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Potentially hazardous Asteroid 2007 LE: Compositional link to the black chondrite *Rose City* and Asteroid (6) Hebe

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ABSTRACT

The research is an integrated effort beginning with telescopic observations and extending through detailed mineralogical characterizations to provide constraints on the albedo, diameter, composition, and meteorite affinity of near-Earth object-potentially hazardous asteroid (NEO-PHA 2007 LE). Results of the analysis indicate a diameter of 0.56 kilometers (km) and an albedo of 0.08. 2007 LE exhibits a 1-μm absorption feature without a discernible Band II feature. Compositional analysis of 2007 LE reveal Fs_{17} and Fa_{19} values, which are consistent with the Fa and Fs values for the H-type ordinary chondrites ($Fs_{14.5–18}$ and $Fa_{16–20}$) and of Asteroid (6) Hebe (Fs_{17} and Fa_{15}). Spectroscopically, 2007 LE does not appear like the average H-chondrite spectra, exhibiting a reddened spectrum and subdued absorption feature. Further investigation of the meteorite classes yielded a black chondrite, *Rose City*, which is both similar in mineralogy and spectrally to PHA 2007 LE. Dynamical analysis could not directly link the fall of the *Rose City* meteorite to 2007 LE. As it stands, 2007 LE and *Rose City* have a compositional link, and both could come from the same parent body/possible family, one known source of the H chondrites is (6) Hebe.

1. Introduction

Although there is general agreement that most meteorites are samples of asteroids, the identification of the specific asteroid parent bodies of individual meteorites or of meteorite types has been a high priority in asteroid science for nearly five decades. Establishment of such links allows the detailed chemical, isotopic and chronological characterizations of meteorite samples in terrestrial laboratories to be placed into a spatial context in the present Solar System, and via dynamical models into a spatial context in the early Solar System. Although many asteroid–meteorite links have been suggested in the past only a few have survived the test of time. Of the ~135 different asteroidal parent bodies represented in the meteorite collections, only a few types have parent bodies identified, with varying degree of certainty. The most agreed upon connection is between Asteroid 4 Vesta and the HED meteorites (McCord et al., 1970 & results of the DAWN mission). Spectrally, the near-Earth Asteroid (3103) Eger and the enstatite achondrites/aubrites are similar (Gaffey et al., 1992), and this may suggest a connection between these meteorites and Eger-like bodies in the Hungaria asteroid family. Interesting links have also been proposed between the LL chondrites and the Flora family (Vernazza et al., 2008), the L chondrites and the Gefion family (Nesvorný et al., 2009), and the mesosiderites and the Maria Family (Fieber-Beyer et al., 2011). It is probable that the H-chondrites and IIE irons came from (6) Hebe (Gaffey and Gilbert, 1998), though caveats exist (e.g., Rubin and Bottke, 2009). The identification of many more large asteroids with H chondrite-like spectra also means that more candidates are now available to serve as a source for these meteorites (Vernazza et al., 2014).

A meteorite may derive from a meteoroid released from a main belt parent body or parent family which then undergoes orbital evolution to put it into an Earth encountering orbit. The meteoroid may also be released from an object already in an Earth-approaching orbit such as a near-Earth object (NEO). In the latter case, the NEO would be an intermediate precursor between the primary main belt parent body and the meteoroid.

On June 2, 2007 the NEO 2007 LE, was discovered by the LINEAR NEO survey and subsequently designated as a PHA (potentially hazardous asteroid) by The Minor Planet Center. On June 03, 2012 UT, 2007 LE passed within 0.049 AU of the Earth. At the time, nothing but the absolute visual magnitude (H) magnitude was known which provided a rough estimate of diameter (D_{eff}). Most

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NEO sizes are not actually measured, but are estimated based on the absolute visual magnitude (*H*) and assumed albedos of 0.05 and 0.25, which corresponds to a factor of 2.2 uncertainty in the estimated diameter and an uncertainly of a factor of 11 in the estimated mass of an NEO. Analysis of NEO data from the WISE satellite has provided size determinations for a few percent of the NEO population (e.g., Mueller et al., 2011; Mainzer et al., 2012). Radar observations are also used to obtain measurements of asteroid shapes, spins, masses, densities, and trajectories. Taxonomic classifications, including ambiguous types, are also available for a few percent of the known NEO population (e.g., Binzel et al., 2004; Fevig and Fink, 2007; DeMeo et al., 2009). Actual compositional determinations and/or identified meteorite analogs are available for less than 1% of the known NEO population. Although most NEOs are believed to originate from collision events on asteroids in the mainbelt, the pathways of these fragments into Earth-crossing orbits are known only in a statistical way.

Sophisticated mineralogical characterizations are critical to establishing the physical nature of individual NEOs and of NEO subpopulations such as the PHAs. While taxonomy provides broad insights into the relationships of asteroid groups, taxonomic classification is not a compositional interpretation. Objects in different taxonomic classes are likely to be composed of different materials, but there is no assurance that objects of the same taxonomic type are composed of similar materials. Mineralogical characterizations are the key to unraveling the history and relationships between asteroids, their parent bodies, and the meteorites derived from them. The research reported here is an integrated effort beginning with telescopic observations and extending through detailed mineralogical characterizations to provide constraints on the albedo, diameter, composition, and meteorite affinity of 2007 LE.

