
When the planets have grown to nearly their final mass, there will be residual material in heliocentric orbits. This material will be the source of the flux of projectiles which have produced the cratered surfaces characteristic of the terrestrial planets, of the present flux of meteoroids and meteorites, and of the present populations of small interplanetary bodies, such as the comets and asteroids. Although an attempt at definitive understanding of subjects such as this is premature, it is possible to isolate relevant yet tractable problems of early solar system history, treat them quantitatively, and then tentatively relate them to the more obscure and complex nature of the real solar system. One such problem will be addressed here: the subsequent history of the small bodies remaining in heliocentric orbit in the vicinity of 1 A.U. after the earth and moon have accumulated to nearly their present size.

The idealized problem which has been studied is the dynamical evolution of a swarm of small objects with semi-major axis near 1 A.U. subject to gravitational perturbations by planets with masses and orbits equal to those of the present solar system. The mean initial geocentric velocity of these bodies is estimated to be 8 km/sec characteristic of the equilibrium between mutual collisional dissipation (1) and gravitational acceleration (2). The Monte Carlo method of Arnold (3) as modified (4) was employed. The effects of the secular resonance $\nu_6$ (5) were included (6). The principal long-term effect of this resonance is to facilitate transfer of material in both directions between earth's orbit and the vicinity of Mars and the inner asteroid belt. Because of the bidirectional nature of this transfer, mean lifetimes are not affected greatly. However achievement of dynamic equilibrium between Mars-crossing and earth-crossing populations is much more rapid.

The typical calculated time dependence of the resulting earth impact rate is shown in figure 1. The lunar time dependence will be similar; the inverse slope of its curve ("instantaneous half-life") will be somewhat (up to $\sim 15\%$) greater as a consequence of the relative effective gravitational radii decreasing somewhat as the mean projectile velocity increases with time. The half-life indicated by the slope of the curve is not at all constant, as is frequently assumed, but increases by a factor of $\sim 10$ during the first 500 m.y. Analysis of the Monte Carlo histories shows this to be the result of a small fraction ($\sim 1\%$) of the bodies becoming pure Mars-crossers, returning to earth on a longer time scale controlled by the combined effects of Mars' perturbations and the $\nu_6$ resonance, rather than in the rapid (15-20 m.y.) time scale characteristic of Earth and Venus-crossing.

The principal certain difference between this model and a plausible early solar system is that in the real solar system mutual collisional fragmentation will be rapid compared to the time scale for accretion by the Earth even for fairly large (i.e. 100 km diameter) bodies present after the earth has reached 99% of its final mass. Larger bodies are likely to be fragmented by approaches to Earth and Venus within the Roche limit (7). Collisional fragmentation per se will not result in more rapid removal of material from the vicinity of the earth. Collisional dissipation will probably establish a relationship between fragment size and mean geocentric velocity such that the
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The gravitational cross section of the earth will be greater for the slower small bodies, and they will thereby be preferentially removed from the swarm.

The effect of inclusion of the effect of fragmentation into the model will be to decrease somewhat the time scale for the already short-lived earth-crossing component. For <200 km bodies, the probability of implantation into purely Mars-crossing orbits is also reduced, because the probability of these bodies surviving for the ~ 50 m.y. required for random walk into relatively "safe" Mars-crossing orbits is small. The collision rate in these Mars-crossing orbits will be lower, especially after a few hundred million years, and the 150 to 200 m.y. half-life for return of these bodies to earth-crossing will be unaffected. Therefore, as far as these smaller bodies are concerned, the difficulties associated with this model for the late heavy bombardment still remain. For large (>10^5 g) bodies, the situation may be different. Once even slightly removed from earth-crossing, these bodies will be immune to Roche limit disruption and are large enough to withstand collisions. They may thereby be preferentially implanted into the 150-200 m.y. Mars-crossing orbits and return to earth-crossing relatively unaccompanied by smaller bodies. Roche limit fragmentation can then occur upon return to earth-crossing, followed by sweep-up of the fragments on the 20 m.y. Earth-crossing time scale. This size dependent Earth-Mars-Earth process removes the major difficulties with the inner solar system models for the late heavy bombardment previously described (7).

These same calculations and consideration of fragmentation lead to the expectation that some large residual earth-crossing bodies will be preferentially implanted into Mars-crossing orbits for the entire history of the solar system. The largest such body is calculated to be 200 to 300 km in diameter, and this should be accompanied by several ~ 100 km bodies. It is tempting to identify these with large asteroids in the inner asteroid belt such as 8 Flora and 6 Hebe. Spectrophotometric data suggest that these bodies are chemically differentiated, and it has been shown that from the dynamical point of view they are the prime candidates for sources of achondrites and iron meteorites (6). The implanted asteroids predicted by these calculations have the possibly serious difficulty that they differ from those observed in making rare close approaches to Mars whereas these observed asteroids never come within 0.02 to 0.15 A.U. of Mars.

In summary, these results argue that:

(1) Essentially all residual earth material which remains in earth-crossing orbit had already been swept up before the formation of the oldest observable lunar surface.

(2) At least some observable ~ 4 b.y. old and younger lunar and Martian craters were produced by residual earth material temporarily stored in Mars-crossing orbits. This material was preferentially concentrated in large (>200 km diameter) bodies and may have played an important role in the formation of large planetary impact basins.

(3) Some of the present Mars-crossing asteroids as well as somewhat more distant larger asteroids may be residual earth material and also sources of differentiated meteorites. However this identification is barely tentative considering the complexity of this aspect of the problem, and possible but
nevertheless speculative assumptions are presently necessary to remove difficulties with this identification.

REFERENCES

1. Safronov, V. S. (1969) Evolution of the Proto-
planetary Cloud, Nauka, Moscow. NASA TFP-677
p. 3245-3257.
(NASA SP-370, in press)
Colloq. 39, Lyon.
p. 1539-1559.

Figure 1. Time of earth impact for initial Earth-
crossing orbit (a = 0.9, e = 0.27, i = 6°, Vg = 7.8 km/sec)