The Astrophysical Journal, 615:L161–L164, 2004 November 10

MATURE AND FRESH SURFACES ON THE NEWBORN ASTEROID KARIN

Takanori Sasaki,[1] Sho Sasaki,[1,2] Jun-ichi Watanabe,[2] Tomohiko Sekiguchi,[2] Fumi Yoshida,[2] Hideyo Kawakita,[3]
Tetsuharu Fuse,[4] Naruhisa Takato,[4] Budi Dermawan,[5,6] and Takashi Ito[2,7]

Received 2004 July 6; accepted 2004 October 4; published 2004 October 14

ABSTRACT

Here we report a near-infrared (*J*, *H*, and *K* bands) spectroscopy of 832 Karin, the brightest asteroid among the Karin cluster group, which is thought to be the remnants of a collisional breakup only 5.8 million years ago. The spectroscopic observation was performed by the Subaru telescope with the Cooled Infrared Spectrograph and Camera for OHS on 2003 September 14. For different rotational phases of Karin, we derived different spectra such as a reddened spectrum like that of an S-type asteroid and an unreddened spectrum like that of ordinary chondrite. Karin could be an impact fragment preserving an old surface and is probably one of the cone-shaped fragments at the low-velocity impact that formed the Karin cluster group. Our result supports the idea that S-type asteroids are parent bodies of ordinary chondrites.

Subject headings: minor planets, asteroids — solar system: general

1. INTRODUCTION

Although S-type asteroids are the most common among the inner-part main belt asteroids as well as near-Earth asteroids, reddened reflectance spectra and derived mineralogy of S-type asteroids are different from those of ordinary chondrites, the most common meteorites. Space weathering is thought to be able to explain these spectral mismatches between asteroid types and meteorite classes (Chapman & Salisbury 1973; Wetherill & Chapman 1988; Chapman 1996; Pieters et al. 2000; Binzel et al. 2003; Burbine et al. 2003; Clark et al. 2003). Recent asteroid surveys suggest a strong link between S-type asteroids and ordinary chondrites (Binzel et al. 1996; Burbine & Binzel 2002). Multispectral observation of Ida by the *Galileo* spacecraft showed that relatively fresh surfaces such as crater interiors and ejecta have reflectance like ordinary chondrites (Chapman 1996). Moreover, the *Near Earth Asteroid Rendezvous*/Shoemaker mission revealed an ordinary chondrite composition of 433 Eros despite a reddened S-type spectrum (McFadden et al. 2001; Clark et al. 2001; Bell et al. 2002). The detailed mechanism of space weathering has remained unsolved until recently, when the laboratory experiments using high-energy pulse laser irradiation confirmed Hapke's old hypothesis (Hapke et al. 1975; Hapke 2001) that the reflectance change forming S-type spectra is caused by the formation of nanophase iron particles within the vapor-deposited rim around regolith particles (Sasaki et al. 2001). The degree of space weathering, i.e., redness of spectral slope, can be used to discuss the age of asteroids (Sasaki et al. 2001). And recently, relations between the color and age of S-type asteroid groups have been found through the Sloan Digital Sky Survey project (Jedicke et al. 2004). Here we have an excellent target. Using numerical integration of asteroid orbits, Nesvorný et al. (2002) recently revealed a newborn group of asteroids named the Karin cluster group, which are thought to be the remnants of a recent breakup only 5.8 million years ago (Nesvorný et al. 2002). In this study, we observed the brightest asteroid 832 Karin (diameter of about 19 km and absolute magnitude of 11.18; Nesvorný & Bottke 2004) in this group in order to investigate whether the new asteroid really has a fresh and unreddened surface.

