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EARTH-APPROACHING ASTEROIDS: POPULATIONS, ORIGIN, AND COMPOSITIONAL TYPES

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Earth-approaching asteroids are small bodies of stellar appearance which pass close to the orbit of the Earth. Some of these asteroids are the easiest bodies to reach by spacecraft, beyond the Moon. Physical observations suggest they have a broad range of composition and that at least a few may be the most primitive solid bodies that are readily accessible for detailed study. Hence they are of special interest for exploration. At least two different kinds of bodies probably are represented among the Earth-approaching asteroids: (1) fragments of main belt asteroids, and (2) extinct comet nuclei. The number of Mars-crossing asteroids appears to be sufficient to sustain no more than 20% of the Earth-crossing asteroid population in steady-state, and the ratio of the number of Earth-crossers to Amor asteroids (1.02 AU $< q \leq$ 1.30 AU) appears to be an order of magnitude higher than that expected, if all near-Earth objects were derived from Mars-crossers. Hence, although Amor asteroids are approximately in equilibrium with and may be derived mainly from shallower Mars-crossers, the Earth-crossing asteroids are inferred to be primarily of different origin. The supply of extinct short period comets seems to be adequate to sustain the population of Earth-crossers, but little is known about the ultimate state of degassed comet nuclei.

Precise physical observations have been made on somewhat more than a dozen near-Earth asteroids. Observed Amors occupy a broad region in the U-B versus B-V color domain, whereas the observed Earth-crossers have a more restricted range of color. The UBV fields of observed Amors and Earth-crossers exhibit moderate overlap. It is commonly believed that extinct cometary nuclei might resemble C-type asteroids, but no more than two C-type objects have been discovered so far, among the near-Earth objects. If Earth-crossers are dominantly of cometary origin, it appears likely that there are unusually strong observational selection effects which decrease the chances of finding C-type objects or that the expectations concerning the color and other properties of extinct comets are in error.

INTRODUCTION

The term Earth-approaching asteroid is used here to designate small bodies of stellar appearance which are on orbits that allow them to pass near 1 AU. A few of the known Earth-approaching asteroids are the easiest bodies to reach by spacecraft, beyond the Moon. Physical observations of these objects suggest that they have a broad range of composition; some probably are the most primitive solid objects that are readily accessible for detailed study.

Besides their intrinsic scientific interest, the Earth-approaching asteroids are especially attractive for exploration because of their very small size and because of unusually small impulses required for rendezvous at aphelion. Landing and escape from these bodies requires miniscule propulsion. A man could achieve escape velocity from most of them by jumping. For some of the Earth-approaching asteroids, spacecraft trajectories can be found where the sum of rendezvous and Earth return impulses is in the range of 2-3 km/sec. What this adds up to is feasibility of sample return. Much of the story that these small wanderers have to tell concerns the early steps of accretion of solid matter in the solar system. But the full story can be wrung from them only with the aid of powerful techniques applied to samples in laboratories here on Earth. The prospect of sample return missions makes the Earth-approaching asteroids of special interest for exploration.

POPULATIONS OF PLANET-CROSSING ASTEROIDS

Somewhat more than 40 Earth-approaching asteroids have been discovered in the course of the past 80 years of astronomical observation. Those asteroids which approach but do not cross the present orbit of the Earth have been called Amor asteroids. This designation is applied here to all asteroids with perihelion distance, q, between 1.017 and 1.300 AU. A little less than half of the Earth-approaching asteroids are Amors. The remaining objects, with $q \leq 1.017$ AU (the present aphelion distance of the Earth), are referred to here as Earth-crossing asteroids. From the standpoint of potential spacecraft missions, it is convenient to distinguish between Earth-crossing asteroids with semimajor axes, a, greater than 1 AU, here referred to by the conventional term Apollo asteroids, and those with $a \leq 1$ AU, which will be designated 1976AA-type asteroids. All known Amor and Apollo asteroids cross the orbit of Mars, whereas the two known examples of 1976AA-type asteroids do not. In addition, there are about 50 Mars-crossing asteroids with $q > 1.3$ AU. These will be designated here simply as Mars-crossing asteroids or Mars-crossers.

While the line drawn between Amor asteroids and Earth-crossers is useful for discussion of spacecraft missions, it is rather arbitrary from the point of view of orbit evolution and origin of these bodies. As a consequence of secular perturbations, at least three known Amors, Quetzalcoatl, Cuyo, and Betulia, are Earth-crossing during part of their secular variation cycle (Wetherill and Williams, 1968; Wetherill, 1976; Williams, personal communication, 1978). A few other Amors, with q slightly greater than 1 AU, may also be part-time Earth-crossers. By the same token, not all asteroids with $q \leq 1.017$ are full-time Earth-crossers. Most Amor asteroids, over long periods of time, probably evolve into full-time Earth-crossers as a result of strong perturbations during close encounters with Mars and with the Earth (Wetherill, 1976).

Three surveys in which planet-crossing asteroids have been discovered are especially useful for estimating the populations of these objects: (1) the Palomar National Geographic Sky Survey (PNGS), conducted with the 122 cm Schmidt camera at Palomar Mountain, California; (2) the Lick Proper Motion Survey (LPM), conducted with the 51 cm astrograph at Lick Observatory, Mt. Hamilton, California; and (3) the Planet-Crossing Asteroid Survey (PCA) conducted with the 46 cm Schmidt camera at Palomar Mountain. Discoveries of planet-crossing asteroids from these three surveys are listed in Table 1. Omitted from Table 1 is the Mars-crossing asteroid 1949OA, discovered in the LPM survey. Because only objects relatively close to the Earth that produced long trails on the PNGS and LPM plates were followed for orbit determination, neither the PNGS nor LPM observations are suitable for estimation of the population of Mars-crossers.

