

DISCOVERY OF M CLASS OBJECTS AMONG THE NEAR-EARTH ASTEROID POPULATION

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ABSTRACT

Broadband colorimetry (0.36 to 0.85 μm), visual photometry, near-infrared (*JHK*) photometry, and 10 and 20 μm radiometry of the near-Earth asteroids 1986 DA and 1986 EB were obtained during March and April 1986. Model radiometric visual geometric albedos of 0.14 ± 0.02 and 0.19 ± 0.02 and model radiometric diameters of 2.3 ± 0.1 and 2.0 ± 0.1 km, respectively, (on the *IRAS* asteroid thermal model system described by Lebofsky *et al.* 1986) were derived from the thermal infrared and visual fluxes. These albedos, together with the colorimetric and (for 1986 DA) near-infrared data, establish that both objects belong to the M taxonomic class, the first of this kind to be recognized among the near-Earth asteroid population. This discovery, together with previous detections of C and S class objects, establishes that all three of the most common main-belt asteroid classes are represented among this population. The similarity in the corrected distribution of taxonomic classes among the 38 Earth-approaching asteroids for which such classes exist is similar to those regions of the main belt between the 3:1 (2.50 AU) and 5:2 (2.82 AU) orbital resonances with Jupiter, suggesting that they have their origins among asteroids in the vicinity of these resonances. The implied mineralogy of 1986 DA and 1986 EB is mostly nickel-iron metal. If this is indeed the case, then current models for meteorite production based on strength-related collisional processes on asteroidal surfaces predict that these two objects alone should produce about 1% of the meteorite falls, i.e., about half of the iron meteorites. Iron meteorites derived from these near-Earth asteroids should have low cosmic-ray exposure ages.

1. INTRODUCTION

a) An Overview

There are an estimated 1500 asteroids with diameters larger than a few hundred meters which cross or closely approach the Earth's orbit (Shoemaker *et al.* 1979). The asteroids comprising this population are divided into three groups on the basis of their present osculating orbital elements. Those with semimajor axes less than 1 AU and which cross the Earth's orbit near their aphelia are referred to as Aten asteroids, those with semimajor axes greater than or equal to 1 AU and with perihelion distance less than or equal to 1.017 AU are called Apollo asteroids, and those with perihelion distance greater than 1.017 AU but less than or equal to 1.3 AU are called Amor asteroids (cf. Shoemaker *et al.* 1979). Asteroids in such orbits can approach the Earth more closely than any other celestial object, barring the Moon or an occasional comet. Most Aten, Apollo, and Amor asteroids are in orbits that are stable for periods of time that are short compared to the age of the solar system, i.e., a few million to a few hundred million years. The ultimate fate of objects in such orbits is to collide with a major planet or be ejected from the solar system; a significant fraction eventually collide with the Earth (Opik 1951, 1963, 1976; Shoemaker *et al.* 1979; Wetherill and Williams 1968; Wetherill 1976). Collisions between the Earth and objects having diameters in the 10 km size range have been postulated as being the trigger responsible for mass biological extinctions (Alvarez *et*

al. 1980). For these reasons we will refer to asteroids in Aten, Apollo, or Amor orbits as "near-Earth" or "Earth-approaching" asteroids.

The fact that there are over a thousand asteroids in short-lived, near-Earth orbits requires that there be a source which replenishes this population on a time scale commensurate with those lifetimes. Opik (1951) believed that source to be the evolution of short-period comets into defunct (nonvolatile) cometary nuclei. Later, this source was revised to include regions from within the asteroid belt as well, particularly regions near the ν_5 and ν_6 secular resonances and the 3:1 and 5:2 commensurabilities with Jupiter (Shoemaker *et al.* 1979).

Near-Earth asteroids are therefore interesting for a number of diverse reasons: they represent a group of objects from which at least some of the meteorites in our museums are derived, may harbor extinct cometary nuclei, have collided with the Earth in the past and will do so again in the future, and are among the most accessible objects in our solar system.

This last fact will become increasingly more important in the next century as mankind establishes a permanent presence in space. The reason for this lies in the fact that asteroids are known to contain significant quantities of water, metals, and perhaps even hydrocarbons. The fact that the Earth-approaching asteroids are small, most having diameters between a few hundred meters and 10 km, and, in a number of cases, in orbits which require less energy to reach than the Moon, makes them the most economical source of resources for building large-scale structures in space.

The first serious suggestion along these lines was made by Samuel Herrick in 1971. Although the idea was considered "premature" at the time, his work was eventually, and posthumously, published (Herrick 1979). Since that time, the matter has been given considerable study (cf. Morrison and

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TABLE I. Log of the observations.

UT Date (1986) Objects(s)	Technique ^a	Telescope/ ^b Observatory	Observers
12 March 1986 EB	Radiometry	IRTF	J. Gradie and E. Tedesco
13 March 1986 DA and EB	Radiometry	IRTF	J. Gradie and E. Tedesco
17 March 1986 EB	Radiometry	IRTF	J. Gradie and E. Tedesco
20 March 1986 DA and EB	<i>UBVR</i>	KPNO	E. Tedesco
05 April 1986 DA and EB	ECAS	KPNO	R. Nelson and E. Tedesco
22 April 1986 DA	Radiometry	IRTF	J. Gradie and E. Tedesco
24 April 1986 DA	<i>JHK</i>	IRTF	M. Buie and E. Tedesco

^a ECAS—visual photometry (at 0.36, 0.44, 0.55, 0.70, and 0.85 μm) on the Eight-Color Asteroid System; *JHK*—near-infrared photometry (at 1.25, 1.65, and 2.2 μm) on the *JHK* system; Radiometry—radiometry (at 10 and 20 μm) on the *N* and *Q* systems; *UBVR*—visual photometry (0.36, 0.45, 0.55, 0.70 μm) on the Johnson *UBVR* system; *UBVR*—visual photometry (at 0.36, 0.44, 0.55, 0.70 μm) on the Johnson *UBVR* system.

