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MUSES-C target asteroid (25143) 1998 SF36: A reddened ordinary chondrite

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Abstract–Near-Earth asteroid (25143) 1998 SF36 is a planned target for the Japanese MUSES-C sample return mission. High signal-to-noise and relatively high-resolution (50 Å) visible and near-infrared spectroscopic measurements obtained during this asteroid's favorable 2001 apparition reveal it to have a red-sloped S(IV)-type spectrum with strong 1 and 2 μm absorption bands analogous to those measured for ordinary chondrite meteorites. This red slope, which is the primary spectral difference between (25143) 1998 SF36 and ordinary chondrite meteorites, is well modeled by the spectrum of 0.05% nanophase iron ($npFe^0$) proposed as a weathering mechanism by Pieters *et al.* (2000). Asteroid 1998 SF36 appears to have a surface composition corresponding to that of ordinary chondrite meteorites and is most similar in spectral characteristics and modeled olivine/pyroxene content to the LL chondrite class.

OBSERVATIONS

Near-Earth asteroid (25143) 1998 SF36 was discovered on 1998 September 26 by the Lincoln Near-Earth Asteroid Research (LINEAR) program. Because of its low inclination orbit, (25143) 1998 SF36 is a highly accessible target for spacecraft exploration. At the time of this writing, this asteroid is the planned target for the Japanese MUSES-C sample return mission anticipated for launch in 2002, encounter in 2005, and return in 2007. A favorable apparition in early 2001 (brightest in late March near V magnitude 14) led to extensive ground-based reconnaissance observations (Binzel and Rivkin, 2001; Binzel, 2001; Hicks *et al.*, 2001; Sekiguchi *et al.*, 2001). Here we report results of visible and near-infrared spectroscopic observations obtained at Kitt Peak National Observatory and the NASA Infrared Telescope Facility (IRTF).

The Kitt Peak measurements were obtained using the 4 m telescope on 2001 March 6 U.T. equipped with the RCSP spectrograph and Tektronix 2048 × 2048 CCD binned 2 × 2 on readout. A GG495 order sorting filter and 5 arcsecond slit width provided 0.50 to 0.92 μm spectral coverage with a dispersion of 10 Å per pixel. All measurements were obtained near the meridian with the 5 arcminute long slit oriented north-south to minimize any atmospheric dispersion effects. The long slit provided ample sampling of the background sky for subtraction. Image reduction was accomplished using the Image Reduction and Analysis Facility (IRAF) software package following the standard techniques described by Bus and Binzel (2001). For reduction to a reflectance spectrum, the spectrum of the solar-like star SA107-684 (Landolt, 1973) was measured immediately after the asteroid measurements and at a similar air mass.

The IRTF measurements were obtained as part of the lead author's long-term program of near-Earth asteroid reconnaissance using SpeX, a medium-resolution infrared spectrograph employing a 1024 × 1024 InSb array. SpeX was used in its low-resolution prism mode to obtain spectra over the range 0.8 to 2.5 μm with the resulting measurements binned at 50 Å per pixel. SpeX observations were obtained on 2001 February 19 and March 28 U.T. and were calibrated with respect to the solar-like stars Bright Star (BS) 4486 and SA107-684 (Landolt, 1973). All observations were made using a 0.8 arcsecond slit width with pairs of exposures ("A" and "B") alternated along the longslit spatial dimension for the purpose of producing near-simultaneous images for sky subtraction. Residual sky values (after A–B and B–A subtraction) were fit and removed in the spectral extraction. Spectra from both nights were reduced using IRAF with their results in excellent agreement. As the March data provide a substantially higher signal-to-noise ratio, only these data are presented and utilized in this analysis.