2. OBSERVATIONS AND DATA REDUCTIONS

A near-infrared spectroscopic observation of Karin was performed by the 8 m Subaru telescope with the Cooled Infrared Spectrograph and Camera for OHS (CISCO; Motohara et al. 2002) on 2003 September 14 (UT) (Table 1). In order to obtain a wide-range near-infrared spectrum, grisms named *zJ* (0.88–1.40 μm), *JH* (1.06–1.82 μm), and *wK* (1.85–2.51 μm) were used. The slit size was $108'' \times 0''.8$ in our observation, and a typical seeing size at the observation was about $0''.3$ in the *K* band. The integration time for Karin was 800 s for each grism, i.e., 2400 s for each setting ($zJ + JH + wK$). We put the asteroid on a slit at two different positions (A and B) to subtract sky background emissions by the (A-B) operation. The nodding angle was $20''$ for our observations. For the cancellation of telluric absorption features, a reference star (G2 V star HIP 3990) was observed just after the Karin observation. For the cross-check of the cancellation of telluric absorptions, other reference stars (A0 star SAO 165395 and A2 star SAO 165274) were observed during the Karin observation. The reference stars were also observed at the A and B positions.

We used the NOAO IRAF astronomical software package to reduce near-infrared spectra obtained by CISCO. First of all, dark subtraction and flat-fielding were applied for all frames. Then OH sky emission lines were used for the wavelength calibration. Karin's raw spectra were divided by the spectra of a reference star to derive the relative reflectance of Karin. Thus we can get a near-infrared reflectance spectrum of Karin. Finally, relative magnitudes were computed using aperture photometry. We used an aperture radius of about twice the FWHM, and sky subtraction was performed using a 5–10 pixel wide annulus around the asteroid or reference stars. Through these procedures, we obtained the magnitude of Karin: 13.64 at the *J* band, 13.48 at the *H* band, and 13.40 at the *K* band. We

---

[1] Department of Earth and Planetary Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; takanori@eps.s.u-tokyo.ac.jp.

[2] National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan.

[3] Gunma Astronomical Observatory, 6860-86 Nakayama, Takayama, Gunma 377-0702, Japan.

[4] Subaru Telescope, National Astronomical Observatory of Japan, 650 North A'ohoku Place, Hilo, HI 96720.

[5] School of Science, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan.

[6] Department of Astronomy, Bandung Institute of Technology, Bandung 40132, Indonesia.

[7] Lunar and Planetary Laboratory, University of Arizona, 1629 East University Boulevard, Tucson, AZ 85721.

TABLE 1
Observational Parameters

Object	UT Time	Total Integrations (s)	Air Mass	Grism
SAO 165395 (A0)	7:31	60	1.401–1.410	*zJ*
Karin (first set)	7:57	750	1.182–1.189	*zJ*
	8:13	800	1.172–1.176	*JH*
	8:30	800	1.168–1.169	*wK*
Karin (second set)	8:46	800	1.169–1.171	*zJ*
	9:02	800	1.175–1.179	*JH*
	9:18	800	1.187–1.195	*wK*
SAO 165395 (A0)	9:43	80	1.155	*wK*
	9:50	60	1.155–1.156	*JH*
	9:56	60	1.156–1.157	*zJ*
Karin (third set)	10:45	800	1.391–1.422	*zJ*
	11:15	800	1.543–1.588	*JH*
	11:39	800	1.718–1.783	*wK*
SAO 165274 (A2)	12:09	80	1.590–1.608	*zJ*
	12:15	80	1.623–1.642	*JH*
	12:21	80	1.665–1.686	*wK*
HIP 3990 (G2 V)	12:35	96	1.228–1.232	*wK*
	12:42	48	1.239–1.241	*JH*
	12:46	48	1.247–1.250	*zJ*

scaled the relative spectra to be consistent with each other by this photometry.