^b IRTF—NASA's Infrared Telescope Facility at the Mauna Kea Observatory; KPNO—Kitt Peak National Observatory; 1.3 m telescope.

Niehoff 1979, and references therein) culminating in the Solar System Exploration Committee of the NASA Advisory Council's 1986 report entitled: "Planetary Exploration Through Year 2000: An Augmented Program" in which, in a discussion on the economic value of asteroidal materials using iron meteorites as an example, it states (p. 159) that, "Iron meteorites are actually chunks of iron-nickel-alloy. They are predominantly iron (about 90 percent by weight), nickel (five to ten percent) and cobalt (0.6 percent), with trace amounts of other elements, including gold and platinum group metals (0.001 to 0.01 percent). Such objects are potential sources of large amounts of metals. A metal asteroid one kilometer in diameter (*if such a thing exists*) could be worth more than \$1 trillion at current market prices" (emphasis ours). In this paper we will present evidence for the existence of not one, but two, such asteroids in Earth-approaching orbits, each approximately 2 km in diameter. In addition, we will demonstrate that the inferred distribution of taxonomic classes among the near-Earth asteroids is consistent with their origin in the main asteroid belt near the 3:1 and 5:2 commensurabilities with Jupiter.

b) The Present Study

The physical study of Earth-approaching asteroids is constrained by the generally long time between close approaches and poorly known orbits. For example, although 88 such asteroids had been discovered through 1985, only 47 had received permanent numbers, i.e., have elements sufficiently reliable to permit their routine recovery (Hahn 1986). This is a consequence of the fact that the observing windows for asteroids in orbits of this type are short, ranging from a few days to several months but typically lasting a few weeks. Hence, many of the near-Earth asteroids discovered during the first half of this century are effectively lost since their orbital elements are too poorly known to allow them to be recovered, even by wide-field Schmidt telescopes. For this reason they are studied in much the same way as astronomers study nonperiodic comets—as targets of opportunity. Thus it was in the case of the two asteroids for which new data are presented here.

1986 DA and 1986 EB were discovered on 16 February 1986 by M. Kizawa, Shizuoka, Japan, and 4 March 1986 by E. Shoemaker and C. Shoemaker at the Palomar Observatory, respectively (IAU Circ. 4181 and 4191). 1986 DA is a member of the Amor group of near-Earth asteroids since its orbital elements ($a = 2.811$ AU, $q = 1.166$ AU;

MPC*10628, 1986) cause it to cross the orbit of Mars but not the Earth, while 1986 EB is a member of the Aten group since its orbital elements ($a = 0.974$ AU, $Q = 1.247$ AU; MPC 10625, 1986) are such that it crosses the orbit of the Earth (and, incidentally, Venus) even though its semimajor axis is less than unity.

In Sec. II we present the observations obtained on these two asteroids. We give the derived results in Sec. III, followed by a discussion of these results in Sec. IV and a summary in Sec. V.

II. OBSERVATIONS

Ground-based physical observations of 1986 DA and 1986 EB were obtained in three spectral regions: visible, near infrared, and thermal infrared. In Table I we present a log of the observations followed by the results therefrom.

a) Visible Wavelength Observations

Photometric observations were obtained on the *UBVR* photometric system on 20 March 1986 UT using the Kitt Peak National Observatory 1.3 m reflector and in five bands of the Eight-Color Asteroid Survey (ECAS) system (Gradie *et al.* 1978; Tedesco *et al.* 1982) on 5 April 1986 UT. The nights on which these data were acquired were assigned to obtain visual light curves of Pluto-Charon mutual eclipse events. The observations reported here were made before Pluto was high enough in the sky to observe. The visual-magnitude observations are presented in Table II and the color indices on the ECAS and *UBV* systems in Table III. A summary of the mean colors for both asteroids in both systems is given in Table IV.

The standard stars used for these nights were taken from Tedesco *et al.* (1982). The Johnson *R* band (0.70 μm ; FWHM 0.22 μm) is similar enough to the ESAS *w* band (0.70 μm ; FWHM 0.06 μm) to allow a $V - R$ color index to be transformed into a $v - w$ color index provided, as was the case, that a sufficient number of ECAS standards were observed through the $V = v$, w , and R filters. Hence, in Table III we report the $v - w$ color index for the observations from 20 March. We used the formulas given in Tedesco *et al.* (1982) for transforming between the Johnson *UBV* and ECAS *ubv* color indices.

*MPC—Minor Planet Circulars. A monthly circular issued by the Minor Planet Center, Commission 20 of the International Astronomical Union, Smithsonian Astrophysical Observatory, Cambridge, MA.

TABLE II. Visual photometry of 1986 DA and 1986 EB.

