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BASALTIC ASTEROIDS: A NEW LOOK ON THE DIFFERENTIATION PROCESS IN THE MAIN BELT

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RESUMEN

A pesar de que el asteroide (4) Vesta es el único objeto grande en el Cinturón Principal que muestra una costra basáltica prácticamente intacta, un número considerable y en aumento de pequeños asteroides con composición superficial similar se ha descubierto en los últimos años. Todos estos objetos, clasificados como tipo-V en diversas taxonomías, tienen una composición superficial similar a los meteoritos Howardites, Eucrites y Diogenites, conocidos como HED. En este trabajo hago una revisión de los nuevos resultados sobre los asteroides basálticos y los meteoritos HED, y discuto como estos resultados dan fuerza a la idea de que la diferenciación fué bastante común en las etapas tempranas de la formación del Cinturón Principal, en contraste con el escenario clásico que considera la formación de de un sólo objeto grande diferenciado, (4) Vesta.

ABSTRACT

Although asteroid (4) Vesta is the only large object in the Main Belt which shows an almost intact basaltic crust, an increasingly large number of small asteroids with a similar surface composition have been discovered in the last years. All these objects, classified as V-type in the diverse taxonomies, have a surface composition similar to that of the Howardites, Eucrites, and Diogenites meteorites, known as HED. In this paper we review the new findings on basaltic asteroids, and on the HED meteorites, and discuss how these reinforce the idea that differentiation was quite common in the Main Belt early stages of formation, in contrast to the classical scenario which considers the formation of just one large differentiated body, (4) Vesta.

Key Words: minor planets, asteroids — solar system: formation — techniques: spectroscopic

1. INTRODUCTION: THE CLASSICAL VIEW

Basaltic material is reckoned as the result of an extensive geochemical differentiation. By this process small chondritic material accrete in larger bodies. Subsequently, partial fusion of this material makes, first, the heavier liquid (Fe-Ni-S) migrate to the center and, second, the lighter silicated liquid (SiO_2) migrate to the surface. The final result of such a process is a body with a dense metallic core, a mantle of lighter olivine-rich material and an even lighter basaltic surface. According to our current understanding this should occur only on large-size objects due to the heat needed to melt the chondritic material (Ruzicka et al. 1997).

(4) Vesta, a 400 km diameter object in the inner Main Belt, is the unique known large asteroid showing an almost intact basaltic crust. This was first inferred by McCord et al. (1970) and was confirmed in all subsequent works (Larson & Fink 1975; McFadden et al. 1977; Binzel et al. 1997; Gaffey 1997). The spectrum of this asteroid presents two deep absorption bands, at $0.92 - 0.94\ \mu$m and at $2.0\ \mu$m, which are representative of basaltic material. Its composition is also similar to that of *basaltic achondrite* meteorites, specifically the Howardites, Eucrites, and Diogenites, collectively known as the HED suite of meteorites. Due to this similarity, (4) Vesta has been considered the parent body of these meteorites (Drake 2001), despite the initial difficulties in identifying the transport mechanism. The discovery of small basaltic asteroids in near-Earth orbits (Cruikshank et al. 1991) led finally to what could be called the *classic scenario*.

The *classical scenario* is based on the hypothesis that there has been just one large asteroid which has achieved the size and conditions to undertake a complete differentiation and resurfacing: (4) Vesta. Great impacts subsequently excavated its surface, producing a swarm of small fragments. Part of them, were injected into resonances which pumped up their eccentricities, and were thus ejected due to close encounters with terrestrial planets. Most of these fragments fell directly into the Sun or escaped from the Solar System, but part of them remained in near-Earth orbits. Further collisions ejected fragments into Earth-colliding orbits, becoming the HED meteorites recovered on Earth (Drake 2001).

