REPORTS

# Discovery of a Main-Belt Asteroid Resembling Ordinary Chondrite Meteorites

Richard P. Binzel, Shui Xu, Schelte J. Bus, M. F. Skrutskie, Michael R. Meyer, Patricia Knezek, Edwin S. Barker

Although ordinary chondrite material dominates meteorite falls, the identification of a main-belt asteroid source has remained elusive. From a new survey of more than 80 small main-belt asteroids comes the discovery of one having a visible and near-infrared reflectance spectrum similar to L6 and LL6 ordinary chondrite meteorites. Asteroid 3628 Božněmcová has an estimated diameter of 7 kilometers and is located in the vicinity of the 3:1 Jovian resonance, a predicted meteorite source region. Although the discovery of a spectral match may indicate the existence of ordinary chondrite material within the main asteroid belt, the paucity of such detections remains an unresolved problem.

More than 80% of the meteorites falling to Earth are stone-like assemblages of olivine and pyroxene that are classified as ordinary chondrites (*1*). They represent samples of the primitive solar nebula that have undergone only modest thermal evolution over the age of the solar system. Although most meteorites are believed to be derived from the asteroid belt, two decades of remote-sensing observations of main-belt asteroids have not previously revealed one whose visible and near-infrared reflectance spectrum matches that of ordinary chondrites as measured in the laboratory. One hypothesis for the mismatch in the abundances of ordinary chondrite meteorites and detected asteroid source bodies is that "space weathering" processes alter ordinary chondrite asteroid surfaces, disguising their measured spectra (*2*). A second alternative is that ordinary chondrite asteroid source bodies exist at sizes below the limits of previous remote sensing surveys (*3*). We report that a new spectroscopic survey at smaller asteroid sizes has yielded the discovery of one main-belt asteroid whose spectrum is similar to ordinary chondrite meteorites.

Previous spectrophotometric surveys have typically sampled main-belt asteroids down to about 30 km in diameter (*4*). A new survey, the Small Main-Belt Asteroid Spectroscopic Survey (SMASS), was initiated at the Michigan–Dartmouth–Massachusetts Institute of Technology (MDM) Observatory in 1991 (*5*). The goals of this survey are to use high quantum efficiency, charge-coupled device (CCD) detectors to sample asteroid spectral properties down to sizes of < 10 km to reveal possible differences in composition between the large and small asteroid populations and to establish new links in the asteroid-meteorite connection. The instrumentation and methods of the SMASS program have been reported (*6*).

A summary of observations for one SMASS asteroid, 3628 Božněmcová, is presented in Table 1. The reduction of observations obtained during December 1991 revealed its spectrum to be unlike that observed for any other main-belt asteroid, characterized by a flat slope shortward of 0.8 μm and a deep, broad absorption band extending out beyond 1 μm (Fig. 1A). Although repeated exposures on a single night consistently showed the same features, the confident interpretation of such a unique asteroid spectrum required additional confirming observations.

Asteroid 3628 was observed repeatedly during its next apparition in early 1993. Visible wavelength spectra obtained through multiple CCD exposures on two nights in January confirmed the previously observed features. To define better the characteristics of the absorption band beyond 1 μm, we used the University of Massachusetts NICMOS3 camera (NICMASS) (*7*) at the MDM Observatory to obtain flux measurements using J and H filters centered at 1.26 and 1.64 μm, respectively (*8*). We achieved a calibration between these infrared data and the visible spectrum through simultaneous (*9*) visible wavelength measurements at the University of Texas McDonald (McD) Observatory using a CCD detector and an R filter centered at 0.67 μm (*10*). The results of these simultaneous measurements are summarized in Table 2, where the intrinsic colors for the asteroid (within the astronomical magnitude system) are derived by the subtraction of the solar colors. To transform the asteroid magnitude measurements (*m*) to relative reflectances (I) (Fig. 1), we use the relation

$$I_2 = I_1\, 10^{0.4(m_1 - m_2)}$$

where $(m_1 - m_2)$ successively corresponds to the tabulated (R−J) and (R−H) reflectances. We establish $I_1 = 1.047$ for the R filter, where this value corresponds to the mean relative reflectance at 0.67 μm as measured from the visible spectrum.

