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POPULATIONS OF PLANET-CROSSING ASTEROIDS AND THE RELATION OF APOLLO OBJECTS TO MAIN-BELT ASTEROIDS AND COMETS

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From discoveries made in several independent surveys of the sky, the number of Apollo asteroids to absolute visual magnitude 18 is estimated to be of the order of 10^3; the ratio of Mars-crossing asteroids to Apollos is estimated to lie between 10 and 60. The loss of Apollos to magnitude 18 over the last 3 billion years, by collision with the planets and ejection from the solar system, is estimated to have been several times 10^4 objects. Mars-crossing asteroids appear to be an inadequate source for all of these objects. Most Apollos probably are dead short-period comets.

The origin and dynamical lifetime of asteroids whose orbits cross or loop through the orbits of one or more of the planets has been the subject of speculation and debate, at least since the discovery in 1932 of Apollo, the first asteroid found that crosses the orbit of the Earth. One approach to evaluating the origin of Apollo objects is to estimate 1) the population of these objects, 2) the rate of loss of objects by collision or ejection from the solar system, and 3) the rate at which new objects can be supplied from various sources (Öpik 1963). If the population is approximately in equilibrium, as suggested by the cratering record on the Earth and Moon, then the postulated sources must be adequate to make up the losses. We have been engaged in a systematic search for planet-crossing asteroids over the past 4 years with the goal of estimating both the populations of various orbital classes of these objects and the rates at which they collide with the planets (Shoemaker and others, in press).

On the basis of three Apollo asteroids discovered in our own survey plus four other Apollos discovered in two other systematic surveys of the sky, we estimate that the number of Apollo asteroids to absolute visual magnitude 18 is 800 ± 400. This estimate is derived from a statistical model of the distribution of Apollo objects in space and an estimate of the volume of space searched for asteroids of a given absolute magnitude in each survey. Our model of the space distribution of the Apollos is derived from the orbital elements of 20 known Apollos for which orbits of usable precision are available. The volume of space searched for objects of a given magnitude is estimated from the area of sky covered in each survey, the frequency distribution of directions with respect to

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the sun for which this coverage has been obtained, the average phase function, determined from a small number of well-observed Apollos, and the magnitude limit for detection of moving objects for a given survey. The form of the phase function of the Apollos at small phase angles has been adopted from that found for main-belt asteroids by Gehrels (1970). The error in the estimated population depends primarily on the small number of objects found under known conditions of search and on errors in our estimate of the magnitude threshold of detection in each survey. Statistical uncertainties in our model of the space distribution of Apollos and uncertainties in the estimates of the volume of space searched are subordinate sources of error.

An estimated rate of collision of Apollo objects with each of the terrestrial planets and with the Moon can be calculated by means of equations of Öpik (1951) from our estimate of the population of these objects. In this calculation, the point of view is adopted that, while the orbits of individual Apollos undergo secular perturbations and also change more drastically as a result of close encounters with the planets, the statistical distribution of orbital elements for the entire population remains nearly invariant. The osculating orbital elements for 20 known Apollos is then assumed to be a representative sample of the steady-state distribution of the elements of the population. The calculated rates of loss of Apollos by collision with the terrestrial planets are as follows:

	Mean collision probability per 10^9 yr	Loss of Apollos to visual magnitude 18 per 10^9 yr
Mars	0.3	~ 200
Earth	4.5	~ 3600
Venus	2.5	~ 2000
Mercury	0.2	~ 200
Moon	0.2	~ 200
Total	7.7	6200 ± 3100

Apollos are also lost as consequence of close encounters with the terrestrial planets that place the Apollo objects either on Jupiter-crossing orbits or on orbits with aphelion distances less than the perihelion distance of the Earth. Those objects placed on Jupiter-crossing orbits are eliminated very rapidly either by collision with the Jovian planets or by ejection from the solar system. The process of occasional strong perturbations during close encounters has been simulated on the computer by Monte Carlo methods (Anders and Arnold 1965; Arnold 1964 and 1965; Wetherill 1968 and 1969; Wetherill and Williams 1968). When the correct formula for deflection of an Apollo by a close planetary encounter is used, the combined losses by collision with the Jovian planets and by ejection is about the same as the losses by collision with the terrestrial planets.

Those objects which are deflected by close encounters with Venus or Mercury into orbits that are too small to cross the orbit of the Earth are essentially lost from view. No objects with this type of orbit are likely to have been found, under past circumstances of discovery of faint asteroids, and none have been discovered. A significant fraction of the Apollos must be deflected into these very small orbits, nevertheless, as shown by the Monte Carlo simulations (Wetherill, personal communication). This process leads in turn, to permanent losses of Apollos by collision with Venus and Mercury that are not accounted for in the table above. Combining the losses by all processes, the total current loss rate of Apollo objects to visual magnitude 18 is, very roughly, 10^4 objects per billion years.