Object	UT date	V (mag)	Distance from Sun (AU)	Distance from Earth (AU)	Phase angle (deg)	$V(1,\alpha)$ (mag)
1986 DA	860320.219	14.29	1.187	0.230	30.65	17.11
	860405.181	14.17	1.166	0.208	33.98	17.25
1986 EB	860320.189	14.48	1.246	0.273	21.01	16.82
	860405.158	15.50	1.245	0.344	38.73	17.34
	860405.218	15.57	1.245	0.344	38.79	17.41
		± 0.02				± 0.02

b) Near-Infrared (JHK) Photometry

JHK photometric observations of 1986 DA were obtained at the NASA Infrared Telescope Facility (IRTF) on 24 April 1986 UT. The results of these observations are summarized in Table V. These observations were made during one hour of a night on which the primary program was the measurement of a Pluto-Charon mutual eclipse event and were made before Pluto had risen. Because it was not possible to measure a network of standards over an appreciable range of airmasses, as is our customary practice, these observations were made differentially with respect to two nearby Elias *et al.* (1982) *JHK* standards (HD 77281 and HD 106965), and nominal values (0.1 mag/airmass) were used for extinction coefficients. As a consistency check we also observed the solar-like star SAO 120107, a star measured on numerous occasions in the past and which we use as a secondary standard on the Elias *et al.* system. The quoted uncertainties reflect the scatter in the measurements of 1986 DA and in their transformation onto the standard system.

c) 10 and 20 μm Thermal Radiometry

Ten- and twenty-micrometer radiometric observations of 1986 DA and 1986 EB were obtained at the NASA IRTF on three nights in March as part of an extensive ongoing survey of faint and unusual asteroids (Gradie and Tedesco 1987). These results are summarized in Table VI. The April observations were made on telescope time "borrowed" from the International Halley Watch program and utilized the standard-star observations made during that night by D. Griep and W. Golish. Our observations were made prior to, and following, the availability of the comet and its standard stars.

The 10 and 20 μm observations were reduced on the photometric system defined by Rieke *et al.* (1985). The values listed in Table VI are given in magnitudes on that system and have not been corrected to monochromatic magnitudes. The uncertainties include both photometric and transformation uncertainties determined or estimated for each night.

III. DERIVED RESULTS

a) Absolute Magnitudes

The V observations were reduced to the absolute-magnitude system adopted by Commission 20 of the International Astronomical Union (IAU) in November 1985. This system is based on the empirical phase relation for atmosphereless bodies derived by Bowell *et al.* (1987) and was adopted by Tedesco (1986) in computing the absolute magnitudes used in reducing the *IRAS* asteroid data (cf. MPC 10193). This system uses a two-parameter phase function: H , the absolute visual magnitude, and G , the "slope parameter." If, as is true with our observations of 1986 DA and EB, there is insufficient data to determine G (i.e., several observations spanning a wide range in phase angle), then a value of G is adopted. In this case we adopted a value of 0.25 for G of both objects in keeping with the scheme for adopting such values determined by Tedesco (1986).

Applying this procedure using the data from Table II results in values of H of 15.94 for 1986 DA and 15.94 for 1986 EB. It is curious that these objects have formally identical absolute visual magnitudes as well as other similar physical properties such as their 0.36 to 0.85 μm color indices (Table IV) and their albedos and diameters (Table VII). Could they have formed coevally or do they share a common parent body?

b) Albedos and Diameters

The thermal observations were combined with the visual photometry to compute model radiometric geometric visual albedos (p_v) and model radiometric diameters for both objects. The albedos and diameters reported here were derived using the thermal model (Lebofsky *et al.* 1986) developed for the reduction of asteroid observations obtained by the *Infrared Astronomical Satellite (IRAS)*. This model is similar to the standard (TRIAD system) model described by Morrison and Lebofsky (1979), except that the absolute vi-

TABLE III. Colorimetry of 1986 DA and 1986 EB.

Object	UT Date	$u-v$	$b-v$	$v-w$	$v-x$	$U-B$	$B-V$
1986 DA	860320.219	0.07 ± 0.04	0.04 ± 0.03	0.07 ± 0.02		0.24 ± 0.04	0.71 ± 0.03
	860405.181	0.03 ± 0.02	0.03 ± 0.02	0.09 ± 0.01	0.14 ± 0.02	0.20 ± 0.02	0.70 ± 0.02
1986 EB	860320.189	0.09 ± 0.04	0.05 ± 0.03	0.06 ± 0.02		0.25 ± 0.03	0.72 ± 0.02
	860405.188	0.04 ± 0.02	0.02 ± 0.02	0.07 ± 0.02	0.15 ± 0.02	0.22 ± 0.02	0.69 ± 0.02

TABLE IV. Mean colors of 1986 DA and 1986 EB.

Object	$u-v$	$b-v$	$v-w$	$v-x$	$U-B$	$B-V$
1986 DA	0.04	0.03	0.08	0.14	0.21	0.70
1986 EB	0.06 ± 0.02	0.04 ± 0.02	0.07 ± 0.02	0.15 ± 0.02	0.24 ± 0.02	0.71 ± 0.02

sual magnitude H and slope parameter G have replaced the $V(1,0)$ used in the "standard model" and the occultation diameters observed for Ceres and Pallas were used to revise the adopted value for the beaming factor (cf. Lebofsky *et al.*). Also, the correction to monochromatic magnitude is now an integral part of the model.

The redefinition of the absolute magnitude required a reformulation of the standard model to account for the numerical change in the absolute magnitude. One effect of this reformulation has been a change in the albedo scale. For this reason the *IRAS* system albedos reported in Table VII cannot be directly compared with albedos from the TRIAD system.

c) Taxonomic Classifications

Broadband UBV colors and the visual geometric albedo p_V are three observable properties that can be used to constrain the compositional characteristics of the asteroids. Bowell *et al.* (1978), Zellner (1979), and Gradie and Tedesco (1982) have used these properties to define taxonomic systems for the asteroids. The taxonomic system of Gradie and Tedesco has been used to study compositional gradations through the asteroid belt. In this system, nearly 90% of the 500 classifiable asteroids fell into one of the three major classes, C, S, or M, shown in Figs. 1 and 2.

