A resonant family of dynamically cold small bodies in the near-Earth asteroid belt

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ABSTRACT

Near-Earth objects (NEOs) moving in resonant, Earth-like orbits are potentially important. On the positive side, they are the ideal targets for robotic and human low-cost sample return missions and a much cheaper alternative to using the Moon as an astronomical observatory. On the negative side and even if small in size (2–50 m), they have an enhanced probability of colliding with the Earth causing local but still significant property damage and loss of life. Here, we show that the recently discovered asteroid 2013 BS45 is an Earth co-orbital, the sixth horseshoe librator to our planet. In contrast with other Earth’s co-orbitals, its orbit is strikingly similar to that of the Earth yet at an absolute magnitude of 25.8, an artificial origin seems implausible. The study of the dynamics of 2013 BS45 coupled with the analysis of NEO data show that it is one of the largest and most stable members of a previously undiscussed dynamically cold group of small NEOs experiencing repeated trappings in the 1:1 commensurability with the Earth. This new resonant family is well constrained in orbital parameter space and it includes at least 10 other transient members: 2003 YN107, 2006 JY26, 2009 SH2 and 2012 FC71 among them. 2012 FC71 represents the best of both worlds as it is locked in a Kozai resonance and is unlikely to impact the Earth. These objects are not primordial and may have originated within the Venus–Earth–Mars region or in the main-belt, then transition to Amor-class asteroid before entering Earth’s co-orbital region. Objects in this group could be responsible for the production of Earth’s transient irregular natural satellites.

Key words: celestial mechanics – minor planets, asteroids: individual: 2003 YN107 – minor planets, asteroids: individual: 2006 JY26 – minor planets, asteroids: individual: 2012 FC71 – minor planets, asteroids: individual: 2013 BS45 – planets and satellites: individual: Earth.

1 INTRODUCTION

During the last two decades, observations of near-Earth Objects (NEOs) have uncovered the existence of a near-Earth asteroid belt made of minor bodies with diameters smaller than 50 m and moving in Earth-like orbits with low eccentricity (Rabinowitz et al. 1993). Putative members of this near-Earth belt have perihelia in the range 0.9–1.1 au, aphelia less than 1.4 au, low eccentricities, a wide range of inclinations and unusual spectral properties (Rabinowitz 1994). This parameter range is sometimes called the Arjuna region (Rabinowitz et al. 1993; Gladman, Michel & Froeschlé 2000) after the hero of Hindu epic poem Mahabharata. Main-belt asteroids are not a plausible source for this near-Earth belt (Bottke et al. 1996; Rabinowitz 1997). Amor asteroid fragments provide a reasonable origin for most members and planetary ejecta from Mars, the Earth–Moon system and Venus may have produced the lowest inclination objects (Bottke et al. 1996). Although the vast majority of NEOs have significant eccentricity and/or inclination, a dynamically cold population that includes objects with both low eccentricity and low inclination exists. Periodic close encounters with the Earth–Moon system make this type of orbits quite unstable; therefore, its members are necessarily transient but, due to their Earth-like orbital elements, they may also easily become temporary co-orbitals, in particular horseshoe librators to the Earth.

The dynamical evolution of asteroids moving in Earth-like orbits has already been studied (Tancredi 1997; Brasser & Wiehert 2008; Kwiatkowski et al. 2009; Granvik, Vaubaillon & Jedicke 2012) but objects in resonance with the Earth have been explicitly excluded. However, the existence, characterization and study of such group could be of great importance not only for planning low-cost interplanetary missions (e.g., Davis, Friedlander & Jones 1993) or asteroid mining (e.g., Lee 2012) but also to reduce the effects of future Earth impact events as those objects are easy to access but, on a dark note, they also have an increased probability of becoming impactors due to their low relative velocities to the Earth (e.g., Lewis 1996). Using data from the JPL HORIZONS system to explore this neglected population, we found that the re-
cently discovered Aten asteroid 2013 BS$_{45}$ exhibits all the orbital attributes expected of an object in such group. Not only its relative (to the Earth) semimajor axis is 0.0024 au but also the values of its eccentricity (0.08) and inclination (0.78) are close to those of the Earth. In fact, its orbit is currently the most Earth-like among those of asteroids moving in Earth-like orbits. The study of the dynamical evolution of 2013 BS$_{45}$ led us to find a previously undiscussed dynamically cold group of small near-Earth asteroids that experience repeated resonant episodes with the Earth. This Letter is organized as follows: in Section 2, we briefly outline our numerical model. Section 3 focuses on 2013 BS$_{45}$ as follows: in Section 2, we briefly outline our numerical model. Section 3 focuses on 2013 BS$_{45}$. Section 4 is devoted to the new dynamically cold resonant family. The relevance of our findings is discussed and our conclusions summarized in Section 5.

