The effect of encounters with interstellar objects of planetary and substellar masses on the Solar system dynamics

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Abstract. We consider the effect of close encounters of interstellar objects of planetary and substellar masses on the dynamics of the Solar System. By means of massive numerical experiments and analytical considerations, the both immediate and long-term consequences of such events for the Solar system dynamics are identified and explained.

Introduction

A free-floating planet (FFP) is understood as a planet that is not gravitationally bound to any star. The upper mass limit for a planet is about $13M_{\mathrm{J}}$ (Jupiter masses); within a larger mass object, deuterium is ignited in the core and the object thus represents a brown dwarf (BD). The upper mass limit for BD is about $75M_{\mathrm{J}}$.

Currently, ordinary planetary systems (including circumbinary ones) are considered to be the main source of origin of FFPs. An opportunity of the FFP formation in interstellar space via gravitational collapse of interstellar gas blobs is also not excluded. Various formation mechanisms may provide, in sum, the FFP presence in the Galactic thin disc in the range from 0.24 to 200 pc^{-3} [1].

Studies of interactions of planetary systems with massive interstellar objects (MISOs), such as FFPs or BDs, is of great interest, since such interactions directly concern the problem of stability and long-term dynamics of planetary systems.

Model set-up

There can be many scenarios for interaction of the Solar system with a MISO, since the choice is broad not only for the MISO mass but also for its orbit's initial conditions. Here, we limit ourselves to studying two nominal approach trajectories of MISOs. We consider the hyperbolic orbits of real interstellar objects 1I/'Oumuamua and 2I/Borisov, which visited the Solar system in 2017 and 2019. These both orbits passed through the inner Solar system.

For each approach orbit, the initial state of the system (positions and velocities) is set to be the same in all our numerical experiments, only the MISO masses is varied. The number of experiments is rather large (about 2000 per orbit), because the MISO mass is varied in small steps over a wide range, see table 1.

MISO type	Mass range, M_J	Step in mass, M_J	ρ, au	τ, yr
FFP	0 – 13	0.01	1.2×10^4	5×10^6
BD	13 – 45	0.05	6×10^4	2×10^6

TABLE 1. MISO mass range and quantities ρ and τ denoting, respectively, the maximum interaction distance and the integration time interval.

The gravitational interaction of the Sun, MISO and eight major planets (from Mercury to Neptune) is considered. At the initial epoch T_0, the MISO is at a distance ρ from the Sun and is approaching the Solar system. After passing the perihelion, the MISO moves further on, and, on reaching the same distance ρ from the Sun, is excluded from the integration. The integration of the perturbed planetary configuration is however continued and is eventually stopped when the time elapsed since the epoch T_0 becomes equal to τ. If, during this time interval, any planet is ejected, the integration is as well stopped. The adopted quantities ρ and τ are given in table 1.

In each numerical experiment, we calculate the maximum values of the planetary eccentricities and inclinations

$$e^j_{\max} = \max e_j, \quad i^j_{\max} = \max i_j, \qquad 1 \leqslant j \leqslant 8, \tag{1}$$

as well as quantities

$$\begin{aligned} d^1_{\min} &= \min(a_3(1-e_3) - a_1(1+e_1)), \\ d^j_{\min} &= \min(a_j(1-e_j) - a_{j-1}(1+e_{j-1})), \quad 2 \leqslant j \leqslant 8, \end{aligned} \tag{2}$$

which provide estimates of the distance between two elliptical orbits, see e.g. [2]. To calculate all 24 quantities $e^j_{\max}, i^j_{\max}, d^j_{\min}$, $1 \leqslant j \leqslant 8$, a time step of 5 yr is used, and the maxima and minima on the RHS of (1) and (2) are taken over the total integration time interval (starting from T_0). At the time moment of the MISO exclusion from the system, the values of the osculating semimajor axes, eccentricities and inclinations

$$a^j_{\text{imm}}, \quad e^j_{\text{imm}}, \quad i^j_{\text{imm}}, \quad 1 \leqslant j \leqslant 8,$$

are recorded. The accuracy of calculations in each experiment was controlled by checking the conservation of the energy integral.

All calculations were performed by the IAS15 high-precision non-symplectic integrator implemented in the REBOUND package [3]. The computing resources of the Joint Supercomputer Center of the Russian Academy of Sciences were used. Each MPI (Message Passing Interface) process ran one instance of REBOUND with a given orbit and a given value of the MISO mass.

Results and conclusions

In the case of substellar-mass ($>$ 13 Jovian masses) interlopers, i.e. free-floating BDs, the general conclusions about the influence of the flyby on the subsequent evolution of the planetary system are as follows.

(1) The immediate (on the timescale of $\sim 10 - 100$ yr) consequence of the passage is a significant increase in orbital inclinations and eccentricities of the outermost planets Uranus and Neptune.

(2) On the intermediate timescale ($\sim 10^3 - 10^5$ yr), Neptune or Uranus (more likely) can be ejected from the system due to close encounters with Saturn, as well as with each other.

(3) On the secular timescale ($\sim 10^6 - 10^7$ yr), the major perturbation wave caused by the secular interactions of the planets reaches the inner part of the Solar system.

Regarding immediate and long-term outcomes with planetary mass intruders, it is found that a FFP flyby is able to cause an immediate entering of a pair of planets into a chaotic mean motion resonance; this, in turn, may cause disruption of the Solar system on a secular timescale.

Any MISO flyby typically sets the planetary system into a more chaotic state; however, a stronger chaos, implying a smaller Lyapunov time, does not necessarily cause a more rapid disintegration, because the Lyapunov timescales and chaotic diffusion timescales can be interrelated in various fashions [4, 5]; and the system, in fact, can be left in a state of “stable chaos,” with no disruption following. Besides, the distributions of disruption times of gravitational systems of the considered type are heavy-tailed [6, 7]; therefore, the disruptive effect of an encounter can occasionally be quite prolonged, with respect to values typically observed in simulations.

Concluding, the long-term stability of the Solar System can be disrupted even if the interstellar object is not very massive (a Jovian mass is enough) and does not experience close encounters with the planets. The disintegration of the planetary system does not necessarily appear immediately, but may take place in several million years.

From the data obtained, it also follows that it is unlikely that the Solar system, which has an age of more than 4 Gyr, in its past was subject to numerous encounters with objects of giant-planet and substellar masses, because such encounters induce large planetary eccentricities and inclinations and may even lead to ejections of outermost planets.

A more detailed discussion of the results obtained, as well as consideration of their differences due to changes in the encounter orbit and the MISO's mass can be found in [8].

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