Meteoritics & Planetary Science 37, 1435–1441 (2002)
Available online at http://www.uark.edu/meteor

Discovery of an asteroid and quasi-satellite in an Earth-like horseshoe orbit

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(Received 2002 April 15; accepted in revised form 2002 July 16)

Abstract–The newly discovered asteroid 2002 AA_{29} moves in a very Earth-like orbit that relative to Earth has a unique horseshoe shape and allows transitions to a quasi-satellite state. This is the first body known to be in a simple heliocentric horseshoe orbit, moving along its parent planet's orbit. It is similarly also the first true co-orbital object of Earth, since other asteroids in 1:1 resonance with Earth have orbits very dissimilar from that of our planet. When a quasi-satellite, it remains within 0.2 AU of the Earth for several decades. 2002 AA_{29} is the first asteroid known to exhibit this behavior. 2002 AA_{29} introduces an important new class of objects offering potential targets for space missions and clues to asteroid orbit transfer evolution.

CO-ORBITAL MOTION

If a small body has a semimajor axis almost exactly the same as that of a planet, and thus almost the same period, the 1:1 mean-motion resonance allows the planet's gravity to play a large role in its motion. The classic coplanar gravitational three-body problem (see, for example, Murray and Dermott, 1999) shows that regions of stability in such motion exist near "Lagrange" points along the planet's orbit, one (L4) preceding it and another (L5) trailing it by 60°, as shown in Fig. 1. "Co-orbital" motion associated with these points is essentially along the parent body's orbit. The motion of a resonant asteroid can be visualized as being in an effective potential well (Namouni, 1999; Namouni *et al.*, 1999). The highest walls of this well are located near the planet itself, with a secondary peak at superior conjunction on the opposite side of the Sun. A body unable to climb that peak is confined to one side of the Sun on a "tadpole" orbit. One able to surmount the secondary peak moves on a "horseshoe", bouncing off the walls of the potential well at either end of its orbit as it approaches the planet. All 1:1 resonant asteroids known before 1997 were "Trojans", remaining near either the L4 or L5 point on tadpole orbits. The first was discovered in 1906, validating J-L. Lagrange's theory formulated 134 years earlier. Over 1200 Trojans are known associated with Jupiter, and six with Mars.

The possibility of horseshoe orbits had been proposed by Brown (1911), shortly after the discovery of the Trojans. Many

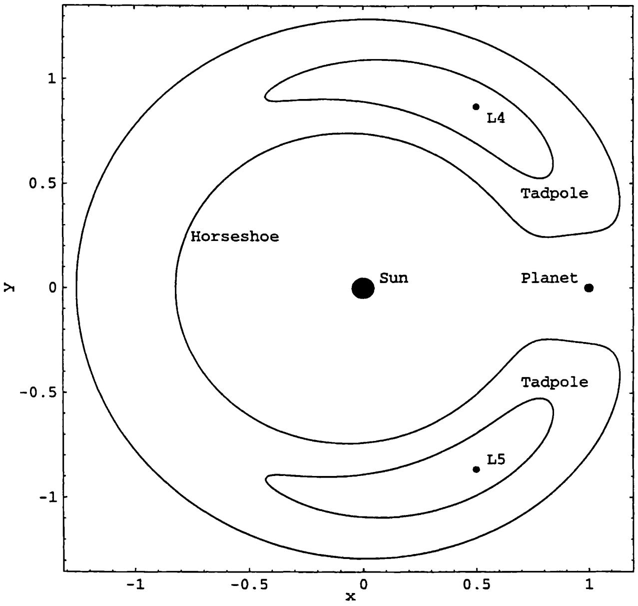

FIG. 1. Some examples of zero-velocity curves associated with tadpole and horseshoe orbits, as viewed in a reference frame that co-rotates with the planet. The respective names are obtained from the characteristic shapes. The L4 and L5 points are each encircled by a "tadpole" or Trojan-like curve. Both the L4 and L5 points are encompassed by a "horseshoe" curve. The width of the orbital regions in the radial direction has been greatly exaggerated for clarity.

