Possible Long-Lived Asteroid Belts in the Inner Solar System

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The recent years have witnessed a carnival of discoveries in the Outer Solar System [1-3]. Here we provide evidence from numerical simulations of orbital stability to suggest the possible existence of two long lived belts of primordial planetesimals in the Solar System. The first is the domain of the Vulcanoids (∼0.09 – 0.21 AU) between the Sun and Mercury, where remnant planetesimals may survive on dynamically stable orbits provided they possess a characteristic radius greater than ∼0.1 km. The second is a belt between the Earth and Mars (∼1.08 – 1.28 AU) on which an initial population of particles on circular orbits may survive for the age of the Solar System. A search through the catalogues of Near-Earth Objects reveals an excess of asteroids with low eccentricities and inclinations occupying this belt, such as the recently discovered objects 1996 XB27, 1998 HG49 and 1998 KG3.

Symplectic integrators [4,5] with individual timesteps [6] provide a fast algorithm that is perfectly suited to long numerical integrations of low eccentricity orbits in a nearly Keplerian force field. Individual timesteps are a great boon for our work, as orbital clocks tick much faster in the Inner Solar System than the Outer. Over a thousand test particles are distributed on concentric rings with values of the semimajor axis between 0.1 AU and 2.2 AU. Each of these rings is located in the invariable plane and hosts five test particles with starting longitudes \( n \times 72^\circ \) with \( n = 0, \ldots, 4 \). Initially, the inclinations and eccentricities vanish for the whole sample of test particles. The test particles are perturbed by the Sun and planets but do not themselves exert any gravitational forces. The full gravitational effects of all the planets (except Pluto) are included. The initial positions and velocities of
the planets, as well as their masses, come from the JPL Planetary and Lunar Ephemerides DE405. For all the computations, the timestep for Mercury is 14.27 days. The timesteps of the planets are in the ratio 1 : 2 : 2 : 4 : 8 : 8 : 64 : 64 for Mercury moving outward through to Neptune. The relative energy error is oscillatory and has a peak amplitude of $\sim 10^{-6}$ over the 100 million year integration timespans (c.f. [5,7]). After each timestep, the test particles are examined. If their orbits have become hyperbolic or have entered the sphere of influence of any planet [8] or have approached closer than ten solar radii to the Sun, they are removed from the simulation. This general procedure is familiar from a number of recent studies on the stability of test particles in the Solar System [9,10]. For example, Holman [9] uncovered evidence for a possible belt between Uranus and Neptune by a similar integration of test particles in the gravitational field of the Sun and the four giant planets. His integrations reached the impressive timescale of 4.5 Gyrs – of the order of the age of the Solar System. Simulations of the inner Solar System are much more laborious, as the orbital period of Mercury is $\sim 88$ days (as compared to $\sim 4332$ days for Jupiter, the giant planet with the shortest orbital period). This forces us to use a much smaller timestep and roundoff error becomes a menacing obstacle to believable results. So, we adopt the strategy of running on a fleet of nearly twenty personal computers of varying processor speeds, so that the calculations are performed in long double precision implemented in hardware. The integration of the orbits of 1050 test particles for 100 Myrs occupied this fleet of computers for over four months.

Fig. 1 shows the results of this calculation. The survival times of the test particles are plotted against starting semimajor axis. There are five test particles at each starting position, so the vertical lines in the figure join five filled circles which mark their ejection times. The locations of particles that survive for the entire 100 Myr timespan are marked by diamonds on the upper horizontal axis. Around each of the terrestrial planets, there is a swathe of test particles that are ejected rapidly on a precession timescale. This band
is much broader around Mars than the Earth or Venus, perhaps because of the higher eccentricity of Mars’ orbit. There are also narrow belts of test particles that survive for the full integration. So, for example, all 50 of the test particles with starting semimajor axes between 0.1–0.19 AU are still present at the end of the 100 Myr integration. The existence of a population of small asteroid-like bodies – known as the Vulcanoids – wandering in intra-Mercurial orbits has been hypothesised before [11-13]. There are 16 surviving test particles with starting semimajor axes between 0.6 and 0.66 AU, suggesting the possible existence of a narrow belt between Mercury and Venus. A somewhat larger third belt of 33 surviving test particles occupies a belt between Venus and the Earth. Their starting semimajor axes range from 0.79 to 0.91 AU. Finally, there is a broad belt between the Earth and Mars from 1.08 to 1.28 AU in which a further 26 test particles survive. The possibility of the existence of belts between Venus and the Earth and between the Earth and Mars was raised by Mikkola & Innanen [10] on the basis of 3 Myr integrations.

