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Discovery of Earth's quasi-satellite

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Abstract–The newly discovered asteroid 2003 YN_{107} is currently a quasi-satellite of the Earth, making a satellite-like orbit of high inclination with apparent period of one year. The term quasi-satellite is used since these large orbits are not completely closed, but rather perturbed portions of the asteroid's orbit around the Sun. Due to its extremely Earth-like orbit, this asteroid is influenced by Earth's gravity to remain within 0.1 AU of the Earth for approximately 10 years (1997 to 2006). Prior to this, it had been on a horseshoe orbit closely following Earth's orbit for several hundred years. It will re-enter such an orbit, and make one final libration of 123 years, after which it will have a close interaction with the Earth and transition to a circulating orbit. Chaotic effects limit our ability to determine the origin or fate of this object.

INTRODUCTION

The asteroid 2003 YN_{107} is the first object known to currently be a quasi-satellite of the Earth. Due to its extremely Earth-like orbit, it is now influenced by Earth's gravity to stay near our planet. The motion near Earth is similar to that of a satellite of high inclination with period of one year (Fig. 1). The term quasi-satellite (Mikkola and Innanen 1997) is used since the geocentric orbit of 2003 YN_{107} is not closed, and is more correctly regarded as being part of the asteroid's orbit around the Sun, heavily perturbed by Earth's gravity. The possibility of similar orbits appears to have been suggested early in the twentieth century (Jackson 1914) as a limiting case for retrograde satellites. The quasi-satellite state is a temporary part of a three-body interaction which also features horseshoe co-orbital motion, with the asteroid closely following Earth's orbit around the Sun (Fig. 2). For several hundred years, before the present encounter with Earth, 2003 YN_{107} slowly librated along Earth's orbit and reversed its course as seen from Earth with each approach to the planet. This formed a heliocentric horseshoe orbit with Earth in the gap of the horseshoe. Only one other body, asteroid 2002 AA_{29} (Connors et al. 2002; Ostro et al. 2003), is known to have a horseshoe orbit extremely similar to Earth's, while two others are known horseshoe librators (Margot and Nicholson 2003; Wiegert et al. 2002) with more eccentric orbits.

The classic theory of three-body motion describes the motion of a planet about the Sun with the possibility of companions in the same orbit. Such motion had, until recently, been known to take only the form of librations around the triangular Lagrange points, spaced 60º from the planet along its orbit. Such "Trojan" asteroids (Murray and Dermott 1999) are well known for Jupiter and have also been observed for Mars, and more recently, for Neptune (Chiang 2003). More complex behavior is possible in the form of horseshoe orbits along the parent orbit, which have been described in most detail for asteroid 2002 AA_{29} (Connors et al. 2002). Yet more complex situations such as that of 3753 Cruithne (Wiegert et al. 1997) also occur. Horseshoe orbits can be described by classic three-body theory at least in the planar case, while Cruithne's orbit is a complex interaction in three dimensions. It is now known to further be possible for the companion to remain near the parent planet over a relatively long period of time in the quasi-satellite state (Mikkola and Innanen 1997). Co-orbital interaction should dominate a small third body's motion, according to expansions under Hill's theory (Namouni 1999), if the guiding center (long term average position) of that body lies in an annulus of semimajor axis a within a distance ε of that of the secondary (planet). Here, $\varepsilon = \left(\frac{m}{3M}\right)^{1/3}$ for an essentially massless asteroid, m and M being the masses of planet and Sun, respectively. For the Earth-Sun system, ε = 0.01, accurate to five decimal places. Thus, co-orbital behavior could be expected for the few asteroids having $-0.01 < a-1 < 0.01$ in units of AU. All other asteroids described above satisfy this condition. The limit of a libration of 2003 YN_{107} slightly exceeds this range as described below. This paper focuses on libration in a, which allows many aspects of horseshoe and quasi-satellite motion to be understood: a more complete description of dynamics for several known objects including 2003 YN_{107} is given by Brasser et al. (2004).

