MIGRATION OF BODIES IN THE ACCUMULATION OF PLANETS

S. I. IPATOV
Institute of Applied Mathematics, Miusskaya Sq. 4, Moscow, Russia

Our investigations of the migration of bodies in the Solar system and the formation of planets were based mainly on the results of computer simulation of the evolution of disks that originally consisted of hundreds of gravitating bodies moving around the Sun (Ipatov 1987, 1993a). The mutual gravitational influence of bodies was taken into account by the Tisserand spheres method, that is two two-bodies problems were considered. Ipatov (1988a) also made analytical studies of the dependence of the time of disk evolution as a function of the number of bodies constituting the disk. For choosing the pairs of encounting (up to the radius of the Tisserand sphere) bodies, Ipatov (1993b) used the probability and deterministic methods. For the probability method, the pairs of encounting bodies were chosen proportionally to the probabilities of their encounters. For the deterministic method, the time to an isolated (from other bodies) encounter of the pair of encounting bodies was minimum. To our opinion, the deterministic method is more physical. Orbits and masses of formed planets, and times to collisions of separate bodies with planets are almost identical for both methods. However, the time of the evolution of disks, consisting of a large number of bodies, and so the time of the formation of the main part of planets' masses obtained by using the deterministic method are ten times less than those obtained by using the probability one. In particular, the time to form 80 % of mass of the Earth did not exceed 10 Myr.

We investigated the evolution of disks that originally consisted of several ring zones corresponding to the feeding zones of the terrestrial planets. Ipatov (1993a) showed that each of these planets incorporated planetesimals from all these zones. After the mass of the Earth's embryo has exceeded 10 % of the present mass of the Earth, the average orbital eccentricities of planetesimals in the feeding zones of the terrestrial planets on the whole exceeded 0.2. Some of these planetesimals penetrated the asteroid belt. Most of the planetesimals that fell onto the Earth underwent collisional evolution. The embryonic masses of unformed terrestrial planets may have exceeded 0.1 of the mass of the Earth.

Ipatov (1987, 1993a) investigated the evolution of various disks corresponding to the feeding zones of giant planets. Most of these disks included almost-formed Jupiter and Saturn. We obtained that average eccentricities of orbits of planetesimals in the feeding zones of Uranus and Neptune exceeded 0.3 during the larger part of disk evolution. A large number of planetesimals

Earth, Moon, and Planets **67**: 217–219, 1995.

from these zones migrated to Jupiter, which ejected them into hyperbolic orbits. The total mass of bodies ejected from the zones of giant planets into hyperbolic orbits may have been ten times as large as the mass of bodies that entered into the planets. The results of our investigations (Ipatov 1987) agree with the values of initial mass of the protoplanet cloud equal to 0.04-0.1 of the mass of the Sun. Jupiter (its nucleus and envelope) might include more ices and rocks than any other planet. The total mass of the bodies from the zone of giant planets, entering the zone of the asteroid belt, could reach tens of Earth's masses. A large amount of water could be delivered to Earth during the accumulation of Uranus and Neptune. The embryos of unformed planets with masses equal to several Earth's masses in the zone of Jupiter and Saturn would be necessary to explain present eccentricities as well as present periods of axial rotation and inclinations of axes of rotation of these planets. Under the influence of migrating bodies the semimajor axis of the orbit of Jupiter may have been shortened by 0.5 AU and those of the other giant planets may have been increased significantly. The embryos of Uranus and Neptune with initial masses equal to several Earth's masses may have originated near the orbit of Saturn and then may have migrated to the present distances from the Sun moving in nearly circular orbits. Some smaller objects may have migrated from the zones of Jupiter and Saturn to the zones of Uranus and Neptune in the same way. The total mass of bodies that penetrated beyond the orbit of Neptune may have reached tens of Earth's masses.

Ipatov (1995b) investigated migration of bodies to the Earth from various regions of the Solar System. We obtained that perihelia or aphelia of orbits of bodies that collided the Earth mainly were near the orbit of the Earth. A large number of objects should exist which orbits lie inside the orbits of Earth and Venus. Most of asteroids of the Amor group should have come from the asteroid belt.