2. Observations/data reduction

Near-infrared spectral observations were obtained at the NASA Infrared Telescope Facility located at Mauna Kea Observatory, Hawai'i. The observational parameters from the observing run are listed in Table 1. Physical properties and orbital elements are listed in Table 2. The spectra were obtained using the facility SpeX instrument in the low-resolution spectrographic mode (Rayner et al., 2003).

A local G-type standard star was selected to provide both a spectral flux calibration and to track the varying atmospheric absorption during the asteroid observations. Asteroid and local standard star spectra were acquired in interspersed sets of ten. A solar analog star was also observed to provide a calibration standard. Extraction of spectra, determination of wavelength calibration, and data reduction were done using procedures outlined by (Clark, 1980; Hardersen et al., 2005; Reddy, 2009; Fieber-Beyer, 2010). Individual raw flux spectra were corrected to a standard pixel array to compensate for the (generally) subpixel shifts of the dispersed spectrum on the array detector (e.g., Gaffey et al., 2002). The first spectrum of each set was discarded due to image persistence on the detector chip and other spectra were discarded due to poor quality because of deteriorating weather conditions.

The local standard star data were used to derive the extinction coefficients ("starpacks") from the variation in flux versus air mass (atmospheric path length) for each channel in the spectrum. Starpacks were computed for various permutations of the standard star observations (e.g., all standard star sets, sets that bracketed individual sets of asteroid observations, etc.).

Each asteroid flux curve was divided by the several permutations of starpacks to identify the starpack that most effectively removed the atmospheric water vapor features to produce a final spectrum. The individual spectra for 2007 LE were averaged, deleting individual points that deviated by more than two standard deviations from the mean. The PHA's average spectrum was then ratioed to an average of the solar analog spectra for its respective night to correct for any non-solar spectral properties of the local standard star.

The position of the absorption features (band centers) and the relative areas of the features (band area ratios, BAR) are diagnostic of the compositions and abundances of mafic silicates (e.g., Adams, 1974, 1975; Cloutis et al., 1986; Gaffey et al., 1993, 2002; Gastineau-Lyons et al., 2002; Burbine et al., 2003, 2009; Dunn et al., 2010). The near-infrared spectrum of 2007 LE exhibits a single absorption feature in the 1 μm region (Fig. 1). The band center (0.94 ± 0.02 μm – Table 3) was measured relative to a linear continuum fitted tangent to the spectral curve outside the absorption feature (e.g., Cloutis et al., 1986). The uncertainty was estimated from several polynomial fits, sampling different ranges of points within the Band I spectral interval (i.e. points sampled to the left and right of the center of the feature, deleting any spurious outlying points). The uncertainty was determined as half the difference between the minimum and maximum values calculated from the polynomial fits.

Temperature affects the band center positions of mafic minerals such as pyroxene (e.g., Roush, 1984; Roush and Singer, 1986; Lucey et al., 1998; Moroz et al., 2000; Hinrichs and Lucey, 2002; Sunshine et al., 2007; Reddy et al., 2011). The Dunn et al. (2010) calibration used below was based on laboratory spectra of ordinary chondrites measured at room temperature (~290 K). We calculated the surface temperature of 2007 LE using the formula from Burbine et al. (2009):

$$T = [(1 - A)\mathrm{Lo}/16\eta\varepsilon\sigma\pi r2]1/4$$

where *A* is the asteroid albedo, Lo is the solar luminosity (3.846×10^{26} W), η is the beaming factor (assumed to be 1.0), ε is the asteroid's infrared emissivity (assumed to be 0.9), σ is the Stefan–Boltzmann constant, and *r* is the asteroid's distance from the Sun in meters. For our derived albedo of 8% (see below), the surface temperature of 2007 LE at a heliocentric distance of 1.058 AU would be 272 K. An increase or decrease of the albedo to 0.09 or 0.07 would only change the temperature by ~1–2°. The ~20 K lower temperature for the asteroid surface compared to the laboratory calibration samples would produce a shift in the Band position of ~−0.002 μm using the calibration for orthopyroxenes by Roush

Table 2
Orbital and physical properties.

Object	*a* (AU)[a]	*e*[a]	*i* (°)[a]	D_{eff} (km)[b]	Albedo[b]	*H*[a]
2007 LE	1.8387	0.5166	29.48	0.5649	0.08	19.7

[a] *a*, *e*, *i* and *H* (semi-major axis, eccentricity, and inclination, respectively) were obtained using JPL Horizons.
[b] Diameter and albedo measurements were obtained from this work.

Table 1
Observational parameters.

Object	Date	UT	R.A.[a]	Dec.[a]	*r* (AU)[a]	*Δ* (AU)[a]	*φ* (°)[a]	V-mag[a]
2007 LE	06/03/12	11:08–12:17	15 35 49.40	+00 57 47.2	1.058	0.0495	27.72	14.53

[a] Observational properties were obtained from JPL Horizons.