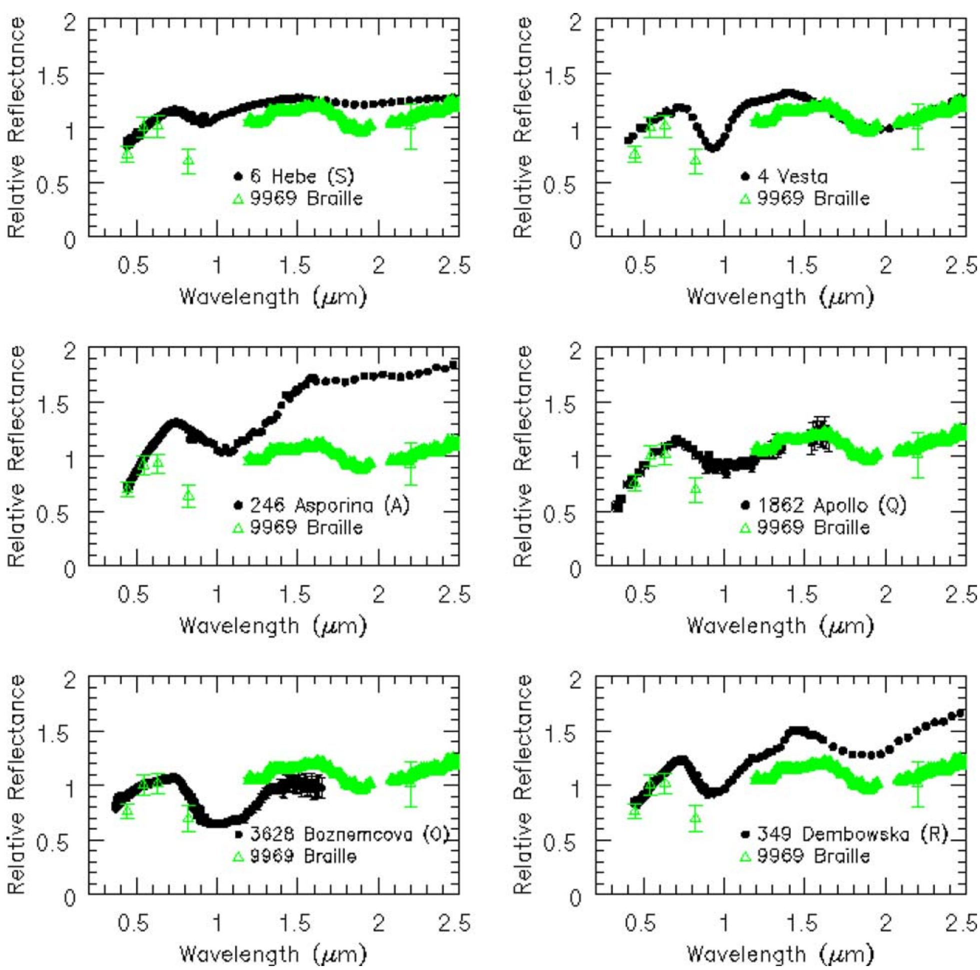

Fig. 2. A comparison of our observations of Braille from Fig. 1 to typical members of six types of stony asteroids. The observations have been normalized to unity at 0.54 µm. The asteroid observations are from (Chapman and Gaffey, 1979; McFadden et al., 1984; Cruikshank and Hartmann, 1984; Xu et al., 1995; Bus and Binzel, 2002; Burbine, 2000; and Binzel et al., 2001). (For clarity, some overlapping points from the individual surveys have been omitted.)

the identification. Indeed, the DS1 SWIR data are the first published in the 1.6 to 2.5 µm spectral range for a Q asteroid.

Dynamical evidence suggests that the origin of the terrestrial meteorites lies in the asteroid belt (Lipschutz et al., 1989; Greenberg and Nolan, 1989). Drawing compositional connections between the major groups of asteroids in the main belt and meteorites is far more problematical. The two key diagnostic features that connect the two classes of objects are their spectra, which indicate the composition, and albedo. However, the main belt is populated with bodies that in only rare instances bear resemblance to meteorites. In the case of stony asteroids, these are the associations of the basaltic achondrite (HED) meteorites with the V-class (Drake, 1979; Binzel and Xu, 1993); the rare pallasites with the S-class or A-class (Gaffey et al., 1989), and the most abundant ordinary chondrites with the Q-class of asteroids (Binzel et al., 2001), Braille's likely taxonomic type. For years, the NEO 1862 Apollo stood as the lone representative of an analog for the ordinary chondrites (McFadden et al., 1985). The Q-class is common in the NEO population but lacking in the main belt (the only one classified so far is 8197 (1992 EA7), see Bus and Binzel, 2002) and there is a compositional transition between the S-types (the most, common asteroid in the main belt) and the Q-type in the NEO population (Binzel et al., 1996, 2001). About a third of NEOs are either Q-types or fall somewhere in the transitional region between S- and Q-types (Hicks et al., 1998; Binzel et al., 2001).

