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MIGRATION OF CELESTIAL BODIES IN THE SOLAR SYSTEM

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We investigated several cases of migration of celestial bodies (planetesimals, forming planets, asteroids, and transneptunian and near-Earth objects) in the forming and present Solar System. These investigations were based on computer simulation results and on some analytical estimates. The evolution of orbits of several gravitating objects mainly was investigated by numerical integration of the N-body problem. The method of spheres (i.e. two two-body problems) was used for investigations of the evolution of discs consisting of hundreds bodies. It was found that the embryos of Uranus and Neptune may have originated near the orbit of Saturn and then due to gravitational interaction with migrating planetesimals may have migrated to their present distances from the Sun moving all the time in orbits with small eccentricities. Under the gravitational influence of the giant planets, some transneptunian bodies can decrease their perihelia from 34 to 1 AU in several tens of million years. Some bodies of the Kuiper belt can migrate from the outer part of this belt to its inner part due to the gravitational influence of the largest bodies of the belt. A large number of small celestial bodies can exist inside the orbit of the Earth.

KEY WORDS Migration, planetesimals, asteroids, the Kuiper belt, near-Earth objects

1 INTRODUCTION

Migration of bodies in the forming and present Solar System is an interesting and important scientific problem. Results of investigations of the process of planet formation (including migration of planetesimals and planet embryos) are the starting points for the models of a structure of the Earth and other planets. Investigations of present migration of celestial bodies to the Earth from various regions of the Solar System help to better understand a distribution of near-Earth objects on masses and orbital elements and to better organize the defence of the Earth from these objects. Various problems of migration of celestial bodies have been studied by many scientists. Some reviews of papers on such problems were made by Ipatov (1992b, 1993a, 1994, 1995a, b).

The real process of planet formation is very complicated and depends on many factors. Nevertheless, our investigations of relatively simple models allow us to draw some important conclusions about the process of planet formation and migration of small bodies in the present Solar System. Some our investigations were based on computer simulation results of the evolution of discs consisting of hundreds of gravitating bodies that move around the Sun.

2 ALGORITHMS USED

We investigated the evolution of orbits of several gravitating objects mainly by numerical integration of the N-body problems. The method of spheres was used for investigations of the evolution of discs consisting of hundreds of bodies moving around the Sun. In this method, bodies move around the Sun in unperturbed Keplerian orbits outside the considered sphere (usually, the sphere of action), and the relative motion of two bodies was treated in the two-body problem within the sphere.

Ipatov (1988b, 1991) suggested another algorithm for calculations of the probability p_{ij} of the encounter of two bodies up to the radius r_s of the considered sphere than that used by Öpik (1951), Arnold (1965), and Wetherill (1985, 1988). In contrast to Öpik's formula, in our algorithm p_{ij} also depends on the synodic period and the sum of the angles with the apex at the Sun within which the distance between the orbit of one (first) encountering body and the projection of the orbit of the second encountering body on to the plane of the first body is less than r_s.

Ipatov (1981) showed that for two bodies orbiting the Sun in the case of close encounters, using the spheres' method and choosing the radius r_s of the sphere in an appropriate way, one can obtain almost the same values $e_{\max}$ of maximum eccentricities during evolution as those obtained by numerical integration. For initially circular orbits, $e_{\max}$ usually does not exceed 7–8 $\mu_1^{1/3}$, where μ_1 is a ratio of the larger body mass to the Sun's mass and $\mu_1 \leq 10^{-5}$. Interaction of two bodies moving around a gravitating centre can be considered as an elementary process in a disc consisting of a larger number of bodies. In the case of initially circular orbits, Ipatov (1994) investigated regions of the values of masses and semi-major axes corresponding to the case of close encounters not only for initial angle φ_0 at the Sun's vertex between the lines to the objects equal to 0 and 180°, as Gladman (1993), but also for some other values of φ_0. These investigations were made by numerical integration of equations of motion on a time span equal to 25 000 orbital revolutions around the Sun. For the case of three identical bodies circling the Sun, the maximum eccentricity can be several tens of times larger than that for two such bodies (Ipatov, 1988a, 1995a).