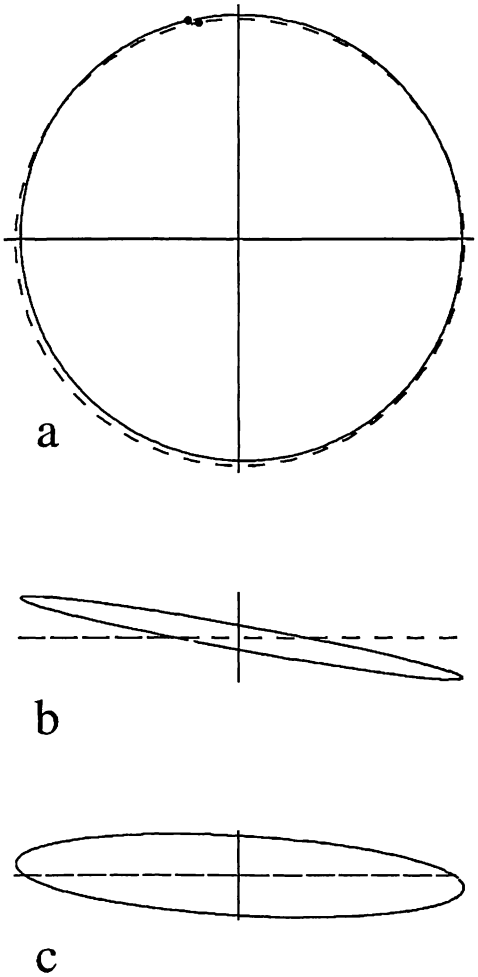

FIG. 2. (a) Orbits of Earth (dashed) and 2002 AA$_{29}$ (solid) in the year 2002 in a fixed frame as seen from the north ecliptic pole. The vernal equinox is to the right. Scale bars are 2.1 AU long. Positions of Earth and 2002 AA$_{29}$ on 2002 January 1 are marked on the respective orbits. (b) Orbits as seen from the direction of the winter solstice (bottom in frame (a)). Scale bar is 0.4 AU long. (c) Orbits as seen from the vernal equinox. Scale as in (b).

studies have shown such orbits to be stable over finite periods of time (Rabe, 1961; Weissman and Wetherill, 1974; Tabachnik and Evans, 2000; Evans and Tabachnik, 2000) for several planets including Earth (Hollabaugh and Everhart, 1973; Mikkola and Innanen, 1990). However, no co-orbital bodies on horseshoe orbits centered on the Sun have previously been found. The only co-orbital horseshoe orbits hitherto known are in the saturnian satellite system (Dermott and Murray, 1981). One heliocentric horseshoe orbit, the intricate interplay of of 3753 Cruithne with Earth, has been described in detail by Wiegert and co-workers (1997). Due to its high eccentricity (e = 0.515), this orbit does not greatly resemble Earth's and Wiegert *et al.* (1998) stressed that it is inappropriate to call it co-orbital. That term (or its variant spelling coorbital) should be reserved for "material that shares the same orbit with a larger perturber", as noted by Murray and Dermott (1999), and as it has consistently been used historically in describing Trojan asteroids and the co-orbital moons of Saturn. Morais and Morbidelli (2002) suggest reserving the term co-orbital only for bodies not deviating from the mean distance by significantly more than the width of the resonant region.

ASTEROID 2002 AA$_{29}$

Our investigation of the asteroid 2002 AA$_{29}$ shows that this body is co-orbital with Earth in the senses described above, due to its Earth-like orbit. We show the similarity of its orbit to Earth's in Fig. 2, where the major difference is seen to be its inclination of 10.7°. In the corotating frame it is moving in a near-classic horseshoe orbit as shown in Fig. 3. In this frame the asteroid librates relative to Earth and follows Earth's orbit except for a small gap near the Earth, making it evident why the term "horseshoe" describes this orbit. The ability to approach Earth near the end of a horseshoe allowed 2002 AA$_{29}$ to become bright enough to be discovered. It was detected on 2002 January 9 at magnitude 19.8 (Minor Planet Center, 2002a) in an automated all-sky search by the LINEAR (LIncoln Near-Earth Asteroid Research) survey described by Stokes *et al.* (2000). At discovery it was 113° from the Sun in the morning sky, near its maximum elongation, which contributed to its brightness at discovery. It is a small object, estimated from its H magnitude of 24 to be <100 m in diameter. On its present visit to the end of its horseshoe, 2002 AA$_{29}$ will not come to opposition, but remain circling in the morning sky in an apparent spiraling path unique among known objects, as shown in Fig. 4. Searches for asteroids near L4, L5, or on horseshoe orbits must be conducted at small elongations, posing observational challenges (Evans and Tabachnik, 2000; Wiegert *et al.*, 2000). To date, co-orbital asteroid searches (Dunbar and Helin, 1983), including recent ones with modern equipment and tracking techniques adapted to take advantage of the expected angular motion of posited Trojans (Whitely and Tholen, 1998; Connors *et al.*, 2000), have not found any bodies near L4 or L5. Extrapolations of the negative results (Tabachnik and Evans, 2000; Dunbar and Helin, 1983) suggest that roughly 100 objects of 100 m or more diameter could exist near each Lagrange point. Finding the first Earth co-orbital object, 2002 AA$_{29}$, provides incentive to search for other horseshoe orbiting objects or Earth Trojans. While deep searches are likely still best conducted near the Lagrange points, wider searches at larger elongations may be fruitful in finding other horseshoe-orbiting bodies.

