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Resonant Outcomes of Interactions of Massive Interstellar Objects with the Solar System

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Abstract—The paper studies the consequences of probable encounters of interstellar objects of planetary mass (free-floating exoplanets) with the Solar System. As a result of such approaches, mean motion resonances may arise in the dynamics of planets, but entering into the resonances is possible only with selected values of the mass of the interstellar object and the initial conditions of its motion. The most significant resonances that can arise as a result of the approaches have been identified.

Keywords: Solar system, mean motion resonances, free-floating exoplanets, interstellar objects
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INTRODUCTION

The study of resonances in planetary dynamics originates from the work of Laplace at the end of the 18th century. The ephemerides of Jupiter and Saturn that had been calculated before Laplace differed significantly from those observed, and Laplace was the first to establish that these deviations were due to the proximity of Jupiter and Saturn to the mean motion resonance 5 : 2 (see, for example, Grebenikov and Mitropolsky, 1992).

Mean motion resonance occurs when in a planetary system the mean motions of any planets (two or more) are in integer commensurability. Secular resonances may also be present, consisting of integer commensurabilities of the angular velocities of change of such elements as the longitude of the pericenter and the longitude of the ascending node. Mean motion resonances and secular resonances can manifest themselves in different ways, but they often have a decisive influence on the long-term dynamics of the planetary system (Morbidelli, 2002; Shevchenko, 2020).

Under the influence of various mechanisms, resonances in planetary systems can both appear and disappear. Such mechanisms include, for example, the processes of planetary migration that occur in the early stages of the formation of a planetary system (see, for example, Papaloizou, 2003). The outflow of matter from the central star can lead to the appearance or disappearance of resonances in an already formed planetary system, as well as in a system in the late stages of evolution (Matsumoto and Ogihara, 2020; Zink et al., 2020; Wang and Lin, 2023).

Resonance can also occur as a result of a planetary system approaching a massive interstellar object (MISO). Indeed, as a result of the approach, the orbital configuration, including the semimajor axes of the planets' orbits, can change significantly. In the work (Mikryukov and Shevchenko, 2024) the influence of encounters with interstellar objects of planetary and substellar masses on the dynamics of the Solar System was investigated. In particular, it was shown that, with a sufficiently close approach, a mean motion resonance in the Solar System can arise even if the MISO has a relatively small mass, comparable to the mass of Jupiter. For example, the flyby of MISO with mass $3M_J$ (M_J is the mass of Jupiter) under certain initial conditions of motion leads to the entry of the Jupiter–Saturn pair into the 5 : 2 resonance. It was shown that resonant outcomes also occur for some other values of the MISO mass under the same initial conditions.

It should be noted that the flybys of MISOs of relatively small masses (much less than the mass of Jupiter), although they usually do not destabilize the planetary system, are capable of significantly affecting the structure of circumstellar (in particular protoplanetary) disks, causing the formation of transient spiral patterns (see Grigoryev and Demidova, 2025). On the formation of spiral patterns in the absence of external disturbances, see (Demidova and Shevchenko, 2015). In the Solar System, past MISO flybys with masses between one and ten Earth masses can be responsible for observed asymmetries in the distributions of asteroids in resonant groups such as the Trojans and Gildas (Li et al., 2023, 2024).

