PHYSICAL PROPERTIES OF NEAR-EARTH ASTEROIDS: IMPLICATIONS FOR THE HAZARD ISSUE

Clark R. Chapman
Planetary Science Institute

Alan W. Harris
Jet Propulsion Laboratory

Richard Binzel
M.I.T.

Submitted to the Space Science Series book on the Impact Hazard
12 August 1993; revised 7 March 1994

Physical properties of NEA's are less well characterized than for large main-belt asteroids. Their properties are of great interest for the scientific understanding of small bodies and for eventual resource utilization. Here we consider their properties in terms of the impact hazard, for which they are relevant in two ways: (a) implications for hazardous impacts, such as different modes of break-up during atmospheric penetration, and (b) implications for potential mitigation techniques. NEA's are believed to be derived from both main belt asteroids and comets, and thus they may have physical and compositional properties ranging from loosely aggregated cometary ices to solid metal. Generally, observed NEA colors and inferred compositions appear similar to those of main-belt asteroids. NEA spins range from rapid (2.3 hr.) to practically non-spinning (many days). They are generally small bodies, with minimal gravity, hence are expected to lack deep regoliths. A few, and possibly many, NEA's are compound bodies rather than monolithic, cohesive objects. The diversity of physical properties of NEA's leads to various behaviors during atmospheric entry for smaller objects of different types. The diversity requires that mitigation involve either (a) precursor missions to identify the nature of an object to be deflected or destroyed, (b) technologies that are largely independent of the nature of the object, or (c) highly flexible technologies, capable of immediately assessing physical characteristics and dealing with a wide range of possibilities.

INTRODUCTION

The physical properties of Aten, Apollo, and Amor asteroids have been reviewed by McFadden *et al*. (1989). The purpose of the present review is more limited. Although we present a tabulation (see Appendix ??? of this volume) of the most up-to-date physical parameters for near-Earth asteroids (NEA's) available as of press time, our discussion is restricted to those physical and compositional parameters that are relevant to the subject of this book, the impact hazard. There are two chief hazard-related reasons for interest in the physical nature of NEA's. First, the potential effects of an impact can vary depending on the specific nature of the impactor. In many cases, the physical nature is *not* important; to first order, consequences are dictated by the kinetic energy of the impactor. But, for a range of smaller sized objects, the composition of the impactor and its effective body strength determines whether it explodes harmlessly in the upper atmosphere, penetrates deeply enough to cause a dangerous airburst, or actually reaches the ground. The second, and more important, reason for considering physical properties of NEA's relates to proposed methods of mitigation. Any mitigation technology to deflect or destroy an impactor involves some type of physical interaction with the object. As we discuss below, the inferred range of physical properties of NEA's is very great and profoundly influences what methods can be successfully and safely used to prevent a dangerous impact from happening.

NEA's are not so well characterized as large main-belt asteroids because they are very small and, despite their Near-Earth status, they are usually about as far away from Earth as other asteroids. They are generally very faint, and many of our remote-sensing techniques cannot be applied with precision to such objects. On occasion, NEA's (especially those capable of being a hazard to Earth) come much closer, but then they are available for only a short period of time (hours to weeks). The vagaries of weather and telescope scheduling procedures interfere with attempts to characterize these objects. Thus the sample of physically characterized NEA's is small, and the quality of the data is generally lower than for main-belt asteroids of similar magnitudes. Although occasional observing campaigns can be mounted to obtain comprehensive data on one object, we must await dedicated programs, preferably using dedicated telescope/s and instrumentation -- or at least routine access to a properly equipped telescope -- to markedly improve on our statistical sampling of the physical properties of NEA's. Coordination with NEA discovery programs would be particularly important, since most NEA's are discovered during highly favorable passages of short duration, and we usually have to wait many years for a follow-up opportunity.