3. RESULTS

We observed Karin at 7:57–8:40 UT, 8:46–9:29 UT, and 10:45–11:50 UT. The synodic rotational period of Karin is 18.348 hr, which was derived from a light curve obtained by supporting observations (Yoshida et al. 2004; Fig. 1). In comparison with the light curve, rotational phases of Karin in our observation are 0.30–0.34 (*red region*, the first set), 0.35–0.38 (*green region*, the second set), and 0.45–0.50 (*blue region*, the third set). Figure 2 shows the relative reflectance spectra of Karin. Red, green, and blue spectra in Figure 2 are those of the first, second, and third observational sets, respectively. The difference in the air mass at the observations of Karin and the reference star was smaller than 0.1 throughout the first and the second sets. Since the range between 1.06 and 1.40 μm was observed by both *zJ* and *JH* bands, we separated the spectra *zJ* and *JH* in Figure 2 for each set of observation. Actually, we have six sets of spectra in this region. There is an obvious difference between the top two (*green and blue*) and the bottom (*red*) spectra. The near-infrared (0.9–1.4 μm) reflectance slope of the bottom spectra is twice as steep as that of the top spectra. We could derive the same difference of spectral slopes between the first set and the second (or the third) set using other reference stars (SAO 165395 and SAO 165274). In general, major color changes with rotation are very rarely observed on asteroids; for example, only a little difference in the gradients of spectra at different rotational phases was observed in Vesta (Gaffey 1997). The present color change of Karin would be the biggest color change ever observed with the rotational phase. The range in which the most significant spectral change was detected was observed by both *zJ* and *JH* bands. We confirmed that the spectral change was detected in both bands. In addition, a gradual change of the spectral slope is also confirmed through *zJ* (first)–*JH* (first)–*zJ* (second)–*JH* (second) data (Fig. 2). Moreover, we verified that the SAO 165395 spectra (*zJ*) were not changed before the first set and after the second set of Karin observation (Fig. 3). This would remove the possibility that the spectral change was caused by an instrumental or atmospheric (and hour angle) effect through the first and second sets of Karin observations.

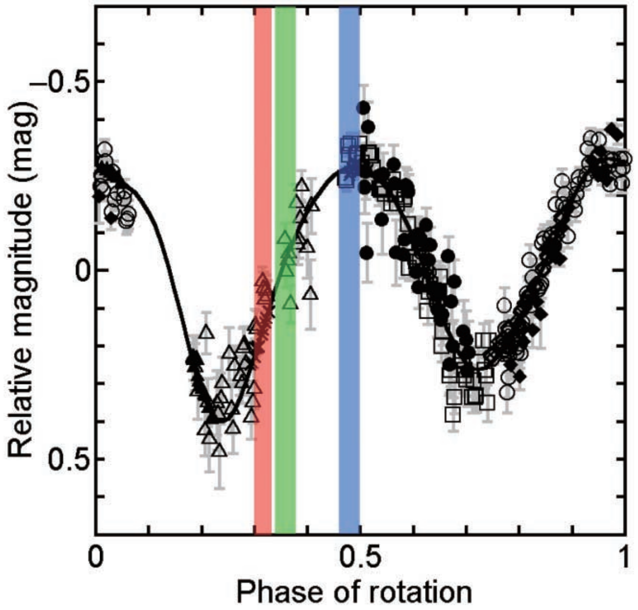

Fig. 1.—Light curve of 832 Karin. Based on data obtained by the 1.8 m VATT at the Vatican observatory at Mount Graham, Arizona, by the 1 m Schmidt telescope at the Kiso observatory, Japan, and by the 40 cm telescope at the Fukuoka University of Education (FEU), Japan. The filled circles, open circles, triangles, squares, upside-down triangles, diamonds, circled crosses, crosses, and circled plus signs correspond to the data of August 22 (at FEU), 23 (at FEU), September 3 (at FEU), 4 (at FEU), 5 (at Kiso), 26 (at VATT), 27 (at VATT), 28 (at VATT), and 29 (at VATT), respectively. Total observing duration is nine nights from 2003 August to September. The rotational period of this asteroid is 18.348 hr. The amplitude of the light curve is 0.7 mag at the zero solar phase angle. The zero phase of rotation is at 2004 July 31 0:00 UT. Assuming that Karin is an elongated ellipsoid with poles on the short axis and that observation direction is vertical to the pole direction, the axis ratio of the Karin ellipsoid (long to short) is about 2 from the magnitude amplitude 0.7. Our observation corresponds to the phase of rotations of red, green, and blue regions. This figure was adopted and modified from Yoshida et al. (2004).

