LUNAR EFFECTS ON CLOSE ENCOUNTERS OF NEAR EARTH ASTEROIDS. Á. Bazsó, Institute of Astronomy, University of Vienna, Türkenschanzstrasse 17, A-1180 Vienna, Austria (akos.bazso@univie.ac.at).

Introduction: The Near Earth Asteroids (NEAs) form a group of objects that can approach or intersect the Earth's orbit. Commonly the criteria for an asteroid to be a NEA are a perihelion distance of less than 1.3 astronomical units (AU), or an aphelion distance of more than 0.98 AU. At least three groups of NEAs can be discriminated by increasing semi-major axes, namely the Atens, Apollos and Amors. The orbits of NEAs are subject to perturbations by the major planets Jupiter and Saturn, but due to their close approaches to the terrestrial planets these have a substantial effect on their orbital evolution, too. The lifetime of NEAs is limited [1, 2], the median value being about 10 million years (Myrs). NEAs either end up colliding with the Sun, being ejected from the Solar System or colliding with a planet. The latter case is most important for impact crater research on Earth, but also from an anthropocentric view for the habitability of Earth.

Previous studies have shown that — although the Moon/Earth mass ration is 1/81 — the Moon's gravitational influence plays a non-negligible role for close encounters and impacts of NEAs to the Earth [3, 4]. These studies found that the Moon contributes to the deflection of asteroids, thus it mitigates objects that would impact on Earth. On the other hand the Moon can also increase the number of impacts. The efficiency of both processes depends mainly on the relative velocity of the NEA to the Moon.

The focus of this study is to investigate the Moon's contribution to the mentioned effects and to derive statistics for the different types of NEAs. In addition the influences of changes in lunar orbital parameters (e.g. smaller geocentric distance in the past) are of interest.

Methods: The two dynamical models adopted for the numerical experiments were chosen to focus on the main point: the dynamics of the Earth–Moon system. First, the restricted three body problem (R3BP) including Sun, Earth and the NEA — which was considered to be massless — provided a basic starting point. The motion of real NEAs was investigated without perturbations by the Moon. The results from this model can also be used for the planet Venus, since the masses of Venus and Earth are similar. Then the integrations were repeated for comparison with the restricted four body problem (R4BP) adding the Moon to the former objects. While the results of the study [3] were obtained in a two-dimensional model, here the full three-dimensional problem is treated.

The equations of motion were integrated by the Lie series method [5], which has already been used for similar purposes [6]. All objects were treated as point masses. The initial conditions for the NEAs were obtained from the Minor Planet Center/JPL NEO Program (neo.jpl.nasa.gov). For each of the three classes (Amors, Apollos, Atens) 300 objects were selected and integrated for 10 Myrs. For close encounters to Earth (encounters within a geocentric distance of 384000 km) the minimal distances and relative velocities were recorded to obtain a statistical description of those parameters.

Results: From the comparison of the two models first an expected result was found: the Amor group asteroids, which in general have the largest semi-major axes among the NEAs, show the lowest number of close encounters. Then for the Apollo and Aten groups the numbers increase sharply, being largest for the Atens. The number of close encounters are: Amors 296/315 for the R3BP respectively R4BP model, for the Apollos 10789/12558, and for the Atens 25258/26425. There is a slight difference of a few percent between the two models, that could be subject to a statistical effect, but apparently there are more close encounters in the R4BP (including the Moon). The duration of close encounters shows less distinct variations between the models, the average values are in both models and for all NEA groups around 0.5 days.

A closer investigation of the minimal distances during close encounters reveals, that in the presence of the Moon consistently a larger fraction of NEAs obtains very small distances, even down to potential impacts. As shown in figure 1 the highest fraction of objects ($\approx 70\%$, regardless of the actual dynamical model) falls into the bin with highest geocentric distance, meaning that most of the encounters are "shallow". Many more NEAs approach Earth at still higher distances, here only those are considered that come closer than 400000 km. Naturally the fraction of objects decreases that come very close, in the log-log plot a linear relation can be established. This relation can help to extrapolate to the actual Earth radius to determine statistically the fraction of impactors from the chosen population.