An exception to the difficulty of observing NEA's is use of radar, which is greatly facilitated by the occasional proximity of these objects compared with the always much more distant main-belt asteroids. This has been a particularly potent method for sampling the properties of some NEA's and has led to some of our most robust views about their nature (including actual delay-doppler maps of shapes, configurations, and even surface features for a few of them).

NEA's are believed to be derived from both the main asteroid belt and from evolved short-period comets (Wetherill, 1988). Those from the main asteroid belt are generally small, multi-generation collisional fragments from larger main-belt objects, which have been dynamically converted into Earth-approaching orbits by chaotic processes associated with the 3:1 Kirkwood gap and other resonances. Those derived from the cometary population are dormant or dead comets, which differ from their still-active cousins only in the degree to which -- through relatively long-term residence in the inner solar system (thousands of years or longer) -- they have lost accessible volatiles and thus no longer appear to be cometary. However, just as asteroid-derived NEA's may be expected to resemble their siblings in the asteroid belt, inactive comets may be expected to be generally cometary in body character (whatever "cometary" means). Of course, we know rather little about what either main belt asteroids or comets are like, so our inferences about the physical traits of NEA's are quite uncertain.

The table in Appendix ??? of this volume gives provisional values of observable properties for Earth-approaching asteroids (Apollos, Atens, and those Amors and other objects that could, theoretically, intersect Earth's orbit; nearly all have perihelion distance $q < 1.3$ AU), derived from McFadden *et al.* (1989) as updated from the literature and unpublished files (as noted) by one of us (AWH). We address the properties of the NEA's in three categories: inferred mineralogy, surface properties, and geophysical properties and configurations.

MINERALOGY OF NEA'S

Gaffey *et al*. (1993) have reviewed asteroid reflectance spectroscopy, the observational technique responsible for most of our information about asteroid compositions and mineralogy. The crudest but most broadly applied type of spectroscopy is colorimetry, where the reflectance spectrum of an object is characterized by photometric measurements in several (typically 3 to 8) broad-band wavelength ranges in the visible and near-infrared. Asteroid taxonomy is derived from statistical analysis of such data. Observations of reflectance spectra over a broader range of wavelengths and/or with higher spectral resolution have been made only for a smaller number of brighter objects. Such data refine the distinctions between NEA's and help to provide real constraints on implied mineralogy. Other techniques, chiefly thermal infrared (radiometric) measurements, provide geometric albedos (and sizes) of NEA's. Additional techniques provide ancillary information about composition. The most important is radar, which is particularly sensitive to the metal content of the near-surface layers of an object -- a trait that is ambiguous in spectral reflectance data alone. For instance, Ostro *et al.* (1987) have claimed unambiguous proof of the metallic nature for at least one NEA.

Our sampling of NEA's for physical observations is strongly biased. The biases are analogous to, but quantitatively different from, those that affect the statistics of main belt asteroid taxonomy (Gradie *et al*., 1989). Proposed corrections for bias among NEA's (Luu and Jewitt, 1989) suggest that the NEA population has approximately the same proportion of S type and C type (or C-like) asteroids as the main belt. Since McFadden *et al*. (1989) conclude that nearly all taxonomic types found in the main belt (especially the inner belt, near the resonance escape hatches) are found among the NEA's, and that the albedo distributions are similar, it is reasonable to conclude that the NEA's have roughly the same compositional distribution as the main belt.

There are caveats to this conclusion. For example, there is a suggestion that there may be a higher fraction of Q's (a rare type with spectra like ordinary chondrites) among the NEA's than in the main belt; although 1862 Apollo is the only confirmed Q among 55 classified NEA's (see table in Appendix ??? of this volume), Q is an allowed type for 4 others, while only a single Q (3628 Božněmcová) has been identified in the much larger population of classified main belt asteroids (Binzel *et al.*, 1993). The similarity between NEA and main belt populations also raises the question about where the dead comets are, since such comets are not expected to be a major component of the main belt. The answer may be that dormant comets are very low albedo objects, which are poorly sampled among NEA's so far (Hartmann *et al.*, 1987).