To classify 1986 DA and 1986 EB in the taxonomic systems noted above, the TRIAD albedo scale must be used since that was the scale employed in these systems. We therefore derived $V(1,0)$ absolute magnitudes for 1986 DA and 1986 EB (using phase coefficients of 0.031 mag/deg, the mean value for M class asteroids found by Bowell and Lumme 1979) and used them to compute albedos on the TRIAD system. The albedos on both systems (*IRAS* and TRIAD) are given in Table VII. Because we will be using the TRIAD taxonomic system (as extended by Gradie and Tedesco 1982) throughout this paper, albedos referred to herein will be on the TRIAD system unless noted otherwise.

Figure 1 is a plot of the $U-B$ vs $B-V$ color indices for the 33 near-Earth asteroids for which these data are avail-

TABLE V. *JHK* photometry of 1986 DA.

Object	UT date	J	$J-H$	$J-K$
1986 DA	860424.273	12.86 ± 0.03	0.46 ± 0.02	0.60 ± 0.02

able (see Table VIII). The positions of 1986 DA and 1986 EB are indicated, and a typical error bar representing the uncertainties in the color indices is given in the lower right-hand corner. Note that the UBV colors alone are suggestive of an M classification. Due to the overlap between the C and M regions and the uncertainty in the color indices, however, this classification is not unambiguous. There are at least two ways to resolve this ambiguity. The first involves use of albedo information and the second employs data on the relative reflectivity at wavelengths greater than that of the V band. Both of these types of data are available and each, as we will demonstrate, confirms the M classification.

As shown in Fig. 2, both 1986 DA and 1986 EB have albedos ($0.07 < p_V < 0.23$) and $U-V$ colors ($0.84 < U-V < 1.05$) that place them securely in the M class. Also, the combination of $J-K$ color and geometric albedo of 1986 DA are distinctly those of an M class object (cf. Veeder *et al.* 1982, 1983). Finally, the $v-w$ and $v-x$ color indices exclude a C classification which requires values for these colors near zero. There is therefore no doubt that 1986 DA and 1986 EB are M class objects, the first such to be recognized among the Earth-approaching asteroid population.

IV. DISCUSSION

The spectral reflectance properties and geometric albedos of the M class asteroids are consistent with compositions analogous to the metallic (iron-nickel) meteorites or the enstatite-metal assemblage of the enstatite-chondrite meteorites (Zellner 1979). Radar observations of the M class asteroid 16 Psyche by Ostro *et al.* (1985) ($U-V = 0.96$, $p_V = 0.094$; Bowell *et al.* (1979) and Morrison and Zellner (1979), respectively, show a radar reflectance indicative of a body with a nearly metallic composition rather than one containing a mixture of enstatite and metal. Radar observations by Ostro *et al.* (1985) of one other M class asteroid, 97 Klotho, are consistent with objects having a range of concentrations, including all metal. The radar observations of 16 Psyche, coupled with similar colors and albedos for 1986 DA and 1986 EB, suggest that these latter objects are also nearly entirely metallic in composition, similar in gross composition to the iron meteorites. We can therefore state with

TABLE VI. 10 and 20 μm (N and Q) observations of 1986 DA and 1986 EB.

Object	UT date	Distance from Sun (AU)	Distance from Earth (AU)	Phase angle (deg)	N (mag)	Q (mag)
1986 DA	860313.46	1.205	0.246	27.6	3.18 ± 0.04	2.03 ± 0.10
	860422.26	1.179	0.211	31.4	3.55 ± 0.04	1.79 ± 0.15
	860422.48	1.180	0.211	31.4	3.79 ± 0.04	1.57 ± 0.12
1986 EB	860312.47	1.237	0.257	16.4	4.23 ± 0.04	2.41 ± 0.06
	860313.52	1.238	0.257	16.4	4.62 ± 0.04	2.71 ± 0.09
	860317.48	1.240	0.262	18.5	4.26 ± 0.04	2.39 ± 0.05

TABLE VII. Mean albedos and diameters of 1986 DA and 1986 EB.

Object	IRAS			Diameter (km)	TRIAD		
	H	G	p_V		$V(1,0)$	β	p_V
1986 DA	15.94	0.25	0.14	2.3	16.18	0.031	0.12
1986 EB	15.94	0.25	0.19	2.0	16.17	0.031	0.17
	± 0.02		± 0.02	± 0.1	± 0.02		± 0.02

reasonable confidence that irons *are* found among the near-Earth asteroid population.

Since the orbits of most near-Earth asteroids are unstable due to perturbations by the terrestrial planets, sources such as asteroids in dynamically unstable regions of the belt, e.g., Kirkwood gaps (cf. Wetherill 1985), or extinct comets (cf. Wetherill 1979), are required. McFadden *et al.* (1985) concluded that the close similarity between the spectral (0.35 to 1.1 μm) properties of seven near-Earth asteroids and some main-belt asteroids argued that a sizable fraction must come from the main belt, in particular the 5:2 Kirkwood gap. They also concluded that, due to the lack of detailed spectral similarities, not all Earth-approaching asteroids had identifiable source bodies in the main belt. Based upon celestial mechanical calculations, Wisdom (1983,1985) suggested that the 3:1 Kirkwood gap was a possible source region as well.