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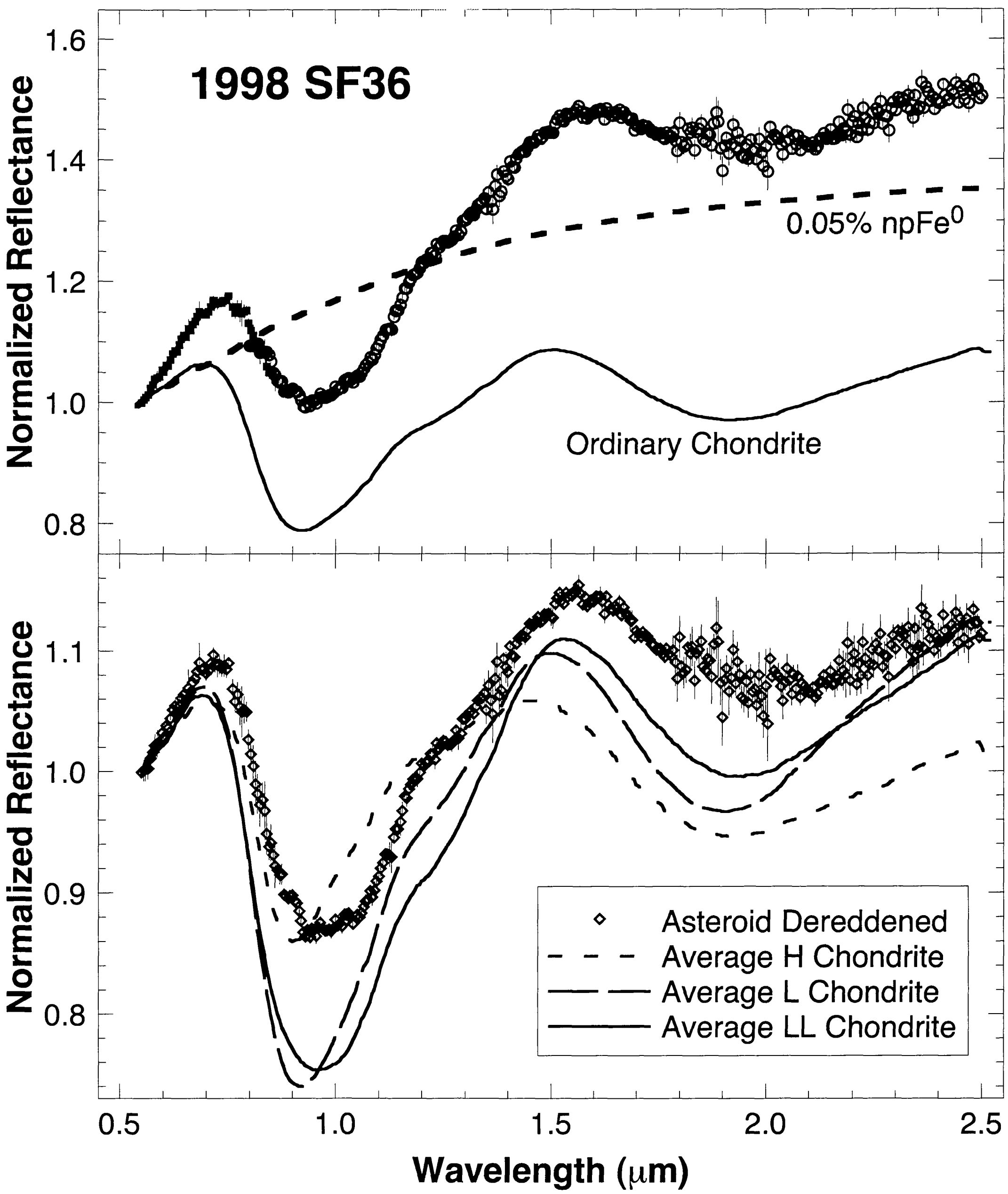