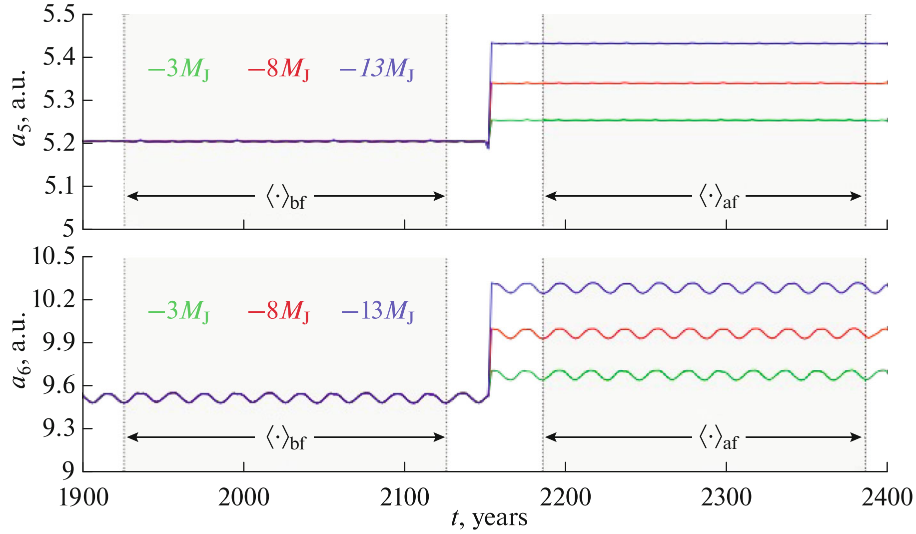

Fig. 1. Scheme for calculating the average values of the semimajor axes of the planets' orbits. The averaging operators are marked with angle brackets. See text for details.

MISO interactions with a planetary system of arbitrary configuration can cause the system either to enter resonance (with a low probability, since it requires fine tuning of the initial conditions/mass of the object), or to exit from an already existing resonance (with a high probability, given a sufficiently strong disturbance). In this paper, we identify and examine in detail the most significant likely resonant outcomes.

IDENTIFICATION OF RESONANCE

Mean motion resonance in a planetary pair with semimajor axes a and a' is determined by the condition

$$\frac{a'}{a} = \left(\frac{p+q}{p}\right)^{2/3}, \tag{1}$$

where are integers $p > 0$, $q \geq 0$; we set $a' \geq a$. In the dynamics of planetary systems, the most important resonances are those for which the resonance order q is small (Subbotin, 1968; Murray and Dermott, 2000).

Direct application of formula (1) is complicated by the fact that the long-term behavior of the elements a and a' is superimposed by short-period low-amplitude oscillations, the periods of which are comparable in order of magnitude to the periods of revolution of planets around a star. Therefore, in practice, to determine the proximity of a planetary pair to resonance, average values $\langle a \rangle$ and $\langle a' \rangle$ of the semimajor axes are usually substituted into formula (1). These average values are obtained by averaging the specified oscillations.

Below we apply the method for calculating the average values of planetary orbital semimajor axes proposed in the work (Mikryukov and Shevchenko, 2024). Let us number the osculating semimajor axes of the orbits of the eight major planets of the Solar System in the order of their distance from the Sun:

$$a_s, 1 \leq s \leq 8. \tag{2}$$

Figure 1 shows the behavior of the elements a_5 and a_6 during MISO flybys of various masses along the trajectory of the interstellar object 1I/'Oumuamua. The interval and time scale are chosen so that the structure of short-period oscillations a_5 and a_6 is clearly visible before and after the MISO flyby. The time is measured from the adopted start of the interaction with the MISO. The light gray color in Fig. 1 indicates two time intervals separated by the period of closest approach to the MISO. We take the length of each of them to be equal to ten periods of small oscillations of the semimajor axis of Saturn's orbit; such a value significantly exceeds the characteristic periods of short-period oscillations of elements (2). The average value of (a_s) was calculated for each interval separately and was determined as the arithmetic mean of the values of a_s obtained during the interval, the evolution of elements (2) was recorded in 2-year increments.

The average value calculated in this way before the MISO flyby is denoted by $\langle a_s \rangle_{\text{bf}}$, and after the flight through $\langle a_s \rangle_{\text{af}}$ (the abbreviations "bf" and "af" stand for "before flyby" and "after flyby," respectively), see Fig. 1. We also set $\Delta\langle a_s \rangle = \langle a_s \rangle_{\text{af}} - \langle a_s \rangle_{\text{bf}}$.