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This scenario is strengthen by diverse facts: the oxygen isotope data of the HED suite indicate an unique origin for these meteorites (Stolper 1977), a Vesta dynamical family has been identified (Williams 1989; Zappalá et al. 1990), the members of the family have a surface composition similar to Vesta (Binzel & Xu 1993), a large impact basin has been discovered on Vesta (Thomas et al. 1997), Yarkovsky effect plays an important role in slowly drifting small asteroids into the resonances (Farinella & Vokrouhlický 1999), and, last but not least, the mean motion and secular resonances can indeed transport fragments to near-Earth orbits (Marzari et al. 1996; Migliorini et al. 1997).

2. PROBLEMS WITH THE *CLASSICAL SCENARIO*

Although supported by diverse observational and theoretical works, the *classical scenario* has always suffered from a fundamental questioning about why just (4) Vesta would have been able to undertake a complete differentiation and resurfacing. More recently, diverse observational findings have further challenged the above scenario. In what follows we will briefly review the main problems raised so far.

2.1. *Vesta × Ceres*

As described above, the differentiation of (4) Vesta was the result of an intense heating process which occured in the earliest phases of Solar System formation. Radio-isotope chronology from the HED meteorites suggests that their parent body differentiated in about 3 million years, much earlier than, for example Mars, which differentiated for nearly 15 million years (Kleine et al. 2002). This is directly linked to the early cessation of accretion in the asteroid belt, assumed to be due to the rapid growth of Jupiter which stirred up the velocities in the nearby region. Therefore, only those objects which achieved to grow to a sufficient size were able to start the differentiation process, due to the decay of short-lived radionuclide, in particular, ^{26}Al, as originally proposed by Urey (1955). It is important to note, however, that (1) Ceres, the first discovered asteroid, has a mean diameter of 974 km, nearly the double of Vesta's, although a much lower density (2100 kg m^{-3}, against 4000 kg m^{-3} of Vesta). Moreover, while the former has a very primitive surface and water-bearing minerals, the latter is a dry, differentiated body whose exterior has been resurfaced by basaltic lava flows.

As a further complication, (1) Ceres and (4) Vesta lie nearby in the Main Belt, at mean distances from the Sun of 2.77 AU and 2.34 AU, respectively. This difference in location cannot possibly be responsible for very distinct compositions in the primordial disk, unless one of the two bodies did not accreted at its present location. This seems very improbable, from a dynamical point of view. Therefore, we remain with the fact that these very different objects were apparently formed relatively close together and that (1) Ceres was able to accrete wet and remain cool (Russel et al. 2004).

Recently McCord & Sotin (2005) have constructed a thermal evolution model for (1) Ceres that results in a rocky core covered with an approximately 100 km thick water and ice mantle. However, they find that (1) Ceres' existence and evolution depend critically on it containing water at formation, and this depends strongly on the combination of when it accreted and the amount of ^{26}Al present in the pre-Ceres 1-km-sized objects; slightly more ^{26}Al or earlier accretion produces a dry Vesta-like object.

2.2. *V-type asteroids in the Vesta region*

In recent taxonomies, asteroids showing a spectrum similar to that of (4) Vesta have been classified as V-type (Tholen & Barucci 1989; Bus & Binzel 2002). The identification of many V-type asteroids located in the region near (4) Vesta, but far away from the limits of the dynamical family (Xu et al. 1995; Burbine et al. 2001; Florczak et al. 2002; Alvarez-Candal et al. 2006), raised the question whether they come from another differentiated parent body.

This point has been explored by Carruba et al. (2005), showing that the interplay of the Yarkovsky effect and nonlinear secular resonances can transport bodies of intermediate size far from the family, but not the small ones. This was somewhat confirmed by the identification of a complex structure of mean motion, as well as linear and non-linear, resonances in the inner main belt which must have played a major role in shaping the distribution of asteroids in the region (Alvarez-Candal et al. 2006). Extensive numerical simulations of the dynamical evolution of Vesta's ejected fragments over timescales comparable to the family age, have shown that a relatively large fraction of the original Vesta family members may have evolved out the family borders (Nesvorný et al. 2008). The results indicate that although the distribution of asteroids with semi major axis $a < 2.3$ AU presents a good match with the observed one, this is not the case for the low inclination objects for which a different origin must be assumed.