THE HELIOCENTRIC HORSEHOE ORBIT

We recognized from the initial orbit solution (Minor Planet Center, 2002a), based on a 6 day arc, that 2002 AA$_{29}$ was in an Earth-like horseshoe orbit. We confirmed this by subsequent observations at the Canada–France–Hawaii telescope (CFHT)

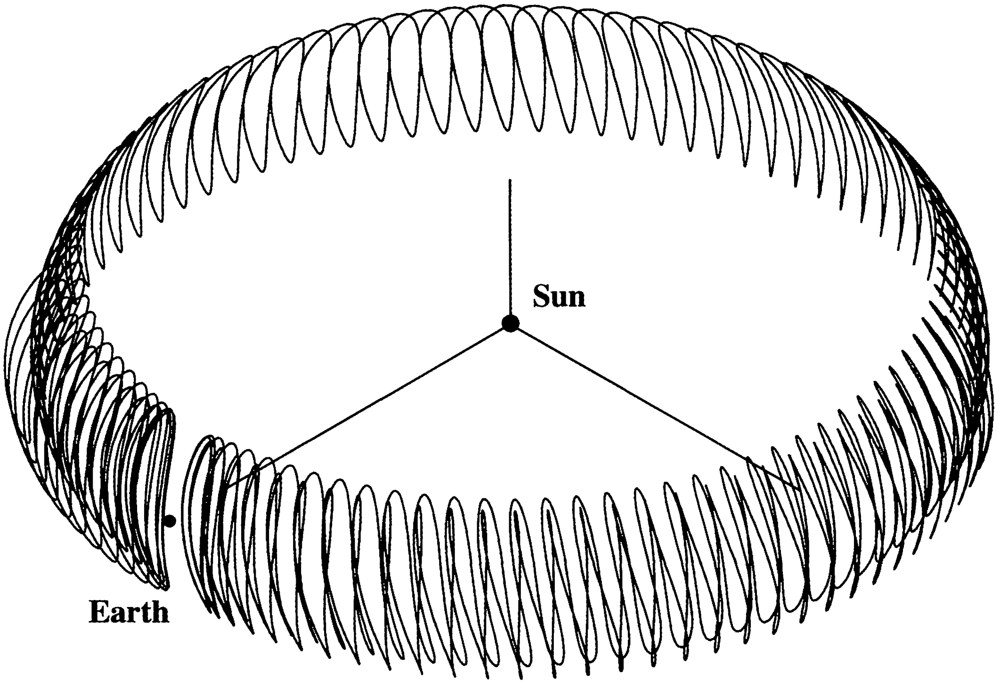

FIG. 3. Oblique view of 2002 AA_{29}'s orbit with respect to Earth. Due to the inclination of the orbit, north–south motions of period 1 year are a prominent feature. The trace starts on the left on 1970 January 1 and proceeds through a blue segment to the close approach to Earth on 2003 January 8. The asteroid moving initially away from Earth is shown in a red segment through 2097 July 13, and then by blue upon reversing direction, until 2109 July 21. The prograde (red) part of the relative path is at a smaller average distance from the Sun than the retrograde (blue) part. The orbit is radially very thin, and for clarity scale has been increased by a factor of 3 in the vicinity of the orbit.

