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

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Introduction. What is a free-floating planet?

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

The study of interactions of planetary systems with massive interstellar objects (MISOs) is of great interest, since they directly relate to the problem of stability and long-term dynamics of planetary systems.

We investigate this problem by simulating and analysing the interactions of MISOs of those types with our Solar system. We study the immediate consequences of such encounters, as well as their impact on the long-term dynamical evolution of the Solar system.

The origin and population of FFP

According to modern estimates (Mróz et al. 2017), in our Galaxy, the number of FFPs with Jovian and greater masses should exceed the number of main-sequence stars by at least several times. According to Goulinski & Ribak (2018), approximately 1% of the number of stars with a mass less than two solar masses experience during their lifetime a temporary capture of an FFP (as a result of which the FFP usually enters an elongated unstable orbit). Hence, it obviously follows that encounters of stars with FFPs should occur much more often.

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

Model set-up. Approach trajectories

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 limit ourselves to considering two nominal MISO approach trajectories. We consider 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, respectively. These orbits are specific in that they intersect the inner zone of the Solar system (see Fig. 1).

For each of these orbits, we implement problem settings that differ only in the MISO mass. Based on the results of our integrations, we estimate the degree of influence of the MISO flyby on the immediate and long-term orbital dynamics of the Solar system.

Approach trajectories

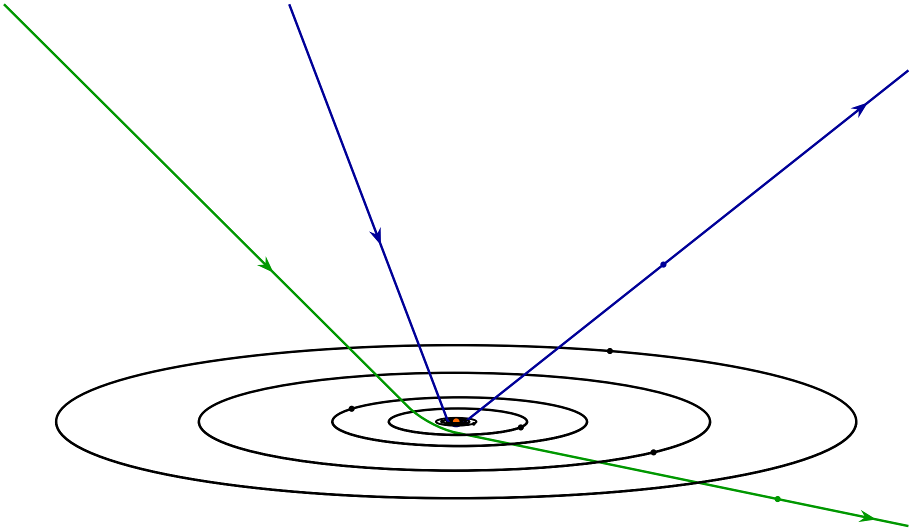


Figure 1. A sketch of orbit I (blue) and orbit II (green) flybys. In this scheme, the outermost planetary orbit is Neptune's.

MISO mass range

The performed numerical experiments are basically of similar methodology kind.

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.