Table 1. Heliocentric Keplerian orbital elements of asteroids 2013 BS$_{45}$, 2003 YN$_{107}$, 2006 JY$_{26}$ and 2012 FC$_{71}$. Values include the 1σ uncertainty. The orbit of 2013 BS$_{45}$ is based on 87 observations with a data-arc span of 24 d. The orbits are computed at Epoch JD 245 6400.5 that corresponds to 0:00 UT on 2013 April 18 (J2000.0 ecliptic and equinox. Source: JPL Small-Body Database.)

|                 | 2013 BS$_{45}$ | 2003 YN$_{107}$ | 2006 JY$_{26}$ | 2012 FC$_{71}$ |
|-----------------|---------------|----------------|---------------|---------------|
| Semimajor axis, $a$ (au) | 0.997 6309±0.000 0003 | 0.988 7187±0.000 0005 | 1.009 863±0.000 0009 | 0.989 53±0.000 02 |
| Eccentricity, $e$       | 0.084 0717±0.000 0006 | 0.013 9379±0.000 0003 | 0.083 072±0.000 011 | 0.087 7±0.000 2 |
| Inclination, $i$ (°)    | 0.786 117±0.000 0005 | 4.321 08±0.000 03 | 1.439 32±0.000 07 | 4.967±0.014 |
| Longitude of the ascending node, $Ω$ (°) | 85.388 2±0.000 6 | 264.431 61±0.000 08 | 43.487±0.004 | 38.708±0.006 |
| Argument of perihelion, $ω$ (°) | 146.064 1±0.000 7 | 87.516 70±0.000 13 | 273.571±0.012 | 347.76±0.02 |
| Mean anomaly, $M$ (°) | 346.006 0±0.000 2 | 254.342 2±0.000 5 | 223.70±0.05 | 186.20±0.04 |
| Perihelion, $q$ (au) | 0.913 7584±0.000 0007 | 0.974 9381±0.000 0002 | 0.925 972±0.000 003 | 0.902 8±0.000 2 |
| Aphelion, $Q$ (au) | 1.081 503±0.000 0003 | 1.002 49948±0.000 0005 | 1.093 755±0.000 009 | 1.076 29±0.000 02 |
| Absolute magnitude, $H$ (mag) | 25.8±0.3 | 26.3±0.7 | 28.3±0.6 | 25.2±0.4 |

Figure 1. Three-dimensional evolution of the orbit of 2013 BS$_{45}$ in three different frames of reference: heliocentric (left), frame corotating with the Earth but centred on the Sun (top right) and geocentric (bottom right). The red point marks 2013 BS$_{45}$, the blue one the Earth and the yellow one the Sun. The osculating orbits are outlined and the viewing angle changes slowly to facilitate visualizing the orbital evolution.

2013 BS$_{45}$ was discovered on 2013 January 20 by J. V. Scotti observing with the Steward Observatory 0.9-m Spacewatch telescope at Kitt Peak (Bressi et al. 2013) and had a close encounter with the Earth on 2013 February 12 at 0.013 au. It is small with $H = 25.8$ which translates into a diameter in the range 20–40 m for an assumed albedo of 0.20–0.04. Radar observations indicate that it may be a very rapid rotator with a period of just a few minutes pointing to relatively recent collisional debris. Even if small, the object is much larger than the previously known tiny (so-called) minimoons 1991 VG (Tancredi 1997) and 2006 RH$_{120}$ (Kwiatkowski et al. 2009). The orbital elements of 2013 BS$_{45}$ (see Table 1) are suggestive of a NEO co-orbital with the Earth, likely of the horseshoe kind. In order to confirm its co-orbital nature, we have performed N-body calculations in both directions of time. The three-dimensional evolution of its orbit for several decades is shown in Fig. 1. Such a path viewed in a frame of reference rotating with the Earth looks like a corkscrew around the orbit of the host planet while both revolve around the Sun. Regular horseshoe orbiters are characterized by the libration of the difference between the mean longitudes of the object and its host planet or relative mean longitude, $λ$. The mean longitude of an object is given by $λ = M + Ω + ω$, where $M$ is the mean anomaly, $Ω$ is the longitude of ascending node and $ω$ is the argument of perihelion. If the libration amplitude is larger than 180°, encompassing $L_3$, $L_4$ and $L_5$ but not reaching the actual planet, it is said that the object follows a symmetric