Combined discoveries from all three surveys are used here to estimate the populations of Earth-approaching asteroids, and discoveries from the PCA survey are used to estimate the population of Mars-crossers. The area of sky photographed as independent fields (excluding overlap of plates) is as follows:

Table 1. Planet-Crossing Asteroids Discovered in Three Systematic Surveys

Survey	Object	Class	a(AU)	e	i	q(AU)	V(1,0)	Discovery Conditions*			
								m_{pv}	Δ(AU)	r(AU)	α
PNGS	Icarus	Earth-crosser	1.078	0.827	22.99°	0.187	16.8	15.0	0.268	1.264	18.0°
PNGS	Geographos	Earth-crosser	1.244	0.335	13.33°	0.827	16.7	14.8	0.264	1.198	32.9°
PNGS	Quetzalcoatl	Amor	2.520	0.582	20.55°	1.052	18.5	13.9	0.077	1.050	29.5°
PNGS	1980	Amor	1.709	0.365	26.84°	1.085	14	14	0.567	1.546	17.0°
LPM	1950DA	Earth-crosser	1.683	0.502	12.15°	0.838	15.5	13	0.150	1.084	47.5°
LPM	Antinous	Earth-crosser	2.260	0.606	18.45°	0.891	15.2	14.0	0.352	1.337	12.0°
PCA	1976UA	Earth-crosser	0.844	0.450	5.85°	0.464	20.7	14.3	0.034	1.024	29.7°
PCA	1976AA	Earth-crosser	0.966	0.183	18.91°	0.790	17.6	13.8	0.130	1.112	14.4°
PCA	1977HA	Earth-crosser	1.601	0.504	23.05°	0.794	18.4	15.2	0.165	1.124	16.5°
PCA	1973NA	Earth-crosser	2.429	0.638	67.99°	0.879	15.6	11.2	0.089	1.100	19.9°
PCA	1977VA	Amor	1.865	0.394	2.97°	1.130	19.6	15.8	0.142	1.132	6.0°
PCA	1974UB	Mars-crosser	2.124	0.359	36.34°	1.361	14.1	14.6	0.687	1.679	5.7°
PCA	1977VB	Mars-crosser	2.304	0.363	26.94°	1.470	15.6	15.7	0.531	1.490	16.1°
PCA	1974UA	Mars-crosser	1.800	0.082	30.08°	1.653	13.4	14.[illegible]	0.695	1.675	9.7°
PCA	197[illegible]SB	Mars-crosser	2.727	0.384	16.76°	1.680	13.6	14.3	0.754	1.752	4.6°
PCA	Cline	Mars-crosser	2.311	0.251	6.84°	1.730	12.7	14.5	1.061	2.05[illegible]	2.7°
PCA	1973SA	Mars-crosser	2.281	0.234	8.38°	1.746	13.9	14.7	0.756	1.74[illegible]	7.2°

*m_{pv} = apparent visual photographic magnitude, Δ = distance from the Earth, r = distance from the Sun, α = phase angle.

PNGS Survey .... 54,000 square degrees
LPM Survey .... 44,000 square degrees
PCA Survey .... 66,000 square degress (first five years)

Estimates of the populations of given classes of asteroids can be obtained by the following method. The magnitude-frequency distribution of each class of planet-crossing asteroids is assumed to be of the form,

$$N_v = Ke^{bv} \tag{1}$$

where N_v is the cumulative number of asteroids equal in absolute magnitude to v or brighter, v is the absolute visual magnitude, v(1,0), and K and b are constants to be determined by observation. The magnitude-frequency distributions of both main belt asteroids and inactive comet nuclei follow this simple exponential law closely; the size-frequency distributions of large craters on the Moon, Mars, and Mercury indicate that planet-crossing asteroids must also have a magnitude distribution of this form. The coefficient in the exponent, b, is observed to be close to 1 for all classes of small bodies.

The constant K in Equation (1) is determined from the systematic surveys by means of the following equation.

$$K = \frac{P_v}{U^{\frac{1}{2}} \int_{v_{min}}^{v_{max}} bF(v)T(v)I(v)e^{bv}dv} \tag{2}$$

where P_v is the cumulative number of asteroids of a given orbital class observed in a systematic survey, U is the square degrees of sky photographed, and F(v) is a function related to the area searched in each orbit plane, for objects of a giver v, when one of the nodes lies at opposition; T(v) is a function related to the mean time spent in the search area by asteroids of a given v, assuming random distribution of the arguments of perihelion; and I(v) is a function related to the mean relative size of the search area, for objects of a given v, with randomly distributed longitudes of the node. A model of the photometric phase function and information on the frequency distributions of perihelion and aphelion for each class of objects are required to solve F(v). Knowledge of frequency distributions of the orbital elements a, e, and i for each class of objects is required to solve the functions T(v) and I(v). The required empirical information is obtained from the sample of known objects in each orbital class.