MISO type	Mass range, M_{J}	Step in mass, M_{J}
FFP	0–13	0.01
BD	13–45	0.05

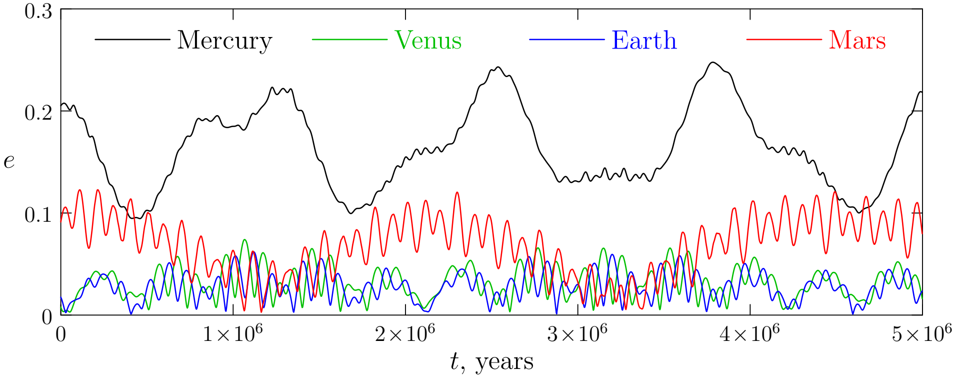
Numerical experiments

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 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 also stopped.

MISO type	Threshold distance ρ, au	Integration time interval τ, yr
FFP	12×10^3	5×10^6
BD	60×10^3	2×10^6

Numerical experiments



Long-term evolution of eccentricities of the terrestrial planets over 5 Myr in the absence of MISO flybys. The time is counted from the present epoch. On the choice of integration time interval τ.

Calculated quantities

In the course of integration, we calculate the maximum values of the planetary eccentricities and inclinations

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

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 a simple estimate of the distance between two elliptical orbits.

To calculate all 24 quantities (1, 2), a time step of 5 yr is used, and the maxima and minima on the RHS are taken over the total integration time interval (starting from T_0).

Calculated quantities

At the time moment of excluding the MISO from the system, the values of the osculating semimajor axes, eccentricities and inclinations

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

are recorded.

In each experiment we also calculate the relative deviation of the energy integral:

$$\varepsilon = \left| \frac{\mathcal{E} - \mathcal{E}_0}{\mathcal{E}_0} \right|,$$

where $\mathcal{E}_0$ and $\mathcal{E}$ are, respectively, the initial and final values of the system's total energy.

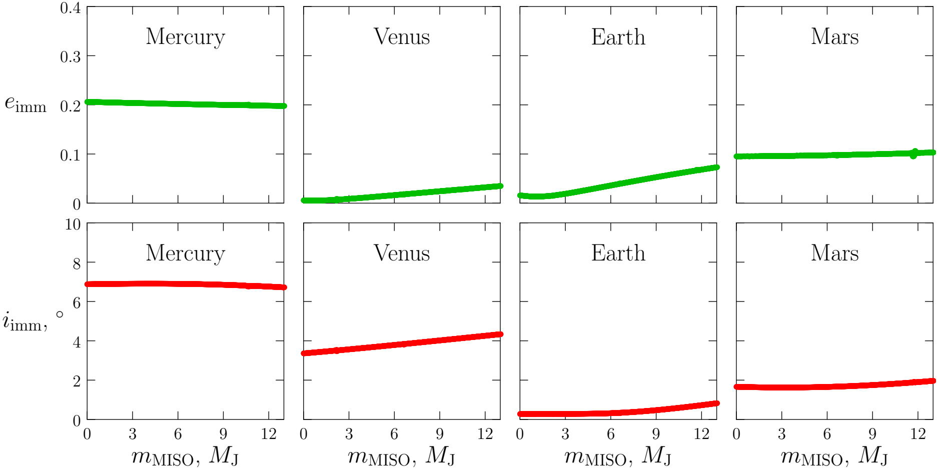
Software and hardware

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

The REBOUND system has many useful built-in features. For example, before starting the integration, REBOUND can reduce the equations of motion into a barycentric reference frame. This feature is especially useful if the computations are performed over long time intervals.