Although the spectrum of asteroid 3628 differs from that previously seen for any other main-belt asteroid, Fig. 1A reveals that its closest similarity is with that of the near-Earth asteroid 1862 Apollo, previously identified as a potential inner solar system source body for ordinary chondrite meteorites (*11*). Mineralogically, the deep absorption band observed near 1 μm can arise from the presence of olivine, pyroxene, and to a lesser extent feldspar, which are commonly found in meteorites (*12*). From a data base of laboratory spectra of meteorites (*13*), we find that the spectral features of asteroid 3628 are most consistent with the properties measured for ordinary chondrites (Fig. 1B). Although we would not necessarily expect a perfect spectral fit between an object measured in space and our collection of meteorite materials, the differences must be carefully examined. Below 0.5 μm, the asteroid data mismatch the presented ordinary chondrite spectra by about 1 σ. If the difference is real, it could arise from minor variations in iron content (*14*). Over the range of 0.5 to 1.0 μm, the data fit well within the range measured for ordinary chondrite samples (*13*), of which only a subset is presented in the figure. The depth of the asteroid spectrum near 1 μm is most consistent with LL6 chondrites, but because the depth is sensitive to both surface particle size and composition, we consider it to be consistent with

**Table 1.** Summary of visible and near-infrared wavelength observations of asteroid 3628 Božněmcová. The telescope aperture sizes are in parentheses.

| Observation date (UT) | Telescope | Observers | Wavelengths (μm) |
|---|---|---|---|
| 91/12/08 | MDM (2.4 m) | R.P.B., S.X. | 0.5 to 1.0 |
| 93/01/21 | MDM (2.4 m) | R.P.B., S.J.B. | 0.5 to 1.0 |
| 93/01/22 | MDM (2.4 m) | R.P.B., S.J.B. | 0.5 to 1.0 |
| 93/03/05 | MDM (1.3 m) | M.F.S., M.R.M., P.K. | 1.26, 1.64 |
| 93/03/07* | MDM (1.3 m) | M.F.S., M.R.M., P.K. | 1.26, 1.64 |
| 93/03/07* | McD (0.7 m) | E.S.B. | 0.67 |

*Simultaneous observations.

R. P. Binzel, S. Xu, S. J. Bus, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.
M. F. Skrutskie and M. R. Meyer, Five College Astronomy Department, Department of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003.
P. Knezek, Department of Astronomy, University of Michigan, Ann Arbor, MI 48109.
E. S. Barker, University of Texas McDonald Observatory, Fort Davis, TX 79734.

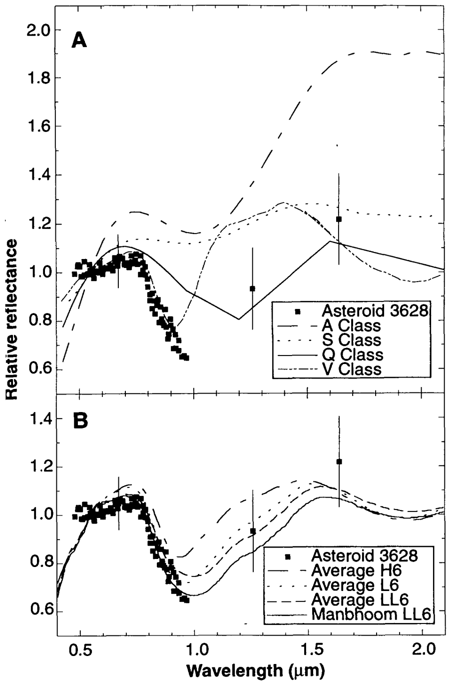


**Fig. 1.** Visible and near-infrared reflectance spectrum of the main-belt asteroid 3628 Božněmcová compared with (**A**) spectra of other asteroids and (**B**) spectra of ordinary chondrite meteorites. Error bars are affixed to the points denoting simultaneous measurements at 0.67, 1.26, and 1.64 μm. The spectral features of asteroid 3628 are presently unique among all measurements of main-belt asteroids, with a 1-μm absorption band that is deeper than that for the common S-class asteroids and the nearly pure olivine A-class asteroids and broader than that for the pyroxene-rich basaltic achondrite (V-class) asteroids. The absorption band is most similar to that for the Q class, corresponding to the near-Earth asteroid 1862 Apollo. In comparison with laboratory spectra of meteorites (B), the asteroid measurements are most consistent with L6 and LL6 ordinary chondrites. Comparison asteroid data for the A class (246 Asporina), S class (3 Juno), V class (4 Vesta), and Q class are from (*5, 11, 21, 22*). The meteorite data are from (*13*). All spectra have been normalized to unity at 0.55 μm.