It is noteworthy that the V-type asteroids present spectra with a redder slope than Vesta's itself. This has been interpreted as a space weathering effect (Hiroi et al. 1995; Hiroi & Pieters 1998; Pieters et al. 2000), probably associated to the size of the particles in the regolith layer (Burbine et al. 2001). Another problem, is the presence of small absorption features detected on (4) Vesta but not on all the V-type (Vilas et al. 2000; Cochran et al. 2004; Shestopalov et al. 2007). If all the V-type asteroids come from (4) Vesta, then the apparently different groups might be explained by two large impacts on (4) Vesta (Marzari et al. 1996) or a single energetic impact, which ejected fragments from the inner layers. This is consistent with the fact that the crust of the HED's parent body is associated with two different mineralogies: a Diogenite lower crust and an Eucrite upper crust (Takeda 1997). Also hydrocode models, simulating the fragmentation of (4) Vesta, indicate that the material from both the crust and the mantle may actually be ejected (Asphaug 1997). Indeed, it has been confirmed that at least one V-type asteroid, (1929) Kollaa, has compositional characteristics compatible with cumulate Eucrite, suggesting that it has been formed deep inside the eucritic crust of Vesta (Kelley et al. 2003). Moreover, the mineralogical study of a large sample of V-type indicated the presence of distinct mineralogies which, however, could not be linked to the fact of an asteroid belonging or not to the Vesta family (Duffard et al. 2004).

2.3. *(1459) Magnya*

The discovery of a small basaltic asteroid in the outer Main Belt, (1459) Magnya, raised a new possible source for the V-type NEAs and the HED meteorites, as well as new problems (Lazzaro et al. 2000). First of all, since the presence of a basaltic surface implies in an extensive geochemical differentiation and resurfacing this should not occur on small-size objects. This suggest that either (1459) Magnya is a fragment of (4) Vesta or it is a remnant of the catastrophic disruption of another large basaltic object. To be a fragment ejected from (4) Vesta to its present location the implied ejection velocity is in excess of 5 km s^{-} (Binzel & Xu 1993). To be a fragment of another catastrophic event an associated family is missing. Although this could be due to the fact that the region around (1459) Magnya is filled with hight-order resonances, which lead to a slow chaotic diffusion of the objects and could disperse a family in a short timescale after its formation (Lazzaro et al. 2000; Michtchenko et al. 2002).

Detailed near-infrared spectral observations of (1459) Magnya confirmed the basaltic composition of the object but its comparison with (4) Vesta's spectral parameters showed discordant pyroxene chemistries (Hardersen et al. 2004). This result strongly suggests that (1459) Magnya originated from a parent body other that (4) Vesta and its progenitor formed in a more chemically reduced region of the solar nebula within the asteroid belt. Although the presence of some other small basaltic objects in this region has been suggested (Roig & Gil-Hutton 2006), no other V-type asteroids have yet been confirmed (Duffard & Roig 2007; Moskovitz et al. 2007).

2.4. *(21238) 1995 WV7*

The recent identification of (21238) 1995WV7 as a V-type asteroid introduced the possibility that a second basaltic asteroid, not connected with the Vesta family, exists (Binzel et al. 2006; Hammergren et al. 2007). It is noteworthy that (21238) 1995WV7 lies on the other side of the 3 : 1 mean motion resonance, with respect to (4) Vesta, and according to our current understanding it would be very unlikely that a fragment survived through the passage of such a powerful resonance. Therefore, Carruba et al. (2007) propose that the origin of this and other, yet undiscovered, basaltic asteroids in the middle belt, could be (15) Eunomia. This asteroid appears to be partially differentiated, showing a mineralogical composition in part of its surface that might indicate the previous existence of a basaltic crust (Reed et al. 1997; Nauthues et al. 2005). Several collisions might have made (15) Eunomia lose its basaltic crust almost completely, and disperse its fragments in the middle belt over the age of the Solar System.