The main belt asteroid population, and thus the NEA population, is dominated by materials that we find among collected meteorites, but it almost surely contains weaker materials that cannot usually penetrate the atmosphere. The former materials include rocks of various strengths, stony-metal assemblages, and nickel-iron alloy. The signature of metal in reflectance spectroscopy is not definitive (most M-types are thought to be metallic), but the inference of metallic composition has been strengthened in the cases of several M-type objects by strong radar backscatter. 1986 DA is an M-type NEA with a strong radar backscatter indicative of metallic composition (Ostro *et al.*, 1987). It is possible that some or all of the common S-type asteroids are stony-irons, so a significant minority of NEA's may have the strength of stony-irons and be much stronger than ordinary rocks. How they actually respond to external forces may depend on their ductility or brittleness, which depends in turn on ambient temperature and nickel content.

A substantial fraction of asteroidal materials (probably of the C or C-like taxonomic classes of carbonaceous composition) are expected to be too weak to penetrate our atmosphere and become part of meteorite collections. There is a general belief, although unproven, that most cometary materials would also be too weak to penetrate the atmosphere intact and survive as meteorites. Thus, as far as we know, we do not have any samples that could be considered to be good analogs of cometary material; we can only speculate about the physical nature of dead comets. Presumably they are like active comets, except that their mantles are thicker. The oldest dead comets might be totally depleted of icy volatiles. (CROSS-REFERENCE COMET PROPERTIES CHAPTER.)

SURFACE PROPERTIES

Little is known about the surface properties of NEA's. Asteroids in general are expected to have soil-like regoliths on their surfaces, but less mature (i.e. less reworked, less altered) than for the well known case of the Moon. The ability of an asteroid to develop and maintain a regolith is expected to diminish with size. Objects smaller than ~10 km in diameter are increasingly likely to have thin regoliths, or none at all, unless the object contains part of an ancient regolith developed on a larger, precursor body. Indeed, solar radiation pressure should "blow away" any micron-sized regolith component on a body less than a few km in diameter, so even if small asteroids retain some regolith, it should become coarser with decreasing size of the body. Radiometric data for several NEA's reduced using the "standard thermal model" (which invokes regolith) yield results that are inconsistent with other datasets, which seems to imply that a number of NEA's have thin or nonexistent regoliths (Lebofsky *et al.* 1979).

GEOPHYSICAL PROPERTIES AND CONFIGURATIONS

The chief data for assessing the spins and shapes of the largest sample of NEA's are photometric lightcurves. Although some objects have been studied in great detail, most of the results are less reliable than comparable lists for main belt asteroids, due to the short durations that most NEA's are available for observation. The table in Appendix ??? of this volume lists NEA spin periods, ranging from 2.27 hours for 1566 Icarus up to ~200 hours for 4179 Toutatis. The period for Toutatis remains poorly known as of this writing; if it is slowly tumbling chaotically, as may be the case (Harris, 1993, submitted to *Icarus*), its period may be inherently indeterminate. An asteroid's spin could presumably complicate a mitigation mission. For this reason, it is well to note that observed NEA's typically spin once every 4 to 8 hours, with some spinning much more rapidly (but never so rapidly that they are in danger of coming apart) and others much more slowly. In fact, there is a small but real, and as-yet-unexplained, excess of very slowly rotating NEA's compared with a Maxwellian distribution. Since the excess exists for small main-belt asteroids as well as NEA's (Binzel *et al.*, 1992), the explanation is probably not NEA-specific (e.g. that slowly rotating ones are extinct comets). Indeed, the similarity in spin characteristics between the main belt and the NEA's may indicate a rather small cometary component (< 25% to 40%) in the NEA population, because cometary spins are statistically different on average (Binzel *et al.,* 1992).