L6 chondrites as well. The H6 meteorites appear to display a 1-μm absorption band more narrow than indicated by the asteroid measurements, making this association less likely. At 1.26 μm, the asteroid measurement falls close to both L6 and LL6 chondrites and remains within 1 σ of H6 chondrites. At 1.64 μm the asteroid measurement uncertainty is large and all ordinary chondrite types are consistent within the 1 σ error.

Figure 2 reveals that the orbital location of asteroid 3628 is in accord with predictions for ordinary chondrite source bodies based on orbital evolution models and meteorite fall-time statistics (*15*). Specifically, it is proximate to the Kirkwood gap at the

**Table 2.** Results for simultaneous visible and near-infrared wavelength observations of asteroid 3628 Božněmcová. Asteroid magnitude measurements for the R filter were 17.72 ± 0.11.

| | Magnitude | |
|---|---|---|
| | R−J | R−H |
| Asteroid measurements | 0.68 ± 0.17 | 1.26 ± 0.19 |
| Adopted solar colors (*20*) | 0.806 | 1.096 |
| Asteroid reflectances | −0.13 ± 0.17 | 0.16 ± 0.19 |

3:1 Jovian resonance, a major transfer zone for asteroidal material to the inner solar system (*16*). The high orbital eccentricity of the asteroid could increase the efficiency with which it contributes meteoritic material to the inner solar system. The long-term stability of its orbit, in the vicinity of the resonance, has yet to be determined.

If the ordinary chondrite interpretation of 3628 Božněmcová's spectrum is correct, what constraints can the SMASS survey statistics place on the abundance of main-belt ordinary chondrite asteroids? As a first step, we derive a value of 7 km for the asteroid's estimated diameter (*17*). The estimated diameters for other SMASS asteroids observed in the vicinity of the 3:1 resonance are shown in Fig. 2B, where 80 of them are <20 km. Asteroid 3628 is one of the smallest surveyed, one of 17 having an estimated diameter <10 km. Although only limited inference can be made from a sample of one, it appears that ordinary chondrite material represents no more than a few percent of the asteroids within the size range surveyed so far.

Can the inferred composition for asteroid 3628 be used to discriminate between the proposed explanations for the apparent mismatch in the abundances of ordinary chondrite meteorites and asteroid source bodies? No. Although the size of the asteroid is consistent with the "small source body" alternative, it can also be argued that the small size does not rule out space weathering because the collisional lifetime for a 7-km asteroid may be $<10^8$ years (*18*). If asteroid 3628 is a young collisional fragment, space weathering processes may have had insufficient time to alter its surface.

The apparent spectral match between a main-belt asteroid and ordinary chondrite meteorites, however, does illuminate a path toward resolving the ordinary chondrite paradox because it demonstrates that such material may be detected with current instrumentation. For the small source body alternative, asteroids having ordinary chondrite spectral properties should become more numerous as surveys are reduced to smaller