In order to draw a connection between NEOs (particularly the Q-type, of which Braille is an example) and terrestrial meteorites, in Fig. 3 we show the spectrum of Braille and 1862 Apollo with laboratory spectra of three meteorites that are associated with parent bodies similar to Braille (Gaffey, 1976). They are a eucrite, which is a basaltic achondrite (HED) meteorite associated with V asteroids; an ordinary LL6 chondrite, which has been associated with O-types (Binzel and Xu, 1993 although Binzel et al., 2001, cast some doubt on the original association); and an LL5 ordinary chondrite representing a class that has been associated with the Q-type (McFadden et al., 1985; Binzel et al., 1996, 2001). The LL5 ordinary chondrite exhibits the closest spectral features, including the position of the olivine reflection peak near 1.6 µm, and the depth of the pyroxene absorption bands at 1.0 and 2.0 µm. Both Braille and the ordinary chondrites have roughly equal parts of olivine and pyroxene, based on the relative absorption strength of these two minerals (Cloutis et al., 1986; Gaffey et al., 1993). Another problem with the LL6 Manbhoom meteorite is that its unnormalized visual albedo is 0.25, while the other samples

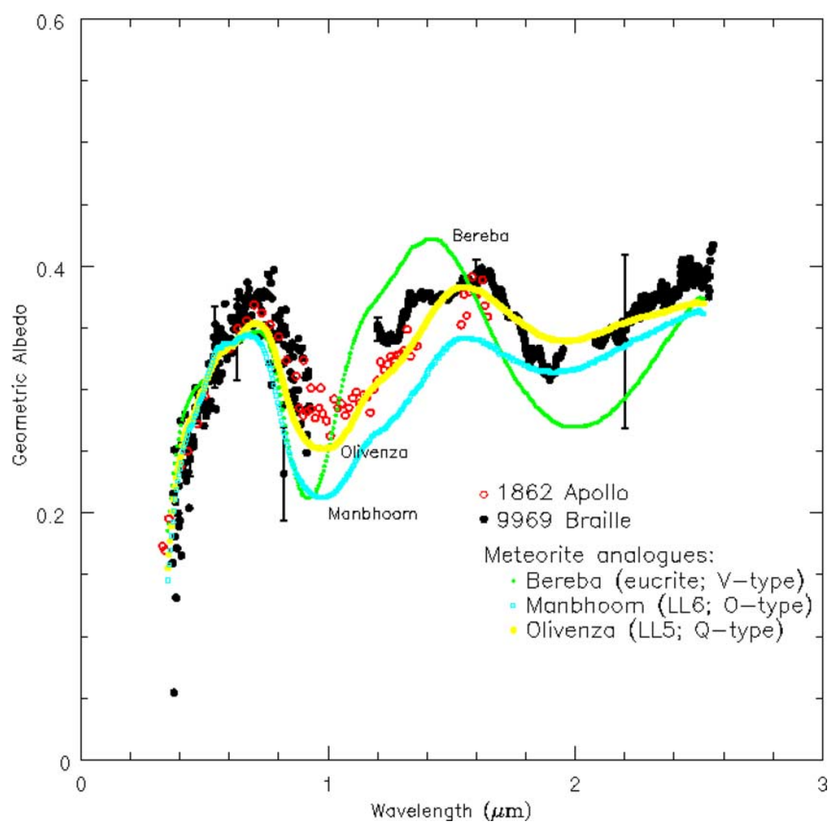

Fig. 3. A comparison of the observations of Braille from Fig. 1 to typical members of meteorite classes that are associated with the asteroid types that most strongly resemble 9969 Braille. The spectrum of 1862 Apollo from Fig. 2 has also been included. Both the meteorite spectra (Gaffey, 1976) and the spectrum of Apollo have been normalized to the Braille measurements at 0.63 µm. Bereba and Olivenza required only slight (10–15%) normalizations, but the reflectance of Manbhoom is 0.25 at 0.63 µm.

have high albedos comparable to Braille. The Deep Space 1 spectrum of Braille between 1.6 and 2.5 μm shows that the depth of the absorption band at 2 μm is similar to that of the ordinary chondrites, which confirms the association of Q asteroids with the most common meteorite.

Why are the spectra of the most common terrestrial meteorites so different from those of the most common asteroids? One possible answer is space weathering, a process by which exposure to alteration mechanisms in space reddens bodies in the visual and mutes mineral absorption bands. A plausible mechanism involving the covering of mineral grains on the asteroid's surface by nanophase iron has recently been published (Pieters et al., 2000; Clark et al., 2002). Our spectrum of the 2 μm absorption band in Q-type objects confirms the viability of space weathering, as the band is much deeper than that of S-type asteroids (upper left cell of Fig. 2). Previous work has shown that Q objects are less red in the visible and have more prominent absorption bands at 1.0 μm (Tholen and Barucci, 1989; Binzel et al., 2001). The gradual transition from S-type to Q-type in the NEO population (Binzel et al., 2001) suggests that the transitional objects have been exposed to processes that cause space weathering for varying time periods. "Classical" Q-objects exhibit fresh recently exposed surfaces (perhaps from a collisional process that led to their placement in the NEO population), while the transitional objects (termed Sq by Binzel et al., 2001) exhibit progressive muting of their absorption bands with passing time in space. Braille's unusually high albedo is also consistent with a fresh "unweathered" surface. The depths of the 1.0 and 2.0 μm absorption bands can be related to the abundance of Ca^{2+} and Fe^{2+}, respectively, in pyroxene (Cloutis et al., 1986; Gaffey et al., 1993). The abundance of these two elements is thus lower for the Q-types in comparison to the V or O asteroids. However, given the effects of space weathering, which tend to mute absorption bands, we consider this claim to be only qualitative.

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