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The Origin of Apollo Objects

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Recent evidence for periodic showers of comets passing through the solar system suggests a new mechanism for the creation of the Apollo objects. The collisions of the comets with the asteroid belt will generate a sufficient number of objects with the size and orbit of the Apollo objects to account for the observed population.

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The source of the Earth-orbit-crossing asteroids has been much debated. (This class of asteroidal bodies includes the Apollo, Aten, and some Amor objects, each with its own orbital characteristics; we shall use the term Apollo objects to mean all Earth-crossers.) It is difficult to find a mechanism which would create new Apollo objects at a sufficient rate to balance the loss due to collision with planets and ejection from the solar system, and thus explain the estimated steady-state number. A likely source is the main asteroid belt, since it has similar photometric characteristics. There are gaps in the main belt which correspond to orbits resonant with the orbits of Jupiter and Saturn, and it has been shown that the resonances can perturb a body into an Earth-crossing orbit[1]. Apollo objects could thus be generated when random collisions between asteroids in the main belt sent fragments into these resonant orbits. Calculations of the creation rate from these random collisions, however, yield numbers too low by a factor of four[2]. This rate could be significantly lower given the uncertainty in the efficiency of the resonance mechanism.

As an alternative, it was suggested that the evaporation of a comet's volatile mantle as it passes near the sun could provide enough non-gravitational force to move the comet into an orbit with aphelion inside of Jupiter's orbit, and thus safe from ejection from the solar system[2]. The probability of such an event occurring is unknown, although the recent discovery of the "asteroid" 1983 TB, with an orbit matching that of the Geminid meteor shower, suggests that such a mechanism has occurred at least once. New evidence from paleontology and geophysics, however, suggests a better solution to the problem of the source of the Apollos.

M. Davis, P. Hut, and R. A. Muller[3] recently proposed that an unseen companion to the sun passes through the Oort cloud every 28 million years, sending a shower of comets to the Earth; this provides an explanation for the periodicity of the fossil record of extinctions found by D. M. Raup and J. J. Sepkoski[4]. W. Alvarez and R. A. Muller[5] have shown that the craters on the earth have an age distribution with a periodicity and phase consistent with this hypothesis. These periodic comet showers would of course pass through the entire solar system, colliding with other bodies besides the earth. When the target is the asteroid belt, many small comets will have sufficient kinetic energy to disrupt large asteroids. This will generate many more fragments in the resonant orbits than would be generated by random collisions of asteroids with each other, and hence more Apollo objects.

In the following, we shall calculate approximately (A) the number of comets per shower which cross the asteroid belt, (B) the probability of collisions with a single asteroid per shower, (C) the number of fragments with radius > 0.5 km which reach Apollo orbits, and (D) the current expected number of Apollos derived from comet-asteroid collisions. Given conservative assumptions, the calculated number is in agreement with observations.

(A) The Number of Comets per Shower

For each periodic perturbation of the Oort cloud, Davis, Hut, and Muller calculate that the number of comets which come within a distance q of the sun is

$$N_q = N_o \, (2q/a) \tag{1}$$

where N_o is the number of comets in the inner Oort cloud, and a is the distance to the inner Oort cloud. We observe present day comets perturbed into the solar system from the outer Oort "halo," not the inner Oort cloud, and thus direct estimates of comet population are for the outer halo. J. G. Hills[6] has calculated the number of comets in the inner cloud necessary to account for the number in the outer halo. He found that at least two orders of magnitude more comets are in the inner Oort cloud, and thus arrived at $N_o = \sim 2 \times 10^{13}$. More recently, P. R. Weissman[7] has estimated that the halo contains 2×10^{12} comets, thus suggesting a value for N_o of $> 2 \times 10^{14}$. Using $a = 3 \times 10^3$ AU (the median value given by Hills), the more conservative $N_o = 2 \times 10^{13}$, and $q = 2.7$ AU for the average heliocentric distance to the asteroid belt, we estimate that $N_q = 3.6 \times 10^{10}$.

This count is based on the number of comets which have been observed, and thus corresponds to comets with radius $r > 0.64$ km, given the recent estimates of 0.3 for comet albedo[8]. To estimate the number of smaller comets, we use the distribution usually assumed for asteroids and comets:

$$dN/dr = C \, r^{-p} \tag{2}$$

for the number of comets dN with radius in interval dr, where p is the size index. Weissman[9] gives the current best values of the size index as $p = 3.2$ for $r \lesssim 3$ km, and $p = 5.4$ for $r > 3$ km. Integrating equation (2) over $0.6 \text{ km} \leq r < \infty$, we can solve for the multiplicative constant, and find $C = (0.82)\, N_q \approx 3 \times 10^{10}$.