FIG. 1. (top panel) Combined visible (solid symbols; 0.5 to 0.9 μm) and near-infrared (open circles) spectra for MUSES-C target asteroid (25143) 1998 SF36. A favorable comparison of overall specral features is seen with respect to an averaged spectrum for ordinary chondrite meteorites (average for H, L, and LL groups shown as a solid line; averages are derived from the complete set published by Gaffey, 1976). The increasing separation with increasing wavelength between the asteroid and meteorite spectra appears to follow a reddening trend such as the model curve for 0.05% nanophase iron ($npFe^0$) (Pieters *et al.*, 2000). (bottom panel) Asteroid 1998 SF36 spectrum de-reddened by the 0.05% $npFe^0$ curve is displayed in comparison with spectra for the individual H, L, and LL ordinary chondrite meteorite groups. (Averages are derived from the complete set published by Gaffey, 1976.) The widths and centers of the 1 and 2 μm absorption bands appear best matched by the LL chondrites. (Vertical scale is expanded to twice that of the top panel. All spectra in all figures are normalized to unity at 0.55 μm.)

ANALYSIS

Figure 1 (top panel) shows the combined visible and near-infrared spectrum for (25143) 1998 SF36. The data are normalized to unity at 0.55 μm and the separate spectra are combined together by a minimum chi-squared fit over their 0.8 to 0.9 μm region of overlap. The 1 μm absorption band is the result of the presence of either pyroxene or olivine, or some combination of both. The 2 μm band is indicative of the presence of pyroxene only. Gaffey *et al.* (1993) used the methodology of Cloutis *et al.* (1986) to estimate proportions of olivine and pyroxene from asteroid spectra. For the spectrum of (25143) 1998 SF36, measurement of Band I (1 μm) and Band II (2 μm) yields: Band I center 0.99 ± 0.01 μm, Band II/Band I area ratio 0.40 ± 0.02. In trying to determine the most likely meteorite analog for (25143) 1998 SF36, we note that these band measurements place the asteroid within the S(IV) class defined by Gaffey *et al.* (1993), who interpret this class as being a pyroxene and olivine mixture that is consistent with the composition of ordinary chondrite meteorites. The clear presence of pyroxene (indicated by the presence of the 2 μm band) also suggests that some type of primitive achondrite may be an appropriate analog. While laboratory measurements of all collected primitive achondrites are not complete, Burbine *et al.* (2001) note that those measured to date tend to be too pyroxene-rich compared with the above band measurement values for (25143) 1998 SF36. Consequently, currently measured primitive achondrites do not appear to provide analogs for (25143) 1998 SF36. Given the S(IV) categorization, the lack of matching band measurements for primitive achondrites, and the overall resemblance of the asteroid's 1 and 2 μm absorption band features to those for ordinary chondrite meteorites, we focus the remainder of our analysis on a possible ordinary chondrite match.

In Fig. 1, we note that the asteroid and ordinary chondrite meteorite spectra diverge by a general reddening trend. This trend appears to follow that described by Pieters *et al.* (2000) arising from the presence of nanophase iron ($npFe^0$). As an *experiment* with the applicability of the Pieters *et al.* (2000) model, the observed asteroid spectrum was divided by the curve for the lowest (non-zero) level of reddening presented by these authors. The reddening model applied is that for 0.05% $npFe^0$ in a semi-transparent matrix as shown in Fig. 4 of Pieters *et al.* (2000) with the digital values provided by C. Pieters (pers. comm.). The results of the de-reddening are shown in the lower panel of Fig. 1, bringing the asteroid spectrum in line with those for ordinary chondrite meteorites. (All comparisons are made using the meteorite spectra data set published by Gaffey, 1976. These data have been corrected for a non-linear wavelength calibration error; Pieters and Pratt, pers. comm.) Here it is seen that the 1 and 2 μm bands in the de-reddened (25143) 1998 SF36 spectrum appear to be at a longer wavelength than the average spectra of H or L chondrites. However the band center, width, and overall 1 μm band structure appear quite consistent with LL chondrites. Similarly, the most reasonable match to the 2 μm absorption in the (25143) 1998 SF36 de-reddened spectrum appears to be the average spectrum for LL chondrites.

