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

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Abstract. We explore the immediate and long-term consequences of close passages of interstellar planet-mass and substellar-mass objects for the Solar system dynamics. Two approach orbits of such objects are considered, namely, the hyperbolic orbits of two real interstellar objects, 1I/'Oumuamua and 2I/Borisov. For each orbit, a series of massive numerical experiments is performed, in which the mass of the interstellar object is varied in small steps over a broad range. It is shown that even if the interloper does not experience any close encounter with a planet of the Solar system, and has a mass typical for a free-floating planet, a disruption of the Solar system may occur on time scales of several million years.

Keywords: planets and satellites: dynamical evolution and stability; ISM: individual objects: 1I/'Oumuamua, 2I/Borisov

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1 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 $13 M_\mathrm{J}$ (Jupiter masses). With a larger mass value, deuterium is ignited in the core and the object thus represents a brown dwarf (BD). The upper mass limit for BD is about $75 M_\mathrm{J}$.

Currently, ordinary planetary systems (including circumbinary ones) are considered to be the main source of origin of FFPs. A possibility of the FFP formation in interstellar space through the gravitational collapse of interstellar gas blobs is also not excluded. Analysis of various formation mechanisms gives an estimate of the FFP concentration in the Galactic thin disc in the range from 0.24 to 200 pc^{-3} (Goulinski & Ribak 2018).

Studies of interactions of planetary systems with massive interstellar objects (MISOs), such as FFPs or BDs, are of great interest, since they directly concern the problem of stability and long-term orbital dynamics of planetary systems. In this work, we explore effects of interaction of MISOs with our Solar system. We study the immediate consequences of such encounters, as well as their impact on the long-term evolution of the Solar system.

2 Model set-up

2.1 Approach trajectories and MISO mass range

There can be many scenarios for the 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 consider two nominal approach trajectories: namely, the hyperbolic orbits of real interstellar objects 1I/'Oumuamua and 2I/Borisov (hereafter orbits I and II, respectively), which visited the Solar system in 2017 and 2019. These both orbits traverse the inner Solar system.

For each of these orbits, the initial state of the system (positions and velocities) is set to be the same in all our numerical experiments, only the MISO mass is varied. The number of experiments is rather large (about 2000 per orbit), since the mass is varied in small steps over a wide range, see Table 1. In this Table, the quantities ρ and τ denote the maximum interaction distance and the integration time interval, respectively (see details below).

2.2 Numerical experiments

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

Table 1. Computation series parameters.

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

from the Sun and is approaching the Solar system. After passing the perihelion, the MISO moves further and further 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 also stopped.

In each experiment, we calculated 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 estimate distances between two elliptical orbits (e.g. Mikryukov & Baluev 2019). To calculate all 24 quantities $e^j_{\max}, i^j_{\max}, d^j_{\min}$, $1 \leqslant j \leqslant 8$, a time step of 5 years is used, and the maxima and minima on the right-hand sides 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

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

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

2.3 Software and hardware

All calculations were performed by the IAS15 high-precision non-symplectic integrator implemented in the REBOUND package (Rein & Spiegel 2015).

The computing resources of the Joint Supercomputer Center of the Russian Academy of Sciences[3] were used. Each MPI (Message Passing Interface) process

[3] https://www.jscc.ru/

ran one instance of REBOUND with a given orbit and a given value of the MISO mass.

3 Results

Here we present the main results obtained in our numerical experiments with MISOs in orbit I. A detailed discussion of the results concerning both orbits I and II can be found in Mikryukov & Shevchenko (2024).

3.1 Planet-mass MISOs

The orbits of outermost planets, those of Uranus and Neptune, are most susceptible to immediate excitation. For other six planets, the inclinations and eccentricities are excited much less, and their parameters $e_{\rm imm}$, $i_{\rm imm}$ show much smaller variations with the increase of MISO's mass.

In the numerical experiments with planet-mass MISOs it is found that a MISO flyby is able to cause an immediate entering of a pair of planets into a mean motion resonance. This, in turn, may cause disruption of the Solar system on a secular timescale.