(B) Probability of Collision

Following Davis, Hut, and Muller, we estimate the probability of collision for a single comet, radius r, passing inside of $q = 2.7$ AU $= 4.04 \times 10^8$ km, with a single asteroid, radius R, to be

$$\frac{\text{(collision cross-sectional area)}}{\text{(total area within q of sun)}} \times 8 = \frac{8\,(R + r)^2}{q^2} \tag{3}$$

where the factor of 8 accounts for the average number of passes through the belt that each comet will make before being lost from the inner solar system by ejection or collision. The probability of collision for the entire comet shower with a single asteroid is thus

$$\begin{aligned} K(R; r_{min}, r_{max}) &= (8/q^2) \int_{r_{min}}^{r_{max}} (dN/dr)\ (R+r)^2\ dr \\ &= (8/q^2) \int_{r_{min}}^{r_{max}} C\, r^{-p}\ (R+r)^2\ dr \\ &= (8C/q^2) \left[-(R^2/2.2)\, r^{-2.2} - (2R/1.2)\, r^{-1.2} - 5\, r^{-0.2} \right]_{r_{min}}^{r_{max}} \end{aligned} \tag{4}$$

where we have substituted the value $p = 3.2$.

We may here anticipate our result by evaluating equation (4) for $R = 1$ km, the approximate expectation value for asteroids larger than $R = 0.5$ km, and $r_{min} = 0.01$ km, which is still large enough to disrupt a 1 km asteroid. (The result is insensitive to our choice of r_{max}; we shall here use $r_{max} = 1$ km.) If we multiply this probability of collision by the number of asteroids larger than $R = 0.5$ km, $N_{R>0.5} = 2.1 \times 10^6$, we can estimate the number of collisions with large asteroids per comet shower will be $\sim 4 \times 10^4$. In the following more careful calculation, we use empirical results to guide our choices of r_{min} and r_{max}, and include the observed distribution of R.

To approximate the smallest comet radius which will disrupt an asteroid, r_{min}, we will use the size of the smallest comet which will generate a crater with radius equal to the asteroid radius. (This is a conservative choice since a smaller crater would still disrupt the asteroid.) E. M. Shoemaker and R. F. Wolfe give an empirical formula for crater size[10]. Converting to our units and notation, we set this equal to the asteroid radius:

$$R = (2.0872)\ c_f\ (g_e/g_a)^{1/6}\left[r_{min}^{\ 3}\ (\rho_c/\rho_a)\ v^2\right]^{1/3.4} \qquad (5)$$

where g_e = 980 cm/sec^2 is the acceleration of gravity at the surface of the earth,

g_a = (2.79 x 10^{-7} cm^3/g s^2) R ρ_a is the acceleration of gravity at the surface of the asteroid,

ρ_c = 1 g/cm^3 is the approximate density of the comet,

ρ_a = 3 g/cm^3 is the approximate density of the asteroid,

v = 31.4 km/sec is the RMS average relative velocity of the impacting comet,

and c_f = 1 is a crater collapse factor which does not play a role for the crater sizes we consider.

Rearranging and evaluating equation (5), we find $r_{min} = (0.01)\ R^{1.32}$.

At the other extreme of comet size, we are limited to collisions which are not so energetic that the asteroid is dispersed into fragments much smaller than the Apollo objects we wish to generate. As a rough indication of this limit, we use the empirical results for impacts on basaltic rocks given by A. Fugiwara, et al.[11] Rewriting their equation (9), the ratio of the largest fragment mass to the target mass is:

$$M_f/M_a = (R_f/R)^3 = 6.61 \times 10^{-5}\ (E_p/M_a)^{-1.24} \qquad (6)$$

where $E_p = (2\pi/3)\ r^3 \rho_c v^2$ is the projectile kinetic energy in (g km^2 s^{-2}) and M_a is in grams. For a projectile (comet) velocity of 31.4 km/sec, we find that a maximum comet size of approximately $r_{max} = (0.024)\ R^{1.8}$ still results in a fragment as large as 0.5 km. Equation (4), with these values for r_{min} and r_{max}, gives the probability of a "candidate collision."

(C) The Number of Fragments in Apollo Orbits

The size distribution of asteroids in families can be used as an indication of the approximate size distribution for collision fragments. Shoemaker[2] takes the size index of ~3, and estimates that the number of fragments with radius greater than 0.5 km resulting from the disruption of an asteroid of radius R is $(2R)^2$. We weight this number of fragments per collision with the probability of a candidate collision and the size distribution of asteroids to find the number of fragments, radius >0.5 km, generated in each shower:

$$N_f = \int_{R_{min}}^{R_{max}} (dN/dR)\ (2R)^2\ K(R; r_{min}, r_{max})\ dR$$

$$= \int_{R_{min}}^{R_{max}} C'\ R^{-p'}\ (2R)^2\ K(R;\ 0.01\ R^{1.32},\ 0.024\ R^{1.8})\ dR$$

$$\approx 42{,}300 \qquad (7)$$

where $C' = .93 \times 10^6$ and $p' = 3.5$ are the asteroid size-distribution parameters[12], R_{min} = 1 km is the smallest asteroid which we will consider as a source for Apollo objects with radius greater than 0.5 km, and R_{max} = 200 km is a typical size for the largest observed asteroids.