A more quantitative comparison between the spectrum of (25143) 1998 SF36 and the average spectra of ordinary chondrites is shown in Fig. 2. Here the modified Gaussian model (MGM) of Sunshine *et al.* (1990, 1999), a physically-based description of electronic transition absorption bands in spectra, is used to resolve absorptions associated with olivine and pyroxene within the 1 μm region. All spectra are modeled with the minimum number of absorptions required to fit the measured spectrum of (25143) 1998 SF36. This simple model consists of six bands (two in the visible, three in the 1 μm region, and one in the 2 μm region) superimposed onto a baseline continuum, which is modeled as a straight line in energy (see Sunshine and Pieters, 1993). The three absorptions in the 1 μm region used in these simple MGM models correspond to pyroxene (denoted by open arrows), olivine (filled arrows), and a combination of the two (not marked). Although a more complex model is likely to be more rigorous, even this simple model provides a consistent approach for spectral comparisons. In particular, the S_{olv}/S_{pyx} ratio in each model fit conveys the relative strengths of the olivine to pyroxene absorption bands (Sunshine *et al.*, 1990; Sunshine and Pieters, 1993). The ratio of the strength of the olivine to pyroxene bands increases from H to L to LL chondrites. This change in relative band strength is consistent with the general modal mineralogy of these classes (*e.g.*, McSween *et al.*, 1991). Comparisons of the MGM results show that the S_{olv}/S_{pyx} ratio for the asteroid (original data; no de-reddening model applied) is most similar that for the average LL chondrite spectrum, particularly in the 1 μm region. Based on the best match in the S_{olv}/S_{pyx} ratios, this mineralogic modeling also suggests that (25143) 1998 SF36 is most similar to the LL class, although we note there is no distinct geochemical boundary between the L and LL classes (Brearly and Jones, 1998). The same conclusion of best correspondence between the asteroid and LL chondrites is reached when the MGM analysis is applied to the de-reddened asteroid spectrum.

DISCUSSION

Achieving correlations between asteroids and meteorites has been a long standing goal in planetary science and one which has seen a long rocky road (*e.g.*, see Wasson and Wetherill, 1979; Wetherill and Chapman, 1988; Chapman, 1996; Burbine, 2000). Cementing a relationship between the ground-based measurable properties of asteroids with their laboratory verified meteorite analogs is one of the propelling scientific goals for the MUSES-C mission.

The ground-based data presented here for (25143) 1998 SF36 show a typically red-sloped S-type asteroid spectrum for which absorption band measurements place it in the S(IV) class defined by Gaffey *et al.* (1993). Placement in the S(IV) category is based on the original spectral data before any experimental de-reddening is applied. The S(IV) group is interpreted by Gaffey *et al.* (1993) to correspond to mineralogies that are within the range measured in the laboratory for ordinary chondrite meteorites. The 2 μm band indicates the presence of pyroxene, which is also common in primitive achondrite meteorites. However, band measurements for primitive achondrites (Burbine *et al.*, 2001) do not match those for the S(IV) category or for (25143) 1998 SF36, seeming to eliminate primitive achondrites for consideration as analogs. (Similarly, the breadth and center of the 1 μm band—interpreted to arise from the presence of olivine—rule out any association with