http://echo.jpl.nasa.gov/asteroids/2013BS45/2013BS45_planning.html
The study of the dynamics of 2013 BS$_{45}$ clearly exposed that, during the co-orbital episodes, its path was constrained to a well-defined region in the orbital parameter space, in particular $a$, $e$ and $i$: $0.985 < a \,(\text{au}) < 1.013$, $0 < e < 0.1$ and $0 < i < 85.6$. During these episodes, the values of the osculating orbital elements $a$, $e$ and $i$ remain restricted to the grey areas in Fig. 3. The boundary is not regular likely because of secular resonances. The results from multiple simulations have been used to outline the region of interest. The level of stability is not the same within the entire region. This behaviour motivated a search for additional objects within that well-defined volume in $a$–$e$–$i$ space that produced 10 candidates for membership in our suspected dynamical family (see Table 2). After performing additional $N$-body calculations analogous to those completed for 2013 BS$_{45}$, we found that 2009 SH$_{2}$, 2003 YN$_{107}$ and 2006 JY$_{26}$ currently are horseshoe librators to the Earth. The orbital evolution of 2003 YN$_{107}$ and 2006 JY$_{26}$ is shown in Fig. 2. As pointed out above, 2003 YN$_{107}$ was identified as an Earth co-orbital shortly after its discovery (Brasser et al. 2004; Connors et al. 2004). Our calculations indicate that it is mainly a regular horseshoe librator not a quasi-satellite but it is currently ending a very brief quasi-satellite episode ($\sim$15 yr). The remaining objects underwent brief horseshoe episodes in the past or will do in the near future. 2010 HW$_{20}$ is not currently co-orbital but it will become one, similar to 2003 YN$_{107}$, in a few hundred years. A similar behaviour is observed for 2012 LA$_{21}$. 2008 KT will become co-orbital in about 2000 yr. 2008 UC$_{202}$ will be co-orbital in 600 yr. 2009 BD was a horseshoe librator about 400 yr ago and it will repeat in about 1400 yr. 2006 JY$_{26}$ is currently a horseshoe librator, leaving the state in about 130 yr. All these ob-
Orbital properties of the dynamically cold members of the near-Earth asteroid belt (source for $\Delta v$: http://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html).

| Designation | $a$ (au) | $e$ | $i$ (°) | $\Omega$ (°) | $\omega$ (°) | $H$ (mag) | $U$ | $\Delta v$ (km s$^{-1}$) |
|-------------|---------|-----|--------|--------------|-------------|----------|----|-----------------|
| 2009 SH$_2$ | 0.992 035 | 0.094 195 | 6.810 19 | 101.483 37 | 6.720 39 | 24.90 | 0.150 998 | 5.070 |
| 2012 FC$_{71}$ | 0.989 531 | 0.087 678 | 4.967 37 | 347.757 12 | 38.707 67 | 25.23 | 0.122 561 | 4.696 |
| 2013 BS$_{45}$ | 0.997 631 | 0.084 072 | 0.786 12 | 146.064 22 | 85.388 07 | 25.85 | 0.085 177 | 4.045 |
| 2010 HW$_{20}$ | 1.010 623 | 0.050 118 | 8.188 72 | 60.114 82 | 39.251 30 | 26.10 | 0.151 383 | 5.690 |
| 2012 LA$_{11}$ | 0.988 356 | 0.096 080 | 5.115 55 | 242.277 07 | 261.209 38 | 26.15 | 0.130 298 | 4.751 |
| 2003 YN$_{107}$ | 0.988 719 | 0.013 938 | 4.321 08 | 87.516 70 | 264.431 61 | 26.28 | 0.075 816 | 4.879 |
| 2008 KT | 1.010 578 | 0.084 823 | 1.984 36 | 102.037 34 | 240.642 59 | 28.21 | 0.091 460 | 4.425 |
| 2008 UC$_{202}$ | 1.009 357 | 0.068 715 | 7.458 96 | 91.258 36 | 37.403 81 | 28.24 | 0.147 130 | 5.479 |
| 2009 BD | 1.008 256 | 0.039 180 | 0.381 33 | 113.468 17 | 59.388 07 | 28.24 | 0.039 195 | 3.870 |
| 2006 JY$_{26}$ | 1.009 863 | 0.083 072 | 1.439 32 | 273.570 56 | 43.487 20 | 28.35 | 0.086 644 | 4.364 |
| 2006 RH$_{120}$ | 0.999 473 | 0.020 577 | 1.561 01 | 183.400 42 | 290.597 99 | 29.53 | 0.034 132 | 3.813 |