A different scenario for the origin of this and another middle belt asteroid, (40521) 1999RL95, is being proposed by Roig et al. (2008): (4) Vesta. This conclusion is reached by combining N-body numerical simulation of orbital evolution and Monte Carlo models, and computing the probability that an asteroid, of a given diameter, evolves from the Vesta family and crosses over the 3 : 1 mean motion resonance, reaching a stable orbit in the middle belt. The results indicate that about 10 to 30% of the V-type bodies with a diameter larger than one kilometer may come from the Vesta family while the remaining 70–90% must have a different origin. In particular, asteroid (21238) 1995WV7, with a diameter of about 5 km, could not have come from (4) Vesta.

2.5. *HED meteorites*

The oxygen isotopic compositions of meteorites provide a powerful tool to assign their parent body.

In particular, the reported ^{16}O, ^{17}O and ^{18}O abundances of Howardites, Eucrites, and Diogenites are consistent with the concept of a single parent body for these three types of meteorites (Stolper 1977). Moreover, these meteorites show evidence that some primitive planetary embryos differentiated into a metallic core and partially molten silicate mantle within the first 10 million years of Solar System history. However, whether such early planetary bodies were in a relatively primitive state with heterogeneities inherited from accretion (Righter & Drake 1997; Mittlefeldt et al. 1998) or well-mixed as a result of a stage of a magma ocean is still unclear. Therefore, it was widely assumed that (4) Vesta, the unique large differentiated body in the asteroid belt, was the "parent body" of the HED.

The first problem with the above scenario came with the discovery that the meteorite Northwest Africa 011, despite its texture and mineralogy similar to some basaltic Eucrites, shows an ^{16}O-rich isotopic composition which suggests that this meteorite is genetically unrelated to the other HED meteorites (Yamaguchi et al. 2002) . More recently, Wiechert et al. (2004) have reported more evidence of oxygen isotopic heterogeneity among HED meteorites indicating incompletely mixed sources. New high-precision oxygen isotope measurements of a large sample of HED meteorites provide evidence that although most of them derived from a common well-mixed pool, there are some that are inconsistent with an unique origin. In total, the meteorite collection could represent several dozen parent bodies, considering also the abundance of iron meteorites which should have been part of the nucleus of distinct differentiated bodies.

3. WHAT COULD BE WRONG WITH THE CLASSICAL MODEL?

Observing smaller and smaller objects, we are finding that there are several basaltic asteroids all around the Main Belt, mostly not associated to dynamical families. These findings are clearly in conflict with the *classical scenario* outlined above, in particular, its premiss on the existence of just one basaltic object. On the other hand, this implies that there is something wrong about our knowledge on the differentiation process, or the basaltic identification, or the collisional and dynamical evolution, or all of these at the same time! Let us discuss separately each one of these points.

3.1. *Differentiation process*

According to our current understanding, the differentiation process requires the accretion of an object of large size (Ruzicka et al. 1997). This because it needs to contain large amounts of ^{26}Al in order to produce the heat necessary to melt the chondritic primordial material. If an object is small, then it will contain too little ^{26}Al which will not be able to reach the temperature needed to melt the material. A small object not only will produce less heat but also it will radiate more rapidly than a large one. By this model, some of the primordial chondritic material would accrete to larger bodies while the rest would remain small. The larger ones would then differentiate and subsequent collisions would form fragments which are the small basaltic asteroids we observe.

As described in the previous section, this model has difficulties in justifying why (1) Ceres did not differentiated and why not all the small basaltic asteroids are related to a collisional family. There is still another problem with this scenario: the lack of olivine. By the differentiation model just described, the final result is a body with a metallic nucleus, a large mantle of olivine and a crust of pyroxene. However, in our meteorite collections we have samples of the nucleus and of the crust, but not from the mantle! The same occurs in the Main Belt, where we find a large number of metal-rich and silicate-rich asteroids but very few olivine-rich. If all the metal-rich asteroids were part of the nucleus of a disrupted differentiated asteroid, where has the olivine gone?