The shape of 0.88–2.5 μm in the first set's spectrum with a steep slope at shorter wavelength is consistent with an S-type object. We identified which S subclass of the classification scheme (Gaffey et al. 1993; Cloutis et al. 1986) can best describe the Karin spectrum. In this classification, the S class is divided into seven subclasses. Since the first set's spectrum of Karin has the peak position of a 1 μm band shorter than 1.0 μm and has an apparent 2 μm band, it is placed among the range of S(III), S(IV), and S(V) classes. Figure 4 shows the normalized reflectance spectra of Karin (the first set and the last set) along with those of the S(IV)-type asteroid 584 Semiramis (Bell 2002) and L6 ordinary chondrite Paranaiba (Pieters 2000). The first set's spectrum of Karin matches well the spectrum of the S(IV) class asteroid. In contrast, the last set's spectrum (blue) of Karin, which has a relatively gentle slope at the wavelength shorter than 1.6 μm, matches (within noise of our spectrum) a typical normalized spectrum of an L6 ordinary chondrite. It is also close to the normalized spectra of some Q-type asteroids. The first set seems to be the reddened spectrum of the last set by space weathering. Laboratory simulations of space weathering also showed relatively intense reddening at wavelengths shorter than 1.6 μm (Sasaki et al. 2001; Yamada et al. 1999).

4. OBSERVATIONS AT VISIBLE WAVELENGTH

In the same season but on different nights (2003 September 26–29), Yoshida et al. (2004) performed a multispectral (*B*, *V*,

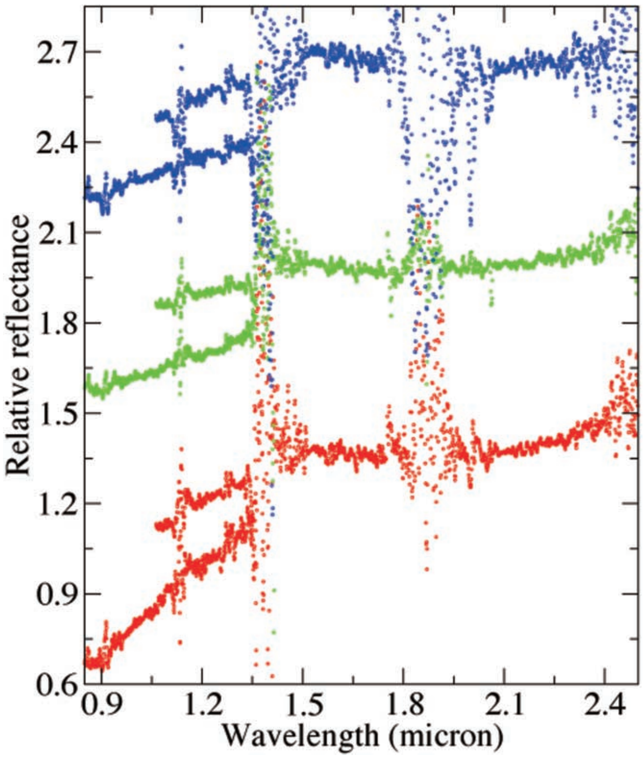

FIG. 2.—Relative spectra of 832 Karin. *Bottom*: Spectrum relative to the first set of the night; *middle*: that relative to the second set; *top*: that relative to the last set. Spectral data are smoothed by a running average of 5 pixels, and top and bottom spectra are vertically shifted by 0.2 for clarity. In our observation, the range between 1.06 and 1.40 μm was observed by both *zJ* and *JH* bands. The spectra *zJ* and *JH* for each set of observations are separated. Actually, we show six sets of spectra in this figure.

R, and I bands) Karin observation using the Mount Graham 1.8 m telescope at the Vatican observatory. Their visible observations of Karin also suggested that the surface at an earlier rotational phase (<0.5) is weathered compared with that at latter phases (>0.5; Fig. 5). Their results are consistent with our observation. Especially in Figure 5, the high $V - I$ magnitude (thus darker at V) at the rotational phase of 0.2 can be explained by a relatively matured (dark and red) visible spectrum. Moreover, a gradual increase in $B - V$ magnitude at a phase less than 0.5 is compatible with the change of weathering degree: laboratory simulation of space weathering suggested that weathered reflectance has a smaller $B - V$ than unweathered reflectance (Sasaki et al. 2001). Changes of relative magnitudes from our observation ($J - H$ and $J - K$) are also shown in Figure 5. Larger $J - H$ and $J - K$ at phase 0.3 (than those at later phase) correspond to weathered and reddened spectra. Thus, the spectral changes according to the rotational phase due to space weathering were detected in both the visible and the infrared observations.