extending the arc to 28 days, as reported in an orbit update (Minor Planet Center, 2002b). Figure 5 shows a post-discovery image of 2002 AA_{29} taken with optimized tracking (Whitely and Tholen, 1998) as is used in motion-targeted Lagrange-point surveys. Figure 3 illustrates 2002 AA_{29} closely following Earth's orbit as it librates over more than 350° of relative orbital longitude between the leading and trailing sides of the Earth. Among asteroids, the orbit of 2002 AA_{29} is the most strikingly Earth-like, since it is very nearly at the same distance from the Sun and also very circular. Its eccentricity at discovery was 0.0120, compared to the mean orbital eccentricity for Earth of 0.0167. By contrast, most near-Earth asteroids have rather eccentric orbits. For example, the 20 other asteroids with semimajor axes closest to Earth's have an average eccentricity of 0.29. Although the asteroid's orbit is very Earth-like, it differs in the important aspect that its inclination is 10.7°. This means that it can be observed at high ecliptic latitudes when near Earth, and also results in the significant north–south motions relative to Earth evident in Figs. 2b–c, 3 and 4. The object will reach its minimum close approach distance of 0.039 AU on the leading side of the Earth on 2003 January 8.8, and begin its libration toward the trailing side, arriving there after 95 years. Variations on the planar three-body problem can explain even inclined orbits, and early computational work by Hollabaugh and Everhart (1973) showed possible orbits remarkably similar to that of 2002 AA_{29}. The basic motion may be understood by examining the semimajor axis of the orbit plotted in Fig. 6, where its periodic changes clearly show the libration period of 190 years. When 2002 AA_{29} approaches Earth on the leading side it does so because its larger semimajor axis, according to Kepler's third law, gives it a mean motion slightly slower than that of the Earth, which therefore catches up. Then, the attraction of Earth's gravity backwards along the orbit removes energy from the asteroid, causing its semimajor axis to decrease and the mean motion to increase, so that it pulls away from Earth. When it finally arrives at the trailing side, the opposite takes place. This delicate balance causes a long-term "to and fro" motion along Earth's orbit. The simple considerations described also form a "dynamical protection" mechanism preventing impact despite the extremely Earth-like orbit of this asteroid.

QUASI-SATELLITE BEHAVIOR AND STABILITY

Stability studies over multiple libration cycles show a remarkable new property: at times 2002 AA_{29} has been, and will become again, a "quasi-satellite" of the Earth, exhibiting a behavior described by Mikkola and Innanen (1997). Three periods as a quasi-satellite are evident in Fig. 6, near 550, 2600 and 3880 A.D. At these times the regular pattern of change in