Lightcurve amplitudes indicate that many NEA's are markedly non-spherical. Several, like 1566 Icarus, have low-amplitude lightcurves, indicating that they have nearly circular equatorial profiles and may even be close to spherical. But lightcurve amplitudes of several tenths of a magnitude are common, and amplitudes in excess of 1 magnitude have been observed. Perhaps it should go without saying, but we will say it anyway: no mitigation scenario should invoke the assumption of a quasi-spherical asteroid. Many NEA's are irregularly shaped bodies, spinning once every few hours.

The best information about NEA shapes, by far, comes from radar. There have been tantalizing hints in some early radar data for two-lobed shapes of a few objects, but the first clear-cut case was for 4679 Castalia (Ostro *et al.* 1990), which was found to have roughly a "contact binary" shape. Far more detailed radar results were achieved for 4179 Toutatis in late 1992 (Ostro *et al.*, 1993, to be published). Toutatis is revealed to be a very irregularly shaped object, also roughly "contact binary" in shape. It is too soon to be certain, but it appears that a significant fraction of NEA's may be compound bodies, with two or several large pieces loosely resting on each other due to their weak mutual gravity. Indeed, the "rubble pile" concept that had been applied to larger asteroids may also apply to smaller asteroids as well. How such small, compound objects can be formed so readily is not yet understood, but there is independent evidence (e.g. the existence of doublet craters on the Earth, Moon, and Mars) that is consistent with a significant percentage of such objects being binary.

Comets have often been seen to split. Often but not always the splitting has resulted from passage within the Roche limit of a planet (e.g. the break-up of P/Comet Shoemaker-Levy 9 [1993e]) or close approach to the Sun. Probably the tensile strength of many comets is not large, and the same could be true of the remnant, dormant population among the NEA's. Therefore, both the cometary component of the NEA's and the fraction of rocky objects that are compound in configuration warn us that we should not regard an approaching hazardous object as necessarily a monolithic object.

IMPLICATIONS FOR HAZARD RELATED TO ATMOSPHERIC ENTRY

If one of the larger of the known NEA's (>1 km diameter) were to strike the Earth, its physical properties would make essentially no difference. To such an impactor, the Earth's atmosphere would be thin, and the object would do damage to the Earth in proportion to the kinetic energy it carries when it explodes at the Earth's surface.

The numerous objects smaller than several hundred meters in diameter may break up in the atmosphere, if they are made of loosely aggregated, weak, low density materials (i.e. "cometary"). Even rocky objects break up in low altitude airbursts if they are smaller than ~70 m, like the ~50 m object that caused the Tunguska explosion. Strong iron meteorites of all sizes can penetrate the Earth's atmosphere practically unscathed. For more details on how the physical properties of the impactor affect its passage through the atmosphere, see Chyba *et al.* (1993), Hills *et al.* (1993), and OTHER CHAPTERS IN THIS BOOK. The implications of this chapter are simply that there is a wide variety of materials among the NEA's, ranging from loose, weak aggregates to solid objects made of metal.

The possibility that a significant proportion of NEA's may be compound bodies raises the possibility of multiple impacts. As we have learned from the example of Comet Shoemaker-Levy 9, it is possible for such bodies to be tidally disrupted by passage through a Roche zone and then have the disrupted pieces collide with the planet. This scenario has been considered for the Earth by Melosh and Stansberry (1991) and is under further development. Passage within the Earth's Roche limit is several times more likely than direct impact, and the question then concerns the ultimate fate of such objects. There has been controversy over the existence of "asteroid streams" (Drummond, 1991), and tidal disruption of NEA's may be one explanation for such observations.