ENTERING RESONANCE

In the work (Mikryukov and Shevchenko, 2024) for the trajectory corresponding to the orbital elements of 1I/'Oumuamua (including the pericenter epoch), a large set of similar scenarios of approach was

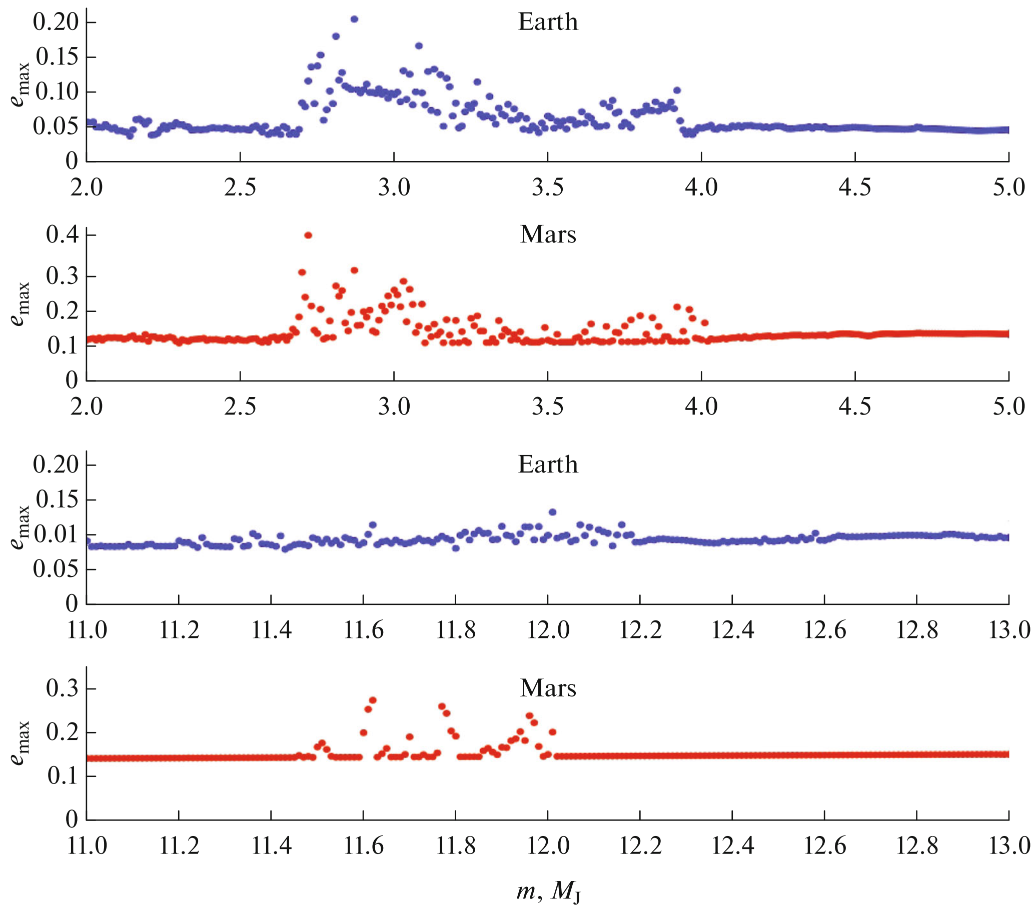

Fig. 2. Maximum values of the orbital eccentricities of Earth and Mars, recorded during the 5 million years after the MISO flyby, depending on its mass m. At $m \approx 3M_J$ and $m \approx 11.7M_J$ the eccentricities of the orbits of the Earth and Mars reach values at which intersections of the orbits become probable. The initial conditions for the MISO flyby correspond to a 1I/'Oumuamua trajectory.

modeled, differing only in MISO's mass m. In this case, the step in m was set to $0.01M_J$ in the range of planetary masses $0 \le m \le 13M_J$. It was shown that at certain values of mass, mean motion resonance arise in the system. In particular, for values of m, located in a relatively small neighborhood of the value $3M_J$, the 5 : 2 resonance appears in the Jupiter—Saturn pair (see Fig. 13 in Mikryukov and Shevchenko, 2024). The entry of Jupiter and Saturn into the resonance further leads to a significant breach of the motion stability of the terrestrial planets: over the course of just a few million years, a significant distortion and disintegration of their orbital configuration occurs. In contrast, for MISO mass values close to (but not within) this neighborhood, the orbital configuration of the Solar System after the encounter remains relatively stable (see the top two panels in Fig. 2).

