Planetary and Space Science 105 (2015) 60–64

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

The Hungaria population: A comparison between sub-groups

M. Cañada-Assandri [a,b,*], R. Gil-Hutton [a,b], A.O. Ribeiro [c]

[a] Complejo Astrónmico El Leoncito (CONICET), Av. España 1512 sur, J5402DSP. San Juan, Argentina
[b] Universidad Nacional de San Juan, Av. Ignacio de la Roza 590 oeste, J5402DCS. San Juan, Argentina
[c] Observatorio Nacional, Rua General José Cristino 77, Rio de Janeiro, 20921-400, Brazil.

ARTICLE INFO

Article history:
Received 20 May 2014
Received in revised form
5 November 2014
Accepted 6 November 2014
Available online 15 November 2014

Keywords:
Solar system
Asteroids
Albedo
Taxonomy

ABSTRACT

To investigate if the two sub-groups in proper inclination found in the Hungaria region by Milani et al. (2010) could be characterized by physical parameters of the objects, we analyze two surfaces properties of the asteroids in the zone: the taxonomical distribution, obtained from the SDSS-MOC4, and the albedo distribution, taken from the WISE data. Our analysis suggests that both sub-groups are different. The asteroids with $\sin i_p < 0.4$ exhibit a majority of X-types objects and an excess of high albedo objects. In contrast, the objects with $\sin i_p > 0.4$ show a taxonomical distribution dominated by S-types asteroids and an albedo distribution without high albedo excess. Based on these results we propose that the sub-group in high proper inclination and dominated by S-types could be the primordial population while the high albedo excess observed in the other sub-group could be the consequence of a contamination in this region with a medium-belt object(s) that filled the Hungaria region with fresh X-types after suffering a catastrophic collision.

1. Introduction

The Hungaria dynamical group is composed of high-inclination asteroids orbiting at about 1.9 AU, just inside the inner edge of the asteroid main belt. They occupy a region with very complex dynamics surrounded by the 5:1 and 4:1 mean motion resonances with Jupiter, and the ν_5 and ν_{16} secular resonances (Scholl and Froeschlé, 1986). As a result of their location in the inner asteroid belt, the members of this group could be the sources of the asteroids that must replenish the short-living Mars-crosser population (Michel et al., 2000; Bottke et al., 2012). The Hungarias are currently clustered in the orbital element space due to long-term dynamical processes, but Williams (1989), Williams (1992) and Lamaitre (1994) identified some dynamical clustering in the proper elements space, possibly indicating the presence of families.

Historically it has been considered that the Hungaria region contained predominantly bright E-type objects because 6 of 13 E-type asteroids classified by Tholen (1984) belong to this region. This assumption has been questioned by the results obtained in spectroscopic and polarimetric surveys performed by Carvano et al. (2001) and Gil-Hutton et al. (2007), respectively, who concluded that this population is not as peculiar as it was previously assumed and has a taxonomical distribution consistent with the inner region of the belt. This result has been confirmed by Assandri and Gil-Hutton (2008) and Cañada-Assandri (2012) using a larger sample and the photometric data from the *Sloan Digital Sky Survey* (SDSS). These authors also found evidences of some dynamical mechanism acting that could bring to this region objects from the external and middle regions of the belt.

Recently Milani et al. (2010), obtained synthetic proper elements for the Hungarias and found that in a plot of proper semimajor axis against proper inclination it is possible to identify a dense core for proper inclinations $20^\circ \lesssim i_p \lesssim 23^\circ$. Around the dense core there is a less dense halo of objects with $\sin i_p > 0.4$ that allow to separate the population in two sub-groups, one with $\sin i_p < 0.4$ and the other with $\sin i_p > 0.4$. The reason for this separation is unclear because the region is dynamically complex, but could be the result of high-order secular resonances operating in the zone (see e.g., Fig. 11 in Milani et al., 2010). It is not clear if exists a relation between these two sub-groups or if they have a common origin and evolution, but the separation of both sub-groups in proper inclination is clear. These authors also found a dynamical family in the low proper inclination sub-group, which could be responsible for the dense core observed, but they can not completely separate it from the background because the large single cluster dominates the population. Previously, Warner et al. (2009) found in this region a family linked to the asteroid (434) Hungaria using pseudo-proper elements, but the inherent difficulties of calculating proper