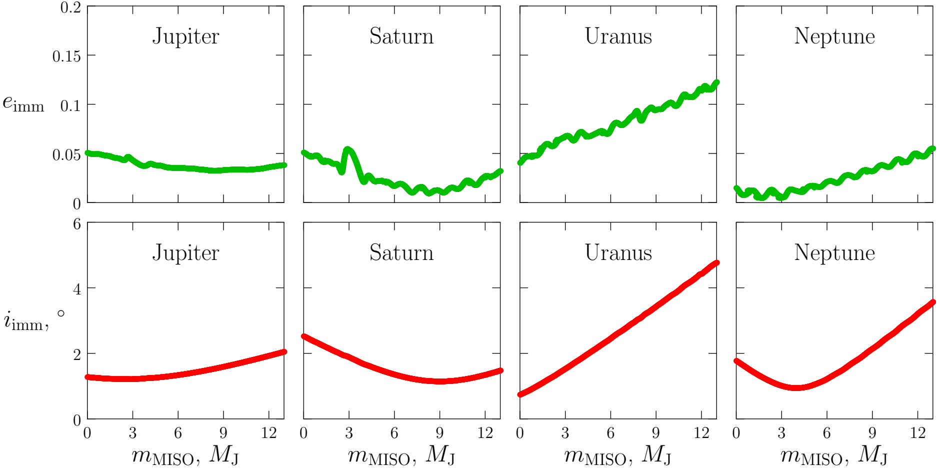
The computing resources of the Joint Supercomputer Center of the Russian Academy of Sciences (JSCC RAS) were used. Each MPI (Message Passing Interface) process ran one instance of REBOUND with a given orbit and a given value of the MISO mass. The numerical experiments typically took time from 15 to 25 h each.

Results. Planet-mass MISOs. Orbit I



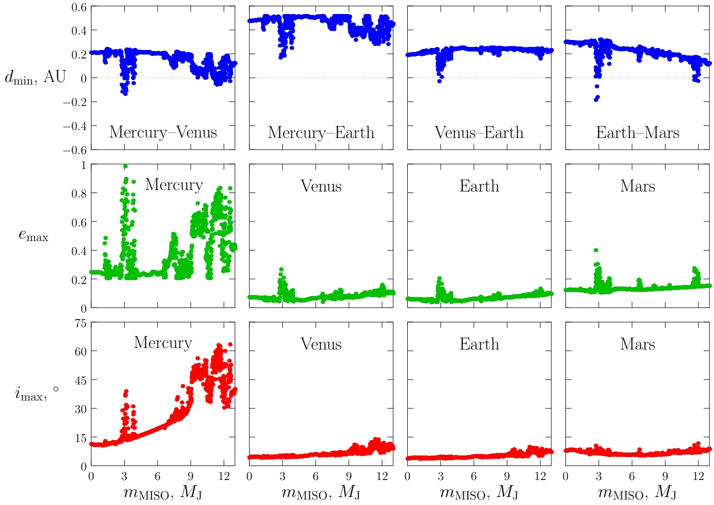
The immediate eccentricities and inclinations of the inner planets.

Planet-mass MISOs. Orbit I



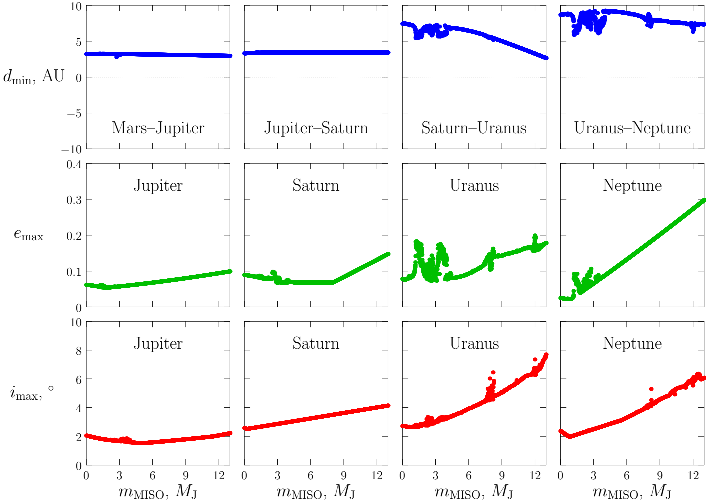
Immediate outcomes for the outer planets. Saturn shows a slight peak in behavior of $e_{\rm imm}$ at $m_{\rm MISO} \approx 3M_{\rm J}$.

