DYNAMICAL BEHAVIOUR OF ASTEROIDS IN THE REGION A < 2 AU

FRANCISCO LOPEZ-GARCIA
Dpto. de Astronomía y and Geofísica, Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de San Juan, Argentina

ADRIAN BRUNINI
Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, and CONICET, Argentina

Abstract. We carried out a series of numerical simulations of the dynamical evolution of test particles and real asteroids in the inner region of the Solar System. We explored two different scenarios: i) including terrestrial planets plus Jupiter and Saturn and ii) including all the planets (except Pluto). We found that there are possible zones of orbital stability where planetesimals may survive 100 Myr. Secular resonances with the inner planets and mean motion commensurabilities with both the inner and outer planets play a key role in the dynamical evolution of this region.

1. Introduction

The observational data of the inner edge of the asteroids belt with $a < 2$ au are the following: a) there are no known bodies inside Mercury's orbits, b) ten objects exist between Earth and Mars orbits, c) in the region $1.08 < a < 1.28$ au, $e < 0.2$ and $i < 10°$ there are seven objects and d) only three planetesimals: 1996 XB27, 1998 HG49 and 1998 KG3 are not planet-crossings, they have both low eccentricity and inclination.

Dynamically, the main belt of asteroids exhibits a sharp boundary at $a \sim 2$ au because of the presence of the wild secular resonance ν_6 (Scholl & Froeschle, 1991; Farinella et al., 1993, 1994). This resonance is one of the most intense sources of delivery of meteorites to the Earth (Gladman et al., 1997). Another observational data is that in the region between 2 au and the main belt only few non Mars crossing asteroids have been discovered up to the present, most of them as members of Hungaria's family.

Some numerical integrations of test particles in the region between Mars and the Earth (Michel & Froeschle, 1997), have shown that, once an object becomes Mars crosser, its dynamical evolution is characterized by a random walk process in orbital energy and angular momentum, induced by repeated close encounters with Mars. All these numerical experiments were mainly foccused on Near Earth Objects (NEOs) or asteroids in already Mars-crossing orbits.

In this region, no very strong mean motion resonance (hereafter MMR) with Jupiter is found, perhaps the exception of the 5:1 MMR, whose dynamical feature have not yet been studied in detail with the exception of the preliminar work by López- García & Brunini, 1999. A number of MMR with Mars and Earth are also interspersed in this region. Williams & Faulkner (1981), Michel & Froeschle (1997) and Michel (1997) have found that several linear secular resonances with the planets, from Venus to Saturn, are present in this region.

A. Celletti et al. (eds.), Modern Celestial Mechanics: From Theory to Applications, 417–422.

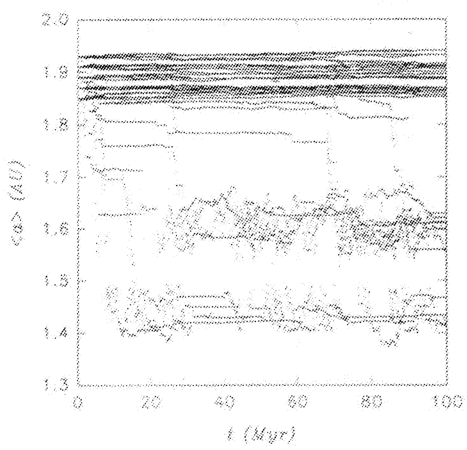

Figure 1. Temporal evolution of semimajor axes, averaged over intervals of 10^5 yr. for one sample of objects in the region near to a = 1.9 au. The evolution is characterized for the presence of several MMR with the Earth and Mars.

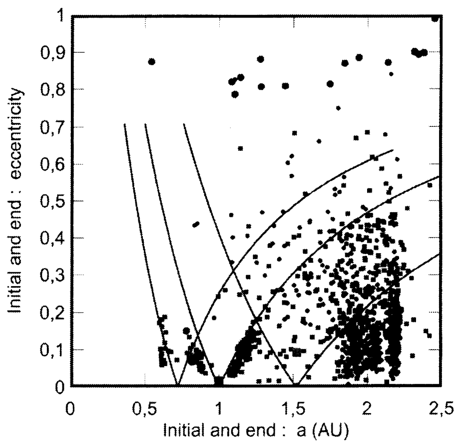

Figure 2. Initial and end evolution of 577 real asteroids in the (a, e) plane with a timespan 50 Myr. Shaded circles are the initial positions and dark squares are the end state of the evolution. The dots at the top of the figure represent the ejected asteroids. Solid lines corresponds to the Tisserand parameter for Venus, Earth and Mars.

2. Numerical Method and Initial Conditions

We have carried out the numerical experiments by means of our own implementation of the second order symplectic integrator by Wisdom & Holman (1991) adequatelly adapted to handle close encounters (Brunini & Fernández, 1999). Two different scenarios were explored:

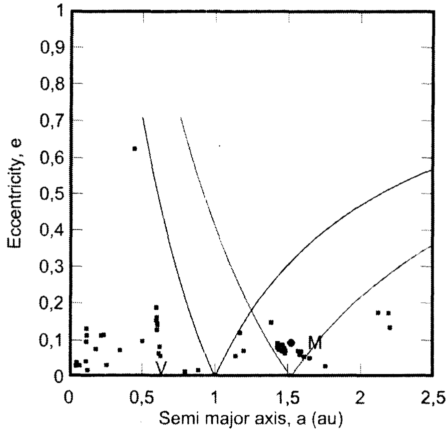

Figure 3. The squares represent the test particles that survive in the inner Solar System after 100 Myr. Between all the terrestrial planets there are narrow belts of stable circular orbits.