* Corresponding author. Tel./fax: +54 264 4213653.
E-mail addresses: micanada03@casleo.gov.ar (M. Cañada-Assandri), rgilhutton@casleo.gov.ar (R. Gil-Hutton), anderson@on.br (A.O. Ribeiro).

http://dx.doi.org/10.1016/j.pss.2014.11.004
0032-0633/

elements for high inclination orbits have delayed any confirmation until the work of Milani et al. was published.

The existence of a family in one of these sub-groups is an important fact. A family of asteroids formed as a result of a collision implies a common origing of its members and then it must be expected certain similarity among their physical properties. Two properties that have a strong relation with the object composition are the taxonomy and the albedo. These physical properties are also related each other since objects of the same taxonomic type show similar polarimetric properties, and the polarimetric parameters are directly related with the albedo (Muinonen et al., 2002; Penttilä et al., 2005; Gil-Hutton et al., 2007). Then, if there is an asteroid family superimposed to a background population it is possible to distinguish the family studying the distribution of taxonomic types and/or albedo of its members and compare them with those found for the background. Milani et al. (2010) tried to separate background objects from family members using this method and colors from the SDSS, but they only obtain a statistical result about the distribution of the Hungaria objects in three broad taxonomical classes.

One possibility to do a comparison of the family members with the background objects is to analyze the properties of the asteroids in the two sub-groups separated in proper inclination. It is clear that the core at low proper inclination is dominated by objects belonging to the family, but those in the halo at high proper inclination could be representative of the background population. To perform this type of comparison between these two sub-groups is desirable to have databases as large as possible to maximize the possibility to find some of the objects of interest in it. Two convenient choices to obtain taxonomy and albedos are the last release of the *Sloan Digital Sky Survey* (SDSS) and the infrared catalog of the *Wide-field Infrared Survey Explorer* (WISE), respectively.

The SDSS has a sub-product called the *Moving Objects Catalog* (MOC), which in its fourth release provides five band photometry for 104,449 asteroids (Ivezić et al., 2001; Jurić et al., 2002). In order to analyze the surface composition of asteroids and to perform a taxonomic classification, multiband photometry is not as precise as spectroscopy, but the amount of data of the SDSS-MOC significantly contrast with the only $\sim$2300 asteroids observed by the major spectroscopic surveys presently available: the SMASS (Xu et al., 1995; Bus and Binzel, 2002b) and the S^3OS^2 (Lazzaro et al., 2004). Moreover, while these spectroscopic surveys reached an average absolute magnitude of H$\sim$11, the SDSS-MOC pushed this value to H$\sim$17, providing taxonomic information of a huge population of very small asteroids for which spectroscopic observations can only be assessed using very large telescopes.

On the other hand, WISE is a NASA Medium-class Explorer mission designed to survey the entire sky in four infrared wavelengths. A description of how the mission was organizing before launch and post launch development can be seen in Mainzer et al. (2005), Liu et al. (2008) and Wright et al. (2010), respectively.

In this paper we present a comparison of the taxonomic and albedo distributions for the two sub-groups of Hungaria objects at different proper inclination to test if there are differences in the surface properties of their respective members. In Section 2 we explain the searching mechanisms and data processing applied to each catalog to extract the data, in Section 3 we present the results, and in Section 4 the conclusions.