The lower limit of integration in Equation (2), v_{min}, is set by the single brightest object given by Equation (1) and is found by iterative solution for K. The upper limit of integration, v_{max}, is controlled by the effective magnitude threshold of detection for fast-moving objects for a given telescope and photographic emulsion. As v_{max} is also dependent on the care with which plates are searched for moving objects, it must be determined retrospectively from the objects of highest magnitude discovered in a given survey. The values of K derived from Equation (2) are highly dependent upon the independently estimated values of b; the resulting values of N_v at v = 18, however, are relatively insensitive to plausible uncertainties in b.

Estimates are given in Table 2 for the populations of the different classes of planet-crossing asteroids to absolute visual magnitude 18 (equivalent to about 0.7 to 1.5 km diameter). Errors listed in the table are ± one standard deviation and are derived solely from the statistical uncertainties associated with the small number of discoveries. The next largest sources of formal error lie in the determination of v_{max} and in the estimation of b. All other formal errors are small by comparison.

Table 2. Estimated Populations of Planet-crossing Asteroids

	Estimate from Systematic Surveys; Cumulative Number to V(1,0) = 18	Estimate by Wetherill (1976); Cumulative Number to B(1,0) = 18
Earth-crossers	800 ± 300	$\sim$600
Mars-crossers		
Amor asteroids	$\sim$500	300-700
Moderate to shallow Mars-crossers	10,000 ± 5,000	$\sim$5,000
Mars-"grazers"	$\sim$5,000	

Aside from the formal errors, there is also a systematic bias in the observations. This bias arises in part from the failure of the observers to detect all the fast-moving objects down to a specified minimum length and density of trail on the photographic plates and also from limitations on the ability of the observers to follow the detected objects with sufficient observations for orbit determination. Thus the estimates of the populations of planet-crossing asteroids should be regarded as lower limiting bounds.

Mars-crossing asteroids are subdivided in Table 2 into two categories, moderate to shallow Mars-crossers and Mars-"grazers." This is done because two out of the six Mars-crossers discovered in the PCA survey, Cline and 1973SA, just barely cross the orbit of Mars on rare occasions during the cycle of secular perturbation of their orbits (J. G. Williams, personal communication, 1977). For asteroids of this type there is a very low probability of close encounters with Mars, and there is little chance that they can evolve into Earth-approaching asteroids, except as fragments from collisions.

Also listed in Table 2 are estimates of the populations (cumulative number to B(1,0) = 18) of Earth-crossers, Amors, and shallower Mars-crossers obtained by Wetherill (1976) using different methods. For typical values of B-V near 0.8 for planet-crossing asteroids, the cumulative number of asteroids to V(1,0) = 18 will be about twice the number to B(1,0) = 18, for any given orbital class. Within the uncertainties, Wetherill's estimates agree with those derived here from discoveries in the systematic surveys.

Another check on the population of Earth-crossers is provided by the cratering history of the Earth and the Moon. As shown by Shoemaker (1977) the number of craters 10 km in diameter and larger on 3.3 billion year old mare surfaces on the Moon and the number of large impact structures found on the craton of North America are consistent with the flux of Earth-crossing asteroids calculated from the population of Earth-crossers given in Table 2.

It may be seen from Table 2 that only a few percent of the Earth-approaching asteroids to absolute magnitude 18 and about 1% or less of the Mars-crossers have been discovered. Earth-crossing asteroids may be slightly more numerous than Amors, and Mars-crossers are about an order of magnitude more numerous than either Amors or Earth-crossers.

ORIGIN AND ORBITAL EVOLUTION OF PLANET-CROSSING ASTEROIDS

At least two different kinds of bodies probably are represented among the known Earth-approaching asteroids: (1) objects or fragments of objects which reside in or were derived from the main asteroid belt, and (2) nonvolatile residua or cores of the nuclei of extinct periodic comets. The former category includes objects which were on Mars-crossing orbits to start with or were initially close to regions of secular resonance or of low order commensurability with Jupiter. The second category of bodies is derived ultimately from much more distant parts of the solar system. Periodic comets are captured from the Oort cloud and perhaps nearer regions of the solar system by close encounters with Jupiter; a small fraction of these periodic comets is trapped in very short period orbits with aphelion distances near 4 AU by a combination of Jupiter encounters and nongravitational forces. An example of such a comet is P/Encke. Whatever nonvolatile residue may remain from such objects after 10^3-10^4 years will be asteroidal in appearance. As a consequence of encounters with the terrestrial planets, further evolution of the orbits of both "asteroidal" and "cometary" near-Earth objects, particularly of Earth-crossers, results in an extensive overlap of the orbital characteristics of the two classes of objects.

As Earth-approaching asteroids are derived, in part, from shallower Mars-crossers, it is of interest to examine first the origin of these latter objects, which are the most numerous of the planet-crossing asteroids. Typical dynamical lifetimes of Mars-crossers are of the order of 1-2 AE (Wetherill, 1976). Hence, many Mars-crossers probably have remained on Mars-crossing orbits since the principal period of planetary accretion. Such objects can be viewed as unaccreted planetesimals of Mars. The dynamical lifetime almost certainly exceeds the fragmentation lifetime of most Mars-crossers near V(1,0) = 18; asteroids in this size range probably are produced chiefly by relatively recent collisional fragmentation of larger Mars-crossers. The estimate of the population of Mars-crossers to V(1,0) = 18, given in Table 2, is extrapolated from observations of larger asteroids on the basis of an assumed magnitude distribution law which, as shown by Dohnanyi (1971), corresponds approximately to an equilibrium fragmentation distribution.

