MIGRATION OF SMALL BODIES TO THE EARTH'S ORBIT FROM THE KUIPER BELT. S. I. Ipatov, Institute of Applied Mathematics, Miusskaya sq. 4, Moscow 125047, Russia; ipatov@spp.keldysh.ru.

The Kuiper and asteroid belts are considered to be main sources of near-Earth objects (NEOs). The comet origin of some NEOs and meteorites was suggested by Öpik (1963). According to Wetherill (1988, 1989) and Weissman *et al.* (1989), it is difficult to explain the number of objects of the Apollo and Amor groups and features of their orbits (for example, their mean inclinations, which are larger than those in the main asteroid belt), if one considers only asteroidal sources. Wetherill (1991) considered that NEOs should come from the Kuiper belt, but not from the Oort cloud in order to supply present inclinations of orbits of NEOs.

Gladman and Duncan (1990), Torbett and Smoluchowski (1990) found that due to gravitational influence of the giant planets the orbits of bodies of the inner part of the beyond-Neptune belt could begin to cross the orbit of Neptune. 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. They finished their calculations of the evolution of test beyond-Neptune bodies when orbits of these bodies began to cross the orbit of Neptune or the body entered inside the Hill sphere of Neptune.

Below we consider migration of objects from the Kuiper belt under the gravitational influence of the giant planets 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 program of symplectic method from the Swift integration package worked out by Levison and Duncan (1994). A time step was the same as in their test, i.e., equaled to 1 yr. This integrator is by an order of magnitude faster than previous methods of integration. We considered various (not only small) initial eccentricities $e_\circ$ and inclinations $i_\circ$ of orbits of beyond-Neptune bodies. Initial values $a_\circ$ of semimajor axis were varied from 35 to 50 AU. Orbital evolution of one hundred of bodies was considered. The considered time span T usually equaled to 20 Myr. In some runs T reached $100-150$ Myr.

Migration of various bodies under the gravitational influence of planets inside the Solar System was considered by Duncan *et al.* (1988), Hahn and Bailey (1990), Steel and Asher (1992), Levison and Duncan (1994), and many other authors. Perihelia of these bodies and even initial orbits of most of the bodies were located inside the orbit of Neptune. In some our runs perihelia of initial orbits were located outside the orbit of Neptune but then some bodies got in the region of the planets. Morbidelli *et al.* (1995) investigated evolution of some resonant beyond-Neptune orbits that did not get deep inside the Solar System.

For some typical orbits (in the case without close encounters), we compared results obtained with the use of the RMVS2 integrator with those obtained with the integrator by Bulirsh and Stoer (1966). It was shown that limits of variations in semimajor axis during 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 $i_\circ = 5°$ and initial values of the longitude of ascending node, the argument of perihelion, and the mean anomaly equal to $\Omega_\circ = \omega_\circ = M_\circ = 60°$, for $a_\circ = 40$ AU and $e_\circ$ =0.15 and for $a_\circ = 39.3$ AU and $e_\circ$ =0.3, the perihelion distance q decreased from 34 and 27.5 AU to 1.25 and 1.34 AU in 25 and 64 Myr, respectively, and these bodies were ejected into hyperbolic orbits in 30 and 70 Myr, respectively. Maximum inclinations $i_{\max}$ in these runs were equaled to 57° and 36°, respectively, and there were large variations in e and i when q was close to minimum. Orbital elements were calculated with a time step equalled to 20,000 yr and actual minimal values of q can be smaller than those presented above. The time interval during which q decreased from 10 to 1.3 AU equaled to 0.3-0.5 Myr, and that for q decreased from 5 AU to 1.3 AU was considerably smaller. For $a_\circ = 39.3$ AU, $e_\circ = 0.15$, $i_\circ = 5°$, $\Omega_\circ = \omega_\circ = 0$, $M_\circ = 30°$, the time interval during which q decreased from 30 to 3 AU was less than 2 Myr.

For some runs q exceeded 10 AU during all time span before the ejection of a body into a hyperbolic orbit. For example, at $a_\circ = 39.3$ AU, $e_\circ = 0.15$, $i_\circ = 5°$, and $\Omega_\circ = \omega_\circ = M_\circ = 0$, a test body was ejected into a hyperbolic orbit after 41.5 Myr, and $q > 15$ AU and $i \leq 33°$ during this time span. For $a_\circ = 40$ AU, $e_\circ = 0.05$, $i_\circ = 5°$, and $\Omega_\circ = \omega_\circ = M_\circ = 60°$, a test body was in elliptical orbit with $q > 10$ AU during the considered time span $T = 100$ Myr, though the variations in orbital elements were large and maximum eccentricity $e_{\max}$ exceeded 0.8. For $a_\circ = 38.9$ AU, $e_\circ = 0.15$, $i_\circ = 5°$, $\Omega_\circ = \omega_\circ = M_\circ = 60°$, and $T = 150$ Myr, we have $q \geq 15$ AU, $e_{\max} = 0.76$, and $i_{\max} = 27°$. During the first 30 Myr, variations in a were small in this run. For larger values of $e_\circ$, the quota of bodies that cross the orbit of Neptune during evolution is larger. The time T_h elapsed until the ejection of a body into a hyperbolic orbit is smaller, as a rule, for smaller values of $i_\circ$. For example, at $a_\circ = 39.3$ AU, $e_\circ = 0.3$, and $\Omega_\circ = \omega_\circ = M_\circ = 60°$, it was obtained that $T_h \approx 70$ Myr for $i_\circ = 5°$ and $T_h \approx 7$ Myr for $i_\circ = 0$.