We next examine the issue of the source(s) of the near-Earth asteroid population using classifications of 38 Earth-approaching asteroids. The *UBV* colors and albedos used to

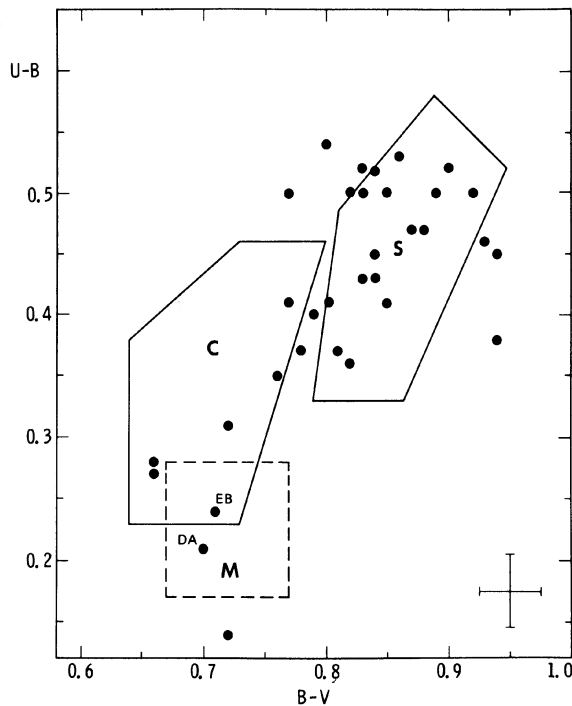


FIG. 1. $U - B$ vs $B - V$ for 33 Earth-approaching asteroids. Boxes delineating the outer limits of the C, S, and M taxonomic class fields are from *Bowell et al.* (1978). Typical uncertainties in the color indices are indicated by the error bar in the lower right-hand corner.

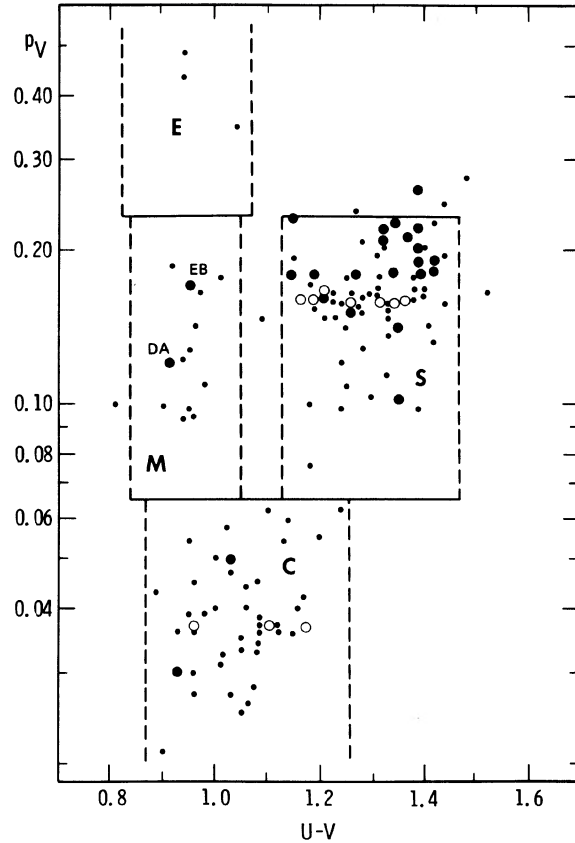


FIG. 2. Visual geometric albedo (p_V) vs $U - V$ for 24 Earth-approaching asteroids for which such data are currently available (dark circles) and for nine additional Earth-approaching asteroids for which only the $U - V$ is known (light circles). The latter have been plotted at $p_V = 0.16$ if their adopted class was S and at 0.037 if their adopted class was C, these being the mean albedos for S and C class objects. Similar data for main-belt asteroids (from Fig. 1 in Zellner 1979) are plotted as small dark circles. Note that the location of 1986 DA and 1986 EB in this parameter space places them squarely among the M class.

assign the asteroids to a class, and the class adopted for each, are presented in Table VIII. Where these data were lacking, or led to ambiguous classifications, other sources were consulted and used as the basis for a classification. Where this was done, it is noted in the remarks column. In cases where data were published before an asteroid had been assigned a permanent number, the provisional designation under which those data were published is given in the remarks column. Those asteroids for which an unambiguous C, S, or M classification could not be assigned were called "Others." This classification scheme is identical to that employed by Gradie and Tedesco (1982) in their study of the distribution of the taxonomic classes as a function of heliocentric distance. The only difference is that they assigned specific classes (e.g., D, E, F, P, R, or U) to each asteroid in their sample, whereas here we simply refer to all such non-C-S-M classes as "other."

We next sought to determine which, if any, region of the asteroid belt had a relative distribution of taxonomic classes similar to that found among the Earth-approaching population by comparing that distribution with the distribution

TABLE VIII. Adopted taxonomic classes for Aten, Apollo, and Amor asteroids.