On the other hand, if the differentiation could occur on small bodies, then we would overcame the above problems. Let us suppose that we can indeed differentiate small bodies. This needs to occur in the very first stages of the formation, when the ^{26}Al was very abundant. Then some of the small differentiated objects would accrete in larger ones, maybe going through a second melting process, while others would remain in the size range of about 10 km. By this model it is possible to form many small differentiated asteroids at the same time that there is no need of much olivine, nor of families. Note that this changes completely the formation sequence of the asteroids: first forming differentiated objects and later on, when most of the ^{26}Al had already decayed, the chondritic ones. This revised scenario for the formation of meteorite parent bodies, originally proposed by Wilkening (1979), has just recently began to be more accepted, due to many important results derived from precise radiative dating (Kleine et al. 2004, 2005; Misawa et al. 2005; Weichert et al. 2004; Trieloff et al. 2003). All these works seem to indicate that the HED parent body formed *before* the H chondrite parent body although we still lack a complete understanding on the growth mechanisms and formation times of asteroids (Scott 2006).

3.2. *Taxonomic identification*

The problem of finding many small basaltic asteroids all around the Main Belt, and not related to any dynamical family, might also be due to an erroneous taxonomic identification. First of all it is important to note that, excluding (1459) Magnya, all other alleged V-type asteroids in the middle and outer belt are very faint (Binzel et al. 2006; Hammergren et al. 2007; Roig & Gil-Hutton 2006; Duffard & Roig 2008; Moskovitz et al. 2007). This implies that, although greater telescope facilities are being used, the noise in the spectra is quite important and can lead to a wrong taxonomic classification, in particular if based only on visible spectra. Note that in the most recent taxonomy (Bus & Binzel 2002) there are at least four classes with a deep 1 μm absorption band: V-, R-, O- and Q-type. The main difference among these is the reddeness of the spectra in the $0.4 - 0.75$ μm region and the position of the minimum of the absorption band. However, in the case of a visible spectra the noise is greater exactly in the $0.9 - 1.1$ μm region. Therefore, it is an hypothesis still to be tested if the alleged V-type asteroids in the middle and outer Main Belt do have basaltic surfaces.

3.3. *Collisional & dynamical evolution*

Last, but not least, our models on the collisional and dynamical evolution in the asteroid belt might also be wrong. Maybe, our dynamical models do not take into account some not yet identified force, or forces, that affect the mobility of objects. In this case, it might be possible that there exist mechanisms able to transport all the observed V-type from (4) Vesta to their current location.

It might also be the case that the assumed collisional evolution model for the Main Belt has problems. A clue to this is the fact that all the spectroscopically analyzed families present an homogeneous taxonomic classification (Cellino et al. 2002; Mothé-Diniz et al. 2005). It is true, however, that the disruption of a differentiated asteroid would produce an inhomogeneous (from a taxonomic point of view) dynamical family. In particular, we should find X-types, coming from the nucleus, A- and/or K-types from the mantle, and S-, V- and/or R-types from the crust. Up to the present just one family, Baptistina, seem to present such a mixture of taxonomic classes among its members (Alvarez-Candal et al. 2006), although this observational result is in conflict with a recent paper by Bottke et al. (2007) which postulates that Baptistina is a chondritic (undifferentiated) family.

4. CONCLUSIONS

As described above, many observations and studies have shown that the currently accepted model on the differentiation process and formation of basaltic objects in the Main Belt is inadequate to explain all the observed features. In particular, these new findings tend to invalidate our "classical scenario" with just one large differentiated body, and reinforce the idea that differentiation was quite common in the early stages of the Main Belt of asteroids. To conclude it is important to stress that, although in this paper we have stressed the much that we do not know, this is NOT a negative result, on the contrary, it is a very promising one for FURTHER work! We need to search for new models and, especially, with a *new look* able to bring together all the pieces of information of what seems to be a very intricate jigsaw puzzle.