Planet-mass MISOs. Orbit I



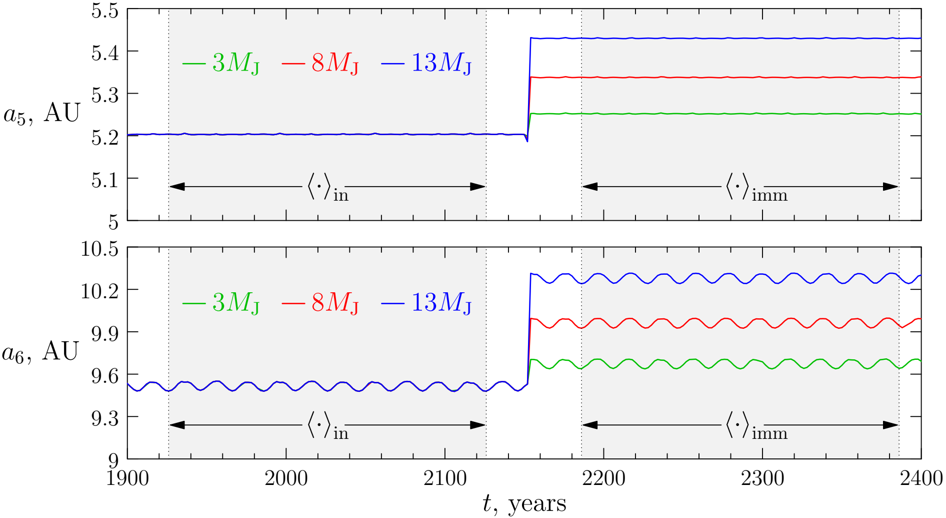
Long-term outcomes for the inner planets. For all four planets, one may clearly observe peaks in behavior of $e_{\max}$, coherently at the same $m_{\rm MISO} \approx 3 M_{\rm J}$ value.

Planet-mass MISOs. Orbit I



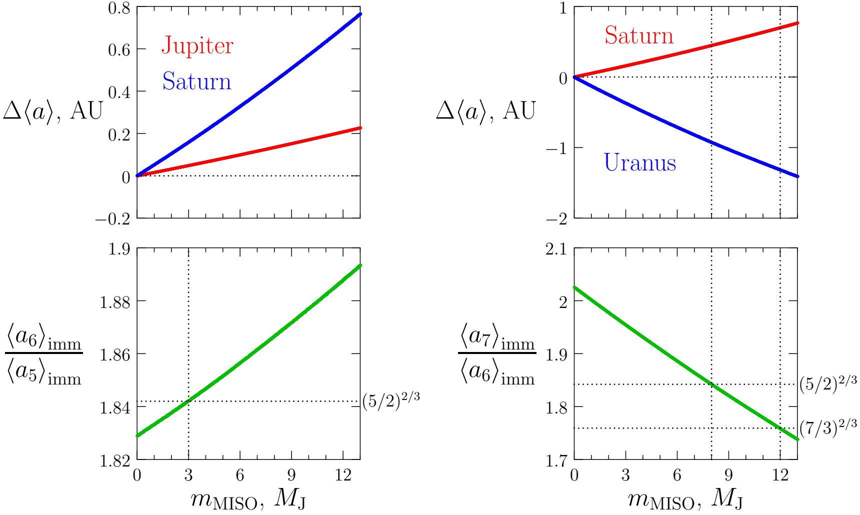
Long-term outcomes for the outer planets. In the case of Uranus and Neptune, at values of m_{MISO} equal to approximately $3M_{\mathrm{J}}$, $7M_{\mathrm{J}}$ and $12M_{\mathrm{J}}$, jumps in the behavior of $e_{\max}$ are also observed.

