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DYNAMICAL CHARACTERISTICS OF HUNGARIA ASTEROIDS

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Abstract. Due to the favorable observing conditions, the Hungaria asteroids may soon become the best known asteroid subgroup of the asteroid population. We have built a large catalog of accurate synthetic proper elements in order to study the dynamical properties of the Hungaria region, both within a purely gravitational model and also accounting for the non-gravitational effects. In the present paper we extend our previous study to more closely investigate the occurrence of close approaches of Hungaria asteroids to Mars, and we present a refined analysis of the dynamics of close couples found in the region.

1. INTRODUCTION

Hungaria region is a densely populated portion of the orbital phase space, located at the inner edge of the asteroid main belt (semimajor axes $1.8 < a < 2$ AU, eccentricities $e < 0.2$, and inclinations $14^\circ < I < 30^\circ$), called in this way after the first discovered object of the group, asteroid (434) Hungaria. Due to the proximity of Hungaria asteroids to the Earth, and to their comparatively high albedo, it is expected that they will be discovered in large numbers by the next generation observational surveys. Soon we should know many more Hungaria with good orbits, than the main belt asteroids we know now, including most of the objects larger than 100 meters of diameter. Therefore, as of recently, this region began to be extensively studied (see e.g. Warner et al. 2009, and the references therein).

In Milani et al. (2010) (hereinafter referred to as Paper I) we presented a comprehensive analysis of the dynamics of the Hungaria region. Using the distribution of some 4,500 numbered and multiopposition Hungaria in the spaces of accurate synthetic proper elements and proper frequencies[1], we studied the dynamical boundaries and the internal structure of the Hungaria region, within a purely gravitational model, but also showing the signature of the non-gravitational effects. We found a complex interaction between secular resonances, mean motion resonances, chaotic behavior and Yarkovsky-driven drift in semimajor axis, as well as a rare occurrence of large scale instabilities, leading to escape from the region. We suggested there is a large collisional family in the region that includes most Hungaria, but not all, and we discussed a possible existence of another family at high inclination. Finally, we examined finer

[1]`http://hamilton.dm.unipi.it/astdys`

structures, the most significant being close couples with very similar proper elements, some of which could have had very close approaches with low relative velocities, in the recent past.

In this paper we would like to extend our previous study in two respects: we more closely investigate the occurrence of close approaches of Hungaria asteroids to Mars, and we present a refined analysis of the dynamics of close couples found in the region.

2. CLOSE APPROACHES TO MARS

It is apparent from Fig. 1 of Paper I that the number density of Mars crossing Hungaria with perihelia below the current aphelion distance of Mars (1.65 AU) is significantly lower than that of the asteroids with perihelia above this value, and even more with respect to the bodies with perihelia above the line corresponding to the maximum aphelion distance Mars (~ 1.71 AU) can attain as a result of secular perturbation of its eccentricity. We have briefly commented that this is obviously due to the different exposure of asteroids to the close encounters with Mars; thus, in the region with nearly zero number density asteroids are Mars crossing all the time, while the maximum density occurs where Mars crossing is a very rare event.

We also noticed that the accuracy of proper elements of Hungaria asteroids can be seriously degraded in the region where close approaches with Mars can occur. Assessing the long term instability of motion resulting from such close approaches we found a number of objects having strongly chaotic orbits, and for 25 of them we have identified repeated close approaches to Mars which appear to be the cause of the fast chaos (Lyapunov times < 5000 yr). The orbits being strongly chaotic, even the occurrence of close encounters is not a deterministic prediction, but rather an event with a significant probability of happening to the real asteroid (whose the initial conditions may actually be somewhat different from the current nominal ones). Having all this in mind, we concluded that the strong instabilities due to close approaches to Mars give rise to depletion of the inner Hungaria zone which thus represents a natural dynamical boundary of the region.

To assess the above observations and conclusions in more detail we analyzed the distribution of close encounters with Mars for Hungaria asteroids for which in 2 Myr integrations we detected approaches to within 0.1 AU. This is certainly a somewhat loose threshold, because Mars encounters are effective only at much smaller distances, but, in our opinion, appropriate for the statistical analysis we are interested in. The integrations were done by using the Orbit9 package, with dynamical model, initial conditions and setup as described in Paper I. Note that here we did not analyze data on the minimum distances and relative velocities at individual encounters, as these are not needed for the present purpose, but they can be easily determined, if necessary, for each detected encounter.