The orbital eccentricity of a body increases significantly only if it encounters several bodies during its evolution. The results of numerical integration of the equations of motion for the plane three-body problem (the Sun and two bodies) showed (Ipatov 1993a)that for initially circular heliocentric orbits and the chaotic variations in orbital elements at $\mu_1 \leq 10^{-5}$ the maximum eccentricity e_{max}usually doesn't exceed $7-8\times\mu_1^{1/3}$, where μ_1 is a ratio of the larger body mass to the Sun mass. For regular orbital variations, e_{max} is smaller. The values of e_{max} and regions of $\varphi_\circ$ and$\varepsilon_\circ = (a_2^\circ - a_1^\circ)/a_1^\circ$ corresponding to various types of orbital variations were investigated by Ipatov (1994) for $10^{-9} \leq \mu_1 \leq 10^{-3}$, where $\varphi_\circ$ is an initial angle with the apice in the Sun between directions to bodies, a_1° and a_2°, are initial values of semimajor axes. These investigations were made for the following types of orbital variations: the motion around triangular points of libration in tadpole and horseshoe synodical orbits, the case of close encounters of bodies, and the chaotic variations in orbital elements when close encounters can't take place. For initially eccentrical orbits and a large time interval, the values of e_{max} depend mostly on initial eccentricities, semimajor axes, and orbital orientations. Ipatov (1981) showed that in the case of close encounters, using the spheres method and choosing the radius of the sphere in an appropriate way, we can obtain almost the same values of e_{max} as those obtained by numerical integration. The "used spheres" method gives even better results, if we consider a larger number of bodies. For the case of three identical bodies circling the Sun, the maximum eccentricities can be several tens of times larger than those for two such bodies (Ipatov 1988b, 1995a).

The results presented above are generally consistent with those obtained by Wetherill (1985), Gladman (1993), and many other scientists. The comparisons of these results were made in our articles listed below.

This work was supported by the Russian Fund of Fundamental Investigations under Grant 93-02-17035.

References

Gladman, B.: 1993, "Dynamics of systems of two close planets." *Icarus*, **106**, N 1, 247-263.

Ipatov, S.I.: 1981, "Computer modeling of the evolution of the plane rings of gravitating particles moving around the Sun." *Sov. Astron.*, **25(58)**, N 5, 617-623.

Ipatov, S.I.: 1987, "Accumulation and migration of the bodies from the zones of giant planets." *Earth, Moon, and Planets*, **39**, N 2, 101-128.

Ipatov, S.I.: 1988a, "Evolution times for disks of planetesimals." *Sov. Astron.*, **32(65)**, N 5, 560-566.

Ipatov, S.I.: 1988b, "Computer simulation of the possible evolution of the orbits of Pluto and bodies of the trans-Neptune belt." *Kinematics Phys. Celest. Bodies*, **4**, N 6, 76-82.

Ipatov, S.I.: 1993a, "Migration of bodies in the accretion of planets." *Solar System Research*, **27**, N 1, 65-79.

Ipatov, S.I.: 1993b, "Methods of choosing the pairs of contacting bodies for investigations of the evolution of discrete systems with binary interactions." *Mathematical Modeling*, **5**, N 1, 35-59 (in Russian).

Ipatov, S.I.: 1994, "Gravitational interaction of two planetesimals moving in close orbits." *Solar System Research*, **28**, N 6 (p. 10-33 in Russian edition).

Ipatov, S.I.: 1995a, "Gravitational interaction of objects moving in crossing orbits." *Solar System Research*, **29**, N 1 (p. 1-13in Russian edition).

Ipatov, S.I.: 1995b, "Migration of small bodies to the Earth." *Solar System Research*, **29**, N 4 (in press).

Wetherill, G.W.: 1985, "Occurrence of giant impacts during the growth of the terrestrial planets." *Science*, **228**, 877-879.