OBSERVATIONS AND ORBITAL BEHAVIOR

The Lincoln Near-Earth Asteroid Research Project (LINEAR) (Stokes et al. 2000) discovered 2003 YN_{107} on December 20, 2003 at magnitude 18.8 (Smalley 2003) and elongation of approximately 105° from the Sun. On December 21, 2003, it passed 0.0149 AU from the Earth (less than 6 lunar distances) with the relatively low velocity of 2.35 km/s. Its absolute magnitude H = 26.7 implies a diameter of about 20 m (if albedo = 0.1; Morbidelli et al. 2002). Our numerical simulations indicate that it has remained within 0.1 AU of Earth since 1997 and will remain within this distance until 2006 (Fig. 1, Fig. 2a). The current (MJD 53000) osculating orbital elements have semimajor axis a = 0.99723 AU, eccentricity e = 0.02352, and inclination i = 4.38º. This orbit is slightly more eccentric than that of 2002 AA_{29} (Connors et al. 2002), hitherto, the most Earth-like orbit known. The low inclination of 2003 YN_{107} compared to the nearly 11º of 2002 AA_{29} makes its orbit now the most Earth-like known. Despite this, the inclination is high enough that an artificial origin can be excluded. The low flyby velocity suggests a correspondingly lower velocity change needed to reach it with a spacecraft than is the case for many asteroids. The asteroid was trapped into the quasi-satellite state after approaching the Earth from behind (evening sky) and will leave the quasi-satellite state advancing in this same direction into the morning sky (Fig. 2a). We note that it is not necessary that an asteroid leave the quasi-satellite state traveling in the same direction it entered. The previous and upcoming quasi-satellite states of 2002 AA_{29} end with reversal of relative motion of the asteroid (Connors et al. 2002). The horseshoe orbit 2003 YN_{107} will enter will lead to a close encounter from behind in 2066, with the object reversing its path. The following encounter in the morning sky will terminate this horseshoe, but the subsequent motion cannot be predicted with confidence. We find that, in the past, the object has been in stable horseshoe orbit for several hundred years, without quasi-satellite states. Most of the previous visits (Fig. 2b) exhibited classical horseshoe reversals of relative motion, without entry into a quasi-satellite state.

Our initial conclusions about the orbit started from orbital parameters from the Minor Planet Center, with orbits integrated backward and forward 300 years using the Mercury symplectic integrator (Chambers 1999) and also from 1600 C. E. to 2200 C. E. with the Horizons online system at the Jet Propulsion Laboratory (Giorgini 1996). The object's inclination and photometric properties suggest a natural object. Similar considerations to those discussed for 2002 AA_{29} by Connors et al. (2002) suggest that, despite the small size, non-gravitational forces would be negligible over the period studied. During most of this period, the use of the Earth-Moon barycentre is a good approximation, along with the gravity of the eight other planets. The Horizons system, however, uses Earth and Moon as separate perturbers and includes the three largest asteroids. Numerous follow-up integrations were done with various integrators and all agreed on the near-term orbit. The quasi-satellite aspect was further verified with 300 dynamical clones with varied orbital parameters within the error range of the observed object, which all exhibited the behavior. Other clone studies can be used to determine the useful time range of integrations before chaotic effects make them meaningless (Brasser et al. 2004). At present, it is difficult to claim that behavior on longer timescales than discussed here can be accurately computed.

The orbit of 2003 YN_{107} is strikingly like Earth's. It is much less eccentric than orbits of most asteroids and is typical of a planet (such as Earth, which has e = 0.0167). The most obvious difference between this asteroid's and the Earth's orbits is the asteroid's inclination i = 4.38º, which changes little during the encounter. The most obvious effect of the encounter is on the eccentricity of the orbit: prior to the encounter the inward and outward excursions of the asteroid were greater than afterwards. Other, more subtle changes also occur, most importantly involving the line of nodes (Brasser et al. 2004). Details of orbital parameters are shown in Fig. 3: a alternates between slightly smaller and slightly larger values than the canonical limits of $|a-1| < \varepsilon$ (i.e. $|a-1| < 0.01$). Such alternation is typical of horseshoe orbits and co-orbital libration, in general. We may interpret being near the a limits as indicating a marginally stable co-orbital configuration: 2002 AA_{29} is stable over at least 4000 years (Connors et al. 2002), while 2003 YN_{107} may be stable only for a few hundred years. The orbital eccentricity e decreases from nearly 0.05 to under 0.02 due to the present encounter. The larger e orbit appeared more stable but the limits of reliable prediction are near the limits of this graph, so no firm conclusion can be drawn. The quasi-satellite phase shows a briefly exceeding 1, and there are indications of brief quasi-satellite behavior also near the start of steady horseshoe libration about 1690.