In Fig. 1 we show a grey scale coded plot of the frequency of close encounters of Hungaria asteroids with Mars in the plane of proper semimajor axis vs. proper eccentricity. The expected general trend of increase of the number of close encounters from bottom-right to upper-left (that is in the direction of decreasing asteroid perihelion distance) is clearly seen in the plot. The non uniformities indicated by the irregular and sometimes disconnected contour lines are due to the intrinsic irregularity of motion of the objects in the region (partly also to the interpolation algorithm of the graphics software).

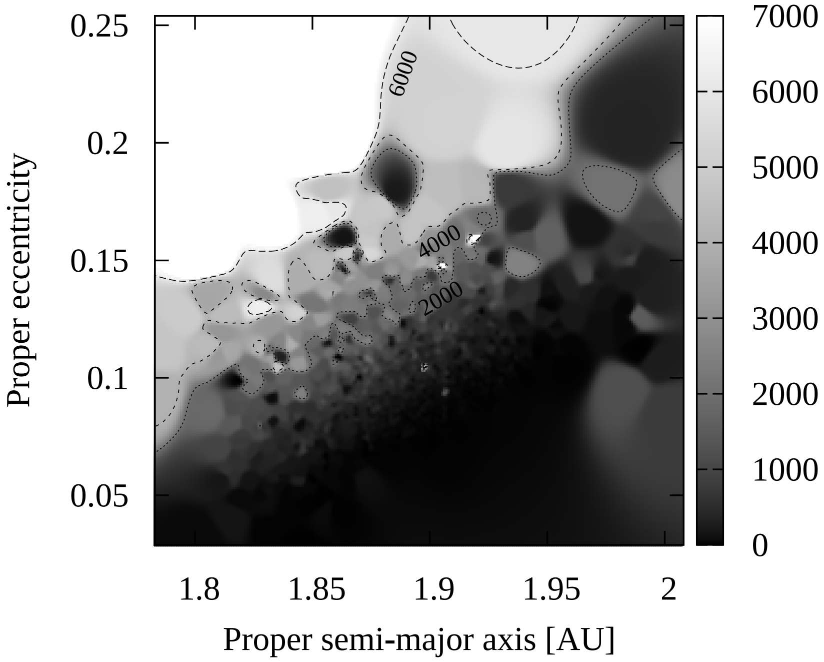

Figure 1: The grey scale coded frequency of close encounters of Hungaria asteroids with Mars in the proper semimajor axis vs. proper eccentricity plane. Contour lines delimit region in terms of the frequency increasing from the right-bottom to the left-upper corner of the plot.

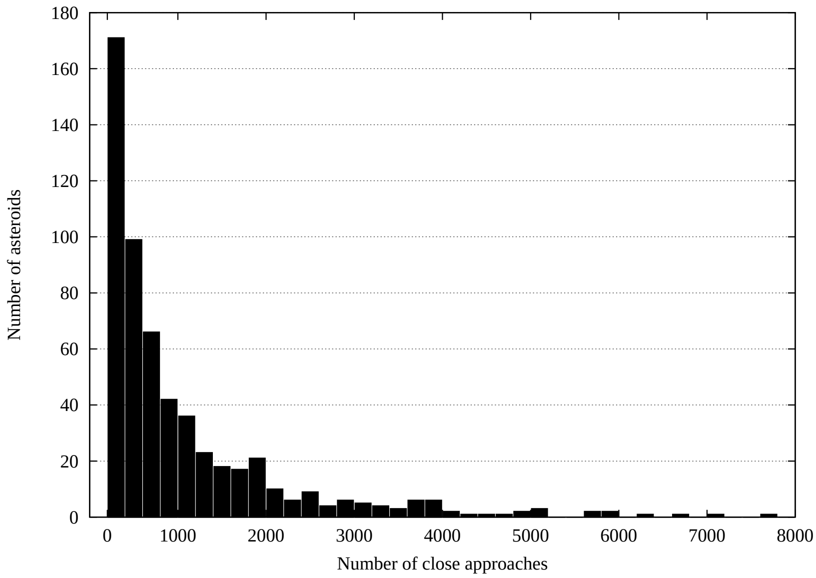

Figure 2: Number frequency distribution of close encounters of Hungaria asteroids with Mars.

In Fig. 2 the number frequency distribution of close approaches per body is shown. Again as expected, the number of bodies quickly diminishes with a number of close approaches. Most of the 25 above mentioned strongly chaotic bodies belong to the high number of encounters tail of the distribution. As discussed above, however, the occurrence of close encounters for chaotic orbits is stochastic, thus when we repeated the experiment with slightly different initial conditions, as much as 6 of them did not have any close approaches to Mars in the period covered by the integration.