For a choice of pairs of encountering (up to r_s) bodies, we used the probability and deterministic methods (Ipatov, 1991, 1993b). For the probability method, the pair of encountering bodies is chosen proportionally to the probability p_{ij} of their eccounter. For the deterministic method, the time τ_{ij} (where $\tau_{ij} \propto p_{ij}$) elapsed up to an isolated (from other bodies) encounter of the pair of bodies is minimum. In our opinion, the deterministic method is more physical. Orbits and masses of formed planets, and times elapsed up to collisions of separate bodies with planets are almost identical for both methods. The results of computer runs showed that if the number of bodies in the disc is not small, then for the deterministic algorithm the characteristic time interval between successive collisions of bodies is smaller by a factor of 10 than for the probability algorithm. In particular, the time to form 80% of mass of the Earth was found not to exceed 10 Myr.

3 MIGRATION OF BODIES DURING THE PROCESS OF PLANET FORMATION

Our investigations of the migration of bodies during the accumulation of planets were based mainly on the results of computer simulation of the evolution of discs that originally consisted of hundreds of gravitating bodies moving around the Sun (Ipatov, 1987, 1993a). The density of these bodies was about that of corresponding planets. We also analytically studied dependencies of the time of disc evolution and the mean eccentricity as functions of the number of bodies constituting the disc (Ipatov, 1988b, 1995a).

Some of the discs considered corresponded to the feeding zone of terrestrial planets. All 960 initial identical bodies were divided into four groups depending on the values of their semi-major axes. Distance of the edges of these groups from the Sun equaled 0.4, 0.6, 0.8, 1.0, and 1.2 au. As Wetherill (1985), we found that the embryo masses of incompletely formed terrestrial planets could exceed 0.1 $m_{\oplus}$, where $m_{\oplus}$ is the Earth's mass. Each terrestrial planet incorporated planetesimals from the feeding zones of all these planets. Ipatov (1993a) obtained a stronger mixing of such planetesimals than Wetherill (1988). The composition of Venus and Earth may be close to the composition of the initial disc.

Some initial discs considered, corresponding to the feeding zones of the giant planets, besides identical bodies included several almost-formed planets. As for analytical estimates earlier made by Safronov (1969), the results of our computer runs show that the total mass of bodies ejected from the zones of the giant planets into hyperbolic orbits may have been 10 times as large as the mass of bodies that entered into the planets. The embryos of unformed planets with masses equal to several Earth masses in the zone of Jupiter and Saturn would be necessary to explain present eccentricities (Ipatov, 1987) as well as present axial rotations of these planets (Safronov, 1969; Vityazev and Pechernikova, 1981). The results of our computer runs (Ipatov, 1987) showed that the mass of solid bodies, which entered into Jupiter's envelope and nucleus, may have been larger than that in any other planet and may exceed the Earth's mass by 20 of 30 times. The total mass of planetesimals that entered inside the orbit of Jupiter and that entered outside the orbit of Neptune during planet formation exceeded by several 10s the Earth's mass. Actual masses of Uranus and Neptune were not obtained in our runs if we considered spatial discs without embryos of these planets. A large amount of water could have been delivered to Earth during the accumulation of Uranus and Neptune.

Zharkov and Kozenko (1990) advanced the hypothesis that the embryos of Uranus and Neptune acquired hydrogen shells of mass $\approx (1\text{–}1.5)m_{\oplus}$ in the growth zones of Jupiter and Saturn. Using computer modelling, Ipatov (1991, 1993a) investigated the evolution of several discs that consisted originally of almost completely formed planets (except for Uranus, Neptune and Pluto), two planet embryos, and several hundred identical bodies for which $8 < a \leq 32$ au. The total mass of these bodies ranged from 135 to $180m_{\oplus}$. The results obtained show that the embryos of Uranus and Neptune with initial masses equal to several Earth masses may have originated near the orbit of Saturn and then may have migrated to their present distances from the Sun moving all the time in nearly circular orbits.