Planet-mass MISOs. Orbit I



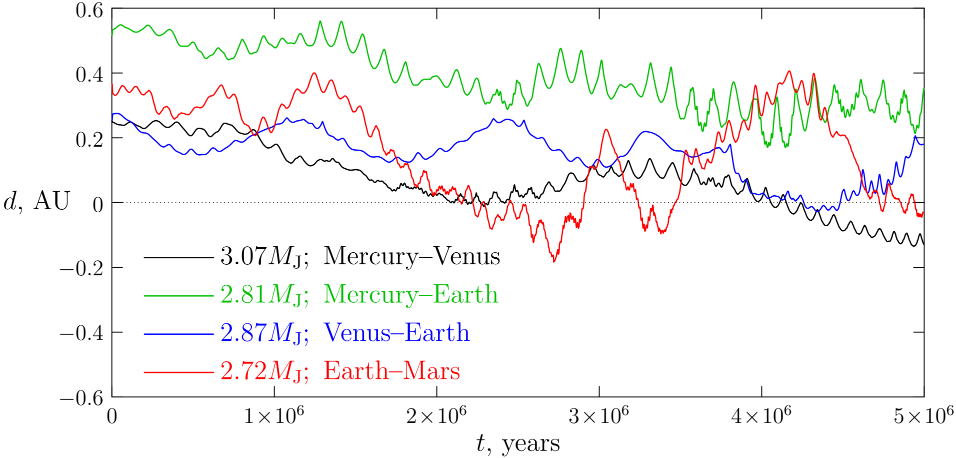
Average value change $\Delta\langle a\rangle = \langle a\rangle_{imm} - \langle a\rangle_{in}$.

Planet-mass MISOs. Orbit I



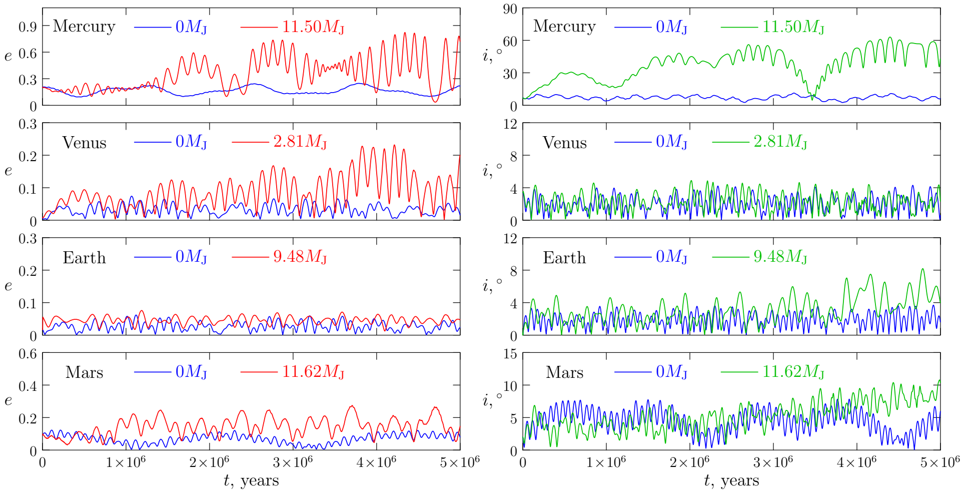
Capture of the Solar system into a mean motion resonance after a MISO flyby. At $m_{\rm MISO} \approx 12 M_{\rm J}$, the $5:3$ resonance also appears in the Earth–Mars pair.