2. Methodology

The Hungaria asteroids were selected from the *Asteroids Dynamic Site* (AstDyS)[1] considering that these objects have a semimajor axis in the range 1.77 AU $< a <$ 2.06 AU and inclination between 16° and 30°. Nevertheless, to avoid objects strongly affected by Mars we discard of the sample the mars-crossing asteroids, i.e., objects with perihelion distance (q) less than 1.666 AU. Following these criteria we obtain 2693 numbered asteroids and 2652 multi-opposition objects, all of them with synthetic proper elements. This Hungarias sample was divided in two sub-groups taking into account their proper inclination obtaining 384 asteroids with $\sin i_p > 0.4$ (H_U sub-group) and 4961 objects with $\sin i_p < 0.4$ (H_D sub-group). The large difference in the number of objects in both sub-groups is due to the presence of the dense core of the Hungarias that belongs to the H_D sub-group.

The next step is to search for these objects in the SDSS and WISE data to obtain new samples for the H_U and H_D sub-groups that allow a taxonomic and albedo comparison between them. The SDSS photometry is based on the u, g, r, i, z system of filters (Fukugita et al., 1996; Stoughton et al., 2002), with band centers at $\lambda_u \sim 3540$ Å, $\lambda_g \sim 4770$ Å, $\lambda_r \sim 6230$ Å, $\lambda_i \sim 7630$ Å, and $\lambda_z \sim 9130$ Å, and bandwidths of $\Delta\lambda_u \sim 570$ Å, $\Delta\lambda_g \sim 1380$ Å, $\Delta\lambda_r \sim 1380$ Å, $\Delta\lambda_u \sim 1530$ Å, and $\Delta\lambda_u \sim 1350$ Å. The photometric observations are performed almost simultaneously in the five filters. Each entry in the MOC corresponds to a single observation of a moving object and provides the apparent magnitudes with their corresponding errors. The fourth release of the MOC has 471,569 entries linked with 104,449 know asteroids (Jurić et al., 2002).

In order to obtain a taxonomic classification we first extract the observations of all the Hungaria asteroids in the MOC catalog. Then we compute the reflectance flux at each band center using the observed colors corrected by the solar contribution. Finally, the taxonomic type of each object was found calculating the dissimilarities between the individual spectrum and mean spectra for the different taxonomic types obtained from Table III of Bus and Binzel (2002a). For a complete description of this procedure see Assandri and Gil-Hutton (2008). We prefer to use a dissimilarity method over a principal component analysis because both methods produce similar results, but with the dissimilarity method is possible to assign directly the object to a broad taxonomic class by comparison with a template. This procedure is easier than try to assign a taxonomic type to a region on a principal component plot.

The WISE satellite observed at 3.4 μm, 4.6 μm, 12 μm, and 22 μm, and provides observations of 157,000 objects including Near-Earth Objects, Main Belt Asteroids, Hungarias, comets, Hildas, Jupiter Trojans, Centaurs, and scattered disk objects (Mainzer et al., 2011). The thermal model used in WISE for the albedo determination is the “Near-Earth Asteroid Thermal Model” (NEATM), proposed by Harris (1998). The objects are modeled as spheres without rotation, with an emissivity of $\epsilon = 0.9$ and a magnitude-phase slope parameter of $G = 0.15$, while the errors of the parameters were obtained from the application of Monte Carlo methods. The effects produced by the object rotation is smoothed along the observation time interval of $\sim$36 h, but it is possible that slow rotators may exhibit bad adjustments. The WISE catalog provides absolute magnitude, diameter, geometric albedo, beaming parameter, fluxes, etc. of each observed body.

Mainzer et al. (2011) noted that WISE exhibits an anomalous concentration of high albedos objects ($p_v > 0.5$) in the region of Hungarias and inner main belt. This could be a consequence of the use of a wrong absolute magnitude (H) because WISE assumes a constant magnitude-phase slope parameter. This problem is perhaps exacerbated by the large phase angle that any object in the inner main belt can reach in comparison with other regions of the belt, producing a large error when the computation process extrapolates the magnitude to zero phase angle. Thus, to avoid contaminating the samples with spurious values we only take into account albedo less than $p_v = 0.5$, which is slightly higher than the highest

[1] AstDyS website: http://hamilton.dm.unipi.it/cgi-bin/astdys/.

albedo known for the Hungarias ($p_v = 0.4552$ for the asteroid (5641) McCleese).

