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ON THE EARLY SCATTERING PROCESSES OF THE OUTER PLANETS

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The gradual scattering of small bodies by the Jovian planets in the late stage of their accretion is simulated by Monte Carlo calculation. The effects of collisional interaction of the scattered planetesimals with the inner planets and asteroidal belt are estimated. The total mass influx injected into the terrestrial zones from the outer planetary zone could be appreciable; however, if the damping effects due to the mutual inelastic or catastrophic collisions among the small bodies were significant, the total mass influx would be greatly reduced. The origin of the cometary Oort cloud in relation to these scattering processes is also discussed. The calculation indicates that, in addition to Jupiter, Uranus and Neptune were likely to be the major contributors to the population of long-period comets if they originated from such scattering processes.

Recently, much attention has been given to the effect of the scattering of small bodies by the protoplanets during the early age of the solar system but late stage of their accretion. In particular, emphasis has been placed on the bombarding and cratering of the Moon and the terrestrial planets by these scattered projectiles (Kaula and Bigeleisen 1975; Kaula 1975). One approach to the simulation of such a process is to assume that the planetesimals have a wide distribution in the solar distance (a) such that when the major planets (Jupiter, Saturn, etc.) have accreted significant masses, the small bodies in circular orbits nearby the planets would start to be "pushed," via secular perturbation, into eccentric orbits crossing those of the protoplanets. On one hand, the protoplanet could accrete more material by this process (Davis 1977); and on the other, close encounters with the protoplanet would cause scattering of the planetesimals either into orbits crossing those of the other planets, or into escape orbits. In this paper, instead of treating the full development of the planetesimal scattering process, we will only consider the simplest case in which most of the projectiles are assumed to original from the rings of residual material remaining in the vicinity of the protoplanets. Here we will call these rings of small bodies in near-circular orbits the jet streams (see Alfvén 1970; Alfvén and Arrhenius 1970; Ip 1974). When the planets have grown to be sufficiently large, the jet stream particles would be scattered into eccentric orbits via random encounter with the massive protoplanets. Of course, if the eccentricities (e) and inclinations (i) of the planets are zero there would not be any dispersion of the jet streams since the encounter velocities (Δv) between the protoplanets and the jet stream particles are invariants in this case.

As a result, the e and i values of the planetesimals will always remain small. However, if the e and i of the planets are non-zero the values of Δv would no longer be invariants during repeated close encounters and they could be gradually increased via the so-called *Fermi acceleration mechanism* (see Arnold 1965; Öpik 1966). Consequently, jet stream particles originally orbiting with small e and i in the vicinity of one planetary zone could later be perturbed into orbits with large e and high i crossing other planetary zones. Impact capture of these scattered planetesimals by the neighboring planets could result in compositional mixing of the planetary material, at least in the surface layers.

The transfer of planetesimals from one terrestrial zone to another has been investigated by Wetherill (1975a,b) using the modified Monte Carlo model developed by Öpik (1950,1961) and Arnold (1965). Based on Wetherill's numerical results, Hartmann (1976) subsequently suggested that appreciable compositional mixing among the terrestrial planets could be produced via impact capture of the