I: The terrestrial planets, Jupiter and Saturn are the only planets present. This case is an approximation to the gravitational effects that disturb the inner Solar System. In this case we have integrated an ensemble of particles from 100 up to 500 equally distributed in the region $0.2 < a < 2$ au, the eccentricity was uniformly distributed in the range $0 < e < 0.2$ and the inclination was generated at random in the interval $0° < i < 5°$. The longitude of the node, the argument of the perihelion and the mean anomaly were choosen at random between 0° and 360°. The inner planets, Jupiter and Saturn were placed in their actual orbits. The trajectories of the test particles were followed by 100 Myr, which is a time scale comparable to the time scale of formation of the terrestrial planets.

II: The full gravitational effects of all the planets were included (except Pluto). We carried out a deeper exploration of those regions in phase space that in the Case I exhibit some diffusion to Venus, Earth and Mars crossing orbits. Those asteroids reaching the region interior to the orbit of the Earth ($q < 0.9$ au, where q is the perihelion distance) were quite examine during all the simulation. The dynamical evolution of Earth crossers was well studied in some previous papers (see for example, Gladman et al.,1998). In all the numerical simulations we used a step size of 0.01 yr. not only to guarantee numerical precision but also to account for all the close encounters with the terrestrial planets. The initial positions and velocities of the planets, as well as their masses and radius, come from the JPL Planetary and Lunar Ephemerides. The test particles are perturbed by the Sun and planets but do not themselves exert any gravitational forces.

3. Results

3.1. The evolution in the (a, e) space of the 200 test particles equally distributed in the region between $1.6 < a < 1.9$ au shows a slow diffusion to Mars crossing orbits in this time scale in almost all the region, with the exception of the zone near $a = 1.778$ au, corresponding to the 5:1 MMR with Jupiter and the zone near a = 1.9 au, where the ν_{16} is present. If our simulation considers all the planets (except Pluto) we observe the same qualitative behaviour of the entire sample, although some individual cases deserve a more detailed discussion. It is noticeable that for semimajor axis around $a \sim 1.8$ to 1.9 au, some fictitious asteroids present stronger variations in its orbital inclination. This is due to a dynamical effect of the secular resonances. There is a secular drift in the location of the secular resonances, mainly due to the variations in both the precession frequencies of the perihelion and the node of the planets.

3.2. MMR 4:1 and 5:1 with Jupiter. We have explored both regions with a = 1.778 and 2.064 au, corresponding to 5:1 and 4:1 MMR with Jupiter, respectively. First, a sample of 200 test particles that were uniformly distributed in the region between $a = 1.76$ and 1.79 au was studied. The orbital eccentricities were chosen such as the asteroids are not originally placed in Mars crossing orbits. All other variables were generated at random in the same way as in the previous simulations. Some interesting features are noticeable: i) There is a remarkable tendency to a diffusion to smaller semimajor axes. ii) Most particles remain near its original location in phase space, but some suffer close encounters with Mars. iii) There is a region around 1.4 au where the asteroids seem to stop their inwards diffusion. iv) Mars'perihelion and also the 3:5 MMR with the Earth are located very near this distance to the Sun. We have found, however, that in these cases, secular resonances with Mars seem to play a major role in the dynamical evolution of them. The secular resonance ν_4 acts as a protection mechanism against close encounters with Mars. Near 10^7 yr., this asteroid escapes from the secular resonance, suffering two consecutive close encounters with Mars and being ejected to $a > 0.9$ au where it is finally eliminated from the simulation. The location of some of the MMR that seem to have some relevant participation in the dynamical evolution of the sampled asteroids are listed in Table 1. These resonances are very narrow and the capture are generally of very short duration.

Location of the MMR with the Earth, Mars and Jupiter

a(au)	1.40	1.421	1.575	1.58	1.76	1.778	1.84	2.064
Earth	3:5			1:2	3:7		2:5	
Mars	8:7				~4:5			
Jupiter		7:1	6:1			5:1		4:1

3.3. $a = 1.9$ au. This region is occupied by the ν_{16} resonance at low inclinations and also there are present the ν_3 and ν_4 resonances at moderate inclinations. The absence of a MMR with Jupiter in the neighborhood of this zone and the fact that the required excentricity for a particle in this region to become Mars crosser is bigger than in the region around $a = 1.778$ au, results in a much slower diffusion to Mars crossing orbits than in the previous case. The evolution of the mean semimajor axes of the asteroids is shown in Figure 1. In this case the action of the several resonances with the inner planets is much more evident than in the case of the 5:1 MMR with Jupiter. Particularly interesting is the case of the 1:2 and the 2:5 MMR with the Earth. One asteroid, after being trapped temporarily in the 2:5 resonance is transferred to the control of the 5:1 MMR with Jupiter at a moderate excentricity (see Figure 1), remaining there up to the end of the simulation.