3. Results

From the SDSS-MOC4 we obtain 109 observations of 71 objects belonging to the H_U group, and 670 observations of 540 asteroids from the H_D group. Then, using the dissimilarity method we determined the taxonomic type for 66 and 513 asteroids of each sub-group, respectively, leaving 5 and 27 objects without classification because the photometric data provided by the catalog result in a dissimilarity too large for a trusted taxonomic classification.

In spite of that it is possible to use this method to assign each asteroid in our sample to anyone of the 26 taxonomic types proposed by Bus and Binzel, it is advisable to group related taxonomic types in a broader class to circumvent the limitations of a few band photometry. Then, we propose five classes to classify the asteroids in our sample: a broad X-class (including X, Xe, Xc and Xk types), a broad D-class (including D, L, Ld and T types), a broad C-class (including C, Cb, Cg, Ch, Cgh and B types), a broad S-class (including S, Sk, Sq, Sl, Sa, Sr, A, K and R types) and a broad O-class (including O, Q and V classes). The number of objects in each one of these broad classes are 13, 7, 5, 36, and 5 objects, respectively, for the H_U group, and 331, 0, 151, 22 and 9, respectively, for the H_D group.

The taxonomic distributions obtained for both samples are shown in Table 1, where it is possible to find that they have remarkable differences. The sample of the H_D sub-group is dominated by X-class objects, while the asteroids in the sample of the H_U sub-group are mainly S-class. Then, in a first approximation, the taxonomic distributions of both samples would be very different. The presence of C-class objects in both samples is in agreement with the results obtained by Carvano et al. (2001) and Gil-Hutton et al. (2007) and could be indicating that there is some dynamical mechanism that allow the transference of objects from the external regions of the main belt to the Hungaria zone (Cañada-Assandri, 2012). However, in spite of that Assandri and Gil-Hutton (2008) shown that the SDSS colors can distinguish very well between C- and X-types it is not possible to rule out a misclassification of a small number of X-class objects as C-types, but in any case both samples are dominated by objects with different taxonomy.

It is possible to find if the H_U and H_D sub-group samples obtained from the SDSS are testing objects of similar bright in both sub-groups applying a Kolmogorov–Smirnov test to a cumulative probability distribution of the absolute magnitudes taken from the JPL database. The test confirms with a significance level of 95% that both samples are similar, so it is reasonable to assume that the differences in the taxonomic distributions indicate a true difference in the surface properties of the objects in each sample.

In order to better evaluate the result obtained with the taxonomy, we extract albedos for the Hungarias from the WISE catalog. We identified 156 numbered asteroids and 9 multi-opposition objects with albedo and diameters well established, 82 of them in the H_U sub-group and the other 83 objects in the H_D sub-group.

Table 1
Comparison of the taxonomic distributions for the H_U and H_D samples.