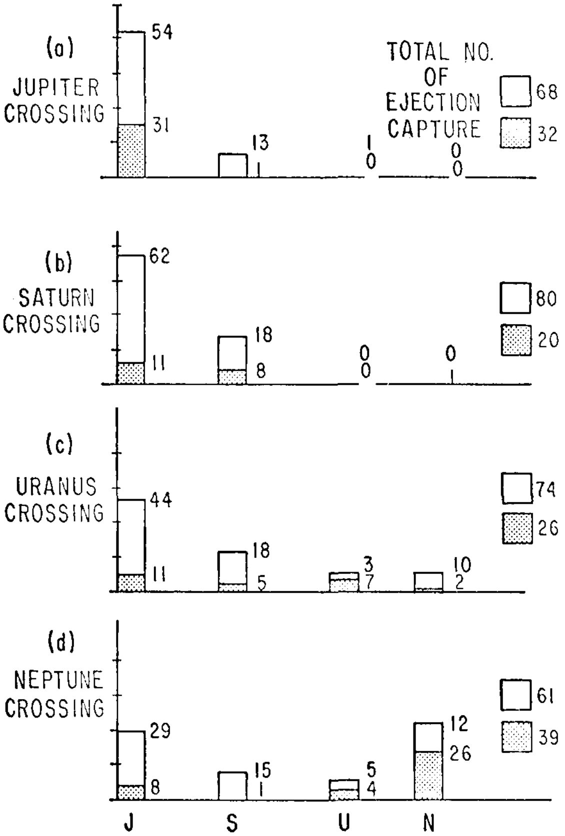

Figure 1. Distribution of the numbers of orbital termination via impact capture or ejection from the solar system by the outer planets. In each of the Monte Carlo calculations, the total number of runs is 100, k = 10 for all planets and the damping factor accounting for the mutual collisional effects of the particles = 1. The starting elements are: (a) a = 5.25 AU, e = 0.05, sini = 0.05; (b) a = 9.60, e = 0.06, sini = 0.06; (c) a = 19.25, e = 0.05, sini = 0.05; (d) a = 30.0 AU, e = 0.01 and sini = 0.02.

planetesimals from the neighboring planetary zones. This is especially true between Venus and Earth. These two planets also share a significant portion of the jet stream particles from the Mars zone. It is interesting to note that, unlike the case of the orbits initially with large e, our calculation (Ip 1976a) indicates that these jet stream particles seldom encounter the fate of being ejected into escape orbits by Jupiter. The total percentage of termination of the orbital calculation because of elimination of the particles either by Jupiter capture, or ejection, is estimated to be <10% for the cases of Venus, Earth and Mars, and nil in the case of Mercury. Therefore, the planetesimals in the terrestrial zones would be rather stably trapped in the inner solar system without significant leakage to the interstellar space.

As will be shown in the following, these results are in sharp contrast to the orbital behavior of the small bodies in the heliocentric jet streams of the outer planets.

Following the Monte Carlo model described by Arnold (1965) we trace the orbital evolution of the particles originally in near-circular heliocentric orbits in the vicinity of Jupiter, Saturn, Uranus and Neptune. For each case 100 runs are performed with the area of the individual target circles set to be 100 times the corresponding gravitational capture cross section (*i.e.*, $k = 10$, see Arnold 1965). The results are summarized in Fig. 1. It is observed immediately that Jupiter plays the dominant role in elimination of these scattered particles. Between 40-85% of the planetesimals will either be captured or ejected by this giant planet. Indeed, except for the initially Neptune-crossing orbits (see Fig. 1.d) Jupiter captures more particles than any other planet. All together, the total probability of ejection is $\approx 0.6 - 0.8$ and the total probability of impact capture is $\approx 0.2 - 0.4$. Therefore, a large number of the planetesimals in the outer zones will be lost to the interstellar space. In the above numerical computations we have also considered the terrestrial planets in the Monte Carlo calculation. The asteroidal belt is simulated by including a body with $a = 2.8$ AU, $e \approx 0.15$, $\sin i = 0.17$ and the capture cross section 2.5 times that of the geometrical cross section of Jupiter (see Arnold 1965; Wetherill 1967). No impact is registered. Since we have set $k = 10$ for all the planets and performed only 100 runs for each case, the statistical significance of this null result may not be too reliable. In any case, from the present calculation, the total probability of impact capture by the terrestrial planets can be guesstimated to be at most ≈ 0.01. Assuming then the total mass of the planetesimals in a jet stream, at the beginning of the scattering process, is about 1% of the planetary mass (*e.g.*, Hartmann 1976); the total mass from the terrestrial zones available for cratering of the inner planets would be $\approx 1 \times 10^{26}$ g while the corresponding mass from the outer ones would be $\lesssim 2 \times 10^{26}$ g. From this point of view, the planetesimals from the outer zone, in principle, could be an important source for the late heavy bombardment of the Moon and the terrestrial planets (Wetherill 1975a,b).