Taken together, the two figures confirm that most of the bodies having only occasional close encounters can survive in the region for a long time; hence there are many of them still there. On the contrary, bodies having a large number of close encounters, sooner or later undergo a very close encounter and change the orbit to the point of escaping from the region. The close encounters region does indeed represent a natural dynamical boundary of the region.

3. CLOSE COUPLES

In our study of the Hungaria region in Paper I, one of the questions that we addressed was the origin of the so called close couples of asteroids. These are pairs of asteroids very close in terms of both, osculating and proper orbital elements. In order to understand the origin of these couples, it is necessary to precisely determine epochs of their closest approaches and the corresponding minimum distances and relative velocities. Different mechanisms have to be taken into account in this case: planetary gravitational perturbations, Yarkovsky thermal effect (Rubincam 1995), and mutual gravitational perturbations of asteroids forming the pair (as during the close approaches their masses cannot be considered negligible). The two latter mechanisms, however, cannot be modeled accurately because of the poorly known physical parameters of the bodies. Thus, only a statistical approach is possible, as demonstrated by Vokrouhlický and Nesvorný (2009) in their analysis of the role of Yarkovsky effect in determination of the closest approach for the pair (6070) Rheinland and (54827) 2001 NQ8.

As an in-depth study of the dynamics of close couples, that would include all these important factors, is beyond the scope of this paper, we will here focus our attention only on the effects of the mutual gravitational perturbations of asteroids, i.e. on the role of their masses. In particular, we analyzed the closest pair found among Hungaria asteroids, that is (88259) - $1999VA_{117}$ (couple 1 of Paper I). To do so, we have somewhat conservatively assumed that minimum and maximum possible values of (otherwise unknown) asteroids albedos are 0.2 and 0.45, respectively, a tentative range based on the albedos of various Hungaria asteroids found in the available literature (Gil-Hutton et al. 2007);[2] we also adopted 1 g cm^{-3} and 3 g cm^{-3} as minimum and maximum density, respectively. Knowing the absolute magnitude H and albedo A, the radius R of a body can be estimated according to the relation (Bowell et al. 1989)

$$R\ (\mathrm{km}) = 1329\ \frac{10^{\frac{-H}{5}}}{2\sqrt{A}} \qquad (1)$$

[2]The albedo of (434) Hungaria itself is estimated at 0.38 and this value was used for all the Hungaria asteroids in Paper I.

With known radius R and density ρ, and assuming spherical shapes of the bodies, we infer minimum and maximum values of the masses. For the asteroid (88259) we found $2.484 \times 10^{-18} M_{\odot}$ as a minimum and $2.515 \times 10^{-17} M_{\odot}$ as a maximum possible mass, while for the asteroid $1999VA_{117}$ corresponding values are $1.309 \times 10^{-19} M_{\odot}$ and $1.326 \times 10^{-18} M_{\odot}$. Note that Hill's radii corresponding to minimum and maximum total mass of the pair (contained essentially in the bigger body) are only 260 km and 560 km, respectively.

Next, we have generated 100 clones of multi-opposition asteroid $1999VA_{117}$ assigning at random initial osculating elements within 3σ orbit uncertainty as provided by AstDys web site. The orbits of each of these 100 clones, plus much more accurate nominal orbit of the numbered asteroid (88259) (hence no need for its clones), were propagated for 50,000 yr using the ORBIT9 integrator. [3] All the integrations were performed three times, using different, purely gravitational, dynamical models including seven planets (from Venus to Neptune) as perturbing bodies. The indirect effect of the Mercury was accounted for by applying the barycentric correction to the initial conditions. In the first set of the integrations we used this basic dynamical model, while the second and third set of integrations were performed using the basic dynamical model plus masses of asteroids, which were set to the above estimated minimum and maximum values, respectively.

In Fig. 3 we show the number frequency distribution of close encounter distances obtained with the basic dynamical model. The distribution peaks at ~ 3000 km, and the lowest value is still by a factor of about 3 larger than the corresponding radius of the Hill's sphere of influence.