DISCUSSION

Discovery of an Earth quasi-satellite and the second object with an extremely similar orbit to that of Earth is interesting for several reasons. The dynamics of the

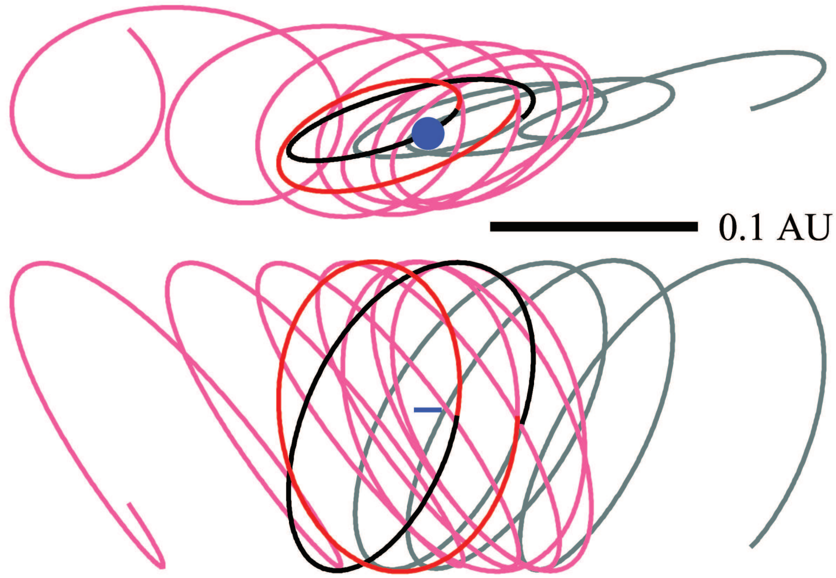

Fig. 1. The motion of 2003 YN_{107} from 1995 (pink endpoint) to 2007 (grey endpoint) shows quasi-satellite loops as viewed from above Earth (top) and from a point outside Earth's orbit looking past Earth in toward the Sun (bottom), in a frame revolving with Earth. The period December 27, 2002 to December 27, 2003 is shown in red, then to December 27, 2004 in black, to highlight the nearly closed, high-inclination "orbits" of a one-year period. Although the loops nearly close at the end of this two-year period, individual loops are not closed. Earth (not to scale) is indicated by a blue dot.