Small Mars-crossers may also be derived by fragmentation of asteroids adjacent to surfaces of secular resonance in the asteroid belt discovered by Williams (1969), or asteroids near the Kirkwood gaps, in particular the gap at the 3:1 commensurability with Jupiter. Mechanisms by which meteorite-sized fragments can be injected from these regions in the main belt into planet-crossing orbits have been described by Zimmerman and Wetherill (1973), Scholl and Froeschlé (1977), and Wetherill (1977). Multiple collisions are required for injection from the margins of the Kirkwood gaps at the 2:1 and 5:2 commensurabilities, and it appears unlikely that more than a few kilometer-sized Mars-crossers can be derived in this way. Main belt asteroids near surfaces of secular resonances, on the other hand, may be an important source of small Mars-crossers, and many known Mars-crossers lie close to these surfaces (Williams, 1971). For example, two out of six Mars-crossers listed in Table 1 lie very close to secular resonances; 1974UA lies adjacent to the Hungaria region, near $\dot{\tilde{\omega}} = \nu_5$, and 1974UB is near $\dot{\Omega} = \nu_{16}$ (Figure 1); 1973SA, near the Flora region, is moderately close to $\dot{\tilde{\omega}} = \nu_6$ (Williams, personal communication, 1978). None of the Mars-crossers discovered in the PCA survey are far removed from a secular resonance.

A significant fraction of the Mars-crossers is possibly derived from extinct comets. A list of half a dozen Mars-crossers with aphelion distance, Q, near 4 AU given by Marsden (1971) and a similar list by Sekanina (1971) may include objects of cometary origin. Close encounters with Mars can reduce Q, moreover, so that some Mars-crossers with less eccentric orbits may also be extinct comets.

A large fraction of the Amor asteroids is, evidently, derived from shallower Mars-crossers. If the Amors were in dynamical equilibrium with Mars-crossers, then the ratio of the number of shallow Mars-crossers should equal the ratio of their respective lifetimes (Öpik, 1963). As seen from Table 2, the ratio of Amors to shallow Mars-crossers is about 1/20 to 1/10, whereas the ratio of the lifetimes of Amors to those of shallow Mars-crossers is about 1/10 to 1/5 (Wetherill, 1976). The number of Amors appears to be slightly low for dynamical equilibrium, but the discrepancy is within the uncertainty of estimation.

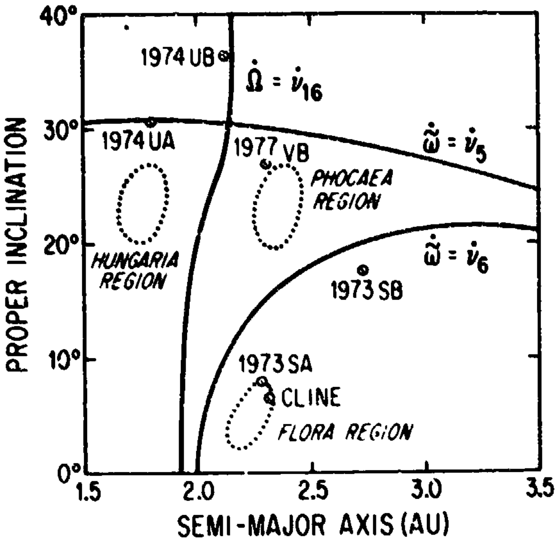

Fig. 1. Surfaces of secular resonance in the asteroid belt (after Williams, 1969) and position of Mars-crossing asteroids discovered in the PCA survey.

A significant number of the Amors, perhaps even the majority (Wetherill, personal communication, 1978) may be of cometary origin. The most likely extinct comet among the known objects is Betulia, which has a maximum Q of 3.9 AU and a present orbital inclination of 52°. Its Jacobi constant with respect to Jupiter suggests it may be a cometary object (Kresak, 1977). It should be noted, however, that Betulia, at times, crosses not only the orbits of Mars and the Earth, but also the orbit of Venus. By close encounter with Mars, Earth, or Venus the Jacobi constant with respect to Jupiter can change abruptly, and the orbit of Betulia can become less or more comet-like with time.

Earth-crossing asteroids, in contrast to the Amors, are clearly not in dynamical equilibrium with shallow Mars-crossers nor are they in direct equilibrium with the Amors. The typical lifetime of Earth-crossers was reported as 0.5×10^8 yr, by Wetherill and Williams (1968) and as $\sim 0.2 \times 10^8$ yr by Wetherill (1976). If Earth-crossers were derived entirely from shallow Mars-crossers and were in equilibrium with Mars-crossers, they should be about 50-100 times less numerous than Mars-crossers and about 10 times less numerous than Amors. The figures in Table 2 show that this is not the case. There are too many Earth-crossing asteroids.

The excess of Earth-crossing asteroids can be seen very simply in another way. If all Earth-crossers were in dynamical equilibrium with Amors, then, with decreasing q, there would be a relatively rapid, order of magnitude drop in the number of asteroids near the threshold of Earth-crossing. The reason for this is that the probability of collision or ejection of an Amor from the solar system as a consequence of encounters with Mars is much smaller than the probability of collision or ejection of an Earth-crosser as a consequence of encounters with the Earth. This is so primarily because the Earth is an order of magnitude more massive, and, therefore, gravitationally an order of magnitude more active than Mars. Contrary to expectation, however, the number of Amors and Earth-crossing asteroids is nearly uniformly distributed as a function of q. There is roughly an equal population of Amors, with q between 1.0 and 1.3 AU, and of Earth-crossers with q between 0.7 and 1.0 AU. Among the discovered objects there are 20 Amors with reasonably well defined orbits in the range $1.0\ \mathrm{AU} < q < 1.3\ \mathrm{AU}$ and there are 14 Earth-crossers with $0.7\ \mathrm{AU} < q < 1.0\ \mathrm{AU}$.

