LUNAR EFFECTS ON CLOSE ENCOUNTERS OF HUNGARIA ASTEROIDS AND NEAR-EARTH ASTEROIDS WITH THE EARTH

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ABSTRACT. The Earth is target to many celestial objects, among them Near Earth Asteroids (NEA) play a significant role. Different dynamical groups have been found, the source of these asteroids is mainly the main belt and, in particular the Hungaria group. We carry out a statistical investigation by numerical integration of the motion of real asteroids and their hypothetical clones in a simplified dynamical model of the solar system up to 100 My. In a first part we present integrations of existing Hungaria asteroids to determine which of them could become NEAs. Then the influence of the Moon on the orbits of these NEAs is investigated. The main goal is to find the frequency of close encounters and deflection angles due to them, possible impacts and the strength of deflection by the Moon.

1. INTRODUCTION

The population of Main-Belt Asteroids (MBA) was found by Hirayama (1918) to be clustered into "families" of asteroids, which share similar orbital elements (i.e. semi-major axis a, eccentricity e, inclination i). Later it turned out that the families can also be discriminated by spectroscopic properties (taxonomic classification by Tholen). These groups and families originated presumably by collisional break-up of larger objects, a process which is still ongoing in the solar system.

One of these groups is the Hungaria group, named after the biggest object (434) Hungaria, located at the inner edge of the main-belt at approximately 2 AU (astronomical units). The Hungaria group is an interesting case to study the dynamics of MBAs, since it is surrounded by several mean-motion resonances (MMR) and secular resonances (SR). On the outer edge the J4:1 MMR with Jupiter effectively removes asteroids, while the inner edge is shaped by Mars encounters at perihelion, additionally the M3:4 MMR acts inside the orbital parameter region of the Hungarias, and the ν_6 secular resonance limits the maximum inclination of the group's members (Milani et al., 2010).

All these constraints lead to the conclusion, that since the scattering of objects from the Hungaria group preferably happens towards the inner solar system (Galiazzo & Bazsó, 2011), there must be an exchange of asteroids between the Hungaria group and the Near Earth Asteroids (NEAs). The spectra of Enstatite achondrite meteorites (McSween, 1999) studied on Earth give indirect evidence for a link to Hungaria asteroids, as they show similar features like the E-type spectral class, and approximately 60% of the Hungaria population belongs to this class (Warner et al., 2009).

To confirm this link we started a study of the dynamics of the Hungaria group with the aim to find out more about the evolution to Near-Earth asteroids and their long-time behaviour. The main point is the investigation of close-encounters to the Earth, where also the influence of the Moon needs to be taken into account. Domingos et al. (2004) verified that the orbits of NEAs can be significantly affected by the Moon at low relative velocities. The gravitational influence of the Moon results in a twofold effect: on one hand the Moon prevents the Earth from collisions, but on the other hand it can enhance the collision rates.

2. DESCRIPTION OF THE MODELS AND METHODS

This study consists of two complementary parts:

1. In the first part from a selection of 200 real asteroids we found 11 Mars-crossing objects that subsequently become NEAs ("escapers", see Table 1 of Galiazzo & Bazsó, 2011). These 11 Hungarias

were cloned, i.e. their initial conditions (orbital elements a, e, i) were slightly modified, to enhance the statistics of close encounters. The dynamical model consisted of the planets Venus to Saturn, the integrations were carried out for 100 million years with the Lie N-body integrator (Hanslmeier & Dvorak, 1984; Eggl & Dvorak, 2010), which is capable of treating close encounters accurately by using an adaptive step-size.

In our sample of Hungarias we have chosen objects that fall into the following intervals of osculating elements: $1.78 \leq a[\mathrm{AU}] \leq 2.03$, $0 \leq e \leq 0.19$, $12 \leq i[\mathrm{deg}] \leq 31$. Their typical diameters range from $\approx 0.5 - 2.5$ km, which is not too distinct from the NEA sizes.

The primary goals were to establish the number of close encounters and impacts, the impact probability and relations between different encounter related parameters.

2. The following part concentrates on the NEAs, as we have previously seen that many Hungarias can evolve into orbits typical for NEAs. We investigate each of the three NEA groups in detail by selecting some hundred objects (100 Atens, 200 Apollos, and 300 Amors) and running numerical integrations for 10 million years using the same code as above. The integration time here is shorter than for the Hungarias, since due to their typically smaller semi-major axes the orbital evolution of NEAs is faster, and additionally the median lifetime of NEAs is of the same order as our integration time (Gladman et al., 1997).

