HORSESHOE ASTEROIDS AND QUASI-SATELLITES IN EARTH-LIKE ORBITS. M. Connors[1], C. Veillet[2], R. Brasser[3], P. Wiegert[4] , P. W. Chodas[5], S. Mikkola[6] and K. Innanen[3], [1]Athabasca University (Athabasca AB, Canada T9S 3A3; martinc@athabascau.ca), [2]Canada-France-Hawaii Telescope (P.O. Box 1597, Kamuela, HI 96743; veillet@cfht.hawaii.edu), [3]York University (Dept. of Physics and Astronomy, Toronto, ON M3J 1P3 Canada; brasser_astro@yahoo.com & kiminn@yorku.ca), [4]University of Western Ontario (Dept. of Physics and Astronomy, London, ON N6A 3K7, Canada; pwiegert@uwo.ca), [5]Jet Propulsion Laboratory (California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109; paul.chodas@jpl.nasa.gov), [6]Turku Univ. Observatory (Tuorla, FIN-21500 Piikkiö, Finland; mikkola@oj287.astro.utu.fi)

Introduction: Newly found asteroid 2003 YN107 is the first and only known current quasi-satellite (QS) of the Earth. Asteroid 2002 AA29 [1] is in a horseshoe orbit (HS) but has periods of QS behavior. Both asteroids closely follow Earth's orbit. 2002 AA29 has inclination *i*~11º while for 2003 YN107 *i*<5º, making the most Earth-like orbit known. 2003 YN107, 2002 AA29, and other Earth-resonant objects in less Earth-like orbits, form an important new class of co-orbital bodies with interesting dynamics and are the best targets for sample return missions to asteroids.

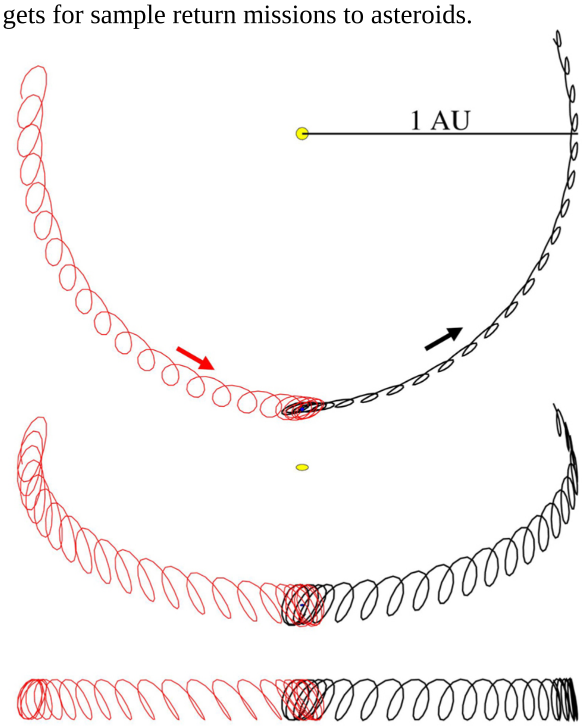

Figure 1. Partial orbit (1981-2026) of 2003 YN107 centered on the current QS episode, in the frame corotating with Earth (blue dot at bottom). Close loops near Earth are the QS and the eccentricity *e* declines as the asteroid moves left to right (pre-encounter is red) through this QS stage. Top view looking down onto ecliptic plane, middle view from 30º elevation, bottom view in toward Sun (at center but not to scale).

Quasi-satellite behavior: 2003 YN107 has an extremely Earth-like orbit (in Fig. 1 the heliocentric orbit very closely follows Earth's). It remains within 0.1 AU of Earth for approximately 10 years (1996-2006), making satellite-like loops of high inclination and apparent period of one year (Fig. 2). During QS the "orbits" around Earth are not completely closed, and more correctly are parts of the asteroid's orbit around the Sun, heavily perturbed by Earth's gravity.

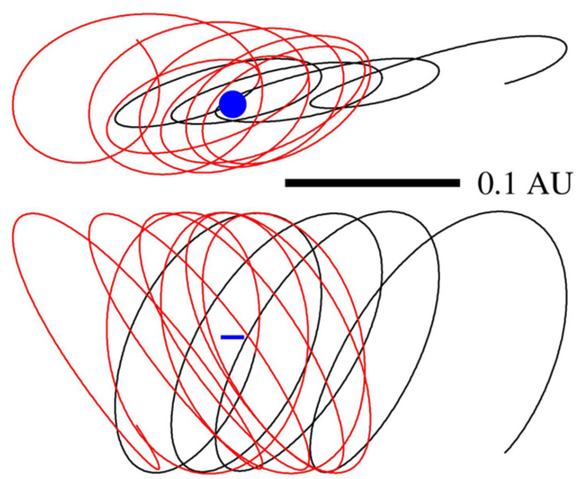

Figure 2. Closeup of QS behavior, top and side views. Earth not to scale, each loop taking one year.