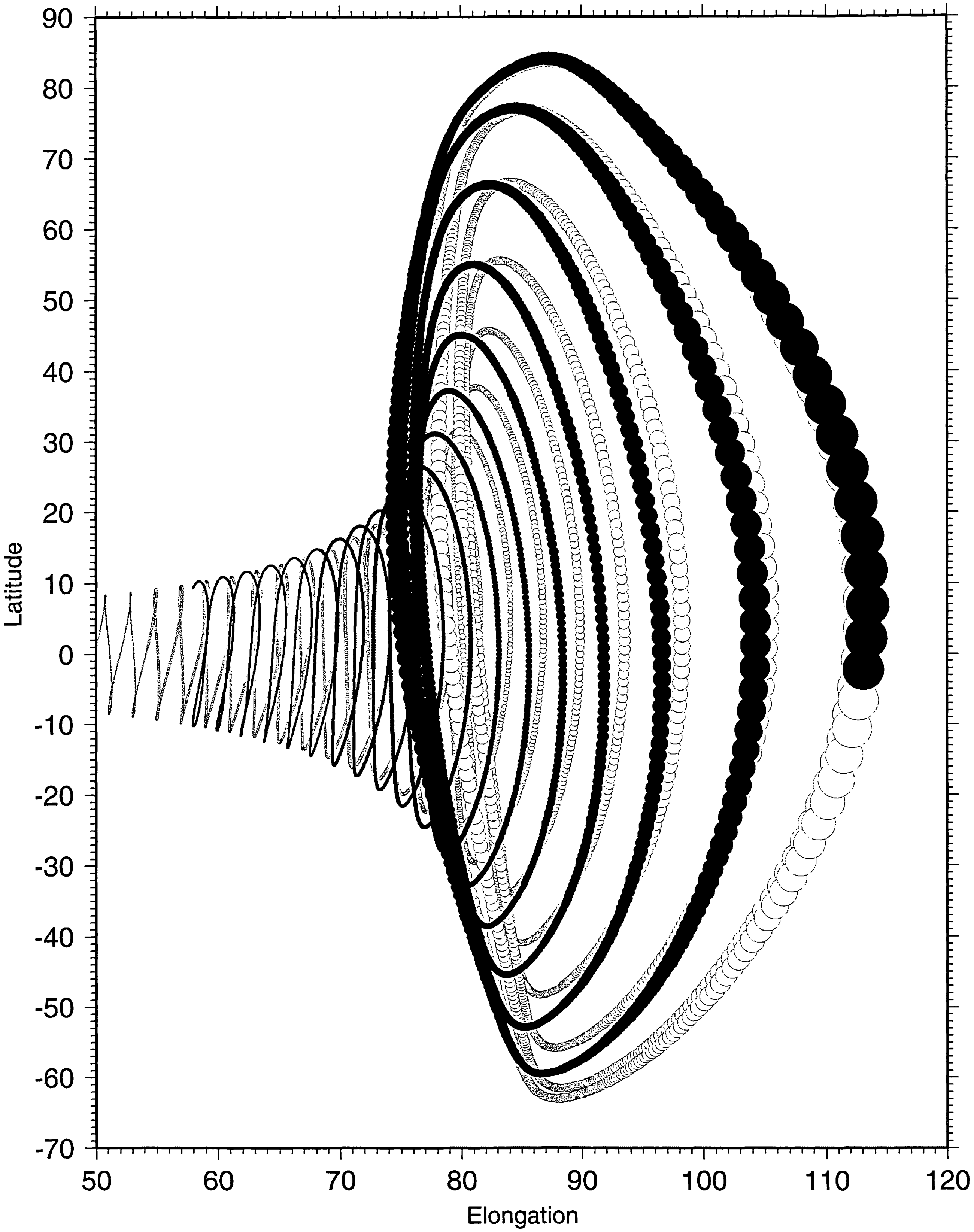

FIG. 4. Apparent orbit of 2002 AA_{29} as viewed from Earth in the morning sky. Ecliptic latitude is plotted *vs.* elongation (from the Sun). Motion when approaching Earth is shown in white and motion when receding is shown in black. The period of north–south apparent motion is very close to 1 year. The interval shown is from 1980 to 2020 and the ephemeris was calculated with the JPL Horizons online system.

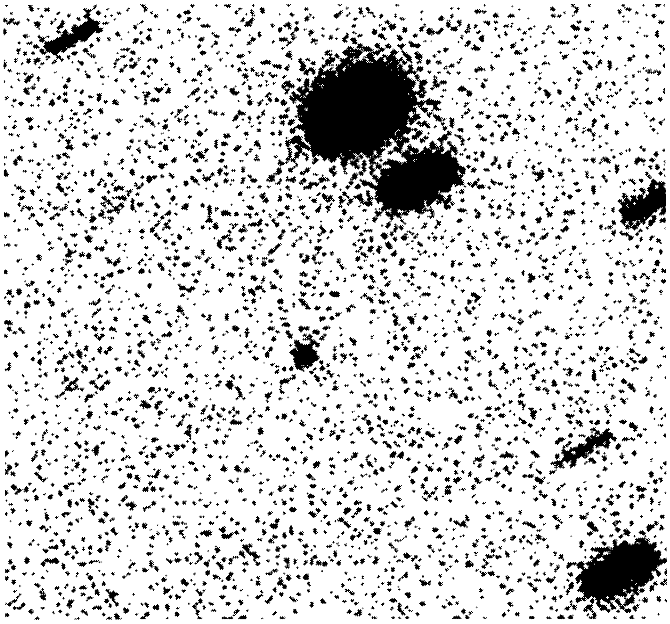

FIG. 5. Image of 2002 AA_{29} exposed 2002 February 6 at the Canada–France–Hawaii telescope. Optimized tracking has been used so that the asteroid appears as a point while star images are trailed.