IMPLICATIONS FOR MITIGATION

One of the most dangerous possible outcomes of an attempt to deflect or destroy an approaching asteroid is the unintended production of several large pieces, which might then do more damage than the single, intact body. For example, a swarm of objects distributed around the Earth could create widespread firestorms (both from the direct bolide and from hot ejecta) that would be less likely from a single impact. If a threatening asteroid is to be destroyed, the method must be sufficient to pulverize an object (or compound object) made of the strongest possible material, which is strong metal. If it is to be deflected, it must be guaranteed that the forces applied actually move the object intact, without inducing even small stresses that would cause the body to split (unless the mitigation scenario additionally considers dealing with all such pieces that might result).

If the asteroid to be deflected is a "rubble pile" of unconsolidated pieces, then the largest single impulsive delta-v which can be applied is of the order of the surface escape velocity of the asteroid, or ~1 m/sec per km diameter of the body (see Ahrens & Harris, this volume). This is because an impulse (e.g. from a surface or stand-off nuclear blast) is unevenly distributed throughout the body, and the various pieces will acquire a dispersion of velocities of the same order as the average delta-v; thus if that impulse exceeds the excape velocity, the pieces will become unbound from one another. For initially solid, rocky objects larger than ~100 m, an impulse great enough to produce a delta-v of ~0.1 m/sec would also lead to widespread fracturing of the body, so the above limitation would apply to that case, as well.

NEA's are inherently heterogeneous bodies of great diversity. Any engineering application will have to involve detailed study of the individual object in question to ascertain its particular physical and compositional characteristics. Likewise, experimentation on destroying or deflecting a benign asteroid may be of little value: the specific characteristics of the threatening object are likely to be different. Extrapolation from existing groundbased data and current speculations would be most unwise. To date, there has been no "ground truth" obtained for any NEA, although the Clementine mission to Geographos is underway. Even the Galileo fly-bys of the main-belt asteroids Gaspra and Ida were at considerable distances and involved only quick-look pictures and remote-sensing data (Chapman, 1994). There is much about our current concepts of the make-up of asteroids and dead comets that could be far from the truth. It would be desirable to build up a data base concerning the properties of diverse NEA's so that, if a threatening object is found, we will have a larger and more reliable context in which to assess its characteristics.

It is beyond the scope of this chapter to develop particular approaches to mitigation that take our poor knowledge of physical properties into account. But we may briefly offer the following generic recommendations: (1) Better characterization of NEA's as a population is highly desirable. In addition, precursor missions to assess the properties of the specific hazardous body are essential, or else such assessment capabilities must be built into the deflection mission itself. Such assessment should concentrate on issues such as body strength (e.g. coherent body or rubble pile), body shape and dynamics, and composition. (2) Mitigation procedures must be designed to be as independent of the specific shapes, compositions, heterogeneity, etc. of the body as possible. (3) A controlled deflection scheme such as stand-off explosions (Ahrens and Harris, 1992) or low-thrust propulsion would help minimize the stresses that might unintentionally disrupt the body into a more dangerous swarm of unpredictable character instead of moving it.

ACKNOWLEDGEMENTS

This work has been supported by NASA grants and contracts. This is Planetary Science Institute Contribution No. 318. PSI is a division of Science Applications International Corporation.

FIGURE 1

[There is no figure reference in the text. However, if it does not appear elsewhere in this volume, a radar image of Toutatis would be appropriate.]

REFERENCES

Ahrens, T. J. and Harris, A. W. 1992. *Nature* **360**, 429-433.

Binzel, R. *et al.* 1992. *Icarus* **99**, 225-237.

Binzel, R. P., Xu, S., Bus, S. J., and Bowell, E. 1992. Origins for the Near-Earth Asteroids. *Science* **257**, 779-782.

Binzel, R. P., Xu, S., Bus, S. J., Skrutskie, M. F., Meyer, M., Knezek, P., and Barker, E. S. 1993. The asteroid-meteorite connection: the discovery of a main belt ordinary chondrite asteroid (abstract). *Meteoritics* **28**, 324.

Chapman, C. R. 1994. The Galileo encounters with Gaspra and Ida. *Planetary and Spa. Sci.*, in press.