Shoemaker uses 5% for an upper bound on the fraction of random asteroid belt collision fragments which would be "resonated" into Earth-crossing orbits[2]. This efficiency fraction is a major unknown in our calculation, and it could of course be lower than 5%. For one resonance which has been modelled in Monte Carlo studies, G. W. Wetherill[1] estimates an efficiency of 30%, for asteroids which start out in the vicinity of that resonance. This suggests that an overall value of 5% is not a gross overestimate. For our case, this fraction would give a yield of $N_s \approx 2100$ Apollo objects, $r > 0.5$ km, per shower.

(D) The Expected Number of Apollos

We can now ask if this yield of Apollo objects is sufficient to account for the current estimated population. A periodic comet shower adds a pulse of N_s Apollos every τ = 28 Myr period, and the resulting number then decays with a lifetime λ (due to collisions and ejections) until the next pulse. Thus just after the P'th pulse, we expect the number of Apollos to be

$$N_P = N_s + N_s e^{-\tau/\lambda} + N_s e^{-2\tau/\lambda} + \dots + N_s\, e^{-(P-1)\tau/\lambda}$$

$$= N_s\, \frac{1 - e^{-(P-1)\tau/\lambda}}{1 - e^{-\tau/\lambda}}$$

$$= N_s / (1 - e^{-\tau/\lambda}) \tag{8}$$

where we have neglected $e^{-(P-1)\tau/\lambda}$ since the sun's companion star which causes the shower should have[3] an orbit which is stable for 2×10^9 yr or P = 70 pulses, and $\tau/\lambda >$ 1/5. The number we would find today, after t = 13 Myr since the last pulse, is

$$N_t' = N_p e^{-t/\lambda}$$

$$= N_s \frac{e^{-t/\lambda}}{1 - e^{-\tau/\lambda}} \tag{9}$$

For $t \sim \tau/2$, and $\lambda > \tau$, this is negligibly different from the result for the steady-state model, if we had introduced the N_s comets over τ years at an even rate of $R = N_s/\tau$:

$$N_t^{steady\text{-}state} = R\lambda = N_s \lambda/\tau \tag{10}$$

In Monte Carlo calculations for the steady-state model, Wetherill and Williams[13] found an Apollo lifetime of 30 Myr. Using this value for λ, the peak to valley ratio is $e^{\tau/\lambda} = 0.4$ for our periodic pulse model. Unfortunately, the current data for craters on the Earth are not complete enough to see the decaying tails of the number of Apollos hitting the Earth.

With $N_s = 2100$, t = 13 Myr, $\tau = 28$ Myr, and $\lambda = 30$ Myr in equation (9), we find the expected number of Apollos today to be approximately 2250. This result is based on the conservative choices of $N_o = 2 \times 10^{13}$ for the number of comets in the inner Oort cloud, and a crater size equal to the asteroid size as the condition for disruption. Weissman's value of $N_o = 2 \times 10^{14}$ would give ten times this yield, while a minimum crater size of R/2 would give a five-fold increase. Conversely, a less efficient resonance mechanism would lower the yield, as discussed above. The best estimates of the current population of earth-crossers with radius greater than 0.5 km, corrected for observational biases, is about 1300,[14] or 2300 if one assumes a significant fraction of unobserved low-albedo objects[2]. Thus if comet showers periodically hit the solar system, their collisions with the asteroid belt could create enough Apollo objects to dominate the current population.

This mechanism for Apollo object creation may answer a possible objection to the periodic comet-shower/extinction hypothesis. If there were a steady-state number of Apollo objects, then one might expect the periodic crater record from comet showers hitting the earth to be "washed out" by the craters from random-time Apollo impacts. Given a pulsed Apollo object population, however, these additional craters may reinforce the periodicity of the comet craters, depending on the time-scale of the resonance mechanism and the actual value of the Apollo lifetime.

A similar mechanism may also be responsible for the creation of the rings of Saturn and Jupiter, as suggested independently by Richard Muller. The moons of these planets—or ejecta from impacts—may have lost enough angular momentum in the flux of comets to fall within the Roche limit, at which tidal disruption occurs. Alternatively, a moon was disrupted by this shower, and the resulting fragments provided the fodder for the rings. Clearly, we are only beginning to explore the significance of periodic comet showers to solar system processes.

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