Class	H_U (%)	H_D (%)
X	19.7	64.5
D	10.6	0.0
C	7.6	29.5
S	54.6	4.3
O	7.5	1.7

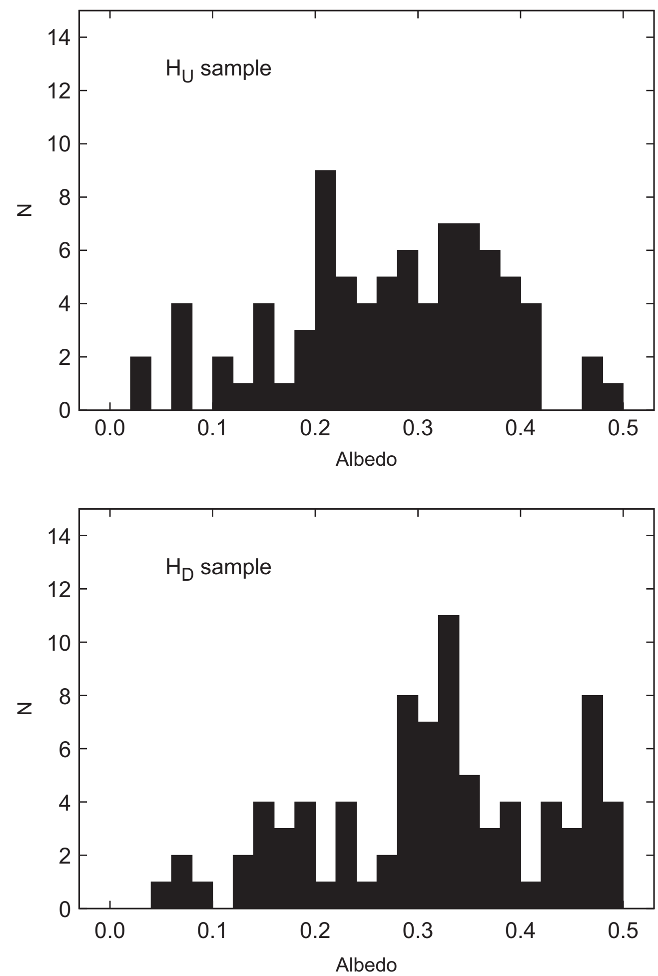

Fig. 1. Albedo distribution of the samples: the H_U sub-group sample is at the top and that for the H_D sub-group sample at the bottom.

The albedo histograms for the samples of the H_U and H_D sub-groups are shown in Fig. 1. The comparison of these two distributions shows that the sample for the H_U sub-group presents a concentration of albedos between 0.20 and 0.40 with very few values outside this range, while the sample for the H_D sub-group shows three different groupings for $p_v \lesssim 0.20$, $0.25 \lesssim p_v \lesssim 0.40$, and $p_v \gtrsim 0.40$. It is possible to test if the albedo distributions of the H_U and H_D sub-group samples are statistically different applying a Kolmogorov–Smirnov test. The test confirms with a significance level of 95% that the albedo distributions are different, so it is reasonable to assume that those differences are the result of the different surface properties of the asteroids in the samples.

It is possible to find if the H_U and H_D sub-group samples obtained from the WISE catalog are testing objects of similar bright in both sub-groups applying a Kolmogorov–Smirnov test to a cumulative probability distribution of the absolute magnitudes taken from the JPL database. The test confirms with a significance level of 95% that both samples are similar, so it is reasonable to assume that the differences in the albedo distributions indicate a true difference in the surface properties of the objects in each sample.

As indicated above, the H_U sub-group sample seems to have a taxonomy distribution dominated by objects belonging to the broad S-class. Since the mean albedo of the taxonomic types included in this broad class varies in the range $0.15 \lesssim p_v \lesssim 0.4$

(Stuart and Binzel, 2004; Thomas et al., 2011), it agrees very well with the albedo distribution obtained for the H_U sub-group sample. In the same way, the H_D sub-group sample seems to be taxonomically dominated by the broad X-class which includes taxonomic types with intermediate and high values for the mean albedo ($\gtrsim$0.25), which also agree with the albedo distribution obtained for this sample using the WISE data. In particular, the excess of objects in this sample with very high albedos ($\gtrsim$0.4) could be indicating the presence of asteroids that could be classified in the old E-type of Tholen (1984).

As it was previously commented, the presence of C-class objects in the Hungaria region was detected by Carvano et al. (2001) and Gil-Hutton et al. (2007), but these authors used observational techniques to find these objects which appear as anomalous for the inner main belt. If the SDSS colors are used to classify asteroids in certain taxonomic class which appear as anomalous types for this region of the belt, it is important to find objects that their assigned taxonomic type and albedo agree to obtain some confidence about the classification methods used. Unfortunately, there is only one object included in the SDSS and WISE samples: (5384) Changjiangcun was classified as a C-class object using SDSS colors and has a WISE albedo of $p_v = 0.069$ indicating in this case a correct identification. In spite of that this is a single case it gives us confidence about the classification method used.

