A Study of Six Near-Earth Asteroids
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Summary

We consider here 6 Earth-orbit-crossing asteroids (ECAs) as possible targets for a future Discovery-class space mission. Five of these bodies have a common feature that their orbits have orbit periods that almost exactly match the one-year orbit period, with various inclinations and eccentricities. As a consequence of perturbations and finite volumes of position and velocity uncertainty that arise for near-encounter events, the long-term motion of multiple encounter asteroids relative to Earth are quasi-periodic. We also examine one non-resonant asteroid (2004 MN4), because it is projected to have three near-impact encounters in 2029, 2034 and 2036. The 2029 encounter miss distance is presently estimated to be ~ 5.6 +/- 1 Earth radii; the subsequent miss distances and associated uncertainty cannot be reliably estimated at present. 2004 MN4 has an estimated diameter of ~400m. An impact by a body of this size may produce significant loss of life and is therefore of obvious significance. We review the orbit evolution and structural properties of these primitive asteroids. It is anticipated that understanding the composition and morphology of these primitive bodies would provide substantial insight into the history of the solar system. The diameter of the ECAs discussed varies from less than 100m to several km. Their near proximity and scientific importance makes them attractive targets for near term missions. Early missions should be aimed at understanding their physical properties and orbits, as well as developing insights that may someday be needed to deflect or destroy these bodies. For the particular case of 2004 MN4, we evaluate all opportunities for near-term missions before the 2029 encounter. Two low energy opportunities are found ~2012 and ~2020. Such missions would provide an opportunity to track the object precisely during the 2029 encounter to accurately predict the subsequent encounters, and finally, to measure seismic response to the Earth’s tidal forces during the encounter; we believe this would help us to understand its structural properties. These launch opportunities are very important.

Introduction

With reference to the sub-figures of Fig 1, the first 5 of the 6 asteroids have periods of approximately one year. The epoch associated with all six of the orbits in Fig 1 is Dec 4, 2005. The slight miss-match between the period of a near-resonant asteroid and the one year period of the Earth, together with the nonlinear perturbations of the asteroid orbit, result in the relative motion being horseshoe orbits. A typical horseshoe orbit for asteroid 3753 Cruithne [2] is shown in Fig 2, each ‘loop’ is approximately a one year period; and the near Earth close encounters are where the encounter-specific large perturbations arise. The horseshoe orbits are the relative position vector of the asteroid in

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a reference frame centered at the Sun, co-rotating with the Earth such that the Sun and Earth are fixed in this frame. If the asteroid had exactly a one year period, the relative orbit would be strictly periodic would be a bean-shaped space curve. The slight period miss-match, and the nonlinear perturbations cause the actual “annual beans” to be open space curves and over long times, to occupy a horseshoe-shaped region, e.g., Fig 2. The actual perturbations experienced when the trajectory passes near the Earth are sensitive to the encounter condition uncertainty - this makes the long-term evolution difficult to predict. Asteroid 2004 MN4 is of particular interest, since our current best estimates have this object passing extremely close to Earth three times over the next 30 years.
Asteroid 2004 MN4 will make a very close encounter in 2029, followed other approaches in 2034 and 2036; the predicted encounter path on April 29, 2029 is shown [1] in Fig. 3. The 2029 uncertainty (+/- 1 Earth radii) is presently large compared to the small miss distance of 5.6 Earth radii. This close encounter, however, is not presently considered a high risk for collision. The subsequent encounters have larger uncertainties and cannot presently be predicted due to the nonlinear propagation of the large 2029 encounter uncertainty. The most common method for approximating the collision probability is to use a Gaussian model of the initial orbit uncertainty, derived from the orbit determination and linear error theory [2] to propagate the covariance forward in time. It is usually necessary [3] to use Monte Carlo or related nonlinear Particle Methods to better approximate the error probability density function. Thus the 2034 and 2036 encounters of 2004 MN4 will require ongoing analysis as more observations are obtained. An early mission to place a transponder and other instruments on 2004 MN4 prior to the 2029 encounter would yield a wealth of needed information.

Rubble Pile Hypothesis

One of the 5 resonant asteroids, namely 1996 FG3, is a binary object consisting of two distinct pieces, separated by a few km. In surveying the rotational speeds of 1000 main belt and near-Earth asteroids, a curious result was noticed by Pravec et al, and is reproduced from Ref. [4] (Fig. 4). Only small diameter asteroids are observed to have high rotational speeds (> 10 revs/day). A large number of asteroids, however, are
clustered near 10 revs/day, including all of the binary NEOs. These data and other considerations give rise to the “rubble pile hypothesis” that a fraction of the primitive asteroids are structurally very weak, and that small angular velocity combined with occasional planetary tidal forces are sufficient to disrupt some of these objects into smaller objects. Evidence from terrestrial and lunar impact craters reveal several instances of two or more near simultaneous impact events. One of the more compelling examples is the Davy Chain of craters on our Moon (47 km long, 23 craters, each 1-3 km across, Fig. 5). The Davy Chain is hypothesized to have been produced by an asteroid that tidally disrupted near Earth then collided with the Moon shortly thereafter. While strong evidence exists that many asteroids may be weak gravitational aggregates, the structural integrity of any particular asteroid is of course very difficult to discern without in situ measurements.