Chyba, C. F., Thomas, P. J., and Zahnle, K. J. 1993. *Nature* **361**, 40-44.

Drummond, J. D. 1991. Earth-approaching asteroid streams. *Icarus* **89**, 14-25.

Gaffey, M. J., Burbine, T. H., and Binzel, R. P. 1993. Asteroid spectroscopy: progress and perspectives. *Meteoritics* **28**, 161-187.

Gradie, J. C., Chapman, C. R., and Tedesco, E. F. 1989. Distribution of taxonomic classes and compositional structure of the asteroid belt. In *Asteroids II*, ed. R. P. Binzel, T. Gehrels, and M. S. Matthews (Tucson: Univ. of Arizona Press), pp. 316-335.

Hartmann, W. K., Tholen, D. J., and Cruikshank, D. P. 1987. The relationship of active comets, "extinct" comets, and dark asteroids. *Icarus* **69**, 33-50.

Hills, J. G. and Goda, M. P. 1993. *Astron. J.* **105**, 1114-1144.

Lebofsky, L. A., Lebofsky, M. J., and Rieke, G. H. 1979. Radiometry and surface properties of Apollo, Amor, and Aten asteroids. *Astron. J.* **84**, 885-888.

Luu, J. and Jewitt,D. 1989. On the relative numbers of C types and S types among near-Earth asteroids. *Astro. J.* **98**, 1905-1911.

McFadden, L.-A., Tholen, D. J., and Veeder, G. J. 1989. Physical properties of Aten, Apollo, and Amor asteroids. In *Asteroids II*, ed. R. P. Binzel, T. Gehrels, and M. S. Matthews (Tucson: Univ. of Arizona Press), pp. 442-467.

Melosh, H. J. and Stansberry, J. A. 1991. Doublet craters and the tidal disruption of binary asteroids. *Icarus* **94**, 171-179.

Ostro, S. J. *et al*. 1990. *Science* **248**, 1523-1528.

Ostro, S. J., Campbell, D. B., Hine, A., and Shapiro, I. I. 1987. Radar echoes from asteroid 1986 DA indicate a metallic composition (abstract). *Bull. Am. Astron. Soc.* **19**, 840.

Wetherill, G. W. 1988. Where do the Apollo objects come from? *Icarus* **76**, 1-18.