3.2 Substellar-mass MISOs

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 the orbital inclinations and eccentricities of the outermost planets — Uranus and Neptune.

(2) On the intermediate timescale ($\sim 10^3$–10^5 yr), Uranus (most likely) and Neptune can be ejected from the Solar 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.

A typical example of the long-term behaviour of eccentricities and inclinations of the outer planets, before Uranus is ejected, is presented in Fig. 1. In this example, a flyby of a MISO with a mass of $m_{\rm MISO} = 28.7 M_{\rm J}$ in orbit I causes the ejection of Uranus in about one million years after the encounter.

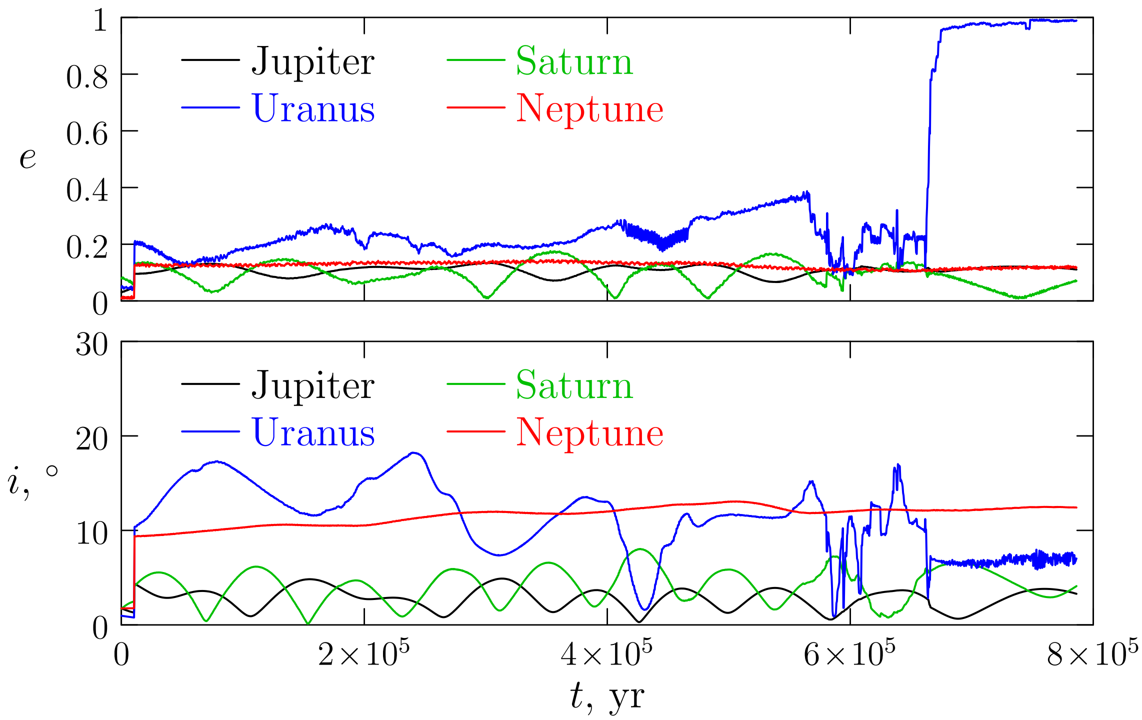

Fig. 1. The long-term behaviour of eccentricities and inclinations of the outer planets before Uranus is ejected, a typical example.

4 Summary

As follows from the performed analysis, the long-term stability of the Solar System can be disrupted even if the interstellar interloper is not very massive (a Jovian mass is enough) and does not experience any close encounter with any planet of the Solar system. The disintegration of the planetary system does not necessarily appear immediately, but may take place in several million years.

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.

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, very different, fashions (Shevchenko 2020; Cincotta et al. 2022); and the system, in fact, can remain in a state of "stable chaos", with no following disruption. Besides, the distributions of disruption times of gravitational systems of the considered type are heavy-tailed (Orlov et al. 2010; Shevchenko 2010); therefore, the disruptive effect of an encounter can occasionally be quite prolonged, with respect to values typically observed in numerical simulations.

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