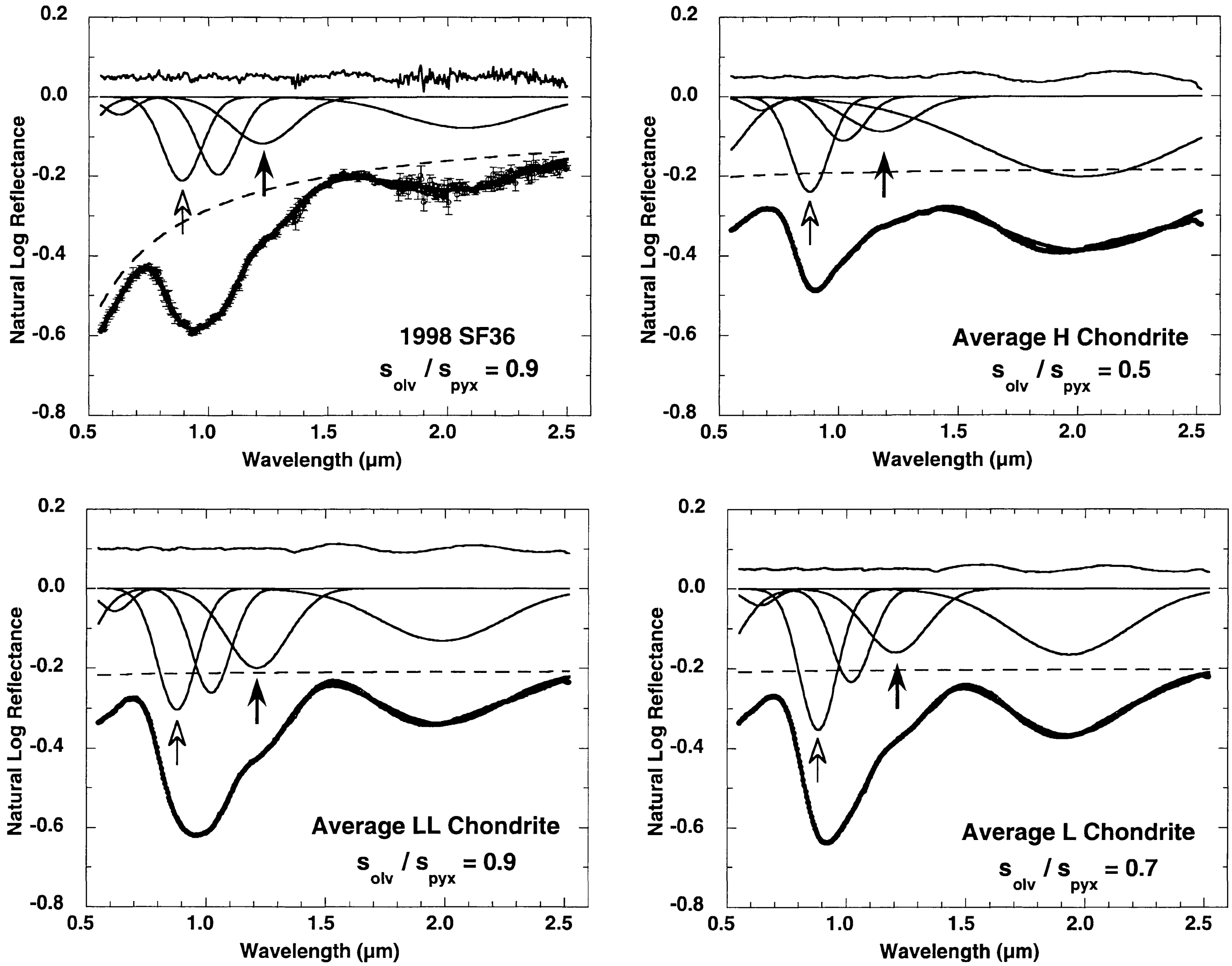

FIG. 2. MGM model fits to the spectrum of (25143) 1998 SF36 (as measured; upper left), average H chondrite (upper right), average L chondrite (lower right), and average LL chondrite (lower left). From top to bottom in each plot: the residual error between the actual and modeled spectra (offset 5% for clarity), the individual modified Gaussian distributions that represent absorption bands, the continuum or baseline onto which these distributions are added (dashed), the modeled spectrum, and the measured spectrum (circles). All spectra are modeled as a function of log reflectance and energy. (For more details see Sunshine *et al.*, 1990.) Absorptions marked with open arrows are unambiguously due to pyroxene while those marked with closed arrows are from olivine. The ratio of olivine to pyroxene absorption strength is noted by S_{olv}/S_{pyx} in each figure. Both qualitatively and quantitatively, these MGM results indicate that ordinary chondrites are excellent spectral analogs to (25143) 1998 SF36. In particular, the average LL chondrite spectrum has the S_{olv}/S_{pyx} ratio that is most comparable to (25143) 1998 SF36.

basaltic achondrites.) In addition to the long held (Gaffey *et al.*, 1993) association between S(IV) asteroids and ordinary chondrite meteorites are the overall characteristics of the 1 and 2 μm bands seen in Figs. 1 and 2. The absorption bands present in the spectrum of (25143) 1998 SF36 closely resemble those for ordinary chondrite meteorites, thereby giving credence to a relationship. The results presented here also show that the greatest difference between the (25143) 1998 SF36 spectrum and ordinary chondrite meteorites is the asteroid's red slope.