4 MIGRATION OF BODIES FROM THE ASTEROID AND KUIPER BELTS

Wisdom (1982), Froeschlé and Scholl (1989), Ipatov (1989, 1992a, b), Yoshikawa (1990, 1991), and other showed that for resonances 3:1, 5:2, 7:3, and 2:1 with Jupiter and for secular resonances ν_5, ν_6, and ν_{16}, some fictitious asteroids can become Mars–crossers during evolution. Ipatov (1989) found for the first time that the outer boundaries of the maximum region of initial values of semi-major axes and eccentricities, for which, at some initial orbital orientations, fictitious asteroids become Mars–crossers during evolution, coincide with the boundaries of the 5:2 Kirkwood gap. Many of these Mars–crossers are also Earth–crossers. Encounters of asteroids with Mars and Earth could be the cause of the origin of the 5:2 Kirkwood gap. Resonant asteroids usually are Mars- and Earth–crossers for certain types of interrelations of the variations in eccentricity and longitude of perihelion. More than 1/6 of debris entering the 5:2 Kirkwood gap at eccentricity $e = 0.15$ can reach the Earth's orbit in 0.1 Myr. This debris can make up an appreciable part of the chondrites of group H whose age is less than 10 Myr. Together with the 3:1 gap, the 5:2 Kirkwood gap may play a noticeable role in the replenishment of the Apollo and Amor groups. For the 5:2 resonance at initial asteroidal inclination $i_0 = 40°$, the maximum inclinations of some fictitious asteroids reached 160°. Some such asteroids can collide the Sun.

As Farinella *et al.* (1993) and Ipatov (1995b) found, mean disruption lifetimes of the main–belt asteroids with diameters less than 100 km are smaller than the age of the Solar System. Bodies migrate to the gaps mainly due to mutual collisions of asteroids. We found that asteroids migrating to the Kirkwood gaps due to the gravitational influence of asteroids can cause only several percent of near–Earth objects.

The first beyond–Neptune object was found in 1992, and 30 objects with semi-major axis from 35 to 48 au were known by the end of 1995. Holman and Wisdom (1993), Levison and Duncan (1993), and Duncan *et al.* (1995) investigated times survived by test beyond–Neptune particles before they became Neptune–crossers. We investigated migration of test bodies from the Kuiper belt not only to the orbit of Neptune but also further inside the Solar System. The gravitational influence of the giant planets was taken into account. We used the RMVS2 integrator of the SWIFT package worked out by Levison and Duncan (1994). This integrator is by an order of magnitude faster than previous methods of integration. We considered various (not only small) initial eccentricities e_0 and inclinations i_0 of orbits of beyond–Neptune bodies. Initial values a_0 of semi-major axis varied from 35 to 50 au. The considered time span equalled several 10s of million years.

For some typical orbits (in the case without close encounters), we compared the results obtained with the use of the RMVS2 integrator with those obtained with the integrator of Bulirsh and Stoer (1966). It was shown that the limits of variations in semi-major axis for 1 Myr differed by less than 5%, and differences in eccentricities and inclinations were smaller.

We found that some bodies of the Kuiper belt can migrate deep inside the Solar System. For example, at $i_0 = 5°$ and initial values of the longitude of ascending node, the argument of perihelion, and the mean anomaly equal to $\Omega_0 = \omega_0 = M_0 = 60°$, for $a_0 = 40$ au and $e_0 = 0.15$ and for $a_0 = 39.3$ au and $e_0 = 0.3$ the perihelion distance q decreased from 34 and 27.5 au to 1.3 au in 25 and 64 Myr, respectively, and these bodies were ejected into hyperbolic orbits in 30 and 70 Myr, respectively. The time interval during which q decreased from 10 to 1.3 au equalled 0.3–0.5 Myr. A small number of LL-chondrites with age $t < 8$ Myr can be caused by the long way of LL-chondrites to the Earth's orbit.