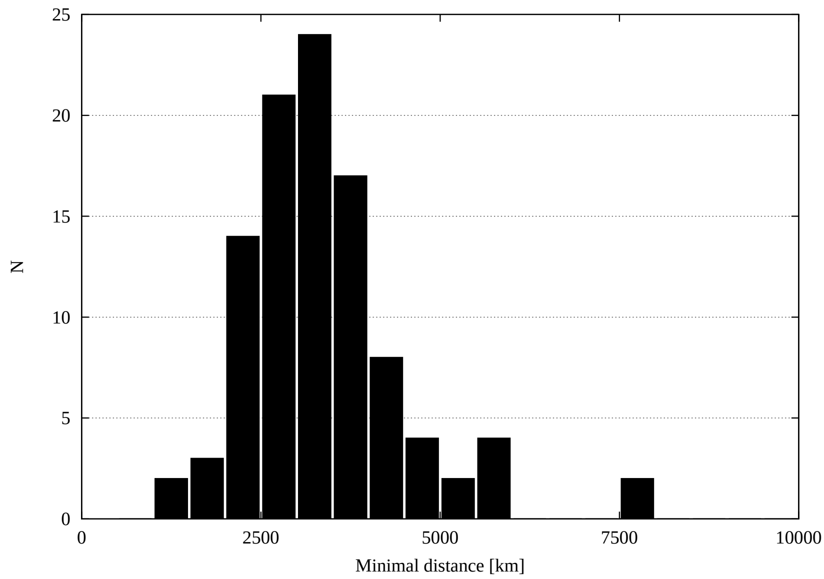

Figure 3: The number frequency distribution of the minimum distances at close encounter for the asteroid (88259) and 100 clones of asteroid $1999VA_{117}$.

[3]Available at http://adams.dm.unipi.it/ orbmaint/orbfit/

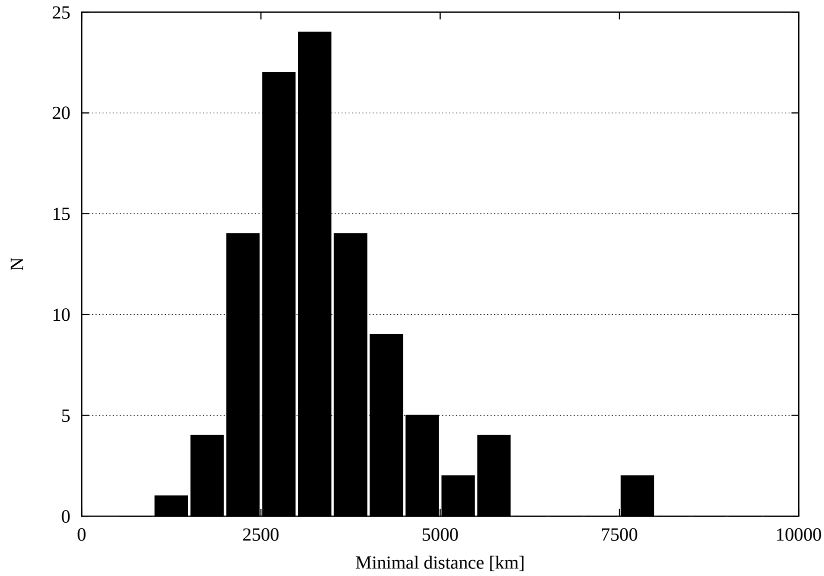

Figure 4: The same as Fig. 3, but for the minimum value of the total mass.

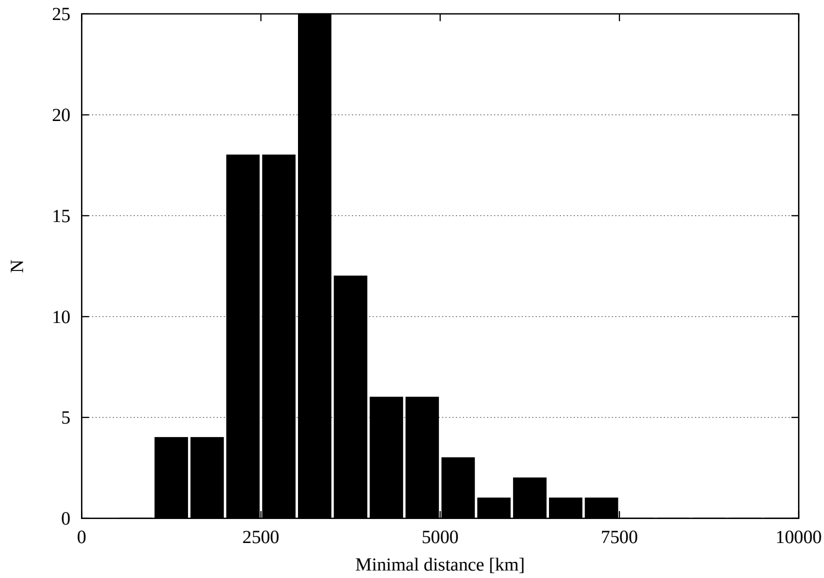

Figure 5: The same as Fig. 3, but for the maximum value of the total mass.