The distribution of asteroids by q in the vicinity of 1 AU appears to be explicable only if the majority of Earth-crossers have been injected more or less directly into Earth-crossing orbits from some source other than Mars-crossers. Progressive evolution of typical Mars-crossers into Earth-crossers may account for, at most, 10-20% of the

Earth-crossers. The remainder must be derived chiefly from somewhat deeper regions of the asteroid belt or from comets. Collision debris from asteroids near the secular resonances can be injected directly into Earth-crossing orbits (Williams, 1973a,b). For the cases studied so far, a few percent of the ejecta becomes directly Earth-crossing (Williams, personal communication, 1978). Other Earth-crossing objects are derived from perturbation by Mars of Mars-crossing debris which was not initially injected as deeply into a resonance (Wetherill, 1977). The combination of direct injection into resonant Earth-crossing orbits and the secondary perturbations by Mars produces one Apollo for every three Amors derived from the secular resonances (Wetherill, personal communication, 1978). A few tens of percent of the Earth-crossing asteroids may be derived this way. Collision fragments derived from the margins of the 2:1 and 5:2 Kirkwood gaps may be injected directly into Earth-crossing orbits, but, because two collisions are required for this, the yield of kilometer-sized bodies probably is very low. So far as the celestial mechanics of the asteroid belt is presently understood, there appear to be no other likely sources of Earth-crossers among the asteroids. A remaining probable source of Earth-crossing asteroids is the family of short-period comets.

All but a few periodic comets are Jupiter-crossing and have extremely short dynamical lifetimes. The Jupiter-crossing comets are unlikely to be captured into very short period orbits by close encounters with terrestrial planets, although this must happen on rare occasions and may produce a few planet-crossing asteroids. A few comets, such as P/Temple 2, P/Clark, P/Grigg-Skjellerup and P/Encke have aphelia inside the orbit of Jupiter. All of these except P/Encke, however, pass within the sphere of influence of Jupiter, and they have a very high probability of being ejected by Jupiter from the solar system. Evidently from the action of nongravitational forces, the aphelion distance of P/Encke has been reduced to 4.1 AU (Sekanina, 1971), a critical threshold below which comets and asteroids are relatively safe from ejection. Comets entering this safe region have much longer dynamical lifetimes, which will permit a significant fraction to be captured into still smaller orbits by encounters with the terrestrial planets.

Two comets in moderately stable orbits appear to be nearly extinct: P/Arend-Rigaux and P/Neujmin 1 have been asteroidal in appearance during recent apparitions, although observations of P/Arend-Rigaux in 1977 revealed a very weak coma and tail (Degewij, 1978). Secular variation of the nongravitational acceleration of P/Encke suggests it may become extinct in 60-70 years (Sekanina, 1972), leaving a kilometer-sized inactive body. The asteroid Hidalgo is Jupiter-crossing and is very probably an extinct comet. Hence there is little doubt that a few comets, at least, are capable of evolving into planet-crossing asteroids, by progressive loss of their volatile constituents during perihelion passages.

The question remains whether the supply of comets entering safe orbits is adequate to sustain the population of Earth-crossing asteroids. It is difficult to give a reliable answer to this question as there is only one known example of such a comet. The population of Earth-crossers to magnitude 18 is roughly 10^3, and they have a mean lifetime near 2×10^7 years. A new magnitude 18 or brighter Earth-crosser must be supplied roughly once every 2×10^4 years to maintain the population in steady-state. Marsden (1971) has estimated that the lifetime of activity of a short-period comet is of the order of 10^3 to 10^4 years. It would be a matter of luck, then, to discover a short-period comet, with a nucleus brighter than magnitude 18, in the process of decaying into an Earth-crossing asteroid. P/Encke appears to be an example of just such a comet (Sekanina, 1971). Within the lifetime of persons now living, P/Encke may join the group of objects which, by the standard criteria of telescopic observation, we recognize as Apollo asteroids.

Finally, it is of interest to examine the orbits of the known Earth-crossing asteroids to see which ones are most comet-like. 1973NA has an aphelion distance of 4.0 AU and an inclination of 68°. Its Jacobi constant with respect to Jupiter is comparable to that of many periodic comets and suggests a cometary origin for this object (Kresak, 1977). With much less confidence, a similar case can be made for Sisyphus, 1981, and 1974MA. Adonis, Antinous, 1976WA, and PLS 6334 all have Q near 4 AU and might also be relatively unevolved extinct comets. These criteria should be used with caution, however. Some asteroids injected by collisions into the Kirkwood gaps or into secular resonances can acquire aphelion distances near 4 AU. Encounters with the terrestrial planets, moreover, greatly modify the orbits of Earth-crossers. Asteroids with very small orbits can be derived from comets with orbits like that of Encke, and objects originating as typical Mars-crossers can be placed on comet-like orbits.

COMPOSITIONAL TYPES AMONG THE EARTH-APPROACHING ASTEROIDS

Precise physical observations have been made on 14 near-Earth asteroids. On the basis of the available data, the Earth-crossing asteroid population appears to be different from the Amor population. The number of Earth-approaching asteroids for which physical observations are available is still very small, however, and it is premature to draw firm conclusions about the differences or the similarities of physical characteristics between the Amors and Earth-crossers on the basis of this small sample.