We find that the red-slope offset between the asteroid and its suggestive meteorite analog corresponds very closely to the model curve for reddening by nanophase iron as proposed by Pieters *et al.* (2000) for a space weathering process. Numerous laboratory experiments involving laser irradiation of meteorite samples (*e.g.*, Moroz *et al.*, 1996; Yamada *et al.*, 1999; Sasaki *et al.*, 2001), and the MGM linear energy continuum used here, all show very similar reddening trends. Thus, our choice of the Pieters *et al.* model is representative of the current state of the field, regardless of the actual reddening process that may be at work. We apply a simple de-reddening model by dividing the asteroid spectrum by the reddening curve corresponding to the minimum degree of weathering (0.05% $npFe^0$). Of course, it is highly uncertain and perhaps doubtful that simple mathematical division by this model curve (both asteroid and model curve anchored to unity at 0.55 μm) is physically analogous to mineralogically removing a space weathering reddening agent. However, as an exercise in combining telescopic data with this weathering model the results provide a surprisingly good match between the asteroid and specific meteorite analogs.

The fit to the red slope and band depths achieved by dividing by the 0.05% $npFe^0$ curve is certainly not perfect (Fig. 1, bottom panel). The asteroid retains a slightly redder slope and more muted absorption band depths than the meteorite analogs. We deliberately resist trying to improve the fit further by, for example, modeling a suite of $npFe^0$ curves. Our purpose in this paper is to demonstrate consistency with the reddening curve produced by $npFe^0$, rather than to quantify the level of its possible presence. For example, an additional complicating factor in perfectly matching the spectra is that remaining differences in the band depths can also arise from differences in the particle sizes on the asteroid's surface and those in the measured laboratory samples (Burbine, 2000).

Adding additional weight to this asteroid-meteorite link is the match of more subtle spectral features (*e.g.*, inflections near 1.2 and 1.3 μm) seen most clearly in Fig. 1 for both the asteroid and meteorite spectra. The MGM modeling curves (Fig. 2) show these inflections to be the result of the superposition of pyroxene and olivine absorptions. The asteroid data both alone and when coupled with the model are consistent with the conclusion that the reflecting surface of (25143) 1998 SF36 has an ordinary chondrite-like composition that is reddened by nanophase iron or some other space weathering agent that is similarly effectual. This match represents one further step in the telescopic link between S-asteroids and ordinary chondrite meteorites, seen in a continuum of spectral properties among asteroids in the smaller size ranges (Binzel *et al.*, 1996, 2001). Spacecraft data on S-asteroids obtained for Ida (Chapman, 1996) and Eros (Ververka *et al.*, 2000; Trombka *et al.*, 2000) also provide strong evidence for an S-asteroid and ordinary chondrite meteorite connection.

Ground truth provided by a returned sample remains the next essential step toward conclusively identifying the parent bodies for ordinary chondrite meteorites. A returned sample from (25143) 1998 SF36 will reveal whether the conclusion of an ordinary chondrite composition determined from the ground-based data presented here is correct. Laboratory analysis will further reveal whether the "best match" of the ground-based data to the subclass of LL chondrites is critically diagnostic. An important caveat is that ground-based spectra represent a hemispheric average for the asteroid and do not reveal the extent of small scale variations on the surface, especially at the scale at which a sample will be obtained. One of the challenges of the *in situ* phase of the MUSES-C mission will be to assess the extent to which the returned sample is representative of the overall composition of this small world. The results of the MUSES-C mission will critically test how well current theories and interpretations of telescopic data can predict the true composition of asteroids among both the near-Earth and main-belt populations.

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