Planet-mass MISOs. Orbit I



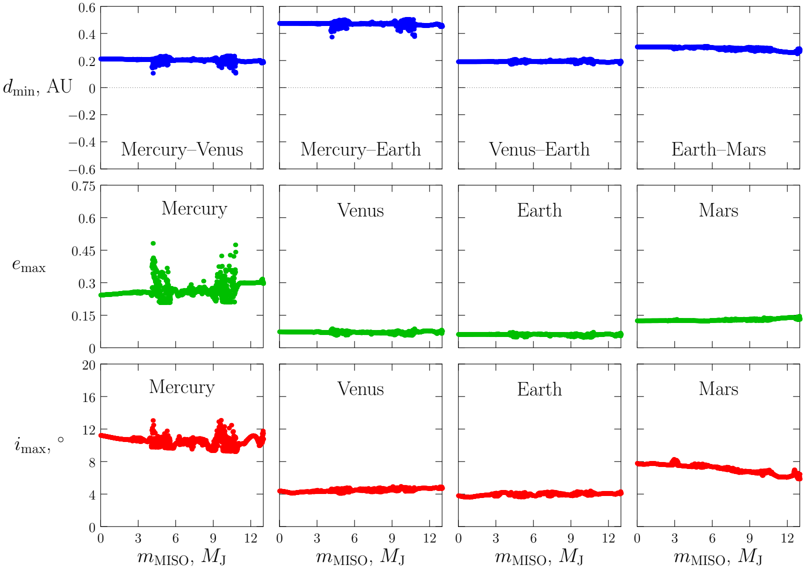
The time behaviour of the parameter $d = q - Q$, where, in a planetary pair, q is the pericentre distance of the outer planet, and Q is the apocentre distance of the inner planet. The vicinity of the resonance value $m_{\mathrm{MISO}} \approx 3 M_J$.

Planet-mass MISOs. Orbit I



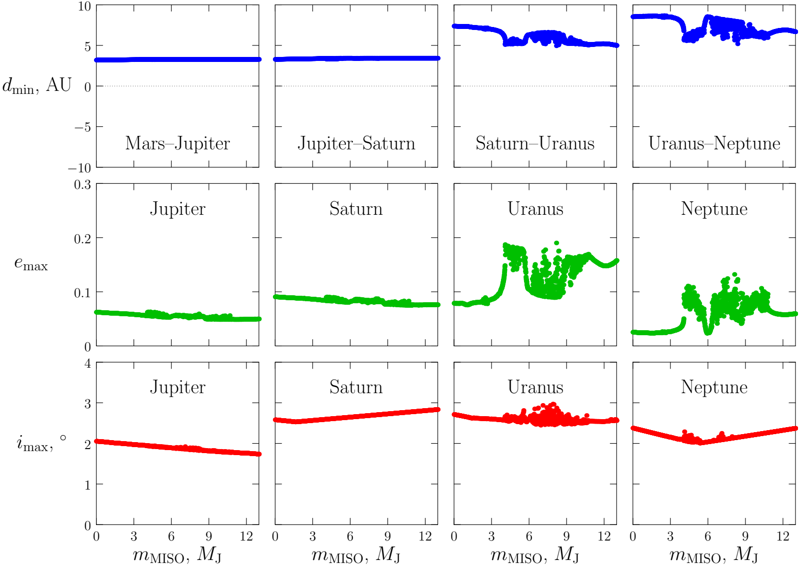
Evolution of the orbital eccentricities and inclinations of the inner planets after a MISO flyby. Time is counted from the epoch T_0.

Planet-mass MISOs. Orbit II



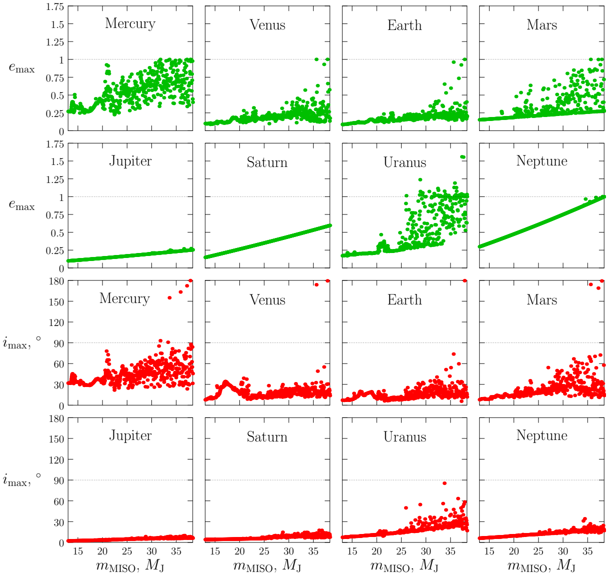
Long-term outcomes for the inner planets.