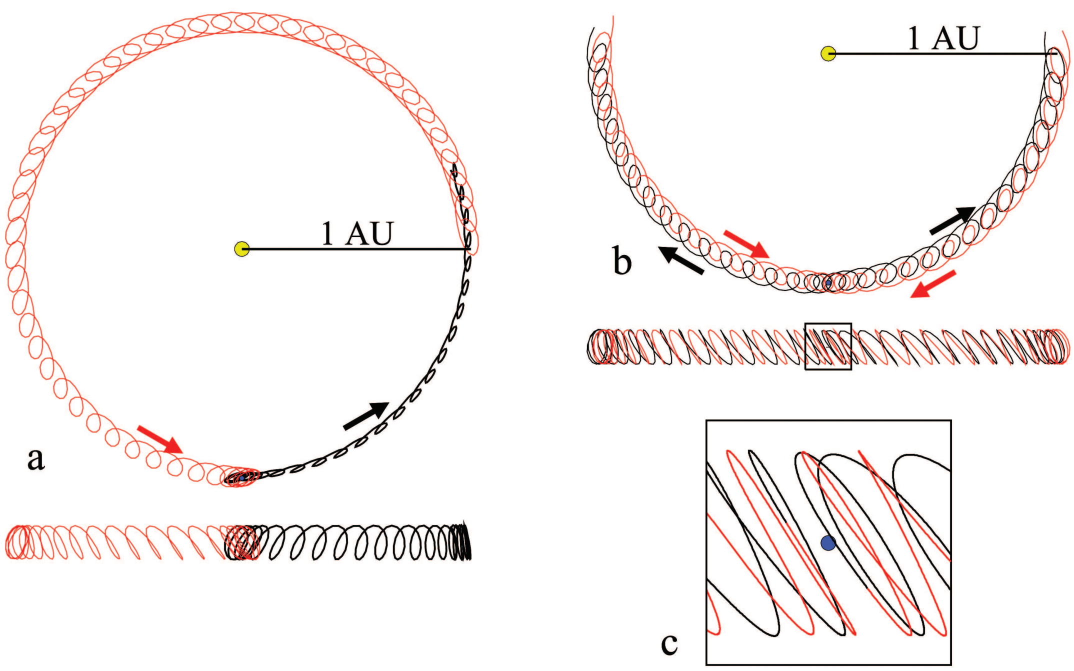

Fig. 2. a) 130 years of relative motion of 2003 YN_{107}, including current encounter with Earth, same views as in Fig. 1. The red portion shows the approach along the horseshoe orbit from 1953 to late 2003. Each loop takes one year and radial motion (best viewed in the top view) is mainly due to eccentricity. Vertical motion (best seen in the side view at bottom of the figure) reflects inclination. Complex overlapping loops during the period of quasi-satellite motion (bottom) were shown enlarged in Fig. 1. During all parts of the horseshoe phase, the asteroid has smaller a than does Earth, thus advances (counterclockwise); e decreases during the encounter, resulting in smaller radial excursions afterwards (black; shown until 2026); i changes little, so that the height of the loops remains nearly constant; b) earlier horseshoe motion with reversals in 1937 (right) and 1875 (left). In 1937 a was initially (red trace) greater than that of Earth, resulting in Earth catching up and perturbing the object to smaller a (black trace) and higher relative speed (black arrow). The situation was reversed in 1885 (left), where again red indicates pre- and black post-encounter; c) enlargement of the interaction region (box) of panel (b) to show the separation of the legs of the horseshoe, with Earth (blue, not to scale) in the gap.

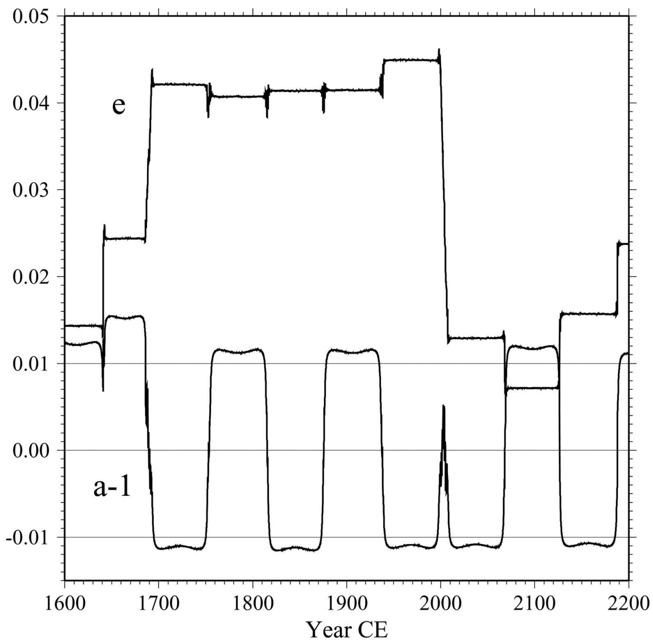

Fig. 3. Orbital elements from 1600 until 2200. The unit offset semimajor axis *a*–1 is shown by the lower (except briefly near 2100) line. The horizontal line at zero ordinate indicates $a = 1$, the semimajor axis of Earth's orbit, while the lines at ordinate of –0.01 and 0.01 indicate the nominal limits for co-orbital motion. Shortly after 2000, the quasi-satellite phase involves a short excursion of *a* above 1. Having $a < 1$ before and after this, the object moves faster than Earth around the Sun, explaining its catching up and then leaving moving forward in the frame relative to Earth. Eccentricity *e* (top line) decreases from nearly 0.05 to less than 0.02 after the present encounter.

interaction with Earth are intrinsically interesting and have implications for astrodynamics (Valsecchi and Perozzi 1998). The origin of such objects is unclear, but, likely, they are temporary objects (Christou 2000; Morais and Morbidelli 2002). 2002 AA_{29} and 2003 YN_{107} move on extremely Earth-like orbits and have been found within two years of each other; 2000 PH_5 and 2001 GO_2 are known to be Earth co-orbitals with higher eccentricity, yet rather Earth-like orbits (Margot and Nicholson 2003; Wiegert et al. 2002); and 3753 Cruithne (Wiegert et al. 1997), and, possibly, other objects are in complex 1:1 resonance with Earth. Bottke et al. (1996) have suggested that low-eccentricity objects could be impact ejecta from the Earth-Moon system; recent radar results (Ostro et al. 2003) suggesting that 2002 AA_{29} is of comparatively high albedo may support this origin. As more objects are discovered, statistical trends may become apparent to help understand the origin of co-orbital objects and likely be relevant to the larger question of origin of near-Earth asteroids, in general. We note that, after initial submission of this paper, asteroid 2004 GU_9 was discovered and is a second current quasi-satellite, more stable than 2003 YN_{107} in this state, despite higher eccentricity and inclination. Some Earth co-orbital asteroids with low relative velocity could be good targets for sample recovery missions and, ultimately, for the exploitation of space resources.

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