   We compare the evolution of NEAs in two models, model 1 (M1) is the spatial elliptic restricted three body problem Sun–Earth–NEA, and model 2 (M2) the spatial restricted four body problem Sun–Earth–Moon–NEA (i.e. we always consider the NEAs to be massless). In this way we can compare the results for close encounters without Moon in M1 with those in M2 with the Moon's contribution added.

For each close encounter[1] of every asteroid we collect data like the minimum distance to the Earth, the relative velocities, the time spent inside the lunar orbit, and the magnitude of deviation from the unperturbed orbit during fly-by. The latter is expressed by the "deflection angle", by which we mean the angle formed by the velocity vectors at the time instants of begin and end of the close encounter. The deflection angle depends on the minimum distance to Earth, the closer the asteroid approaches the higher the angle gets since the trajectory is strongly influenced.

3. RESULTS

The data for close encounters (see Table 1) are at first glance as expected. The Amor group asteroids with typically relatively large semi-major axes ($a \geq 1.5$ AU) have the fewest encounters with Earth. On the contrary there is a sharp increase for both the Apollos ($a \geq 1$ AU) and Atens ($a < 1$ AU), as both are Earth orbit crossing populations, whereas the Amors only approach Earth at their perihelia. The table also shows that there is a difference in the relative velocities for Amors vs. Apollos/Atens, although the average velocity for Amors (M2) is almost as high as for the other NEA groups. The other velocities do not exhibit such big differences, for each group the values lie within the $1 - \sigma$ interval. Considering the deflection angles it is obvious that a lower relative velocity result in a higher deflection, if the asteroids pass close enough by the Earth or Moon.

The number of close encounters is not given for the Hungarias in Table 1, because the numbers depend strongly on the clones chosen, and that would make an average very unreliable. There are even clones completely lacking close encounters, which are derived from an object that itself does have close encounters, thus showing how sensitive the results are with respect to the initial conditions, and that the reliable orbit determination after a close encounter is not trivial. Higher relative velocities for Hungarias in the table are due to the fact, that they first increase their eccentricities to leave the main belt and become Mars crossers, then having Mars encounters further increases the eccentricity. So when they finally evolve into Earth orbit crossing asteroids they quite often have a higher mean eccentricity than other NEAs.

For the deflection angle we find a quite simple relation to the minimal distance. When both are plotted as in Figure 1 a fitting function of the form $y = a/x^b + c$ can be used, where the exponent $b \approx 1$. This fit also holds in the case of NEAs, with the angles being larger, reaching up to more than $90°$ in extreme

[1] We define a "close encounter" of an asteroid to the Earth, if the mutual distance of the two bodies is less than 0.0025 AU, which is the average lunar distance of 384400 km.

group (model)	total number of encounters	relative velocity [km/s]	deflection angle [deg]	duration [days]
Amors (M1)	296	10.5	6.77	0.54
Amors (M2)	315	14.0	7.71	0.36
Apollos (M1)	10789	14.7	1.83	0.43
Apollos (M2)	12558	13.5	2.06	0.46
Atens (M1)	25258	14.4	1.45	0.44
Atens (M2)	26425	15.1	1.37	0.42
Hungarias (M1)	—	20.3	0.8	0.35
Hungarias (M2)	—	20.1	12.8	0.34

Table 1: Summary of the close encounter count with direct comparison between the two models M1/M2 for NEAs (The numbers for Hungaria escapers are not given, see text for explanation). For every group the total (absolute) number of encounters within 0.0025 AU is shown, first for model 1 where there is no influence by the Moon, and second for model 2 including the additional gravitational effect caused by the Moon. Also shown are the averaged values for the relative velocity, deflection angles and durations, i.e. the time elapsed between entering and exiting the region inside 0.0025 AU.

cases where there would be an impact. The scattering of points in the plot is a natural consequence of the variation in encounter velocity, which itself depends on the osculating elements (eccentricity, inclination) at the given time. Apart from the values shown in the table, when considering all the clones, the duration of close encounters seems to be shorter (or at most similar) in the case of model 1 (without Moon), while the deflections angles are systematically larger in model 2 (with Moon).

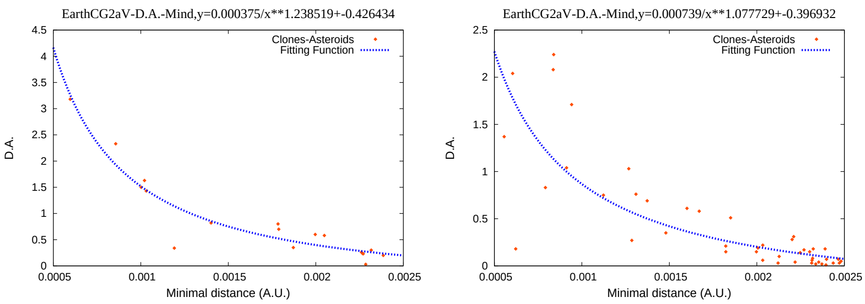

Figure 1: Dependence of the deflection angle on the minimal distance to Earth for close encounters with velocities less than 11.2 km/s. Every point in the plot corresponds to a separate close encounter event. The left figure shows the case for a Hungaria asteroid without the Moon, on the right the same object with the Moon.