Planet-mass MISOs. Orbit II



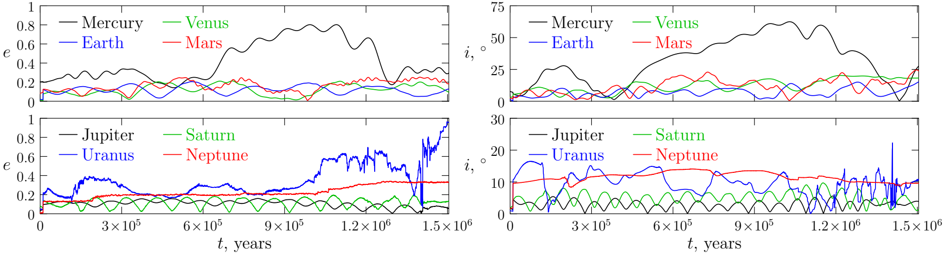
Long-term outcomes for the outer planets.

Substellar-mass MISOs. Orbit I



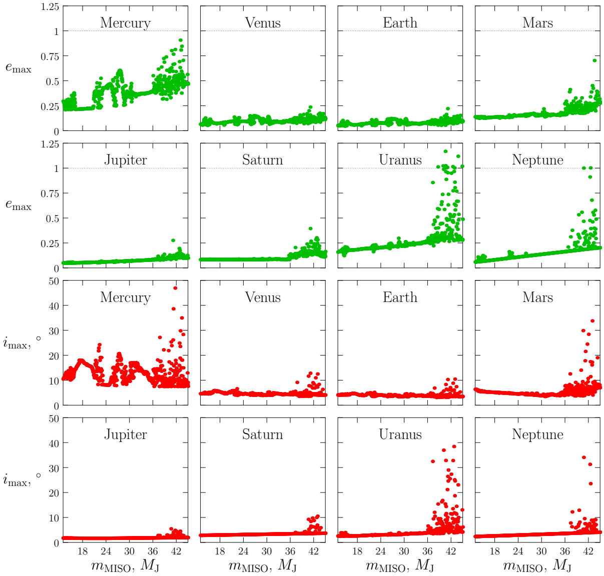
Maximum values of eccentricities and inclinations.

Substellar-mass MISOs. Orbit I



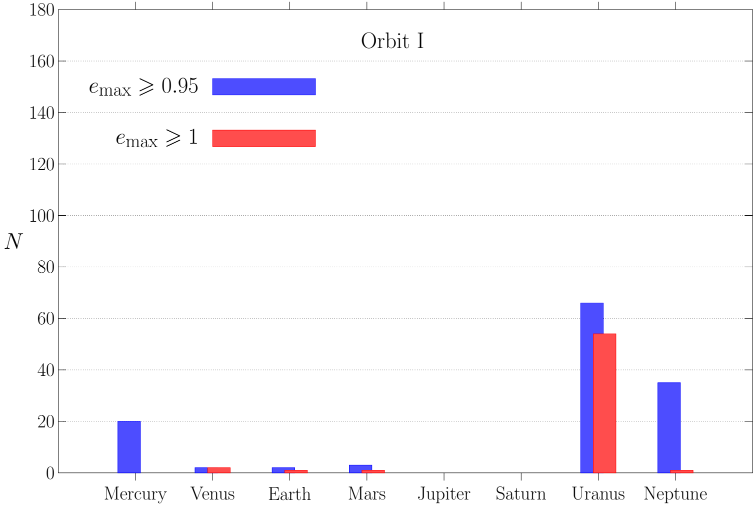
Evolution of eccentricities and inclinations of all planets until ejection of Uranus. At $m_{\mathrm{MISO}} = 29.25 M_{\mathrm{J}}$ Uranus leaves the system at $t \sim 1.5$ million years.