3.4. Distribution of semimajor axis, $0.1 < a < 2.2$ au. Our study was completed numerically integrating real asteroids, the orbital elements were obtained from the Ephemerides Minor Planets (EMP), and fictitious asteroids distributed in the following way: $0.1 < a < 2.2$ au, $0 < e < 0.2$, $0° < i < 5°$, and the angular elements at random. The results at the end of simulation are shown in the Figures 2 and 3. Figure 2 shows the end of dynamical evolution of 577 real asteroids in the (a, e) plane with a timespan of 50 Myr. Near Mars a few asteroids are close, while there are non asteroids near the Earth after this time simulation. Near Venus only two asteroids are close. After, we integrated the orbits of 1000 test particles for 100 Myr. The results of this integration are plotted in the (a, e) plane, Figure 3, where the squares are stable orbits that survive the full integration. Lines are Jacobi's curves for Earth and Mars. The full gravitational effects of the terrestrial planets plus Jupiter and Saturn were included. The locations of particles that survive in that simulation show that only those that have low excentricity maintain stable orbits. Around each of the terrestrial planets, there is a narrow band of test particles that survive for the full integration. So, for example, between 0.1 and 0.3 au are still present test particles at the end of the integration. Another possible existence of a narrow belt there is between 0.6 and 0.7 au. A third belt between Venus and the Earth that occupies a narrow band is located in the range $0.8 < a < 0.9$ au. Finally, there is other belt between the Earth and Mars from 1.1 to 1.3 au. The possibility of the existence of belts between Venus and the Earth and the Earth and Mars was raised by Mikkola and Innanen (1995). Of course, these results must be considered as preliminary, since 100 Myr is approximatively 2% of the age of the Solar System. This results agree with those announces recently published by Wyn Evans and Tabachnik (1999).

4. Discussion and Conclusions

Our study was limited to a short temporal interval early in the history of the Solar System, because our interest was focussed in the primordial sculpting of this region. We found that, when the inner planets are not present, the region is globally stable, and only those asteroids near the 5:1 MMR with Jupiter and the region near 1.9 au, corresponding to the ν_{16} secular resonance, are potential sources of planetesimals reaching the inner portion of the Solar System. From the narrow unstable regions, the one near the 5:1 MMR with Jupiter is the most interesting as a primordial source of Mars crossing asteroids. We have not found, however, any temporary capture of a test particle as a satellite of Mars during our numerical simulations. The dynamical evolution of the objects in this region is very complex by the presence of both, mean motion and secular resonances. Mean motion resonances with the inner planets are numerous but weak. Several objects fall in some MMR (notably the 1:2 MMR with the Earth) staying there for a relatively short time. One of the most interesting features we have found in our simulations is the role played by the ν_4 secular resonance. Several particles in our simulations experience succesive close encounters with Mars, reaching the region near $a = 1.4$ au and an orbital excentricity such that the particle is Mars crosser but with its aphelion and perihelion inside the orbit of Mars. In this situation, when the particle is trapped in the ν_4 secular resonance a close encounter with Mars is not possible. Although there are no bodies inside the Mercury's orbit, some test particles may survive to the numerical simulation with stable circular orbits and low inclination. Between Mercury and Venus, Venus and the Earth and the Earth and Mars there are narrow belts of stable orbits with $e < 0.1$ and $i < 5°$, that survive for the full duration of integration of 100 Myr.

Acknowledgements

FLG is grateful to the staff of CASLEO for their assistance in the preparation of this manuscript. He also thanks partial support by a grant from CICITCA, UNSJ.

References

Brunini, A. and Fernández, J.A.: 1999, *Plan.Space Sci,* **47**, 591.
Farinella, P., Gonczi, R.,Froeschlé, Ch. and Froeschlé, C.: 1993, *Icarus,* **101**, 174.
Farinella, P., Froeschlé, Ch. and Froeschlé, C. et al.: 1994, *Nature,* **371**, 314.
Gladman, B.J., Migliorini, F., Morbidelli, A. et al.: 1997, *Science,* **277**,197.
López-García, F. and Brunini, A.: 1999, *Proceedings IAU Coll.* **172**, J.Henrad and S. Ferraz Mello, eds., p. 377.
Michel, P.: 1997, *Icarus* **129**, 348.
Michel, P. and Froeschlé, Ch.:1997, *Icarus,* **128**, 230.
Mikkola, S. and Innanen, K.: 1995, *Mon.Not.Royal Astron.Soc.,* **277**, 497.
Scholl, H. and Froeschlé, C.H.: 1991, *Astron.Astrophys.,* **245**,316.
Williams, J. and Faulkner, J.: 1981, *Icarus,* **46**, 390.
Wisdom, J. and Holman, M.: 1991, *Astron. J.,* **102**, 1528.
Wyn Evans, N. and Tabachnik, S.:1999, *Nature,* **399**, 41.