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Existence of Asteroids in the Inner Solar System

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Abstract. Ensembles of in-plane and inclined orbits in the vicinity of the Lagrange points of the terrestrial planets are integrated for up to 100 million years. Mercurian Trojans probably do not exist, although there is evidence for long-lived, corotating horseshoe orbits with small inclinations. Both Venus and the Earth are much more promising, as they possess rich families of stable tadpole and horseshoe orbits. Our survey of in-plane test particles near the Martian Lagrange points shows no survivors after 60 million years. Low inclination test particles do not persist, as their inclinations are quickly increased until the effects of a secular resonance with Jupiter cause de-stabilisation. Numerical integrations of inclined test particles for timespans of 25 million years show stable zones for inclinations between 14° and 40°. Both Martian Trojans 5261 Eureka and 1998 VF31 lie deep within the stable zones, which suggests they may be of primordial origin.

1. Theoretical and Observational Motivations

Lagrange's triangular solution of the three body problem was long thought to be just an elegant mathematical curiosity. The three bodies occupy the vertices of an equilateral triangle. The detection of 588 Achilles near Jupiter's Lagrange point in 1906 by Wolf changed matters. More than 800 Jovian Trojans are now known, though the total population exceeding 15 km in diameter may be as high as ~ 2500. Roughly 80% of the known Trojans are in the L_4 swarm. The remaining 20% librate about the L_5 Lagrange point, which trails 60° behind the mean orbital longitude of Jupiter. There are also Trojan configurations amongst the Saturnian moons.

The first non-Jovian Trojan asteroid, 5261 Eureka, was discovered by Holt & Levy (1990) near the L_5 point of Mars. Surprisingly, the orbit of 5261 Eureka is inclined to the plane of the ecliptic by 20.3°. The discovery of a second Mars Trojan, 1998 VF31, soon followed (see e.g., (Tabachnik & Evans, 1999).

This paper is concerned with the existence of coorbiting asteroids near the triangular Lagrange points of the four terrestrial planets. We propose to map out the zones in which coorbital asteroids of the terrestrial planets can survive for timescales up to 100 million years.

2. Results

The orbits of the planets and the asteroids (represented as massless test particles) are integrated using a mixed variable symplectic integrator scheme with

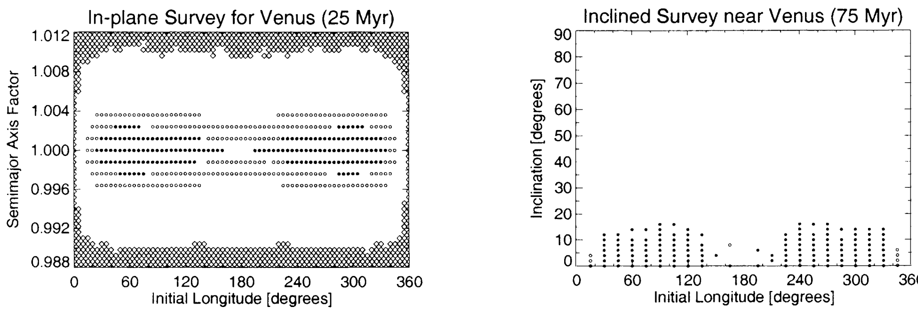

Figure 1. This shows the surviving test particles near Venus. On the left figure, the survivors are plotted as circles in the plane of initial differential longitude and semimajor axis factor after 25 Myr. Filled circles are tadpole orbits, open circles are horseshoe orbits. Unstable test particles in the restricted three body problem comprising the Sun, Venus and asteroid are shown as diamonds. The right figure shows that inclined ($i \gtrsim 16°$) Venusian asteroids are unstable after 75 Myr.

individual time steps (Saha & Tremaine, 1994). For each of the terrestrial planets, we carry out two surveys. The first is restricted to test particles in the orbital plane of the planet while the second survey explores the stability zones of inclined trajectories. As the test particles' orbits are integrated, they are examined at each time step. If their trajectories become parabolic or hyperbolic orbits, they are removed from the survey. In addition, test particles which experience close encounters with a massive planet or the Sun are also terminated.

2.1. Mercury

For the Mercurian in-plane survey, only $\sim 7\%$ out of the original test particles remain after 100 million years. The most striking point to notice is that the stable zones do not include the classical Lagrange points themselves. In fact, all the survivors follow horseshoe orbits and there are no surviving tadpole orbits. The inclined survey suggests that only low inclination ($i < 6°$) test particles on horseshoe trajectories are stable for 100 Myr.

2.2. Venusian and Terrestrial Surveys

Perhaps one of the likeliest planets in the inner Solar System to harbour undiscovered Trojans is Venus. Fig. 1 shows the results of the in-plane and inclined survey of Venusian test particles. 51% of the initial in-plane survey survived after 25 million years. With an averaged eccentricity of 0.027 and inclination of less than 1° this population appears to be very stable. Out of the 407 remaining test particles, 168 are on tadpole orbits. Horseshoes and tadpoles are of course divided by a separatrix in phase space. The break-up of the separatrix is associated with a chaotic layer, and this is responsible for erosion between the filled and open circles in the stable zones. For the inclined survey, most of the objects that do survive are true Trojans with $\langle e \rangle = 0.041$ and $\langle i \rangle = 6.9°$.

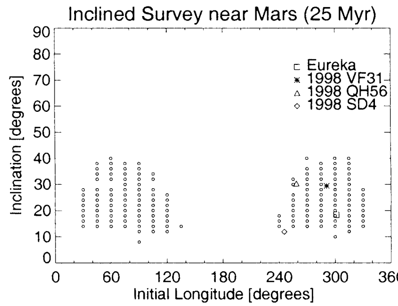

Figure 2. This shows the results of the survey of inclined test particles near Mars after 25 Myr. The horizontal axis marks the longitude measured from Mars and the vertical axis the inclination with respect to Mars of the starting positions of test particles. Also shown are the instantaneous positions of the two Martian Trojans, namely 5261 Eureka and 1998 VF31, as well as the asteroids 1998 QH56 and 1998 SD4.

Terrestrial results are very similar in the case of the in-plane survey (semi-major axis factor ranging from 0.994 to 1.006, $\langle e \rangle = 0.038$ and $\langle i \rangle = 1.3°$). Stable inclined test particles near the Earth belong to a bimodal distribution. One band of stability is observed at low inclination ($i \lesssim 16°$) and another one at moderate starting inclinations ($24° \lesssim i \lesssim 34°$).

3. Martian Survey

Mars is the only terrestrial planet already known to possess Trojan asteroids : 5261 Eureka and 1998 VF31. Both have moderate inclinations to the ecliptic, namely 20.3° and 31.3° respectively. The in-plane Martian survey presents no survivors after 60 million years. The inclined survey is shown in Fig. 2, together with the positions of the two Trojans, 5261 Eureka (marked by a square) and 1998 VF31 (asterisk). Two further asteroids – 1998 QH56 (triangle) and 1998 SD4 (diamond) – have been suggested as Trojan candidates, although improved orbital elements together with detailed numerical simulations (Tabachnik & Evans 1999) now make this seem rather unlikely.

References

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Saha, P., & Tremaine, S. 1994, AJ, 108, 1962
Tabachnik, S.A., & Evans, N.W. 1999, ApJ, 517, L63