Asteroid	Type	p_V	p_V Ref.	$U-B$	$B-V$	UBV Ref.	Adopted class	Remarks
433 Eros	Amor	0.18	1	0.52	0.90	1	S	
887 Alinda	Amor	0.18	1	0.43	0.84	1	S	
1036 Ganymed	Amor	0.15	2	0.42	0.84	1	S	
1566 Icarus	Apollo	0.18	3	0.54	0.80	1	Other	1
1580 Betulia	Amor	0.03	4	0.27	0.66	1	C	
1620 Geographos	Apollo	0.19	3	0.50	0.89	1	S	
1627 Ivar	Amor	0.23	5	0.47	0.87	1	S	
1685 Toro	Apollo	0.14	3	0.47	0.88	1	S	
1862 Apollo	Apollo	0.21	6	0.50	0.82	1	S	
1863 Antinous	Apollo	0.18	2	0.37	0.77	1	S	
1864 Daedalus	Apollo			0.50	0.83	1	S	1971 FA
1865 Cerberus	Apollo			0.40	0.79	1	S	2
1866 Sisyphus	Apollo						S	3
1915 Quetzalcoatl	Amor	0.23	5				S	2
1916 Boreas	Amor			0.41	0.85	1	S	
1943 Anteros	Amor	0.18	5	0.45	0.84	1	S	
2061 Anza	Amor			0.35	0.76	1	C	
2062 Aten	Aten	0.20	1	0.46	0.93	1	S	1976 AA
2100 Ra-Shalom	Aten	0.05	7	0.31	0.72	1	C	1978 RA
2201 Oljato	Apollo			0.36	0.82	2	Other	1947 XC = 1979 XA
2212 Hephaistos	Apollo			0.41	0.77	1	C	1978 SB
2340 Hathor	Aten			0.50	0.77	1	Other	1976 UA
2368 Beltrovata	Apollo			0.52	0.83	1	Other	1977 RA
2608 Seneca	Amor			0.41	0.80	1	S	1978 DA
3102 1981 QA	Amor			0.52	0.84	1	S	
3199 Nefertiti	Amor	0.22	2	0.38	0.94	1	S	1982 RA
3200 Phaethon	Apollo	0.17	8				Other	1983 TB, 4
3288 Seleucus	Amor	0.19	2	0.50	0.92	1	S	1982 DV
1977 VA	Amor			0.14	0.72	1	Other	Possibly M
1978 CA	Apollo			0.50	0.85	1	S	
1979 VA	Amor			0.28	0.66	1	C	
1980 AA	Amor			0.37	0.81	3	S	
1980 WF	Apollo	0.18	2	0.45	0.94	1	S	
1982 XB	Apollo	0.22	9	0.53	0.86	1	S	
1983 SA	Amor						Other	5
1984 KB	Apollo						S	6
1986 DA	Aten	0.12	10	0.21	0.70	4	M	
1986 EB	Amor	0.17	10	0.24	0.71	4	M	

Notes to TABLE VIII— p_V References

- 1—Morrison and Zellner (1979) (radiometric albedo).
- 2—Gradie and Tedesco (1987) (converted to TRIAD system).
- 3—Morrison and Zellner (1979) (polarimetric albedo, or albedo limit set by a polarimetric parameter, e.g., a P_{\min}).
- 4—Lebofsky *et al.* (1978).
- 5—G. Veeder (personal communication in McFadden *et al.* 1985).
- 6—Lebofsky *et al.* (1981).
- 7—L. Lebofsky (personal communication in McFadden *et al.* 1985).
- 8—Veeder *et al.* (1984).
- 9—L. Lebofsky and E. Tedesco (unpublished).
- 10—This paper.

Notes to TABLE VIII— UBV References

- 1—Tedesco (1986) (A combination of Bowell *et al.* (1979) and UBV derived color indices from Zellner *et al.* (1985)).
- 2—Bowell and Harris, IAU Circ. No. 3436.
- 3—Harris, IAU Circ. No. 3450.
- 4—This paper.

Notes to TABLE VIII—Remarks

- 1—Other means not an unequivocal C, S, or M.
- 2—cf. McFadden *et al.* (1985).
- 3—Bell *et al.* (1987).
- 4—Veeder *et al.* (1984).
- 5—L. Lebofsky and E. Tedesco (unpublished).
- 6—Bell and Brown (1987).

TABLE IX. Distribution of taxonomic classes among Observed Aten, Apollo, and Amor Asteroids.

Taxonomic class	Observed number	Relative populations in percent					
		Earth-approaching		4:1 2.06	3:1 2.50	5:2 2.82	2:1 3.28 (AU)
		Observed	Corrected				
C	5	13 ± 5	40	10	40	65	60
S	24	63 ± 8	40	40	35	20	5
M	2	6 ± 4	5	0	10	10	0
Other	7	18 ± 6	15	50	15	5	35

found by Gradie and Tedesco for main-belt asteroids.

The results of this study are shown in Table IX. The number of asteroids in the near-Earth population is given as the number observed in each class, the fraction of the total for each class, and the uncertainty in that number using standard statistical methods. We have attempted to account for the factor of 4 differences in albedo and, hence, in discovery rate between the C and the S and M classes by increasing the number of C objects from five to 20 and recalculating the estimated relative abundance. These new estimates are given as "corrected" values. These values are compared with the percentages of C, S, M, and "other" class asteroids as determined by Gradie and Tedesco (1982) for the asteroid population near the 4:1 (2.064 AU), 3:1 (2.500 AU), 5:2 (2.824 AU), and 2:1 (3.277 AU) resonances.

The gross similarities between the compositional structure of the Earth-approaching population and the asteroids found near the 3:1 and 5:2 Kirkwood gaps is suggestive of an asteroidal rather than cometary source for the Earth-approaching objects, an idea originally suggested by Wetherill (1979) on the basis of dynamical arguments. The still-existent paucity of low-albedo C class objects in the near-Earth group relative to their abundance in the vicinity of the 3:1 and 5:2 resonances may be due to a smaller number of source bodies presently located near these unstable zones or, more likely, as suggested by Greenberg and Chapman (1983) and others, the C class material is the most friable of the three major classes and is therefore the least likely to survive the transport time from the main belt to Earth-approaching orbits. If the source of the near-Earth population is primarily asteroidal, then it is possible to speculate that the end product of at least some comets is simply dust and meteor streams, i.e., the majority of comets may lack volatile-free cores. Alternatively, as in the case of the survivability of C class material, the core of a comet may be so friable that it cannot survive intact as long as asteroidal materials.