Similar phenomena occur with other planetary pairs. Figure 3 shows the change in values of $\Delta\langle a_6\rangle$ and $\Delta\langle a_7\rangle$ depending on the mass m of the MISO, approaching the Solar System along the 1I/'Oumuamua trajectory. The behavior of $\Delta\langle a_6\rangle$ and $\Delta\langle a_7\rangle$, as well as the ratios $\Delta\langle a_7\rangle_{af}/\Delta\langle a_6\rangle_{af}$ has a monotonic character. The graph shows that in the Saturn—Uranus pair, at $m \approx 8M_J$ and $m \approx 12M_J$ the 5 : 2 and 7 : 3 resonances arise, respectively. These resonances are of a fairly high order (3rd and 4th, respectively), but their influence is clearly visible in Fig. 6 in the work (Mikryukov and Shevchenko, 2024), which shows a noticeable destabilization of Uranus' orbit during the evolution following the MISO flyby.

Mean motion resonances also occur among the terrestrial planets. The 2nd order resonance 5 : 3 manifests itself in the Venus—Earth and Earth—Mars pairs at $m \approx 2.2M_J$ and $m \approx 11.7M_J$, respectively (see Figs. 4, 5). In the Earth—Mars pair, this resonance results in a marked increase in the eccentricity of Mars' orbit for several million years after its approach to the MISO (see the bottom panel of Fig. 2). Interestingly, the occurrence of the 5 : 3 resonance in the Venus—Earth pair does not have a noticeable effect on the dynamics of the terrestrial planets, although these are the two most massive planets in this group.

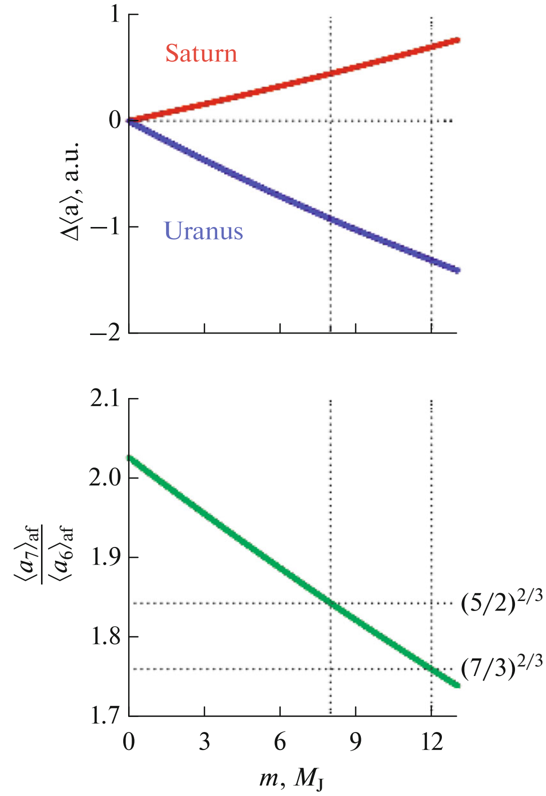

Fig. 3. Variation of the mean semimajor axes of the orbits of Uranus and Saturn and their ratios depending on the mass m of the MISO under given initial conditions. See text for details.