REFERENCES

Alvarez-Candal, A., Lazzaro, D., & Michtchenko, T. 2006, Icarus, 158, 343

Asphaug, E. 1997, Meteoritics Planet. Sci, 32, 965

Binzel, R. P., Gaffey, M. J., Thomas, P. C., Zellner, B. H., Storns, A. D., & Wells, E. N. 1997, Icarus, 128, 93

Binzel, R. P., Masi, G., & Foglia, S. 2006, BAAS, 38, 627

Binzel, R. P., & Xu, S. 1993, Science, 260, 186

Bottke, W. F., Vokrouhlický, D., & Nesvorný, D. 2007, Nature, 449, 48

Burbine, T. H., et al. 2001, Meteoritics Planet. Sci. 36, 761

Bus, S. J., & Binzel, R. P. 2002, Icarus, 158, 146

Carruba, V., Michtchenko, T. A., & Lazzaro, D. 2007, A&A, 473, 967

Carruba, V., Michtchenko, T. A., Roig, F., Ferraz-Mello, S., & Nesvorný, D. 2005, A&A, 441, 819

Cellino, A., Bus, S. J., Doressoundiram, A., & Lazzaro, D. 2002, in Asteroids III, ed. W. F. Bottke, A. Cellino, P. Paolicchi, & R. P. Binzel (Tucson: Univ. Arizona Press), 633

Cochran, A. L., Vilas, F., Jarvis, K. S., & Kelley, M. S. 2004, Icarus, 167, 360

Cruikshank, D. P., Tholen, D. J., Hartmann, W. K., Bell, J. F., & Brown, R. H. 1991, Icarus, 89, 1

Drake, M. J. 2001, Meteoritics Planet. Sci., 36, 501

Duffard, R., Lazzaro, D., Licandro, J., De Sanctis, M. C., Capria, M. T., & Carvano, J. M. 2004, Icarus, 171, 120

Duffard, R., & Roig, V. 2008, in Asteroids, Comets, & Meteors, Paper #8154, ed. A. W. Harris Ê. Bowell (Houston: Lunar & Planetary Institute; astro-ph/0704.0230)