Cosmic-ray exposure ages of iron meteorites determined from the abundance of $^{41}\text{K}/^{40}\text{K}$ range from 90×10^6 to 2.3×10^9 yr (Voshage 1967; Buchwald 1975) with distinct clusterings for certain iron groups at $400 \pm 100 \times 10^6$ for the IVA irons and $650 \pm 100 \times 10^6$ yr for the IIIAB irons (Wasson 1985). The cosmic-ray exposure ages of the abundant chondritic meteorites are much shorter, generally on the order of a few million years. These latter ages are on the order of the mean time between catastrophic collisional disruptions of an Earth-approaching asteroid, hence the suggestion that the difference in cosmic-ray exposure ages between the irons and the chondrites is due mostly to the difference in strength of the materials: weaker stony objects of meter size are destroyed in a few million years, whereas stronger metallic objects survive intact tens to hundreds of times longer.

Wetherill and Williams (1968) and Wetherill (1976)

have used the long cosmic-ray exposure ages of the irons to argue that the sources of iron meteorites must be in orbits with mean lifetimes longer than those of the Aten, Apollo, and Amor populations. Greenberg and Chapman (1983) suggest that the source cannot be in the near-Earth asteroid population but must be in the main asteroid belt since only there can strong meter-sized objects survive for 10^9 yr. McFadden *et al.* (1985) support this idea by noting that they were unable to identify any metallic iron analog among the Earth-approaching asteroid population.

The discovery of two M class objects, probably metallic iron in composition, suggests that a near-Earth source may exist for at least some of the iron meteorites. Alternatively, the M class near-Earth asteroids may not be the source but rather a part of the same population from which the iron meteorites are derived. Greenberg and Chapman's (1983) model for the production of meteorites infers that the yield of meteoritic material ejected from a 20 km diameter iron body in the asteroid belt (near a resonance) and delivered to the surface of the Earth should be about eight times that from a weak (stony) object of the same diameter when factors such as ejecta production, communication with resonances, mean lifetime against collisional destruction, and passage through the atmosphere are considered.

For objects in Earth-approaching orbits, one need not consider the degree to which the ejecta will communicate with the resonance. Greenberg and Chapman estimate, based upon numerical simulations of cratering processes on small bodies by Greenberg *et al.* (1978), that a 2 km diameter iron object is no less than 1/3 as efficient as a stony body for producing ejecta that escape the gravitational field. This value is strongly influenced by the dependence of meteorite production from small bodies, which Greenberg and Chapman (1983) estimate to be efficient for small stony bodies but not for small iron bodies. Irons, though, are five times more likely to survive passage through the atmosphere. Also, iron objects apparently have mean lifetimes against collisional destruction by other meteoroids (although not against collisions or ejections by planets) that are ten times longer than those for stony materials. Hence, an iron object in an Earth-approaching orbit is 15 to 20 times more effective at producing meteorites than a stony object, at least according to the Greenberg and Chapman model. A simple calculation based upon the assumption that the asteroids listed in Table VIII are a reasonable cross section of the Earth-approaching population, and assuming that the meteorite production (ejecta) rate is proportional to the diameter squared (area), indicates that 1986 DA and 1986 EB should produce about 20% of the meteorites produced from the other observed Earth-approaching asteroids. However, according to the Greenberg-Chapman model, only about 5% of all meteoritic material falling onto the Earth is produced

by near-Earth asteroids and, hence, only about 1% of the meteorites in our collection can be expected to come from these two asteroids. In actual fact, about 2% of all meteorites are irons (Anonymous 1986). If half of these are from 1986 DA or 1986 EB, then about half the iron meteorites should have cosmic-ray exposure ages near that of the dynamical lifetimes (10^6 – 10^8 yr) of these asteroids.

The lack of iron meteorites with short cosmic-ray exposure ages is surprising since our simple calculations show that about half the iron meteorites should have exposure ages less than 10^8 yr. A possible explanation, suggested by Wasson (1985), is that the small number of iron meteorites with ages less than 200×10^6 yr may result from experimental bias. In any case, the fact that some irons have cosmic-ray exposure ages greater than 10^8 yr is significant and apparently can only be explained by sources in orbits stable for many hundreds of millions of years.

V. CONCLUSIONS

The Earth-approaching asteroids 1986 DA and 1986 EB are found to belong to the M class of asteroids. These are the first of this class to be identified among the Aten, Apollo, and Amor populations. The inferred composition of the M class asteroids is primary metallic iron. If this is indeed the case, then current models for meteorite production based on strength-related collisional processes on asteroidal surfaces predict that these two objects alone should produce about 1% of all meteorite falls. The discrepancy between the actual number of iron meteorites found and their observed long cosmic-ray exposure ages brings into question the validity of

meteorite-production models for irons and the true distribution of cosmic-ray exposure ages for iron meteorites.

The relative abundances of classes C, S, M, and "other" among the near-Earth asteroid population are remarkably similar to those found in the inner asteroid belt between the 3:1 and 5:2 resonances, i.e., between 2.50 and 2.82 AU. This dominating presence of the three major asteroid taxonomic classes among the Earth-approaching population argues strongly in favor of an asteroidal source for most such objects. This conclusion leads to the suggestion that "extinct" comet nuclei, if of a composition other than that found in the asteroid belt, are rare, if they exist at all. The hypothesis that comets do not have residual, "rocky" cores cannot be dismissed.