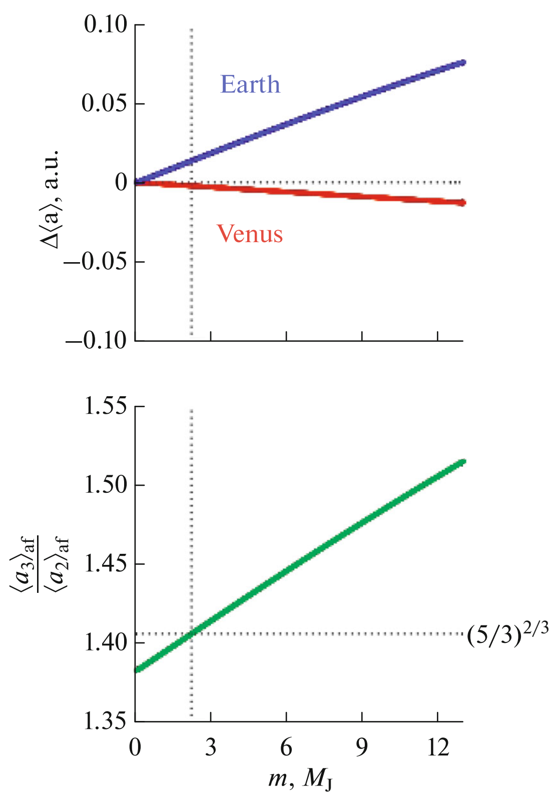

Fig. 4. The same as in Fig. 3, but for Venus and Earth.

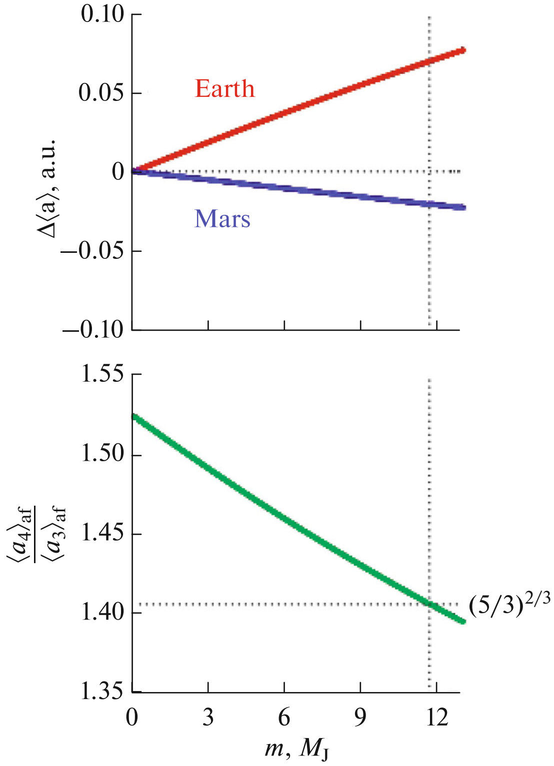

Fig. 5. The same as in Fig. 3, but for Earth and Mars.

CONCLUSIONS

According to the results of our calculations, the dependence of the change in the semimajor axes of the planets' orbits on the mass of the MISO is generally monotonic. Two conclusions follow from this. Firstly, the MISO flyby in a close orbit to the system could cause a mean motion resonance in the Solar System. Secondly, the entry of the Solar System into resonance as a result of such a flyby should be a rare phenomenon, since it can only occur at selected values of the mass of the MISO moving along a particular orbit. These conclusions are qualitatively valid for planetary systems of other stars as well. Note that in systems with a small number of planets, the occurrence of resonances as a result of encounters with a MISO is not as likely as in multiplanet systems.

The magnitude of the shift of the planetary semimajor axis can be theoretically estimated (see, for example, Roy and Haddow, 2003; Valtonen and Karttunen, 2005). This shift depends on the parameters of the MISO orbit. Therefore, among the many possible orbits, there may be trajectories along which the flight of an MISO of a certain mass leads to the appearance of a resonance among three or more planets.

Interactions of interstellar objects with a planetary system of arbitrary configuration can cause either the entry of the system into resonance (with a low probability, since fine tuning of the initial conditions/MISO mass is required) or the exit from an already existing resonance (with a high probability under a sufficiently strong disturbance). If a resonance in a planetary system plays a stabilizing role, preventing close encounters of bodies in resonance (as, for example, in the Neptune–Pluto or Io–Europa–Ganymede systems), then exiting the resonance (breaking the resonant chain) will lead to destabilization of the system. And here, fine-tuning of the mass and initial conditions for the MISO is not required, it is enough that the disturbance is large enough.

In this paper, only mean motion resonances were considered. The question of how MISO flybys affect secular resonances in the Solar System deserves a separate study.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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