Substellar-mass MISOs. Orbit II



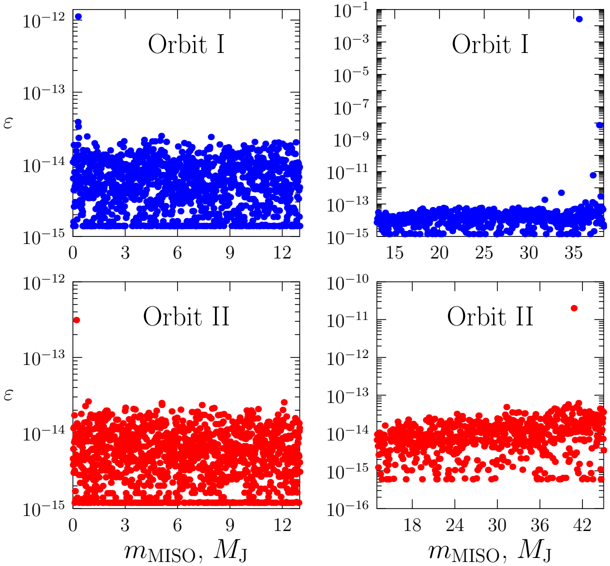
Maximum values of eccentricities and inclinations.

Substellar-mass MISOs. Orbit I



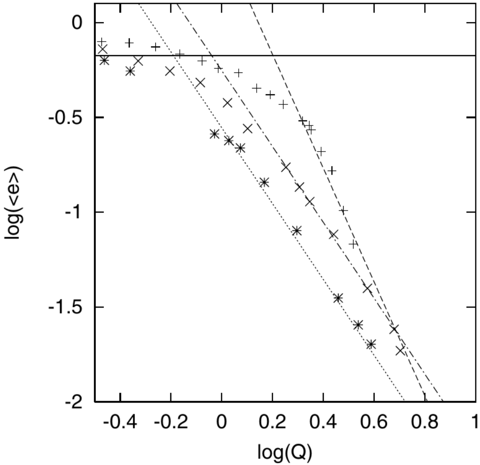
The number of ejections from the system. Uranus and Neptune are the most prone to ejections. The interval $13M_{\mathrm{J}} \leqslant m_{\mathrm{MISO}} < 38.4M_{\mathrm{J}}$.

The energy integral



Parameter ε, which controls the reliability of numerical calculations.

Discussion. Eccentricity jumps



The average change of eccentricity as a function of $Q = r/a$, where r is the pericentric distance of the passing object, and a is the semimajor axis of the traversed binary (Valtonen & Karttunen 2005, fig. 10.13).

Consequences of encounters with substellar-mass MISOs

Flybys of MISOs of substellar masses may disrupt the stability of the Solar system.

The **immediate** (on the timescale of ~ 10–100 yr) consequence of the passage is a significant increase in orbital inclinations and eccentricities of the outermost planets Uranus and Neptune.

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.

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.

Conclusions

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.

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 this would induce large planetary eccentricities and inclinations and could even lead to ejections of outermost planets.

To compile a general picture of MISO interactions with the Solar system, covering all possible encounter orbits, it is necessary to perform a much larger amount of computations with a broad choice of initial conditions. However, it is already clear from the just-described results that flybys of typical FFPs and BDs can lead to a loss of stability and relatively rapid (in comparison with the system age) disintegration of our planetary system.

A more detailed discussion of the results obtained can be found in the article:

D.V. Mikryukov, and I.I. Shevchenko,
Rendez-vous with massive interstellar objects, as triggers of destabilization,
Monthly Notices of the Royal Astronomical Society (2024),
v. 528, pp. 6411–6424.

Thank you for your attention!
Спасибо за внимание!