4. Conclusions

With the aim to test if the separation in two sub-groups exhibit by the Hungaria population in proper elements space is based in physical grounds, we have analyzed this population using two different surface characteristics: the taxonomical distribution, obtained from the SDSS-MOC4, and the albedo distribution from the WISE data. The samples used to performing our analysis where obtained extracting the Hungaria asteroids with proper elements determined that are present in both catalogs.

Work samples were subjected to a statistical study that resulted, with 95% confidence, in which the absolute magnitude distributions in the samples are equal; therefore the samples are comparable. In this context, we analyze the observed differences and conclude that is possible to assume that the observed differences involve discrepancies in the surfaces characteristics analyzed.

The catalogs were also studied to assess the possibility of an observational bias in favor of larger objects. All catalogs samples exhibit asteroids between $13 \gtrsim H \gtrsim 17$ which leads to medium sized objects, reason why this possibility can be discarded.

The results present in this paper show that this separation could be real, since the sub-groups samples show differences in taxonomy and albedo. Taxonomically, the H_U sample is dominated by the broad S-class and this is in agreement with the results obtained from WISE albedos. Instead, the H_D sample seems dominated by objects belonging to the broad X-class; and its albedo distribution indicate an absence of objects with low albedo values. In this last group, the S-class objects are few, in complete agreement with the albedo observations. The differences found between the H_U and H_D samples support our original hypothesis of two different groups of asteroids in this region of space.

The observed over abundance of high albedo objects in the H_D sample could be explained as a result of a fragmentation of a high albedo parent body in this zone as a consequence of a catastrophic collision which would be associated with the Hungaria family. On the other hand, for the H_U sample we do not propose a collisional family as an explanation for the S-type objects observed because *a priori* they not exhibit a distribution in proper element space in agreement with a recent family formation event (Milani et al., 2010). Furthermore, this is the taxonomic type that we expected to found at this heliocentric distance; as we can observe in the Phocaea region: this asteroid group is very close in orbital elements space and exhibit a taxonomic distribution completely dominated by the S-class. Then, the H_U group could be a relic of the original population formed in this zone and conforming the background; which may have been modified or contaminated by one or more X-type object who suffered collisional events, forming the Hungaria family and overpopulating the region with fresh X-types. This behavior is supported by dynamical simulations performed by several authors in the last few years: Migliorini et al. (1998), Michel et al. (2000), Milani et al. (2010), Bottke et al. (2012).

There is a widespread agreement about the complex dynamic acting in the Hungaria region, so we expect to perform in the near future some dynamical studies of zone that allows a better understanding of the observed distributions; like an analysis of proper frequencies to verify if the H_U group population is a family (Carruba and Michtchenko, 2007) and a research of the collisional evolution in the region that allows us to understand how the families are formed there. Also would be important a more complete study of the resonances inside the region to find if any of them can act on the asteroids causing the observed separation in proper inclination.

Acknowledgments

The authors thank the reviewers R. Di Sisto and A. Harris for their reviews, which led to an improvement of the paper. M.C.A. gratefully acknowledges the partial financial support by CICITCA (Universidad Nacional de San Juan) and SCyT (Gobierno de San Juan) through a research grant. R.G.H. gratefully acknowledges financial support by CONICET through PIP 114-200801-00205 and PIP 114-201101-00358.