The mean time up to the instant of ejection of a body into a hyperbolic orbit was smaller for smaller i_0. For some ejected bodies, the minimum value of q exceeded 10 au, and some bodies remained in the Kuiper belt for a long time. Limits and character of variations in orbital elements can depend highly on initial orientations of the orbits not only for resonant orbits but also for some non-resonant beyond–Neptune orbits. Therefore, small variations in orbital elements due to mutual gravitational influence of beyond–Neptune bodies can cause large variations in orbits under the gravitational influence of the giant planets.

Ipatov (1988a, 1995a) investigated the gravitational influence of the largest objects of the Kuiper belt. These investigations were based on results of orbital evolution of three gravitating objects moving around the Sun obtained by numerical integration and the spheres' method and on analytical estimates of evolution of discs consisting of a large number of bodies. It was shown that due to this influence some bodies from the outer part of the Kuiper belt can migrate to its inner part and then to the orbit of Neptune.

5 NEAR-EARTH OBJECTS (NEOs)

Computer simulations of the evolution of discs that originally consisted of planets and hundreds of bodies located in various regions of the Solar System were carried out by the spheres' method (Ipatov, 1995b). We found that some bodies, which migrated to the Earth from these regions, replenished the family of bodies the orbits of which lie entirely inside the Earth's orbit (and some orbits lie inside the orbit of Venus). The number of observed bodies of this family is not large, because it is difficult to observe such bodies. Among the bodies which came from the zones of the giant planets, the fraction of bodies moving in Earth–crossing orbits is one order of magnitude greater than the fraction of bodies that are only Mars–crosses, and, usually, $e > 0.6$. These results indicate that the majority of asteroids of the Amor group (i.e. with $1.02 < q < 1.33$ au) should have come from the asteroid belt. Either the perihelia or aphelia of bodies colliding with the Earth lay mainly near the Earth's orbit.

The orbit of an actual asteroid usually strongly varies before its collision with another celestial body, and the mean characteristic time up to the instant of this collision is less than the value of the characteristic time obtained for mean values of eccentricities and the angle Δi between the orbits of two colliding bodies. For example, if Δi varies from 0 to 30°, then the time up to the instant of a collision of an Earth–crossing object (ECO) with the Earth is 2.5 times smaller than that at fixed $\Delta i = 15°$. We found that half of all ECOs that collide with the Earth collide with it within $t \leq 5$ Myr after these objects became ECOs. A collisional lifetime of 1 m ECO was found to be several times less than 5 Myr. This result agrees with the fact that rock meteorites are usually the result of several destructions. The number N of ECOs with diameter $d > D$ does not change during evolution, if the rate of objects with $d > D$ becoming ECOs equals $\eta = N(\kappa + 1)/T$, where $1/\kappa$ is the ratio of the number of ECOs colliding with the Earth to the number of ECOs ejecting into hyperbolic orbits or colliding with other planets or the Sun and T is the mean time elapsing up to a collision of an ECO with the Earth. For $N = 1000$ (i.e. $D \approx 1$ km), $\kappa + 1 = 10$, and $T \leq 75$ Myr (Ipatov, 1995b), we have $\eta \geq 130$ per Myr^{-1}. The mean time T/N between impacts of 1 km bodies with the Earth may not exceed 0.1 Myr. The estimates of time intervals between impacts increase (but probably, on average, not by more than a factor of 2), if we take into account the time during which bodies are in resonance with the Earth. Though the distribution of observed small NEOs in orbital elements differ from that of larger NEOs, these distributions may be almost the same for all small and large actual NEOs.

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