Of course, these results must be treated with considerable reserve, as 100 Myrs is just \( \sim 2\% \) of the age of the Solar System since the assembly of the terrestrial planets (\( \sim 5 \) Gyr). It is straightforward to estimate that if this simulation in long double precision were to be continued till the integration time reaches even 1 Gyr, then it would consume \( \sim 3.5 \) years of time. Accordingly, we use the standard, albeit approximate, device of re-simulating with greater resolution and extrapolating the results. At semimajor axes separated by 0.002 AU, five test particles are again launched on initially circular orbits with starting longitudes \( n \times 72^\circ \) with \( n = 0, \ldots, 4 \). The number of test particles \( N(t) \) remaining after time \( t \) is monitored for each of the four belts. Table 1 gives the results of fitting the data between 1 Myr and 100 Myr to the following logarithmic and power-law decays:

\[
N(t) = a + b \log_{10}(t[\text{yrs}]), \quad N(t) = \frac{10^c}{(t[\text{yrs}])^d}
\]  

(1)

In the last two columns, the expected number of test particles remaining after 1 Gyr and
5 Gyr is computed. The uncertainties in the fitted parameters suggest that the logarithmic fall-off is a better – and more pessimistic – fit to the asymptotic behaviour than a power-law (c.f. [9,14]). Our extrapolations suggest that two of the belts – those lying between Mercury and Venus, and between Venus and the Earth – will become almost entirely depleted after 5 Gyr. However, even taking a staunchly pessimistic outlook, it seems certain that some of the Vulcanoids and some of the test particles with starting semimajor axes between 1.08 – 1.28 AU in the Earth-Mars belt may survive for the full age of the Solar System.

We can make a crude estimate of present-day numbers by extrapolation from the Main Belt asteroids (c.f. [9]). Assuming that the primordial surface density falls inversely like distance, we find that the Earth-Mars belt may be occupied by perhaps a thousand or so remnant objects. Of course, these objects are now outnumbered by the more recent arrivals, the asteroids ejected via resonances from the Main Belt, which may number a few thousand in total [15].

A systematic search for Vulcanoids has already been conducted by Leake et al. [12], who exploited the fact that bodies so close to the Sun are identifiable from their substantial infrared excess. No candidate objects were found. However, the survey was limited to a small area of just 6 square degrees and was estimated to be $\sim 75\%$ efficient to detection of bodies brighter than 5th magnitude in the L band. This result places constraints on the existence of a population of objects with radii greater than $\sim 50$ km, but minor bodies with the typical sizes of small asteroids ($\sim 10$ km) will have evaded detection. On theoretical grounds, Vulcanoids have been proposed to resolve apparent contradictions between the geological and the geophysical evidence on the history of the surface features on Mercury [11,12]. The robustness of the Vulcanoid orbits partly stems from the fact that there is only one neighbouring planet and so may be compared to the stability of the Kuiper-Edgeworth belt. Even after 100 Myr, some 80% of our Vulcanoid orbits still have eccentricities $e < 0.2$ and inclinations $i < 10^\circ$. It is this evidence, together with the low rate of attrition of their
numbers, that suggests that they can continue for times of the order the age of the Solar System. The outer edge of the Vulcanoid belt is at \( \sim 0.21 \) AU. Objects beyond this are dynamically unstable and are excited into Mercury-crossing orbits on 100 Myr timescales. The inner edge of the belt is not so sharply defined. Small objects close to the Sun may be susceptible to destruction both by Poynting-Robertson drag [16] and by evaporation [17]. Taking the mean density and Bond Albedo of a typical Vulcanoid to be the same as that of Mercury, we find that objects with radii satisfying \( 0.1 \lesssim z \lesssim 50 \) km can evade both drag and evaporation in the Vulcanoid belt. This is one of the most dynamically stable regimes in the entire Solar System. If further searches do not detect any intra-Mercurial objects, this is a strong indicator that other processes – such as planetary migrations – may have disrupted the population.

Although there are no known intra-Mercurial bodies, we can find candidate objects for the Earth-Mars belt. Suppose we search an asteroidal database [18] for objects with inclinations \( i < 10^\circ \) and eccentricities \( e < 0.2 \) between the semimajor axes of Earth and Mars, then we find that there are ten objects. Of these, seven lie within our suggested Earth-Mars belt (1.08 – 1.28 AU), which is evidence for an enhancement of nearly circular orbits in this region. An even more striking test is to search through the objects between the Earth and Mars for low eccentricity and inclination asteroids that are not planet-crossing. Then, there are only three objects (1996 XB27, 1998 HG49 and 1998 KG3) among the entire asteroids in the database, and all three lie between 1.08 and 1.28 AU. Most of the \( \sim 50 \) asteroids with semimajor axes presently located in our Earth-Mars belt are moving on orbits with large eccentricities and inclinations. They are not dynamically stable and will evolve on timescales of the order of a few Myrs. Most of these objects are believed to be asteroids ejected from resonance locations in the Main Belt, although a handful may even be comets whose surfaces have become denuded of volatiles [19]. However, the seeming enhancement of circular orbits in this region hints at a primordial population whose orbits
are very mildly eccentric and mildly inclined. Ejection from the Main Belt will tend to increase the eccentricity of an asteroid [20]. So, the mildly eccentric objects may well be remnant planetesimals, the original denizens of the region before it was colonized by asteroids from the resonance locations in the Main Belt.