UBV photometry represents the most complete set of physical observations obtained on the Earth-approaching asteroids (Figure 2). Amor asteroids are distributed over a

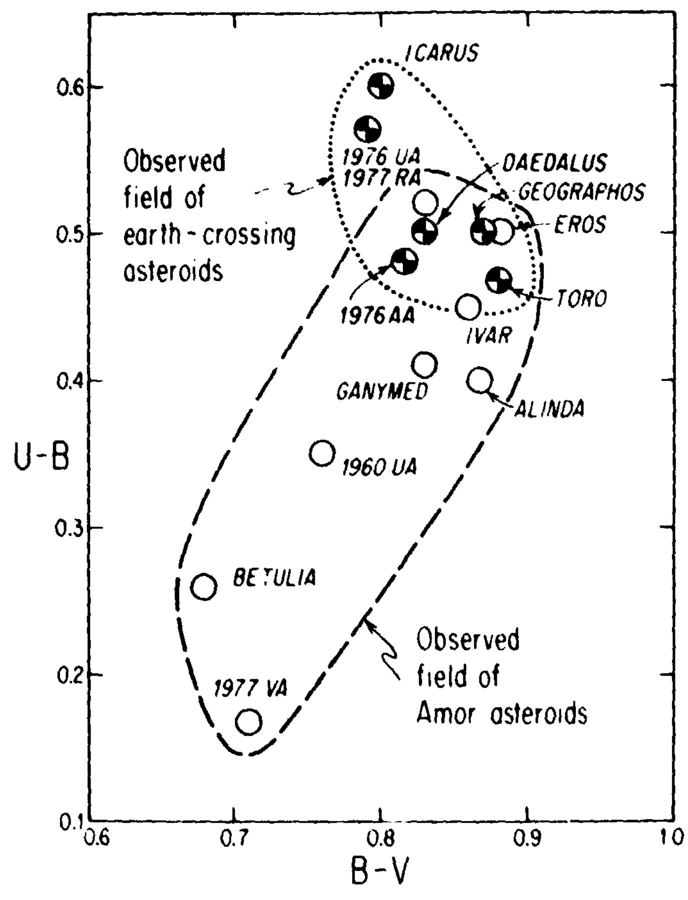

Fig. 2. UBV colors of Earth-approaching asteroids. Amor asteroids are shown with an open circle and Earth-crossers with a target symbol. Data are from TRIAD file and from Degewij (1977), and Degewij *et al.* (1978).

Table 3. Classification of Earth-Approaching Asteroids by Compositional Type

Amor Asteroids			Earth-Crossing Asteroids		
	Compositional Type	Reference		Compositional Type	Reference
433 Eros	S	2	1566 Icarus	O	2
887 Alinda	S	2	1620 Geographos	S	2
1036 Ganymed	S	2	1685 Toro	U	2
1580 Betulia[1]	C	2	1864 Daedalus	O	2
1627 Ivar	S	2	1976AA	S?	5
1977RA	S?	3	1976UA	O?	6
1977VA	M? or E?	4			

[1]Although listed as an Amor asteroid, Betulia is Earth-crossing part of the time. 1960UA may also be Earth-crossing part of the time.

[2]Zellner and Bowell (1977).

[3]Based on data from Degewij, *et al.* (1978).

[4]Based on data from Degewij (1977).

[5]Based on data from Gradie (1976).

[6]Based on data from Zellner and Bowell (unpublished).

broad field in the U-B versus B-V color domain. Earth-crossing asteroids, on the other hand, occupy a smaller field which is characterized by relatively high U-B values (excluding, for the moment, the special asteroid Betulia). Most Amors with UBV colors close to the Earth-crossing asteroid field are classed as S-type asteroids by Zellner and Bowell (1977) and Zellner (1978) (see Table 3). The predominance of S-type asteroids among the Amor group is consistent with the derivation of these objects primarily from shallower Mars-crossers, as suggested by dynamical considerations. As shown by Chapman *et al.* (1975), Morrison (1977) and Zellner and Bowell (1977), S-type asteroids are the dominant type on the inner edge of the main asteroid belt, the principal region from which shallow Mars-crossers are, in turn, derived.

Only one Earth-crosser, Geographos, is certainly an S-type asteroid. Besides Geographos, the Apollo asteroid Toro falls within the Amor asteroid UBV field, but Toro is distinguished on other physical characteristics from S-type Amors. The Earth-crossers 1976AA and Daedalus lie on the margin of the S field as defined by Zellner (1978). Daedalus was classified as an O-type asteroid, along with Icarus, by Zellner and Bowell (1977) although polarimetric albedo determinations used by them in distinguishing this class have now been revised. Icarus and 1976UA, which show extreme values of U-B, near 0.6, and intermediate values of B-V, near 0.8, are clearly distinct from S-type asteroids and from all measured Amors.

It has been widely supposed that extinct cometary nuclei might resemble C-type asteroids. The basis for this expectation is the belief that comets are very primitive objects and that C-type asteroids are similar to carbonaceous meteorites, which are the most primitive meteorites recovered. If many Earth-approaching asteroids are of cometary origin, it is plausible that some or perhaps most carbonaceous meteorites are derived from extinct comets.