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REFERENCES

- Alvarez, L. W., Alvarez, W., Asaro, F., and Michel, H. V. (1980). *Science* **208**, 1095.
- Anonymous. (1986). *Antarctic Meteorite Newsl.* **8**, No. 2, 15.
- Bell, J. F., and Brown, R. H. (1987). In preparation.
- Bell, J. F., Hawke, B. R., Owensby, P. D., and Gaffey, M. J. (1987). In preparation.
- Bowell, E., Harris, A. W., and Lumme, K. (1987). In preparation.
- Bowell, E., and Lumme, K. (1979). In *Asteroids*, edited by T. Gehrels (University of Arizona, Tucson), p. 132.
- Bowell, E., Chapman, C. R., Gradie, J. C., Morrison, D., and Zellner, B. (1978). *Icarus* **33**, 313.
- Bowell, E., Gehrels, T., and Zellner, B. (1979). In *Asteroids*, edited by T. Gehrels (University of Arizona, Tucson), p. 1108.
- Buchwald, V. F. (1975). *Handbook of Iron Meteorites* (University of California, Berkeley).
- Elias, J. H., Frogel, J. A., Matthews, K., and Neugebauer, G. (1982). *Astron. J.* **87**, 1029.
- Gradie, J., and Tedesco, E. F. (1982). *Science* **216**, 1405.
- Gradie, J., and Tedesco, E. F. (1987). In preparation.
- Gradie, J., Tedesco, E., and Zellner, B. (1978). *Bull. Am. Astron. Soc.* **10**, 594.
- Greenberg, R., and Chapman, C. R. (1983). *Icarus* **55**, 455.
- Greenberg, R., Wacker, J. F., Hartman, W. K., and Chapman, C. R. (1978). *Icarus* **35**, 1.
- Hahn, G. (1986). *Uppsala Astron. Obs. Rep.* No. 38.
- Herrick, S. (1979). In *Asteroids*, edited by T. Gehrels (University of Arizona, Tucson), p. 222.
- Lebofsky, L. A., Veeder, G. J., Lebofsky, M. J., and Matson, D. L. (1978). *Icarus* **35**, 336.
- Lebofsky, L. A., Veeder, G. J., Rieke, G. H., Lebofsky, M. J., Matson, D. L., Kowal, C., Wynn-Williams, C. G., and Becklin, E. E. (1981). *Icarus* **48**, 335.
- Lebofsky, L. A., Sykes, M. V., Tedesco, E. F., Veeder, G. J., Matson, D. L., Brown, R. H., Gradie, J. C., Feierberg, M. A., and Rudy, R. J. (1986). *Icarus* **68**, 239.
- McFadden, L. A., Gaffey, M. J., and McCord, T. B. (1985). *Science* **229**, 160.
- Morrison, D., and Lebofsky, L. A. (1979). In *Asteroids*, edited by T. Gehrels (University of Arizona, Tucson), p. 184.
- Morrison, D., and Niehoff, J. (1979). In *Asteroids*, edited by T. Gehrels (University of Arizona, Tucson), p. 227.
- Morrison, D., and Zellner, B. (1979). In *Asteroids*, edited by T. Gehrels (University of Arizona, Tucson), p. 1090.
- Öpik, E. J. (1951). *Proc. R. I. Acad.* **54A**, 165.
- Öpik, E. J. (1963). *Adv. Astron. Astrophys.* **2**, 219.
- Öpik, E. J. (1976). *Interplanetary Encounters: Close-Range Gravitational Interaction* (Elsevier, New York).
- Ostro, S. J., Campbell, D. B., and Sapiro, I. I. (1985). *Science* **229**, 442.
- Rieke, G. H., Lebofsky, M. J., and Low, F. J. (1985). *Astron. J.* **90**, 900.
- Shoemaker, E. M., Williams, J. G., Helin, E. F., and Wolfe, R. F. (1979). In *Asteroids*, edited by T. Gehrels (University of Arizona, Tucson), p. 253.
- Tedesco, E. F. (1986). In *IRAS Asteroid and Comet Survey* (Preprint Version No. 1), edited by D. Matson. JPL internal document No. D-3698.
- Tedesco, E. F., Tholen, D. J., and Zellner, B. (1982). *Astron. J.* **87**, 1585.
- Veeder, G. J., Matson, D. L., Hoover, G., and Kowal, C. (1983). *Astron. J.* **88**, 1060.
- Veeder, G. J., Matson, D. L., and Kowal, C. (1982). *Astron. J.* **87**, 834.
- Veeder, G. J., Kowal, C., and Matson, D. L. (1984). *Lunar Planet. Sci.* **XV**, 878.
- Voshage, H. (1967). *Z. Naturforsch.* **22a**, 477.

- Wasson, J. (1985). *Meteorites* (Freeman, New York).
- Wetherill, G. W. (1976). *Geochem. Cosmochim. Acta* **40**, 1297.
- Wetherill, G. W. (1979). *Icarus* **37**, 96.
- Wetherill, G. W. (1985). *Meteoritics* **20**, 1.
- Wetherill, G. W., and Williams, J. G. (1968). *J. Geophys. Res.* **73**, 635.
- Wisdom, J. (1983). *Meteoritics* **18**, 422.
- Wisdom, J. (1985). *Nature* **315**, 731.
- Zellner, B. H. (1979). In *Asteroids*, edited by T. Gehrels (University of Arizona, Tucson), p. 783.
- Zellner, B., Tholen, D. J., and Tedesco, E. F. (1985). *Icarus* **61**, 355.