semimajor axis breaks down, replaced by irregular change of smaller amplitude. While in this quasi-satellite state, the asteroid remains in the neighborhood of the Earth, but its orbit is still dominated by the gravity of the Sun. As both Earth and asteroid orbit the Sun, the relative looping motion of the asteroid in some ways resembles a satellite orbit, with an apparent period of 1 year. This additional complexity, beyond that of the classical horseshoe/tadpole picture, occurs because the large inclination of 2002 AA_{29} adds an extra degree of freedom to the system. The motion can still be understood as that of a particle in an averaged effective potential (Christou, 2000). This potential is sensitive to the location of the particle's nodes, the points at which it crosses the orbital plane of the planet. In the case of 2002 AA_{29}, the movement of its nodes (due largely to the gravitational influences of the planets) allows a "door" on one side of the Earth to open on occasion and let it slip in. It cannot immediately escape because the movement of its nodes changes once it is in the potential well, rapidly shutting the door behind it, to open again only at a later time. Quasi-satellite behavior is a current feature of the orbit although 2002 AA_{29} is not now a quasi-satellite. It was one last in 572 A.D., and will again become one in the year 2575. The quasi-orbital intervals last ~50 years. The effective potential barrier prevents impact now and during quasi-orbital periods. Our calculations indicate that for the next several thousand years, whether in quasi-satellite mode or not, 2002 AA_{29} does not pose any impact danger. Its distance remains beyond 0.03 AU (4.5×10^6 km or ~12× the Moon's distance). Orbital simulations become chaotic after that time, whereupon impact cannot be ruled out.

To check the robustness of our results, we computed a large set of orbits varying from the nominal solution but still consistent with the observations. For all orbits within two standard deviations of the presently best-known orbit (Minor Planet Center, 2002b), similar quasi-satellite behavior arose. The basic horseshoe character of the orbit is an even more robust result. Computations were done with both a classical Adams multistep (Krogh, 1974) and modern symplectic integrators (Mikkola and Palmer, 2001; Wisdom *et al.*, 1996) fully incorporating the effects of Earth's moon and the planets. The variable order Adams method used NASA Jet Propulsion Laboratory (JPL) planetary ephemeris DE406 to obtain the positions of the perturbing bodies, and included perturbations by the three largest asteroids (Ceres, Pallas, Vesta) as well as by Earth's moon. The symplectic method was an alternating stepsize Wisdom–Holman integrator with modified kick. This has an error of order $O(\epsilon^6) + O(\epsilon^4)$, where ϵ is the order of magnitude of perturbation to the approximating Kepler orbits. To include the Moon we used what may be called the Tycho-method (due to similarity to Tycho Brahe's solar system model): we arrange the Jacobian coordinate system such that the bodies are indexed in the order: Earth–Moon–Sun–Mercury–Venus–2002 AA_{29}–Mars–Jupiter, and so on. All the major planets were taken into account. This method allows inclusion of the Moon, without code modification, but does not provide special advantage for the integration of the asteroid motion. Thus, to ensure accuracy, we used the very short stepsize of only 0.1 days. Over 300 trajectories were computed using this method. We estimated, using the results of Spitale and Greenberg (2001), that the most pronounced possible effects from the Yarkovsky mechanism would result in 1000 km of negative change in semimajor axis over a libration cycle, whereas the two standard deviation change within which the described behavior occurred represented up to 6000 km of change. This suggests that the general Yarkovsky effect does not significantly change the motions described, over the period before the motion becomes chaotic.

DISCUSSION

The interesting dynamics and relevance to space resource and hazard studies (Valsecchi and Perozzi, 1998), and the clues it may hold about asteroid orbit transfer mechanisms and stability of the inner solar system make 2002 AA_{29} an object worthy of further study. It is also essential to determine whether it is unique, the first of an important new class, or related to other near-Earth objects, possibly those pointed out by Rabinowitz (1994) to be in near-Earth but currently non-resonant orbits of low eccentricity. As evolutionary schemes for near-Earth asteroid orbits, including co-orbitals, develop (Morais and Morbidelli, 2002), further "data points" are needed to validate the theoretical understanding. The existence of Earth co-orbital objects is now demonstrated and we have described observational techniques effective in searching for them. It is