5. DISCUSSIONS

Our result indicates that Karin's surface is inhomogeneous for each rotational phase, which reflects the difference of surface composition or the degree of space weathering between the first and other sets. In the former case, Karin's parent body was partially differentiated, while in the latter case, Karin has fresh and mature surfaces, and we have observed these two faces in one night. However, the aforementioned spectral similarity between the first set's spectrum of Karin and the S-type asteroid is in favor of the latter space weathering idea. Hence, we can conclude that the differences of Karin's spectra would reflect the difference of the degree of space weathering. At the impact fragmentation forming the Karin cluster group, Karin, which was one of the large fragments, could keep the weathered original surface of the parent body, although we cannot eliminate the possibility that Karin could be the fragment of a differentiated parent body and thus would have variable surface compositions. The mature and fresh surfaces' spectra in one body strongly stand up for the idea that S-type asteroids are parent bodies of ordinary chondrites (Chapman 1996). The presence of fresh surface on Karin is evidence that the space weathering should not proceed in a duration as short as 5.8 million years.

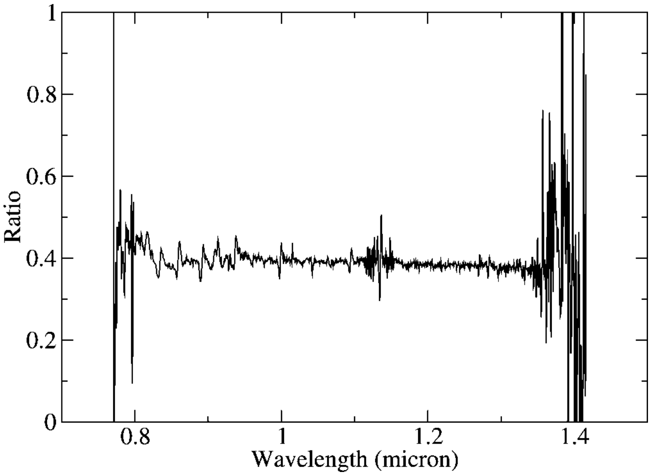

FIG. 3.—Ratio of two spectra of the reference star SAO 165395; *zJ* spectrum observed before the first set of Karin over that after the second set. The difference of absolute value between these spectra just reflects the difference of air mass and the difference of exposure time for the frame (10 s for the former set and 5 s for the latter set).

Let us reflect on the spectral change of Karin according to rotational phase. Around the rotational phase of 0.35, which is the boundary between the first and second sets, a rapid shift in the degree of space weathering is observed. As the cross

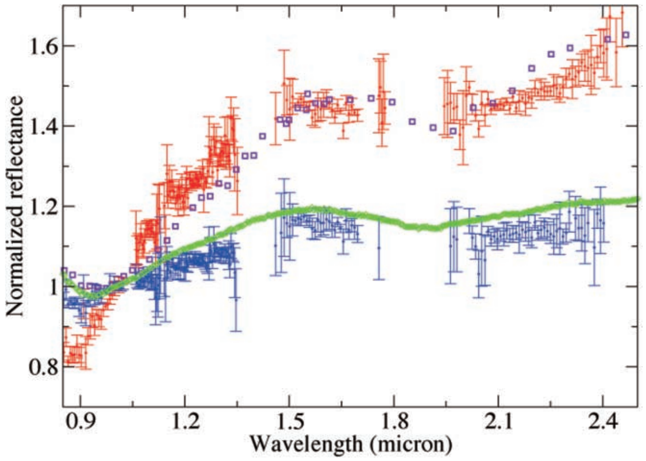

FIG. 4.—Reflectance spectra of 832 Karin (first set: *red circles*; last set: *blue circles*) along with the spectra of S(IV)-type asteroid 584 Semiramis (*violet squares*) and L6 ordinary chondrite Paranaiba (*green diamonds*) normalized to the unity at 1.0 μm. The data points corresponding to the mean values for every 10 pixels are plotted with their error bars of standard deviation. The data are removed in the wavelength range where the telluric absorptions were strong and the error bars are large. The data for asteroid Semiramis are from the SBN Data Set 52 Color Catalog, and the data for chondrite Paranaiba are from the RELAB Public Spectroscopy Database.