Similarly, in Figs. 4 and 5 we show analogous distributions for minimum and maximum estimated masses. All three distributions qualitatively resemble each other, with the only significant difference pertaining to the number of clones with the smallest minimum distance, which increases slightly with mass. In view also of the corresponding increase of the radius of the sphere of influence, the two approach each other to the point that their ratio drops to ~ 2. Still, the general impression is that the changes are minute, and bearing in mind also the presumably much more important non-gravitational effects not included in this analysis, one may easily erroneously conclude that the effect is overall negligible.

Therefore, to better appreciate the change introduced by the completion of the dynamical model, in Fig. 6 we plotted the distribution of differences of minimum distances for individual clones in the sense model-with-maximum-mass minus basic model. As one can easily observe, the differences can be significant, reaching, in particular in the direction of decreasing distances, quite large values. Actually, in this case inclusion of the massive asteroids in the model gives rise to smaller minimum distances for 60% of clones. The amount of change represents typically a significant fraction of the corresponding nominal value, thus proving the importance of the effect and the need for it to be taken into account in the accurate computations.

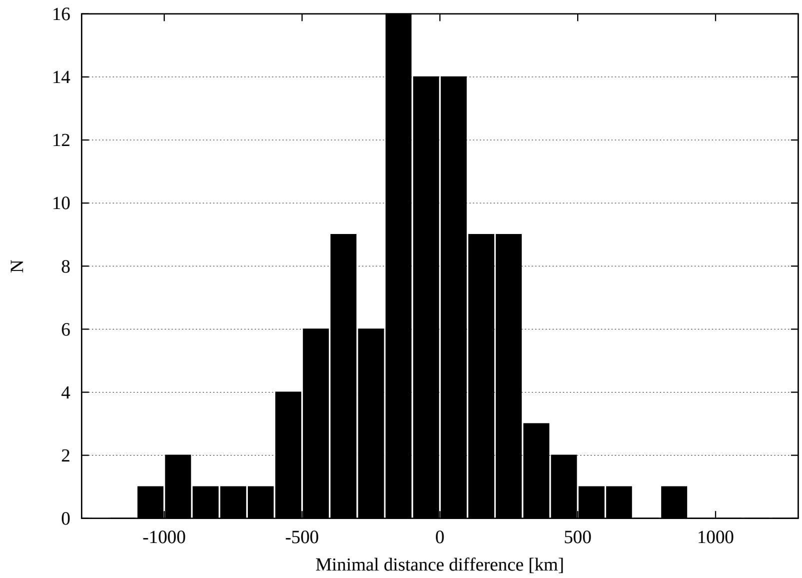

Figure 6: Differences of minimum distance for individual clones in the sense model-with-maximum-mass minus basic model.

4. CONCLUSIONS

In the present paper we investigated the occurrence of close approaches of Hungaria asteroids to Mars, and we presented an analysis of the changes introduced by accounting for asteroid masses in the dynamics of close couples found in the Hungaria region.

The main conclusions of this work can be summarized as follows:

- We confirmed that, as expected, most of the bodies in the region, having only occasional close encounters with Mars, can survive there for a long time; this explains the fact that there are many of them still there. However, bodies having a large number of close encounters, sooner or later undergo a very close encounter and change the orbit to the point of escaping from the region. The close encounters region, in this way, does indeed represent a natural dynamical boundary of the region.

- Accounting for the masses of asteroids forming close couples gives rise to significant changes of their computed minimum distances (typically by $20 - 30\%$). In our example these changes were preferentially in the sense of reducing the minimum distances with respect to the distances derived from the model with massless asteroids. The effect needs to be taken into account in the accurate computations.

Acknowledgments

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References

Bowell, E., Hapke, B., Domingue, D., Lumme, K., Peltoniemi, J., Harris, A. W.: 1989, In: Asteroids II; Proceedings of the Conference, Tucson, AZ, Mar. 8-11, 1988 (A90-27001 10-91). Tucson, AZ, University of Arizona Press, 524.

Gil-Hutton, R., Lazzaro, D., Benavidez, P.: 2007, Polarimetric observations of Hungaria asteroids. *Astron. Astrophys.*, **458**, 1109.

Milani, A., Knežević, Z., Novaković, B., Cellino, A.: 2010, Dynamics of the Hungaria asteroids, *Icarus*, in press.

Rubincam, D. P.: 1995, Asteroid orbit evolution due to thermal drag. *Journal of Geophysical Research*, **100**, 1585.

Vokrouhlický, D., Nesvorný, D.: 2009, The Common Roots of Asteroids (6070) Rheinland and (54827) 2001 NQ8. *Astron. J.*, **137**, 111.

Warner, B. D., Harris, A. W., Vokrouhlický, D., Nesvorný, D., Bottke, W. F.: 2009, Analysis of the Hungaria Asteroid Population, *Icarus*, **204**, 172.