Recently, more direct evidence has been obtained which strengthens the supposition that the relatively nonvolatile constituents of comets are carbonaceous. A team of investigators headed by D. E. Brownlee has succeeded in collecting substantial numbers of small particles of extraterrestrial origin from the stratosphere (Brownlee *et al.*, 1976; Brownlee *et al.*, 1977). Most of these particles resemble carbonaceous meteorites in composition but are very different in structure. The presence of large concentrations of ^{4}He (Rajan *et al.*, 1977) shows that they entered the Earth's atmosphere as small particles. Comets are the most likely source for interplanetary particles of this type.

A second and more direct observation linking comets to C-type objects is the UBV photometry of the asteroid Hidalgo reported by Degewij *et al.* (1977). This object, although asteroidal in appearance, is almost certainly an extinct comet (Kresak, 1977); its orbit is Jupiter-crossing and resembles the orbits of active periodic comets. It has a low albedo and its UBV color lies on the margin of the field for C-type asteroids.

No more than two out of 14 Earth-approaching asteroids studied to date are of the C type. Betulia is an unequivocal C-type asteroid (Lebofsky *et al.*, 1978; Tedesco *et al.*, 1978). Because its present perihelion distance is greater than 1.017 AU, it is generally listed among the Amors, but as shown by Wetherill and Williams (1968), large oscillations in eccentricity and inclination of the orbit of Betulia are produced by secular perturbations; more than half of the time Betulia is Earth-crossing. The Jacobi constant of Betulia relative to Jupiter suggests it could be a relatively recent extinct comet.

The Amor object 1960UA may also be a C-type asteroid, but the observations are insufficient for classification. Its UBV color is on the margin of the C field; observation of its albedo will be required to determine whether or not it is of the C type. The perihelion distance of the orbit of 1960UA is less than the maximum aphelion distance of the Earth, and it may be Earth-crossing part of the time. The present aphelion of 1960UA is 3.5 AU; its orbit could have evolved from one more like that of P/Encke by a succession of encounters with the Earth or Mars.

The paucity of C-type asteroids among the Earth-crossers seems to be in conflict with the dynamical arguments for cometary origin of a major fraction of Earth-crossers. This conflict may be more apparent than real, however. Two selection effects discriminate against observation of C-type objects among the Earth-crossers. First, among asteroids of the same size, C-type objects are fainter and therefore are less likely to be observed. This selection effect led to serious underestimation of the abundance of C-type asteroids in the initial studies of the main belt. Half of the Earth-crossers studied to date are, in fact, among the brighter known. However, none of the intrinsically faint objects--Icarus, 1976AA, and 1976UA--are of the C type. Secondly, there is a strong bias in the existing observations of Earth-crossers with regard to the semimajor axes of the asteroids. All of the Earth-crossers for which UBV or other physical observations have been made have semimajor axes less than 1.5 AU (*i.e.*, less than the semimajor axis of Mars). The observed objects all lie within the first 45th percentile of the semimajor axis-cumulative frequency distribution of Earth-crossers (Figure 3). This bias is partly related to the fact that objects with semimajor axes close to that of the Earth tend, on the average, to move slowly with respect to the Earth, and therefore are easier to observe. This circumstance made possible extended observations of 1976AA during its discovery apparition, for example. Part of the bias is also due to the fact that the first three asteroids for which secure orbits were obtained, apparently by chance, had small semimajor axes; because the orbits were well determined, observational campaigns were mounted for these asteroids during close passes to the Earth.

As shown by Monte Carlo simulations of orbit evolution by close encounters with the terrestrial planets (Wetherill, 1977 and personal communication, 1977), asteroids with initial orbits like those of typical Mars-crossers are more likely to be perturbed into orbits with small semimajor axes than are extinct comets with orbits like that of P/Encke. The proportion of Earth-crossers of asteroidal origin, therefore, should be highest among

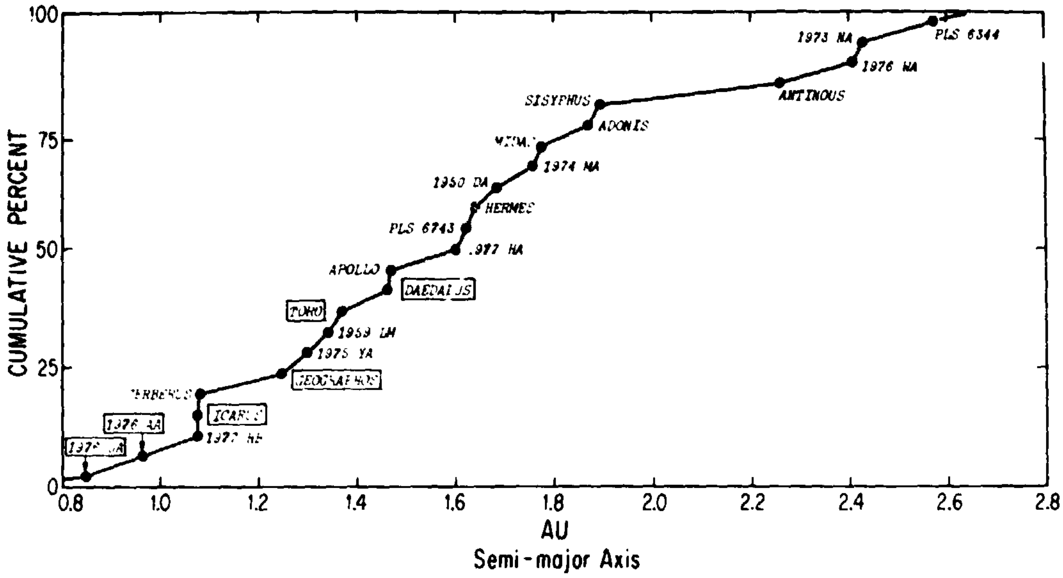

Fig. 3. Frequency distribution of semimajor axes of Earth-crossing asteroids. Names of asteroids for which UBV observations have been made are shown with boxes.

the objects of small semimajor axis, where the S-type object Geographos and possible S-type 1976AA are, indeed, found. A larger fraction of Earth-crossers of large semimajor axis (right-hand side of Figure 3), on the other hand, probably are of cometary origin.