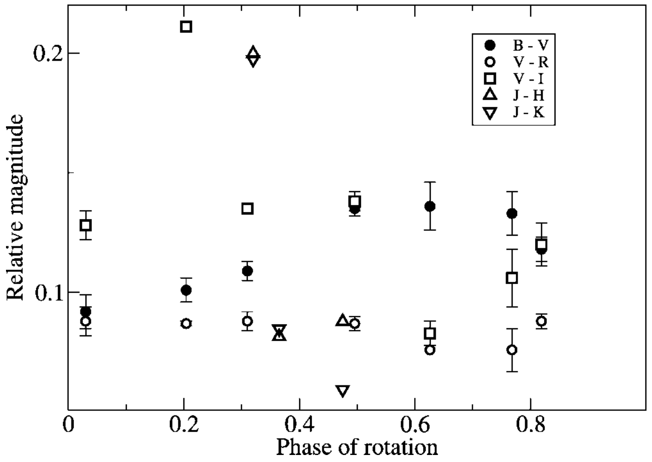

FIG. 5.—Color variation on Karin's surface. The filled circles, open circles, squares, triangles, and upside-down triangles denote the $B-V$, $V-R$, $V-I$, $J-H$, and $J-K$ colors, respectively. Data at visible wavelength (B, V, R, and I bands) are taken over four nights between 2003 September 26 and 29 using VATT, which is the 1.8 m telescope at the Vatican observatory (Mount Graham, Arizona). Filter characteristics at VATT are as follows: B band: center of the wavelength (CWL) $= 0.435932$ μm, FWHM $= 0.102679$ μm; V band: CWL $= 0.539484$ μm, FWHM $= 0.087738$ μm; R band: CWL $= 0.633814$ μm, FWHM $= 0.118635$ μm; and I band: CWL $= 0.810487$ μm, FWHM $= 0.162378$ μm. Data at the infrared wavelength (J, H, and K bands) are from our observation. These magnitude data were transformed from the spectral data at the J band (1.12 μm), H band (1.64 μm), and K band (2.13 μm). This figure was adopted and modified from Yoshida et al. (2004).

section area of Karin increases (Karin being brighter), the matured redder surface is replaced by an immature fresh surface. More reddened spectra could be observed at a phase earlier than 0.3, and the spectrum of our first set of Karin could be averaged data of the unreddened spectrum and the much more reddened spectrum. The light curve in Figure 1 has double peaks of magnitude (where the phases are around 0.2 and 0.7, respectively), which have too big a luminous intensity amplitude to be explained by albedo variation. The double peaks may indicate that Karin has an elongated-shaped body, and a small difference between the magnitudes at 0.2 and 0.7 could tentatively imply that the surface around 0.2 is mature and darkened by space weathering while the surface around 0.7 is fresh, although the shape difference might be more responsible for this peak height difference.

We would like to propose as one speculative possibility that the change of the space weathering degree on Karin's surface could be explained if Karin were one of the cone-shaped fragments at low-velocity impact forming the Karin family. Impact disruption experiments suggest that in the low-velocity impact regime ($v \leq 1$ km s^{-1}), the target is shattered into cone-shaped fragments pointing toward the impact point (Fujiwara et al. 1989). Indeed, the impact that formed the Karin group could be low-velocity because the relative velocity between celestial bodies would be low in the main asteroid belt. In this case, the base of the cone is mature surface–darkened by space weathering, and it would be observed at a rotational phase of 0.2.