Appendix ???. Table 1. Physical Properties of NEA's

Asteroid	a	e	i	H	Alb	Dia	Cl	Per	Amp	Rad
433 Eros	1.46	.223	10.8	11.16	0.12	22.	S	5.270	0.05-1.5	2
887 Alinda	2.49	.559	9.3	13.76	0.31	4.2	S	73.97	0.35	
944 Hidalgo	5.84	.658	42.4	10.77	d	38.	D	10.064	0.6	
1036 Ganymed	2.67	.537	26.5	9.45	0.19	39.	S	10.31	0.12-0.45	1
1221 Amor	1.92	.435	11.9	17.70	m	1.0			0.1*	
1566 Icarus	1.08	.827	22.9	16.40	0.51	1.0	S	2.273	0.05-0.22	1
1580 Betulia	2.19	.490	52.1	14.52	0.08	5.8	C	6.130	0.21-0.50	2
1620 Geographos	1.24	.335	13.3	15.60	0.25	2.0	S	5.223	1.10-2.03	1
1627 Ivar	1.86	.397	8.4	13.20	0.14	8.1	S	4.797	0.25-0.60	1
1685 Toro	1.37	.436	9.4	14.23	0.31	3.4	S	10.196	0.6 -0.8	3
1862 Apollo	1.47	.560	6.3	16.23	0.25	1.5	Q	3.065	0.15-0.60	1
1863 Antinous	2.26	.606	18.4	15.54	0.24	2.1	S	4.02	0.12	
1864 Daedalus	1.46	.615	22.2	14.85	m	3.7	SQ	8.57	0.85	
1865 Cerberus	1.08	.467	16.1	16.84	0.22	1.2	S	6.800	1.48-2.0	
1866 Sisyphus	1.89	.539	41.1	13.00	0.16	8.2	S	2.48	0.12	1
1915 Quetzalcoatl	2.54	.574	20.5	18.97	0.21	0.5	S	4.9	0.26	1
1916 Boreas	2.27	.451	12.9	14.93	m	3.5	S			
1917 Cuyo	2.15	.505	24.0	13.90	m	5.7		2.697	0.43	1
1943 Anteros	1.43	.256	8.7	15.75	0.17	2.3	S	long	0.04	
1951 Lick	1.39	.062	39.1	14.70	m	3.9	A	4.417	0.28*	
1980 Tezcatlipoca	1.71	.365	26.8	13.92	0.25	4.3	S	7.853	0.74*	
1981 Midas	1.78	.650	39.8	15.00	m	3.4	S	5.218	0.85*	1
2061 Anza	2.26	.537	3.7	16.56	d	2.6	TCG:	11.50	0.3	
2062 Aten	.97	.183	18.9	16.80	0.26	1.1	S			
2100 Ra-Shalom	.83	.437	15.8	16.05	0.06	3.4	C	19.79	0.34	2
2101 Adonis	1.87	.764	1.4	18.70	m	0.6				1
2201 Oljato	2.18	.711	2.5	15.55	0.54	1.4	S?	24.?	>0.1	1
2212 Hephaistos	2.17	.833	11.8	13.87	m	5.7	SG		0.05*	
2340 Hathor	.84	.450	5.9	20.26	m	0.3	CSU			
2368 Beltrovata	2.11	.414	5.2	15.21	0.27	2.3	SQ	5.9	0.84	
2608 Seneca	2.49	.581	15.3	17.52	0.21	0.9	S	8.	0.5	
3102 1981 QA	2.15	.449	8.4	16.70	m	1.6	QRS	147.8	>1.0	
3103 1982 BB	1.41	.355	20.9	15.21	0.64	1.5	E	5.709	0.72-0.9	2
3122 1981 ET3	1.77	.423	22.2	14.20	m	4.9		5 or 10	0.25*	
3199 Nefertiti	1.57	.284	33.0	14.84	0.42	2.2	S	2.82	0.12	1
3200 Phaethon	1.27	.890	22.1	14.60	0.09	6.9	F	4.0	0.12*	
3288 Seleucus	2.03	.457	5.9	15.00	0.22	2.8	S	75.	1.0	
3360 1981 VA	2.47	.743	21.7	16.20	0.17	1.8				
3361 Orpheus	1.21	.323	2.7	19.03	l	0.3	V	3.58	0.32*	
3362 Khufu	.99	.469	9.9	18.10	0.21	0.7				
3551 1983 RD	2.09	.488	9.5	16.81	0.37	0.9	V	4.930	0.11-0.15	
3552 Don Quixote	4.24	.714	30.8	13.00	0.03	19.0	D	7.7	>0.41	
3554 Amun	.97	.280	23.4	15.82	0.20	2.0	M	2.53	0.16*	
3671 Dionysius	2.19	.543	13.6	16.30	m	1.9		2.4	0.26	
3691 1982 FT	1.77	.284	20.4	14.50	m	4.3		days?	*	
3757 1982 XB	1.84	.446	3.9	18.95	0.18	0.5	S	9.012	0.20	1
3908 1980 PA	1.93	.458	2.2	17.30	0.23	1.0	V	4.426	0.25-0.46	1
3988 1986 LA	1.54	.317	10.8	18.30	m	0.7		8.	0.2†	
4015 1979 VA	2.64	.623	2.8	15.99	d	3.4	CF	3.556	0.06	
4034 1986 PA	1.06	.444	11.2	18.10	m	0.8				1
4055 Magellan	1.82	.327	23.2	14.50	0.23	3.4	V	7.5	0.5‡	
4179 Toutatis	2.51	.641	.5	14.00	m	5.4	S	200.	1.	
4197 1982 TA	2.30	.773	12.2	15.40	0.37	1.8				
4544 Xanthus	1.04	.250	14.1	17.10	m	1.3				1
4688 1980 WF	2.23	.515	6.4	18.60	0.18	0.6	SQ			
4769 Castalia	1.06	.483	8.9	16.90	m	1.4		4.088	1.0	1
4954 Eric	2.00	.449	17.5	12.50	m	10.8	S	>11.	0.6*	
5332 1990 DA	2.16	.456	25.4	14.90	m	3.6	S	5.816	0.36	
5370 1986 RA	3.35	.631	19.0	15.90	d	3.6	C		0.02	
1977 VA	1.86	.394	3.0	19.40	m	0.4	XC			
1978 CA	1.12	.215	26.1	16.90	0.09	1.9	D?	3.756	0.8	
1980 AA	1.89	.444	4.2	19.40	m	0.4	S	2.697	0.12	