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Fig. 1.— The survival time (in years) is plotted against starting semimajor axis (in astronomical units) for test particles in the Inner Solar System. At each semimajor axis, five test particles are launched at equally spaced longitudes and their initially circular orbits are integrated for 100 Myrs. The times of ejection are marked with filled circles and joined with solid vertical lines. Test particles close to the terrestrial planets are rapidly removed. However, between all the terrestrial planets, there are narrow belts of stable circular orbits that survive for the full duration of integration of 100 Myrs. The semimajor axes of the surviving test particles are marked by diamonds at the top of the figure, together with symbols marking the locations of the terrestrial planets. Test particles survive in the following four regions – between the Sun and Mercury (0.1 – 0.19 AU), between Mercury and Venus (0.6 – 0.66 AU), between Venus and the Earth (0.79 – 0.91 AU) and between the Earth and Mars (1.08 – 1.28 AU). The two test particles that remain after 100 Myrs at an initial semimajor axis of 1 AU are actually librating about the Earth’s Lagrange points. [This calculation has been performed on personal computers that employ 80 bits internally and which offer the option of compilation in long double precision with a 64 bit mantissa. At least 64 bits are required to keep Mercury’s longitude error below 0.01 radians over 100 Myr timescales (see [21]). Standard double precision offers a mantissa of just 53 bits.]
The labels V, M-V, V-E and E-M refer to the Vulcanoids (0.09 – 0.21 AU), the Mercury-Venus belt (0.58 – 0.68 AU), the Venus-Earth belt (0.78 – 0.93 AU) and Earth-Mars belt (1.08 – 1.28 AU) respectively. Test particles are placed at semimajor axes separated by 0.002 AU in each of the belts and the orbits are re-simulated for 100 million years. The initial number of test particles in each belt $N_0$ is given. In each case, the data $N(t)$ is fitted for $1 \text{ Myr} < t < 100 \text{ Myr}$. The parameters in the logarithmic and the power-law fits to the number of remaining test particles $N(t)$ after time $t$ are listed in the upper and lower tables. The last two columns of the tables give the extrapolated number of test particles estimated to remain after 1 Gyr and 5 Gyrs. The estimated uncertainties in the fitted parameters indicate that the logarithmic law is a better guide for extrapolation – it is also more pessimistic than the power-law fit. This suggests that only the Vulcanoid orbits and the Earth-Mars belt can be accepted as candidate repositories for long-lived objects. [The simulation of the Vulcanoid belt has been performed in long double precision on personal computers, the remaining three belts in double precision on a supercomputer.]

| Belt  | $a$       | $b$       | $N_0$ | $N_{\text{exp}} (1\text{Gyr})$ | $N_{\text{exp}} (5\text{Gyr})$ |
|-------|-----------|-----------|-------|-------------------------------|-------------------------------|
| V     | 472.34 ± 5.0 | −26.03 ± 0.68 | 300   | 238                           | 220                           |
| M-V   | 681.7 ± 3.7  | −69.73 ± 0.52 | 250   | 54                            | 5                             |
| V-E   | 1041.1 ± 3.9 | −111.51 ± 0.56 | 375   | 38                            | –                             |
| E-M   | 1229.2 ± 3.2 | −118.26 ± 0.46 | 500   | 165                           | 82                            |

| Belt  | $c$       | $d$       | $N_0$ | $N_{\text{exp}} (1\text{Gyr})$ | $N_{\text{exp}} (5\text{Gyr})$ |
|-------|-----------|-----------|-------|-------------------------------|-------------------------------|
| V     | 2.743 ± 0.008 | 0.040 ± 0.001 | 300   | 241                           | 226                           |
| M-V   | 3.445 ± 0.017 | 0.167 ± 0.002 | 250   | 88                            | 67                            |
| V-E   | 3.725 ± 0.007 | 0.189 ± 0.001 | 375   | 106                           | 78                            |
| E-M   | 3.531 ± 0.008 | 0.133 ± 0.001 | 500   | 215                           | 173                           |