We thank M. Yuasa for the comments on celestial mechanics on the newborn asteroid family. We thank S. Sawabe, M. Haji, R. Saito, M. Hirai, and Y. Sato for visible observation data of Karin to derive the light curve, and S. Hasegawa for useful suggestions about S-type asteroids' spectra. F. Y. and T. I. thank M. Nelson, G. Consolmagno, S. Tegler, and T. Gehrels for the observing use of the Vatican Advanced Technology Telescope (VATT). We also thank J. F. Bell for asteroid Semiramis data and C. M. Pieters for meteorite Paranaiba data. We thank C. R. Chapman for his constructive comments, which led us to greatly improve this Letter. We thank the anonymous reviewer for constructive reviews.

REFERENCES

Bell, J. F., III. 2002, SBN Data Set 52 Color Catalog, http://pdssbn.astro.umd.edu
Bell, J. F., III, et al. 2002, Icarus, 155, 119
Binzel, R. P., Bus, S. J., Burbine, T. H., & Sunshine, J. M. 1996, Science, 273, 946
Binzel, R. P., Lupishko, D. F., Martino, M. D., Whiteley, R. J., & Hahn, G. J. 2003, in Asteroids III, ed. W. F. Bottke et al. (Tucson: Univ. Arizona Press), 255
Burbine, T. H., & Binzel, R. P. 2002, Icarus, 159, 468
Burbine, T. H., McCoy, T. J., Meibom, A., Gladman, B., & Keil, K. 2003, in Asteroids III, ed. W. F. Bottke et al. (Tucson: Univ. Arizona Press), 653
Chapman, C. R. 1996, Meteoritics Planet. Sci., 31, 699
Chapman, C. R., & Salisbury, J. W. 1973, Icarus, 19, 507
Clark, B. E., Hapke, B., Pieters, C. M., & Britt, D. 2003, in Asteroids III, ed. W. F. Bottke et al. (Tucson: Univ. Arizona Press), 585
Clark, B. E., et al. 2001, Meteoritics Planet. Sci., 36, 1617
Cloutis, E. A., Gaffey, M. J., Jackowski, T. L., & Reed, K. L. 1986, J. Geophys. Res., 91, 11641
Fujiwara, A., Cerroni, P., Davis, D., Ryan, E., Di Martino, M., Holsapple, K., & Housen, K. 1989, in Asteroids II, ed. R. P. Binzel et al. (Tucson: Univ. Arizona Press), 240
Gaffey, M. J. 1997, Icarus, 127, 130
Gaffey, M. J., Bell, J. F., Brown, R. H., Burbine, T. H., Piatek, J. L., Reed, K. L., & Chaky, D. A. 1993, Icarus, 106, 573
Hapke, B. 2001, J. Geophys. Res., 106, 10039
Hapke, B., Cassidy, W., & Wells, E. 1975, Moon, 13, 339
Jedicke, R., Nesvorný, D., Whiteley, R., Ivezić, Z., & Jurić, M. 2004, Nature, 429, 275
McFadden, L. A., Wellnitz, D. D., Schnaubelt, M., Gaffey, M. J., Bell, J. F., III, Izenberg, N., Murchie, S., & Chapman, C. R. 2001, Meteoritics Planet. Sci., 36, 1711
Motohara, K., et al. 2002, PASJ, 54, 315
Nesvorný, D., & Bottke, W. F. 2004, Icarus, 170, 324
Nesvorný, D., Bottke, W. F., Jr., Dones, L., & Levison, H. F. 2002, Nature, 417, 720
Pieters, C. M. 2000, RELAB Public Spectroscopy Database, http://www.planetary.brown.edu/relab
Pieters, C. M., et al. 2000, Meteoritics Planet. Sci., 35, 1101
Sasaki, S., Nakamura, K., Hamabe, Y., Kurahashi, E., & Hiroi, T. 2001, Nature, 410, 555
Wetherill, G. W., & Chapman, C. R. 1988, in Meteorites and the Early Solar System, ed. J. F. Kerridge & M. S. Matthews (Tucson: Univ. Arizona Press), 35
Yamada, M., et al. 1999, Earth Planets Space, 51, 1255
Yoshida, F., et al. 2004, PASJ, submitted