Limits of variations in a, e, and i may differ considerably for runs with the same values of $a_\circ$, $e_\circ$, and $i_\circ$, but with different values of $\Omega_\circ$, $\omega_\circ$, and $M_\circ$. In the main asteroid belt such influence of initial orbital orientations was obtained only for resonant orbits. In the Kuiper belt we obtained this influence for the resonance 2:3 with Neptune ($a_\circ \approx 39.4$ AU) and also for some nonresonant orbits. For example, at $a_\circ = 39.3$ AU, $e_\circ = 0.15$, and $i_\circ = 5°$, we investigated evolution of 12 orbits with various values of $\Omega_\circ$, $\omega_\circ$, and $M_\circ$ during a time span $T = 20$ Myr. All these orbits were resonant. It was obtained that maximum eccentricity $e_{\max} < 0.2$ for 5 runs and $e_{\max} > 0.3$ for 3 runs. For nonresonant value $a_\circ = 40$ AU at $e_\circ = 0.15$, $i_\circ = 5°$, $\Omega_\circ = M_\circ = 60°$ and the same time span, we obtained $e_{\max} = 0.19$ at $\omega_\circ = 0$ and

$e_{\max} = 0.36$ at $\omega_\circ = 60^\circ$. For $a_\circ = 42$ AU, $e_\circ = 0.05$, $i_\circ = 5^\circ$ and $T = 20$ Myr, we have $e_{\max} = 0.07$, $i_{\max} = 5.7^\circ$, and the minimum value of q is equal to $q_{\min} = 39$ AU at $\Omega_\circ = \omega_\circ = M_\circ = 60^\circ$ and $e_{\max} = 0.33$, $i_{\max} = 9.6^\circ$, and $q_{\min} = 31$ AU at $\Omega_\circ = \omega_\circ = M_\circ = 0$. The above examples show that limits of variations in orbital elements can highly depend on initial orientations of beyond-Neptune orbits. Therefore, small variations in orbital elements due to collisions and mutual gravitational influence of beyond-Neptune bodies can cause large variations in orbits under the gravitational influence of the giant planets.

For all considered runs and a time span equaled to 20 Myr, the variations in a and maximum values of e and i during evolution exceeded 0.6 AU, 0.05 and 3°, respectively. Therefore, the values of e and i of beyond-Neptune bodies can not be small for a long time.

A small number of LL-chondrites with the age $t < 8$ Myr may be caused by their long way from the Kuiper belt to the Earth. Ipatov (1995) investigated migration of small bodies under the gravitational influence of all planets with the use of the method of spheres of action. Hundreds of bodies were considered in these runs, and it was obtained that individual bodies decreased their aphelion distances from the beyond-Neptune zone to the values even less than 1 AU.

This work was supported by the Russian Foundation for Fundamental Research, project no 96-02-17892. Computer simulations of the evolution of beyond-Neptune orbits under the gravitational influence of the giant planets were made in 1995 during the visit to FUNDP (Namur, Belgium) supported by ESO grant no. B-06-018.

REFERENCES

Bulirsh, R. and Stoer, J., *Numer. Math.*, **8**, 1-13, 1966.

Duncan, M., Quinn, T., and Tremaine, S., 328, L69-L73, 1988.

Duncan, M.J., Levison, H.F., and Budd, S.M., *Astron. J.*, **110**, 3073-3081, 1995.

Gladman, B. and Duncan, M., *Astron. J.*, **100**, 1680-1696, 1990.

Hahn, G. and Bailey, M.E., *Nature*, **348**, 132-136, 1990.

Holman, M.J. and Wisdom, J., *Astron. J.*, **105**, 1987-1999, 1993.

Ipatov, S.I., *Solar System Research*, **29**, 261-286, 1995.

Levison, H.F. and Duncan, M.J., *Astrophys. J.*, **406**, L35-L38, 1993.

Levison, H.F. and Duncan, M.J., *Icarus*, **108**, 18-36, 1994.

Morbidelli, A., Thomas, F., and Moons, M., *Icarus*, **118**, 322-340, 1995.

Öpik, E.J., *Adv. Astron. Astrophys.*, **2**, 219-262, 1963.

Steel, D.I. and Asher, D.J., In *Periodic comets* (edited by J.A. Fernandez and H. Rickman). Montevideo, Uruguay, 65-73, 1992.

Torbett, M. and Smoluchowski, R., *Nature*, **44**, 722-729, 1990.

Weissman, P.R., A'Hearn, M.F., McFadden, L.A., and Rickman, H., In *Asteroids II* (edited by R.P. Binzel, T. Gehrels, M.S. Matthews), Tucson: Univ. Arizona Press, 880-919, 1989.

Wetherill, G.W., *Icarus*, **76**, 1-18, 1988.

Wetherill, G.W., *Meteoritics*, **24**, 15-22, 1989.

Wetherill, G.W., In *Proc. of the IAU Colloquium 121 "Comets in the post-Halley era"* (edited by R.L. Newburn, J. Rahe, and M. Neugebauer), Amsterdam: Kluwer Academic Publishers, 537-556, 1991.