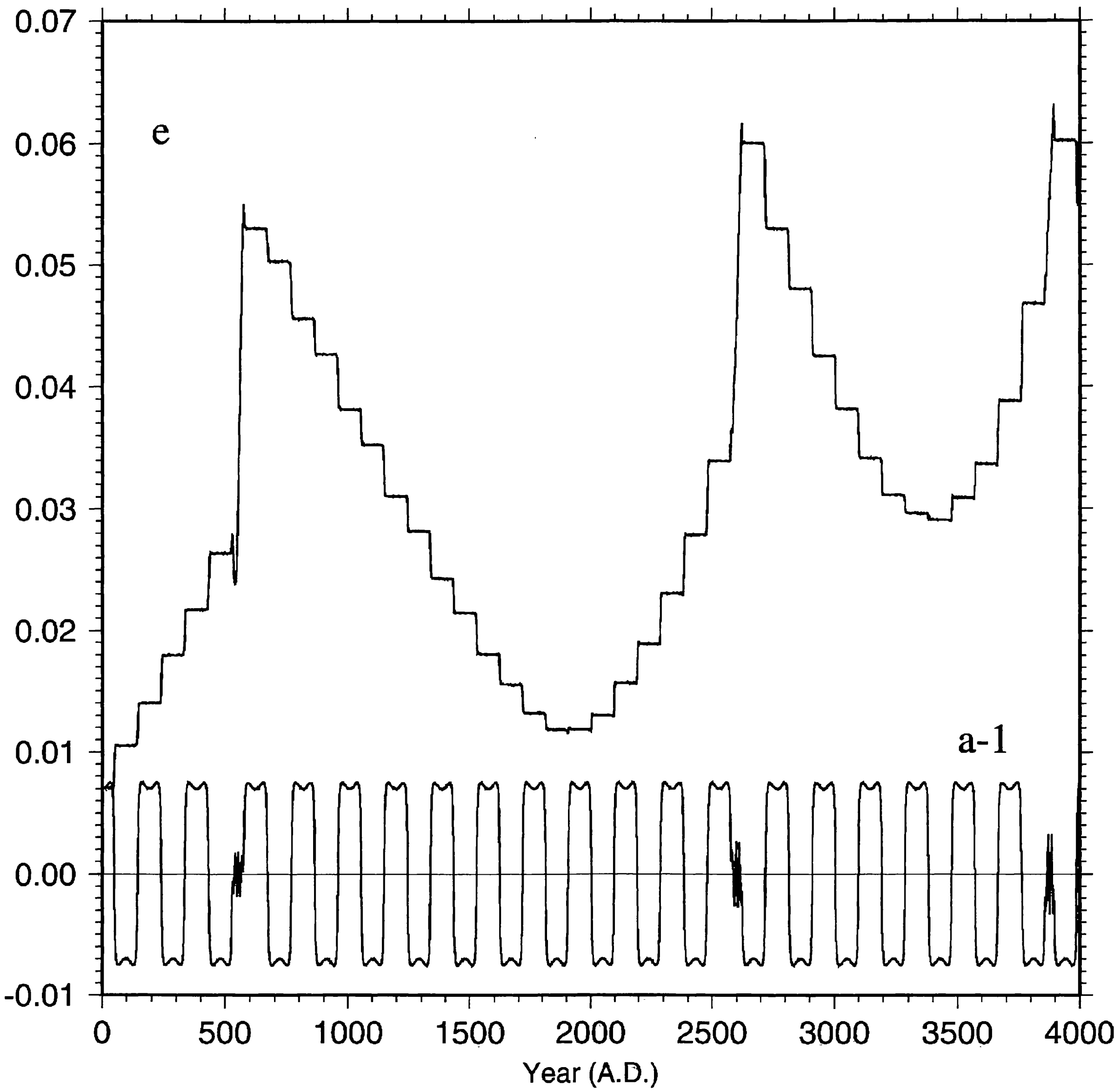

FIG. 6. The evolution of the semimajor axis *a* and eccentricity *e* of the asteroid 2002 AA_{29}. For clarity 1 has been subtracted from *a*. The horseshoe-orbital behavior is recognizable in the behavior of *a*, with the asteroid falling to small *a*, moving ahead of Earth in the orbit, then being perturbed and moving to large *a* and falling behind. This is broken occasionally (near 550, 2600 and 3880 A.D.) by transition to quasi-satellite behavior, with lesser variations in *a*. In these events the asteroid moves next to the Earth for several decades, and the eccentricity changes rapidly. The satellite may leave this state moving in the same (last case) or opposite direction (other cases) from that in which it entered.

hoped that this discovery will stimulate further observational and theoretical work on Earth co-orbitals.

Acknowledgements–This work was supported in part by the Natural Sciences and Engineering Research Council of Canada. Part of this research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. The Canada–France–Hawaii telescope is operated by the National Research Council of Canada, le Centre National de la Recherche Scientifique de France, and the University of Hawaii. M. C. acknowledges the hospitality of the University of California, Los Angeles, during preparation of this article.

Editorial handling: A. Cochran

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