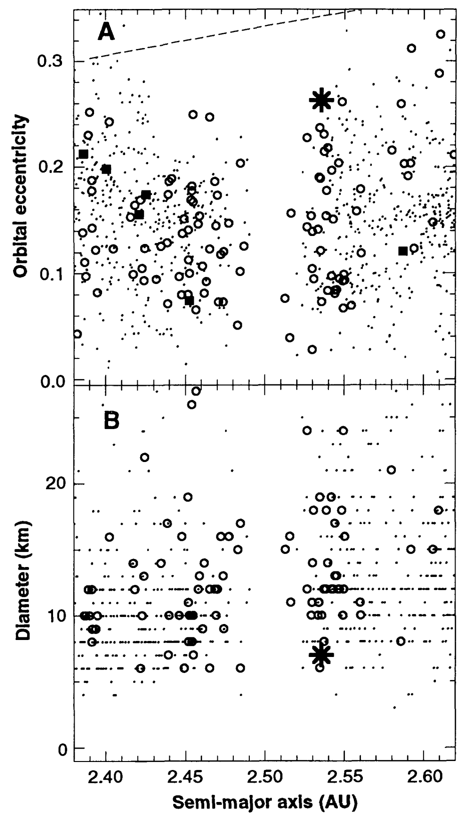


**Fig. 2.** Distribution of (**A**) asteroid orbital eccentricities and (**B**) asteroid diameters versus distance from the sun in the vicinity of the 3:1 Jovian resonance Kirkwood gap (2.50 AU), a predicted meteorite source region. The location of asteroid 3628 is depicted by an asterisk at 2.54 AU, and all other asteroids spectroscopically surveyed by the SMASS program are depicted by open circles. A subset of asteroids within the taxonomic S class may have ordinary chondrite mineralogies if their spectral characteristics are disguised by space weathering processes (*19*). Their orbital locations are indicated by squares. Proper orbital elements (*23*) have been used to depict the asteroid locations. The high orbital eccentricity of asteroid 3628 places it near a Mars-crossing orbit (dashed line at top). The asteroid's orbital inclination (i) is modest, having a value sin *i* = 0.2625.

sizes. For the space weathering alternative, a spectrally disguised ordinary chondrite mineralogy is considered possible for a subset of S-class asteroids (*19*) (Fig. 2A). Confirmation of this hypothesis could arise if small ordinary chondrite asteroids are found to be preferentially clustered in the vicinity of some of these larger parent bodies, where the small asteroids could be fresh "unweathered" fragments excavated by collisions in a manner similar to that observed for the Vesta family (*6*).

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8. These data were calibrated with the use of infrared standard stars from a list compiled at the United Kingdom Infrared Telescope [M. M. Casali, *JCMT UKIRT Newsl.* **4**, 33 (1992)] transformed into the California Institute of Technology (CIT) photometric system [J. Elias *et al.*, *Astron J.* **87**, 1029 (1982)]. All infrared data in this report are quoted in the CIT system, which matches the natural system of the NICMASS instrument within the errors of measurement.
9. The MDM Observatory is located on Kitt Peak near Tucson, AZ, and McD Observatory is located on Mount Locke near Fort Davis, TX. Simultaneous observations from these observatories were performed on 7 March 1993 UT. The J and H filter measurements were made at Kitt Peak over the interval of 6:04 to 6:50 UT, while the R filter measurements were made in Texas during 6:13 to 6:56 UT. The observations were coordinated from the first author's kitchen table in Lexington, MA, with a notebook computer and modem connection to the Internet communications network.
10. All references to the R filter in this report correspond to the Kron-Cousins system [A. W. J. Cousins, *Mem. R. Astron. Soc.* **81**, 25 (1976)].
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14. Transition metals and their cations, for example, $Fe^{2+}$, give rise to most geologically diagnostic absorptions (*12*). Independent physical processes create the absorptions at short and long wavelengths such that their characteristics are not highly correlated. Below ~0.5 μm, absorptions are caused by charge transfers between electron orbital shells within many silicate and oxide minerals. Beyond 1 μm, absorptions are caused by field splitting arising from the crystal structure of the specific minerals present. In general, the long wavelength absorptions are much more diagnostic of the mineralogy.
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17. Starting with the measured magnitude in the R filter (Table 2), we assume solar-like V-R filter colors to estimate a V filter magnitude of 18.07. At the time of observation, the asteroid was 3.257 AU from the sun, 2.322 AU from the Earth, and at a solar phase angle of 6.92°. We assume the same value for the phase coefficient, $G = 0.12$, as is tabulated for 1862 Apollo [E. F. Tedesco, in (*3*), pp. 1090–1138]. We also assume the tabulated albedo for Apollo, $\rho_V = 0.21$ [L. A. McFadden, D. J. Tholen, G. J. Veeder, in (*3*), pp. 442–467]. From these geometric and assumed values, we derive an absolute magnitude $H = 13.13$ and diameter of 7 km using the relations presented by E. Bowell and colleagues [in (*3*), pp. 524–556].
18. The age of 951 Gaspra, the 1991 flyby target for the Galileo spacecraft, is estimated to be $\sim 3 \times 10^8$ years, as predicted by N. Namiki and R. P. Binzel [*Geophys. Res. Lett.* **18**, 1155 (1991)].
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24. Data reported here were obtained in part at the MDM Observatory. We thank B. Barr (MDM Observatory) and J. Martin (McD Observatory) for exceptional technical support that allowed these observations to be made, L. Hillenbrand for assistance with the NICMASS observations, and two anonymous reviewers for their helpful suggestions. Supported by National Aeronautics and Space Administration grants NAGW 1450 (R.P.B.) and NAGW 1477 (McD Observatory) and by the Astrophysical Research Consortium through its role in the infrared component of this work through the Detector Development Consortium.