5 DISCUSSION AND CONCLUSIONS

It should be noticed that the orbits of these objects are highly chaotic, with e-folding times of 10–100 yr, but they remain as NEOs for nearly 1 Myr. Only a fraction of that time, typically < 10 000 yr, the objects stay in the region defined above in some cases they remain there for nearly 0.3 Myr. Although the current dynamical status of these objects is reliable, predictions beyond a few hundred years can only be made in statistical terms due to frequent close encounters, well below the Hill radius of 0.0098 au, with the Earth–Moon system (see Fig. 2, panel A). Objects in this group may experience repeated co-orbital and Kozai episodes and transitions are triggered by the encounters. The most usual state is symmetric horseshoe but quasi-satellite and Trojan episodes have also been observed during the simulations. Due to their low relative velocities to the Earth most of the objects studied here undergo a large number of brief episodes (1–30 d) in which their Keplerian geocentric energy becomes negative even if they are several Hill radii from the Earth. In Table 2 the value $U$ is the dimensionless encounter velocity with respect to the Earth at infinity ($U = v_i / v_E$, where $v_i$ is the relative velocity between the object and the Earth, and $v_E$ is the circular velocity of the Earth at 1 au), given by $U = \sqrt{3 - T_E}$, where $T_E$ is the Tisserand parameter related to the Earth. All the objects have very low values of $U$. 2006 RH$_{120}$ was an actual natural satellite of the Earth for over a year in 2006 (Kwiatkowski et al. 2009): it has experienced similar episodes in the past and it will probably repeat them in the future. Besides 2006 RH$_{120}$, the only other object that has been involved in temporary capture events as defined by Granvik et al. (2012) is 2009 BD but only during a few days; both objects have the lowest values of $U$. The existence of this dynamical group provides a natural source for the so-called Earth’s irregular natural satellites. Our analysis suggests that many other objects currently in the neighbourhood of the volume of the orbital parameter space described above (see Fig. 3, grey areas) may be former members of this dynamical group, like 1991 VG, or may join it in the future. It is not surprising that this dynamically cold family has not been reported earlier. Hidden in plain sight, all the proposed members in Table 2 have been discovered during the last decade. They are small or very small objects with typical maximum apparent magnitude not less than 18 and can only be observed when they get close to the Earth, every 50–80 yr (twice per horseshoe period), remaining within 0.5 au from the Earth for
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about 5–10 yr with typical minimum distances of 0.01 au. Only during these favourable windows of opportunity are these objects relatively easy to observe, easily accessible, and have risk of impact. In terms of observability, the situation is even worse for the Kozai resonators as they never get that close to the Earth (see Fig. 4) and encounters typically occur every 55 yr; if all of them are like 2012 FC71 or smaller, then the vast majority are well beyond reach of current NEO surveys and they may be very numerous.

Although the objects described here have sizes in the range 2–50 m, they are still large enough to provoke a significant amount of local destruction if they enter the atmosphere. On the positive side, these objects are also the ideal targets (see $\Delta \nu$ in Table 2, $\Delta \nu$ is the minimum total variation of speed for transferring from low-Earth orbit to rendezvous with the object, the equivalent $\Delta \nu$ to reach the Moon is 6 km s$^{-1}$) for commercial mining of minerals in outer space (e.g., Lee 2012). They can also be used to reach the far side of Earth’s orbit, the Lagrangian point L3, at basically no cost. This has multiple astronomical applications for solar-powered, fully automated observatories. These observations can enable the study of the NEO population from the inside, finding about possible impactors well before they get close enough to become a threat. In their way to L3, these objects also visit L4 and L5 where primordial material in the form of dynamically cold, very small Trojans may still be trapped. Instead of using the Moon as an extraterrestrial astronomical observatory, they represent a much cheaper and flexible alternative. Minor bodies moving in orbits with low-eccentricity, low-inclination and Earth-like period are sometimes called Arjuna asteroids (Lewis 1996; Lee 2012). Further observations are needed to expand the list of objects moving in Arjuna-type orbits.

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