1984 BC	3.44	.457	22.4	16.00	d	3.4	D			
1984 KB	2.22	.765	4.9	16.60	0.21	1.4	S			
1986 DA	2.82	.582	4.3	15.90	0.15	2.3	M	3.58	0.32	1
1986 JK	2.80	.680	2.1	18.90	d	0.9	C		0.05	1
1988 TA	1.54	.479	2.5	20.90	d	0.4	C			
1989 DA	2.16	.544	6.4	17.90	m	0.9		7.867	0.12*	
1989 JA	1.77	.484	15.2	16.40	m	1.8			*	1
1989 UP	1.86	.473	3.9	20.60	m	0.3		6.983	1.2*	
1989 VA	.73	.595	28.8	16.90	m	1.4			>0.15*	
1989 VB	1.86	.461	2.1	19.90	m	0.4		>24.	>0.3*	
1990 HA	2.57	.692	3.9	16.90	m	1.4		8.51	0.06*	
1990 KA	2.20	.433	7.6	15.90	m	2.3		6.	>0.4	
1990 MF	1.75	.456	1.9	18.50	m	0.7				1
1990 OS	1.67	.459	1.1	19.90	m	0.4				1
1990 SA	1.96	.430	37.5	16.90	m	1.4	S		*	
1990 TR	2.14	.437	7.9	14.50	m	4.3	S	6.25	0.19	
1990 UA	1.72	.552	1.0	19.40	m	0.4		long	0.08	
1990 UP	1.33	.169	28.1	20.50	m	0.3		>20.	>0.07*	
1991 AQ	2.16	.769	3.2	17.50	m	1.1			*	1
1991 EE	2.25	.624	9.8	18.50	m	0.7		3.00	0.12*	1
1991 JX	2.53	.599	2.3	18.50	m	0.7				1
1992 AC	2.10	.421	16.1	13.60	m	6.3			<0.02*	

* An asterisk in the amplitude column indicates that the photometry is from the unpublished files of the late Wieslaw Wisniewski, one of the most prolific and dedicated observers in recent years.
† Unpublished data from E. Bowell.
‡ Unpublished data from A. Harris.

a - semi-major axis

e - eccentricity

i - inclination

H - Absolute magnitude, H-G system

Alb - Visual albedo. When not measured but inferred from taxonomic class, listed as d for "dark" 0.06), m for "medium" (0.15), or l for "light" (0.4)

Dia - measured diameters (km) from radiometry, or for inferred albedos, computed from H and above albedo values.

Cl - Taxonomic classification

Per - Rotation period in hours

Amp - lightcurve amplitude in magnitudes, or observed range of amplitudes

Rad - number of apparitions for which successful radar observations have been obtained