Farinella, P., & Vokrouhlický, D. 1999, Science, 283, 1507

Florczak, M., Lazzaro, D., & Duffard, R. 2002, Icarus, 159, 178
Gaffey, M. J. 1997, Icarus, 127, 130
Hammergren, M., Gyuk, G., & Puckett, A. 2007, BAAS, 38, 203
Hardersen, P. S., Gaffey, M. J., & Abell, P. A. 2004, Icarus, 167, 170
Hiroi, T., Binzel, R. P., Sunshine, J. M., Pieters, C. M., & Takeda, H. 1995, Icarus, 115, 374
Hiroi, T. C., & Pieters, C. M. 1998, in Antarctic Meteorite Research, ed. T. Hirasawa (Tokyo: Natl. Inst. Polar Research), 163
Kelley, M. S., Vilas, F., Gaffey, M. J., & Abell, A. P. 2003, Icarus, 165, 215
Kleine, T., Mezger, K., Münker, C., Palme, H., & Bischoff, A. 2004, Geochim. Cosmochim. Acta, 68, 2935
Kleine, T., Mezger, K., Palme, H., Scherer, E., & Münker, C. 2005, Geochim. Cosmochim. Acta, 69, 5805
Kleine, T., Münker, C., Mezger, K., & Palme, H. 2002, Nature, 418, 952
Larson, H. P., & Fink, U. 1975, Icarus, 26, 420
Lazzaro, D., et al. 2000, Science, 288, 2030
Marzari, F., Cellino, A., Davis, D. R., Farinella, P., Zappalà, V., & Vanzani, V. 1996, A&A, 316, 248
McCord, T. B., Adams, J. B., & Johnson, T. V. 1970, Science, 168, 1445
McCord, T. B., & Sotin, C. 2005, J. Geophys. Res., 110, E5, IDE05009
McFadden, L. A., McCord, T. B., & Pieters, C. 1977, Icarus, 31, 439
Michtchenko, T., Lazzaro, D., Ferraz-Mello, S., & Roig, F. 2002, Icarus, 158, 343
Migliorini, F., Morbidelli, A., Zappalà, V., Gladman, B., Bailey, M. E., & Cellino, A. 1997, Meteoritics Planet. Sci., 32, 903
Mittlefehldt, D. W., McCoy, T. J., Goodrich, C. A., & Kracher, A. 1998, in Rev. Mineralogy 36, Planetary Materials, ed. J. J. Papike (Chantilly: MSA), 4.1
Misawa, K., Yamaguchi, A., & Kaiden, H. 2005, Geochim. Cosmochim. Acta, 69, 5847
Moskovitz, N. A., Willman, M., Lawrence, S. J., Jedicke, R., Nesvorný, D., & Gaiados, E. J. 2007, Lunar Planet. Sci. Conf., 38, 1663
Mothé-Diniz, T., Roig, F., & Carvano, J. M. 2005, Icarus, 174, 54
Nauthues, A., Mottola, S., Kaasalainen, M., & Neukun, G. 2005, Icarus, 175, 452
Nesvorný, D., Roig, F., Gladman, B., Lazzaro, D., & Carruba, V. 2008, Icarus, 193, 95
Pieters, C. M., et al. 2000, Meteoritics Planet. Sci., 35, 1101
Reed, K. I., Gaffey, M. J., & Lebofsky, L. A. 1997, Icarus, 125, 446
Righter, K., & Drake, M. J. 1997, Meteoritics Planet. Sci., 32, 929
Roig, F., & Gil-Hutton, R. 2006, Icarus, 183, 411
Roig, F., Nesvorný, D., Gil-Hutton, R., & Lazzaro, D. 2008, Icarus, 194, 125
Russel, C. T., et al. 2004, Planet. Space Sci., 52, 465
Ruzicka, A., Snyder, G. A., & Taylor, I. A. 1997, Meteoritics Planet. Sci., 32, 825
Scott, E. R. D. 2006, Icarus, 185, 72
Shestopalov, D. I., McFadden, L. A., & Golubeva, L. F. 2007, Icarus, 187, 469
Stolper, E. 1977, Earth Planet. Sci. Lett., 42, 239
Takeda, H. 1997, Meteoritics Planet. Sci., 32, 841
Thomas, P. C., Binzel, R. P., Gaffey, M. J., Storrs, A. D., Wells, E. N., & Zellner, B. H. 1997, Science, 277, 1492
Tholen, D., & Barucci, M. A. 1989, in Asteroids II, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews (Tucson: Univ. Arizona Press), 298
Trieloff, M., et al. 2003, Nature, 422, 502
Urey, H. C. 1955, Proc. Natl. Acad. Sci., 41, 127
Vilas, F., Cochran, A. I., & Jarvis, K. S. 2000, Icarus, 147, 119
Wiechert, U. H., Halliday, A. N., Palme, H., & Rumble, D. 2004, Earth Planet. Sci. Lett., 221, 373
Wilkenin, L. L. 1979, in Asteroids, ed. T. Gehrels (Tucson: Univ. Arizona Press), 61
Williams, J. G. 1989, in Asteroids II, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews (Tucson: Univ. Arizona Press), 1034
Xu, S., Binzel, R. P., Burbine, T. H., & Bus, S. J. 1995, Icarus, 115, 1
Yamaguchi, A., et al. 2002, Science, 296, 334
Zappalá, V., Cellino, A., Farinella, P., & Knezevic, Z. 1990, AJ, 100, 2030