Feasible Missions to The Six Asteroids

Using Battin’s Lambert algorithm [5], the two-point boundary value problem can be solved for the solar trajectory connecting positions at time 2 prescribed times, and thereby sweep out the family of orbit transfers from the Earth (at time $t_{\text{launch}}$) to the asteroid at time $t_{\text{arrive}}$. The velocity at infinity relative to Earth, to a good approximation, should match the vector difference between the earth’s orbital velocity and the required velocity (from the Lambert solution) on the transfer trajectory at time $t_{\text{launch}}$. The velocity at infinity relative to the asteroid is the vector difference between the arrival velocity on the transfer trajectory (from the Lambert solution) and the velocity of the asteroid at time $t_{\text{arrive}}$. By sweeping the times ($t_{\text{launch}}, t_{\text{arrive}}$) and making a family of calls to the Lambert algorithm, the set of solutions can be swept out and any property of the solution can be contour plotted as a “porkchop” surface as a function of launch time versus time of flight along the transfer trajectory. See Fig. 6 for a diagram of a typical orbit transfer.

The Lambert algorithm was executed for each of the 6 asteroids; and the launch times were swept (daily) over each calendar year. For each launch time, the time of flight was swept daily from 120 days to 365 days. Thus each year yields three porkchops for required velocity, one for required velocity relative to earth $V_{\infty/B}$ (actually, we plotted $C_3 = V_{\infty/B}^2$) upon exiting the Earth’s gravity field. Only a portion of these surfaces are presented to provide an indication of the trends. First some qualitative observations. It is evident in Fig. 1 that two of the resonant asteroids (namely Cruithne and FG3) are relatively eccentric and have significant orbit inclinations), whereas the other three resonant asteroids...
Figure 7: Minimum C3 vs Launch Date for Six Near-Earth Asteroids

Figure 8a C3 vs Launch Date

Figure 8b Spacecraft Trajectory

Figure 8 Launch Porkchop for 1996 FG3 for Launches During 2011

Figure 9a C3 vs Launch Date

Figure 9b Spacecraft Trajectory

Figure 9 Launch Porkchop for 2003 YN107 for Launches During 2008

Figure 10a C3 vs Launch Date

Figure 10b Spacecraft Trajectory

Figure 10 Launch Porkchop for 2004 MN4 for Launches During 2020
have either low eccentricity and/or low inclinations. We might anticipate that the first 2 asteroids will be more difficult to reach, vis a vis required energy and small launch windows, than the latter 3. Furthermore, since 4 of the 6 asteroids (namely Cruithne, PH5, AA29 and YN107) have periods of almost 1 yr, we should anticipate that the required transfer orbits will vary only slightly in successive years. These observations agree with the numerical results obtained. For all 6 asteroids, we developed porkchops for launch years swept over years 2008 through 2025. See some results from our mission studies in Figs 7 – 10. In Fig. 7, we show \( C \equiv \frac{V_{\infty}}{\sqrt{\beta}} \) variation with launch date for the 6 asteroids.

In particular, 2011 and 2020 are the most favorable times to launch missions to FG3 and MN4. Further, in Figs 8 and 9, we show the launch porkchops for FG3 and YN107 for launches in calendar years 2011 and 2008 respectively. For MN4, the launch porkchop is shown in Fig 10 and we see a sample mission (of many feasible) shown in Fig 10b. This window (~2018 to 2022) should be given high priority when studying the possible need to deflect MN4. The early window (~2010 to 2014) would be very attractive to land a transponder so the orbit can be refined to a high degree of accuracy before the second window in 2020 +/-; in case a deflection mission proves necessary.

**Discussion**

In this paper, we have summarized several issues with regard to a set of 6 ECAs with particular emphasis upon the launch energy cost associated with near-term missions. Asteroid 2004 MN4 is of particular interest due to the 3 close encounters in 2029, 2034 and 2036. It has been found that two attractive launch opportunities exist for missions to 2004 MN4: The 1st launch is in the 2011-2012 time frame and the 2nd launch is in 2019-2020 time frame (permits arrival 8-9 years before the 2029 approach). Both of these opportunities should be considered carefully as we evaluate options to learn more about the structure and orbit of asteroid 2004 MN4 before and during the 3 earth encounters.

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**References**