References

Assandri, M.C., Gil-Hutton, R., 2008. Astron. Astrophys. 488, 339.
Bus, S.J., Binzel, R.P., 2002a. Icarus 158, 106–145.
Bus, S.J., Binzel, R.P., 2002b. Icarus 158, 146–177.
Bottke, W.F., Vokrouhlický, D., Minton, D., Nesvorný, D., Morbidelli, A., Brasser, R., Simonson, B., Levison, H., 2012. Nature 485, 78.
Cañada-Assandri, M., 2012. Taxonomy of Objects in the Inner Main Belt.
Carruba, J.M., Michtchenko, T.A., 2007. Astron. Astrophys. 475, 1145.
Carvano, J.M., Lazzaro, D., Mothé-Diniz, T., Angeli, C.A., 2001. Icarus 149, 173–189.
Fukugita, M., Ichikawa, T., Gunn, J.E., Doi, M., Shimasaku, K., Schneider, D.P., 1996. Astron. J. 111, 1748–1756.
Gil-Hutton, R., Lazzaro, D., Benavidez, P., 2007. Astron. Astrophys. 468, 1109–1114.
Harris, A.W., 1998. Icarus 131, 291.
Ivezić, Ž., et al., 2001. Astrophys. J. 122, 2749–2784.
Jurić, M., Ivezić, Ž., Lupton, R.H., Quinn, T., Tabachnik, S., Fan, X., et al., 2002. Astrophys. J. 124, 1776–1787.
Lamaitre, A., 1994. In: Kozai, Y., Binzel, R.P., Hirayama, T. (Eds.), Seventy-five Years of Hirayama Asteroid Families: Astronomical Society of the Pacific Conference Series, vol. 63. San Francisco, pp. 140–145.
Lazzaro, D., Angeli, C.A., Carvano, J.M., Mothé-Diniz, T., Duffard, R., Florczak, M., 2004. Icarus 172, 179–220.
Liu, F., Cutri, R., Greanias, G., et al., 2008. In: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 7017, Soc. of Photo-Optical Instrum. Engineers Conf. Series. p. 16.
Mainzer, A., Einserhardt, P., Wright, E.L., et al., 2005. In: MacEwen, H.A. (Ed.), Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 5899, Soc. of Photo-Optical Instrum. Engineers Conf. Series. pp. 262–273.
Mainzer, A., Bauer, J., et al., 2011. Astrophys. J. 731, 53.
Michel, P., Migliorini, F., Morbidelli, A., Zappalà, V., 2000. Icarus 145, 332–347.
Migliorini, F., Michel, P., Morbidelli, A., Nesvorný, D., Zappalà, V., 1998. Science 281, 2022.
Milani, A., Knežvić, Z., Novaković, B., Cellino, A., 2010. Icarus 207, 729.
Muinonen, K., Piironen, J., Shkuratov, Y.G., Ovcharenko, A., Clark, B.E., 2002. In: Binzel, R.P., Gehrels, T., Matthews, M.S. (Eds.), Asteroids III. University of Arizona Press, Tucson, p. 123.

Penttilä, A., Lumme, K., Hadamick, E., Levasseur-Regourd, A.-C., 2005. Astron. Astrophys. 432, 1081.
Scholl, H., Froeschlé, C., 1986. Astron. Astrophys. 170, 138–144.
Stuart, J.S., Binzel, R.P., 2004. Icarus 170, 295.
Stoughton, C., Lupton, R.H., Bernardi, M., Blanton, M.R., Burles, S., Castander, F.J., et al., 2002. Astron. J. 123, 485–548.
Tholen, D.J., 1984. Asteroid Taxonomy from Cluster Analysis of Photometry (Ph.D. thesis). University of Arizona, Tucson.
Thomas, C.A., Trilling, D.E., Emery, J.P., et al., 2011. Astron. J. 142, 85.
Warner, B.D., Harris, A.W., Vokrouhlický, D., Nesvorný, D., Bottke, W.F., 2009. Icarus 204, 172.
Williams, J.G., 1989. In: Binzel, R.P., Gehrels, T., Matthews, M.S. (Eds.), Asteroids II. University of Arizona Press, Tucson, pp. 1034–1072.
Williams, J.G., 1992. Icarus 96, 251–280.
Wright, E.L., Eisenhardt, P.R.M., Mainzer, A.K., et al., 2010. Astron. J. 140, 1868.
Xu, S., Binzel, R.P., Burbine, T.H., Bus, S.J., 1995. Icarus 115, 1–35.