However, we must realize that besides the effect of planetary scattering, the jet stream particles are also subjected to collision process among themselves. There are two effects which might lead to the reduction of the mass injection into the terrestrial zones. First, inelastic collision of the jet stream particles and viscous interaction with the gaseous resisting medium (if any) would tend to reduce the value of Δv. Therefore the evolution of the initially near-circular orbits into eccentric ones due to the *Fermi acceleration mechanism* would be delayed. Second, from Monte Carlo calculation based on the model developed by Wetherill (1967) it can be estimated that the probability of collisional destruction of the jet stream particles with large value of Δv (near the upper limit of the velocity distribution) is a factor of 5-10 larger than that of the particles with small Δv (near the lower limit) (Ip 1976b,c). This is because of the fact that the larger the impact velocity (and hence impact energy) the easier it will be for the colliding bodies to fragment. Therefore, even though planetesimals with larger Δv value would have smaller probability of of collision (p_i), the actual probability for destructive collision (P_d) could be larger if assuming $P_d \propto P_i v^2$, say. Consequently, the high speed component of the jet stream particles would be preferentially depleted. Following these arguments, it seems possible that the influx from the outer planetary zones contributing to the impact cratering of the terrestrial planets could be greatly suppressed. To explore the damping effect qualitatively we compare the distributions of the minimum perihelion distance (*i.e.*, $q = a\ (1 - e)$) for the scattering of Jovian jet stream particles with (a) the angular deflection reduced by an ad hoc factor of 10; (b) by a factor of 5; and (c) without reduction. The results are summarized in Fig. 2. It is clear that at the very beginning of the scattering process (Fig. 2.a) only very few planetestimals could reach the terrestrial zones. In fact, almost 100% of the particles will be captured by the proto-Jupiter. In the later stage (*e.g.*, Fig. 2.b), the orbital diffusion into the inner solar system is still very limited. Only when the condition of free-scattering is reached, *i.e.*, the coupling via collisional interaction among the particles is small, would a large population of the scattered projectiles cross the orbits of the terrestrial planets. Therefore the mass influx from the outer planetary zones is very much dependent on the dynamical evolution of the associated jet streams.

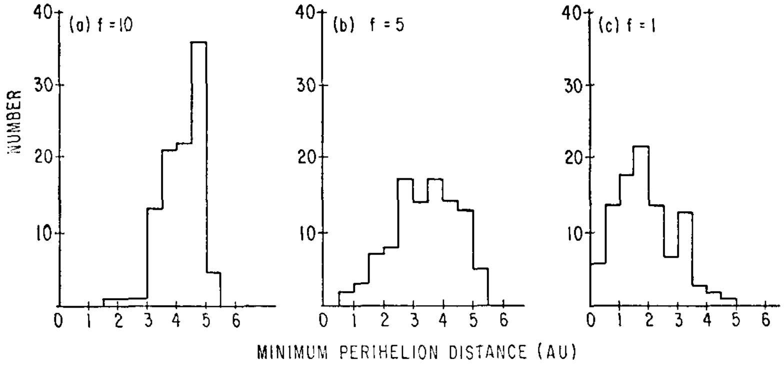

Figure 2. Distribution of the minimum perihelion distance of the Jupiter-crossing jet stream particles; (a) the angular deflection is reduced by an ad hoc damping factor f of 10; (b) f = 5; (c) f = 1.

Finally, we would like to turn our attention to the question concerning the origin of the cometary Oort cloud at large distances from the sun ($a \simeq 5 \times 10^4$ AU). It is rather tempting to relate the whole early scattering process in some way to the ejection of cometary-like objects into long period and eccentric orbits. Much work on this subject has been done by Everhart (1973,1976). As suggested by Everhart (1973) a good measure of comet productivity of the outer planets is the distribution of the orbital lifetime (t_o) of the scattered planetesimals. In Table I is summarized the result from the Monte Carlo calculation with no damping effect. Both the Jupiter-crossing and Saturn-crossing particles have rather small values of t_o ($< 10^9$ yr). Only the Uranus-crossing particles and the Neptune-crossing particles could be scattered into long-lived orbits ($t_o > 10^9$ yr). From this point of view, in addition to Jupiter (Öpik 1973), Uranus and Neptune also could be the major contributors to the Oort cloud.

Most of the "long-period comets" produced in such a way have $i < 90^o$. Since the observed distribution in inclination for the long-period comet popula-

TABLE I

	Orbital Lifetime (yr)					
Class of Orbits	$< 10^5$	10^5-10^6	10^6-10^7	10^7-10^8	10^8-10^9	$> 10^9$
Jupiter-Xing	23	32	33	9	3	0
Saturn-Xing	30	26	53	13	5	0
Uranus-Xing	0	2	7	47	34	10
Neptune-Xing	1	5	8	31	45	10

tion is more or less uniform for i between 0^o and 180^o, the origin of the Oort cloud cannot be explained by the early scattering effect alone. Furthermore, because of the small sample we have considered here, it is impossible to evaluate other parameters such as the distribution of the semimajor axis of the long-period orbits and compare them to those of the long-period comets (Marsden and Sekanina 1973). Similar difficulty exists in the estimation of the mass injection into the terrestrial zones from the outer planetary zones. In any event, we believe collisions with the stray bodies associated with the planetary jet streams must have played an important role in these scattering processes. We hope that further work along this line can help clarify these interesting problems.

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