It should be borne in mind that comet nuclei may have much greater spectrophotometric diversity than is commonly supposed. One particular mechanism by which diversity might arise is suggested by the orbital characteristics of Icarus and 1976UA, two objects which have nearly the same UBV color and which have extreme U-B values. At perihelion, Icarus approaches within 0.18 AU of the surface of the Sun. At this distance the peak temperature of a blackbody of low thermal inertia and an albedo of the order of 0.2 or less be about 600°C. Gibson (1976) has shown that about 50% of the carbon is lost from the carbonaceous meteorite Murchison by heating to 600°C for three days. At 900°C (corresponding to a perihelion distance of about 0.1 AU) 95% of the carbon is driven off. Thus, the albedo and color of Icarus may have been altered significantly by repeated close approach to the Sun, especially if its perihelion distance were once somewhat less than it is at present. It is conceivable that Icarus was once a C-type object. 1976UA presently grazes the orbit of Mercury at perihelion (q = 0.464). At this distance, maximum temperatures are of the order of 270°C, which probably are too low to expel much carbon from the surface. It is entirely possible, however, that the perihelion distance of 1976UA was also at one time much smaller.

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DISCUSSION

ANDERS: Is it fair to compare the numbers of Apollos and Amors? Shouldn't one instead compare masses of the two populations, because fragmentation goes on all the time? The number doesn't stay constant during the time the Mars-crosser supposedly evolved to an Apollo. More likely one Mars-crosser gives several Apollos just by fragmentation.

SHOEMAKER: The numbers are all given to the same magnitude (and hence size) limit, and the magnitude-frequency distribution observed for main belt asteroids was used in calculating the number of V(1,0) = 18. it appears that this magnitude-frequency distribution is approximately an equilibrium fragmentation distribution. Hence the effect of fragmentation of Mars-crossers is taken into account.

ANDERS: Then you are integrating to a larger size limit for the Mars-crossers than for the Apollos.

WETHERILL: It is not necessary to consider fragmentation, as the ν_6 resonance has the effect of rapidly equilibrating the Apollo and Amor populations. They should have nearly the same steady-state size distributions, except for objects like 1036 which is in an unusually stable orbit for an Amor. In addition to considering the Amor/Apollo ratio, it is also possible to calculate the rate at which Apollos and Amors are produced from the large main belt asteroids. I think you could make 10% of them without too much trouble. But to make more than half seems very difficult.

ANDERS: The paradox is not as great as it was ten years ago. You should try to apply a correction for fragmentation and see how much of a discrepancy remains. I think your factor of ten will be reduced by fragmentation.

WETHERILL: I think the difference between ten years ago and now is that we have identified new mechanisms to transport objects from the main belt to Earth-approaching orbits. This decreases the discrepancy to something like a factor of ten rather than a factor of 100. On the other hand, I think the factor of ten is much better established; it's a much more sophisticated number.

ANDERS: Part of the problem is that, at the moment, the statistics on Mars-crossers rest on four objects.

SHOEMAKER: There are two estimates in Table 2. One is based upon the four discovered objects, the other on a larger set of arguments. I think the estimates are reasonably congruent, and neither is likely to be off by more than a factor of ten. If Apollos were really derived by a process which generally involves an evolution of Mars-crossers into Amors, although not in every case, then you would expect to see a much larger number of Amors in proportion to the Apollos.

NIEHOFF: There could be another explanation for the discrepancy, and that is when an object becomes an Apollo, its lifetime goes up for some yet unexplained reason.

ANDERS: If the dynamicists are correct, and I think they are, there is no gimmick except a very odd resonance occasionally.

WETHERILL: Apollos are not in that kind of resonance.

SHOEMAKER: You might invoke some resonances like that found for 1685 Toro, which would slightly extend the lifetimes.

ARNOLD: Other possible mechanisms for the origin of Apollos and Amors are also going to be called upon to explain why they are roughly equal in number. These other models might also give you the correct ratio of Mars-crossers to main belt asteroids. Suppose they are made from comets or something; once they cross the orbit of the Earth they are much more vulnerable, their lifetime gets much shorter. So again there is a discrepancy.

WETHERILL: There is something to what you say. However, comets are more likely to have an aphelion near Jupiter, so their lifetime is also shortened by interactions near aphelion as well as by Earth-crossing. To really make it work, you have to say that a comet with a small perihelion is more likely to be decoupled from Jupiter by nongravitational effects into an orbit like that of Comet Encke than are ones with a larger perihelion. This may not be the case because the total amount of gas loss, *i.e.*, the integral of the nongravitational forces, should be the same. But it could be that the process is nonlinear, that getting near the Sun changes the lag angle or something like that in such a way it favorably places extinct comets into orbits with small periods.

ARNOLD: The first explanation is likely to be perhaps a 20% effect. The second may not be right either, but it is well worth investigating.

SHOEMAKER: The anomalous ratio of Apollos and Amors is the principal argument for invoking cometary sources for the majority of those asteroids.