In the integrations the majority of close encounters takes place at a rather large distance, so most of the time only "shallow encounters" occur. This behaviour is well visible in Figure 2, where the highest fraction of events (around 70%) falls into the right-most bin, representing minimal encounter distances just below the lunar distance. Here qualitatively no difference between Hungarias and NEAs is found, in any case one can observe a linear trend in these log-log plots (minimal distance vs. number).

For the two selected Hungaria asteroids shown in the right part of Figure 2 there were no impacts, so the minimal distances are well above the "critical" value of 6400 km, while for the NEAs the figures show several cases with impacts, that fall either into the bin at 3.5 or 3.8. It is also visible that the fraction (relative number of cases) is systematically higher for the lowest distance bins in model 2 (including the Moon) compared to model 1. When computing the impact probability P_c for the Hungarias using the method of Dvorak & Pilat-Lohinger (1999) we get for M1 $P_{c,1} = 9.7 \times 10^{-8}$/year, and for M2 $P_{c,2} = 1.1 \times 10^{-8}$/year. Here we see that the impact probability is higher without the Moon.

4. CONCLUSIONS

Considering the data presented we argue, that the Moon does have a non-negligible effect on close

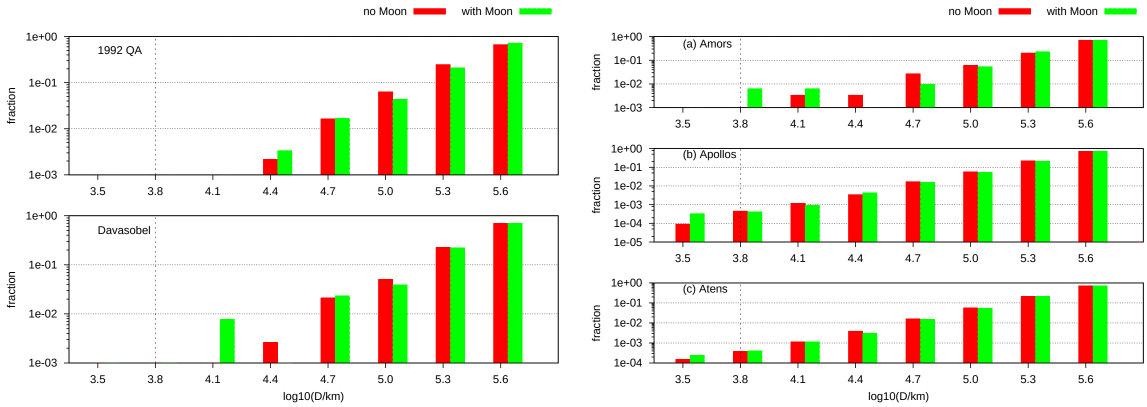

Figure 2: Histograms for the distribution of the distances for two selected Hungarias (left) and the NEA groups (right). The bars represent the fraction of cases (number per bin normalised by the total number of close encounters) for the distance D being lower than a certain value. The red (left) resp. right (green) bars indicate model 1 resp. model 2. Note that the distance is on a logarithmic scale, i.e. the plot range corresponds to an interval of $3200 < D < 400000$ km. The vertical lines at 3.8 indicate the collision distance of approximately one Earth radius, $D = 10^{3.8} \approx 6300$ km.

encounters of both Hungarias and Near Earth asteroids. We have shown that there are distinct differences whether or not the Moon's gravitational influence is taken into account. The number of close encounters is similar in both models, and is only comparable for objects belonging to the same group of NEAs. Although the absolute numbers depend on the arbitrary choice of the limit distance (for a larger value of 0.01 AU instead of 0.0025 AU the number of close encounters increases by an order of magnitude at least), a normalisation still gives good results. The deflection angles and impact probabilities indicate that in the Moon's presence incoming asteroids are more effectively scattered, which is why the first values are higher and the latter lower. The interesting shift of minimal encounter distances to lower values in model 2 gives rise to additional questions, that we need to tackle in future work. We will continue our work to better understand the role of the Moon, but we are aware that we need more data to draw decisive conclusions.

5. REFERENCES

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