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# SSZ-26 and SSZ-33: Two Molecular Sieves with Intersecting 10- and 12-Ring Pores

Raul F. Lobo, Ming Pan, Ignatius Chan, Hong-Xin Li, Ronald C. Medrud, Stacey I. Zones, Peter A. Crozier, Mark E. Davis*

**The framework structures of two closely related molecular sieves, SSZ-26 and SSZ-33, are described. These materials possess a previously missing but desired structural feature in a group of industrially significant zeolites. They contain a three-dimensional pore system that provides access to the crystal interior through both 10- and 12-rings. This property is a consequence of the organic structure–directing agents used in the synthesis of these materials. These materials are examples of the purposeful design of a micropore architecture. Both SSZ-26 and SSZ-33 contain the 4=4−1 building unit that had been previously found only in natural zeolites.**

Inorganic molecular sieves, such as zeolites, are extensively used in catalytic and separation processes, especially in the petrochemical and refining industries (*1*, *2*). New large-pore materials, those with pores bounded by rings composed of 12 tetrahedral (T) atoms (such as Si, Al, and B) with open-pore diameters of ~7 Å (*3*, *4*), can be used for controlled shape-selective catalysis of molecules with relatively complex architectures. Large-pore materials with intersecting channels also have increased resistance to fouling and enhanced intracrystalline diffusion properties over materials with unidimensional channels; however, only a few zeolites are known with pores that are both large and intersecting. Zeolites Y and beta have intersecting 12-ring pores and have extensive application in refinery processes, as does zeolite ZSM-5, which has intersecting 10-ring (medium) pores. Additionally, as environmental factors play more significant roles in the design of new process chemistries, zeolite solid acids—because of their ease of handling and disposal—are receiving close attention as possible substitutes of the currently used liquid acids.

A molecular sieve with intersecting 10- and 12-ring pores is likely to offer a combination of reaction activity, selectivity, and stability not found in any other material (*4*). Only recently, a zeolite with intersecting 10- and 12-ring pores was found in the rare mineral boggsite (*5*). Additionally, the synthetic material NU-87 (*6*) has a 10- and 12-ring pore system, but access to the crystal interior can only be achieved through the 10-ring pores. Thus, this type of zeolite is of interest for catalytic applications in the petrochemical industry but, until now, was only available in the minute quantities of boggsite, too low for even laboratory-scale evaluation.

Several factors prompted us to study the structures of the synthetic zeolites SSZ-26 and the related SSZ-33. First, preliminary sorption experiments indicated that these materials had a multidimensional pore system with at least one of the pores being a 12-ring. Second, the structure-directing agents used for the synthesis of both materials were carefully chosen such that they would form a multidimensional pore system (*7*). Additionally, the concepts of structure-direction could be tested if a close relation between the structure-directing agent and the pore geometry could be found.

SSZ-26 and SSZ-33 (*7–9*) are synthesized

R. F. Lobo, H.-X. Li, M. E. Davis, Chemical Engineering, California Institute of Technology, Pasadena, CA 91125.
M. Pan and P. A. Crozier, Center for Solid State Science, Arizona State University, Tempe, AZ 85287–1704.
I. Chan, R. C. Medrud, S. I. Zones, Chevron Research and Technology Company, Richmond, CA 94802–0627.
*To whom correspondence should be addressed.