The equations of Öpik (1951) which we have used are based on the assumption that, over a long period of time, the arguments of perihelion of the Apollo objects are randomly distributed. Observed resonances in the perturbations of the orbits of Apollos, however, make this assumption invalid in certain specific cases. Thus it is of interest to compare the calculated collision rates with the geologic record of cratering on the Earth and on the Moon. The contribution of active comets to the total production of impact craters on the Earth and the Moon is estimated to be at least an order of magnitude less than that of Apollo asteroids and, therefore, does not need to be reckoned in making rough comparisons. Adopting a mean visual geometric albedo of 0.2 and a density of 3.3 gm/cm^3 for Apollo objects, the production rate of impact craters 10 km in diameter and larger is $(0.7 \pm 0.4)10^{-14}$ km^{-2} yr^{-1} on Earth and $(0.6 \pm 0.3)10^{-14}$ km^{-2} yr^{-1} on the Moon. This may be compared with an average rate of production of craters 10 km in diameter and larger in the central United States of $(2.2 \pm 1.1)10^{-4}$ km^{-2} yr^{-1} during the last half billion years, estimated from the occurrence of 4 structures thought to correspond to impact craters at least 10 km across in an area of 770,000 km^2. The rate of collision of Apollos calculated with aid of Öpik's equations appears to be comparable to or slightly below the rate indicated by this small sample of the impact record on Earth. Our analysis of the record of craters on the lunar maria yields an average rate of production of craters 10 km in diameter and larger for the last 3.3 billion years of $(0.6 \pm 0.3)10^{-14}$ km^{-2} yr^{-1}, which is indistinguishable from the present rate of cratering calculated from the Apollo objects.

A source or sources appear to be required for several tens of thousands of Apollo objects during the last 3 billion years. Probably they have been supplied partly by strong perturbation of Mars-crossing asteroids during close encounters with Mars, and partly from nonvolatile cores or other parts of the nuclei of short-period comets.

On the basis of three Mars-crossing asteroids and two possible very shallow Mars-crossers found in our systematic survey, we estimate that the present total number of Mars-crossers to absolute visual magnitude 18, including those asteroids that are only rarely Mars-crossing, lies between about 10,000 and 50,000. The number of Mars-crossers remaining, in other words, is of the same order as the number of Apollos lost during the last 3 billion years. If Mars-crossing asteroids were the sole source of Apollos, we should expect to see a decline in the lunar and terrestrial cratering rates during this time, unless the population of Mars-crossers is, itself, in equilibrium. The population of Mars-crossing asteroids may be partially sustained by collisional fragmentation and slight dispersion of the fragments from asteroids in otherwise stable orbits along the Mars-crossing boundary of orbit phase space mapped by Williams (1969 and 1971). Some Mars-crossers also may be derived from degassed short-period comet nuclei (Marsden 1971, Sekanina 1971).

Öpik (1963) and Wetherill and Williams (1968) have calculated that the ratio of Mars-crossing asteroids to Apollos must be in the neighborhood of 300 to 500 in order to maintain the population of Apollos in equilibrium solely by perturbation of Mars-crossers. The true ratio appears to be an order of magnitude lower. The processes of perturbation of Mars-crossers into Earth-crossing orbits by close encounters with Mars are complex, however, and should be studied further.

Assuming that the population and the statistical distribution of orbital elements of Apollo objects is in equilibrium and that our present sample of Apollo orbits is not seriously biased, we find that the harmonic mean lifetime of the Apollo objects is about 10^8 years. This mean lifetime is about twice the mean lifetime found by Wetherill and Williams (1968) by Monte Carlo simulations of the dynamical history of individual Apollos. Part of the difference arises from the fact that the mean inclination of the 20 Apollos now known is about 50 percent higher than the mean inclination of 10 Apollos (including Betulia as an Apollo) studied by Wetherill and Williams. Most of the reamining difference arises as a result of our neglecting the loss of Apollos by deflection into very small non-Earth-crossing orbits and subsequent collision with Venus and Mercury.

Finally, we may inquire whether short-period comets are an adequate source for Apollo objects. If the lifetime of activity of a short-period comet is of the order of 10^3 to 10^4 years, as suggested by Marsden (1971), then the ratio of Apollo objects to short period comets on their way to becoming Apollos should be on the order of 10^4 to 10^5. As the population of Apollos to magnitude 18 is only about 10^3, it would be somewhat surprising actually to find an active comet in the process of decaying to an Apollo of magnitude 18 or brighter. Sekanina (1971) has suggested that P/Encke is an example of such a comet. If this is true, the supply of dead comet nuclei may well be adequate to maintain the population of Apollos in equilibrium.

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