Another key point is the imbalance between the two models at the lowest relative distances. There are more objects reaching distances of less than one Earth radius in the R4BP than in the R3BP. This result can be directly attributed to the Moon's influence.

For testing the direct short time lunar effects a different experiment was conducted. A NEA was randomly selected before one of its close encounters to the Earth in the R3BP. By repeating the integration from that instant it was verified, that a close encounter would occur again. After that the NEA's coordinates were slightly changed to simulate additional objects ("clones") in the

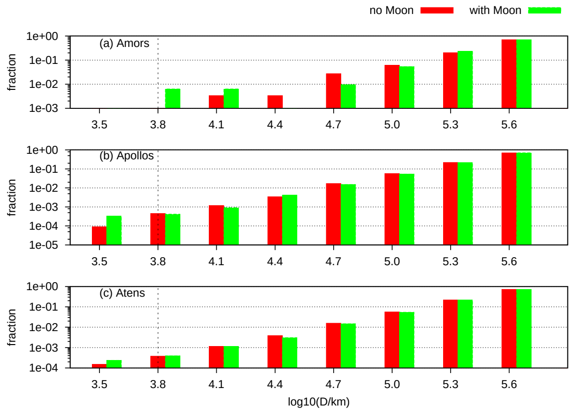

Figure 1: A histogram plot comparing the number of close encounters of different NEA groups. On the horizontal axis the logarithm of the geocentric distance (in km) is given, while the vertical axis displays the fraction of close encounters per bin normalized by the total number per group and model. The majority of close encounters occurs at high distances; while the lowest distances occur preferably in the R4BP model ("with Moon"). From top to bottom the Amors, Apollos and Atens are shown; please take into account that the scales are different due to the different number of encounters (given in the text). The vertical line at 3.8 indicates the physical Earth radius, any close encounter at or below that value would result in an impact.

parameter space in the neighborhood of the original object. These clones were again integrated in both models for a short interval of time of 10000 years. A direct comparison of the results is shown in figure 2. While it is visible that in both models close encounters occur, the minimal distances are clearly smaller if the Moon is present and perturbs the orbits of NEAs. shows that again including the Moon the minimal close encounter distances are lower than without the Moon. As a special remark there are two clones that even achieve a distance of less than the Earth's physical radius, thus showing that the Moon's gravitational effect can enhance the collision probabilities.

Conclusions: As demonstrated by the numerical integrations the Moon affects the close encounter distances of Near Earth Asteroids, leading to an enhanced probability of very close encounter, or even impacts. It was shown by a direct comparison of two models that with the Moon's presence (a) more close encounters take place, (b) these encounters result in lower minimal distances, and (c) collision are probably enhanced by lunar perturbations of the orbits. This study suggests that even at high relative velocities the Moon can influence the trajectories of NEAs. For future investigations these results should not be neglected.

References: [1] P. Michel, et al. (2007) *Meteoritics and Planetary Science* 42:1861. [2] B. J. Gladman, et al. (1997) *Science* 277:197. [3] R. C. Domingos, et al. (2004) *Advances in Space Research* 33:1534. [4] T. Ito, et al. (2010) *A&A*

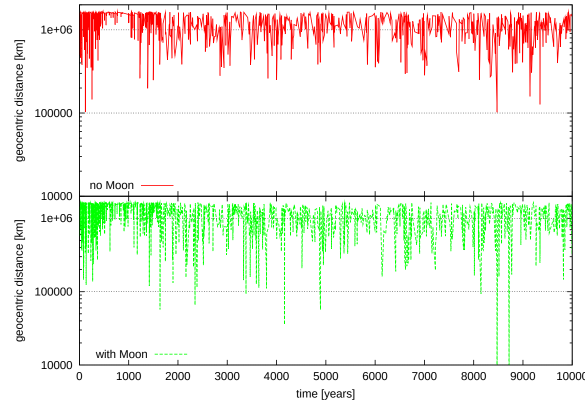

Figure 2: A direct comparison of the time-evolution of clones of the same object in the two models of interest. The axes show the time versus the minimum geocentric distance of the close encounter for an interval of 10000 years. As the upper picture shows without the Moon's gravitational influence no close encounter occurs below 100000 km, whereas in the lower picture there are clearly more encounters below that value, and additionally two clones can even have collisions.

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