QS motion is a temporary part of a three-body interaction also featuring HS co-orbital motion, with the asteroid librating along Earth's orbit and bouncing when it encounters Earth in the gap of the horseshoe (see below). Prior to QS, 2003 YN107 had been in a HS orbit closely following Earth's for several hundred years. It entered QS approaching Earth from behind (evening sky; red in Figs. 1 and 2) and will leave QS at nearly the same semimajor axis *a* and advance into the morning sky (black traces). It will re-enter HS orbit, make one final libration of 123 years, then after a close interaction with Earth, transition to a circulating orbit.

Classic three-body theory describes motion of a planet and small companions about the Sun. This had until recently been known only as "Trojan" librations around the triangular Lagrange points, for Jupiter, Mars, and more recently Neptune [2]. More generally, HS, QS, and more complex cases such as that of 3753 Cruithne [3] can occur. HS orbits can be described by classic three-body theory at least in the planar case, while Cruithne has a complex interaction in three dimensions. The QS state as now observed also requires consideration of the third dimension [4,5].

Horseshoe orbits: 2002 AA29 is currently in a HS orbit (Fig. 3). It has been a QS in the past [1], and will become one again in over 500 years. On current approaches to Earth it is perturbed to larger *a* if approaching Earth from the evening, and falls behind; vice versa if Earth catches up to it in the morning sky.

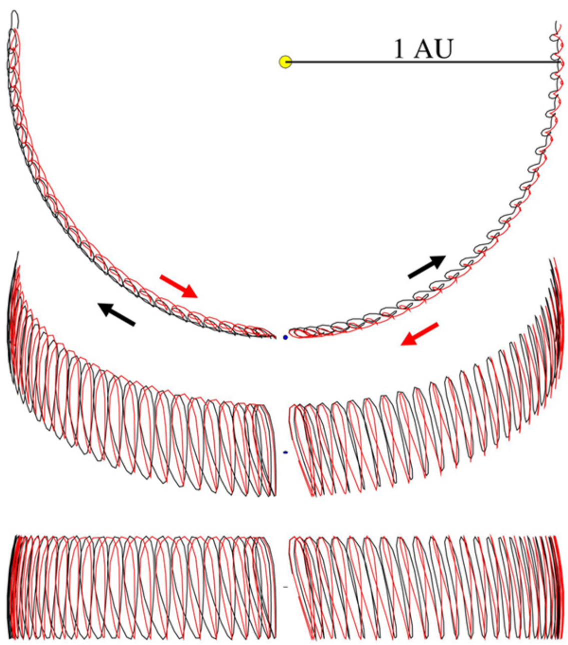

Figure 3. Partial orbits of 2002 AA29 in 1881-1933 and 1976-2028, views and scale as in Fig. 1. The current visit is shown at right, on approach in red. The larger semimajor axis *a* resulted in Earth catching up. The asteroid was perturbed to smaller *a* to pull ahead (black). Last visit, centred in 1908 (left) the asteroid approached at small *a* (red) and was perturbed to larger *a* and fell behind (black). Larger inclination causes the loops to be larger vertically than for 2003 YN107.

Orbital integrations: Using osculating elements from the Minor Planet Center [6], orbits for 2003 YN107 were integrated back- and forward 300 years using Mercury [7] and also from 1600 to 2200 C.E. with the Horizons online system at JPL [8]. Numerous subsequent integrations, including 300 clone orbits within the errors limits of the refined orbit, all showed the same basic behavior with little dependence on treatment of the Earth-Moon system. Discussion of the longer-term evolution of 2003 YN107 will be published elsewhere, as has been done for 2002 AA29 [1].

Observations: 2003 YN107 was discovered by LINEAR [9] on Dec. 20 2003, at V~18.8 and elongation ~105º. On Dec. 21, 2003, it passed 0.0149 AU from Earth (less than 6 lunar distances) with low velocity of 2.35 km/s. Discovery circumstances of 2002 AA29 were similar [1]. Being away from the opposition zone acts against discovery of asteroids on HS and QS orbits. The two asteroids are small objects in the 20 m diameter class [10]. Followup observations were done to secure the orbits, by us and for 2003 YN107 by R. H. McNaught and G. J. Garradd. 2002 AA29 was investigated by radar but without an improved orbit being detemined [11]. There is some indication of rapid rotation periods for both objects.

Discussion: Discovery of objects with extremely similar orbits to Earth's is interesting for several reasons. The dynamics of QS/HS interaction are intrinsically interesting, with implications for astrodynamics [12]. The origin of such objects is unclear, but likely the orbits are temporary [5]. 2002 AA29 and 2003 YN107 move on extremely Earth-like orbits; 2000 PH5 [14,15] and 2001 GO2 [15] have higher *e* yet Earth-like orbits; and 3753 Cruithne [5] and possibly other objects are in complex 1:1 resonance. Low-*e* objects could have an origin in the Earth-Moon system [13]. Radar results [11] suggest 2002 AA29 is of comparatively high albedo, and may support this origin. As more objects are discovered, statistics may help determine the origin of co-orbital objects and relation to other NEAs [16]. The low velocity of Earth co-orbital asteroids makes them good targets for sampling missions and ultimately for space resources [1,14,15].

References: [1] Connors, M. et al. (2002), *Met. Plan. Sci. 37,* 1435-1441. [2] Chiang, E. (2003), *IAU Circ. 8044,* 3. [3] Wiegert, P. et al. (1997), *Nature 387*, 685-686. [4] Mikkola, S. and Innanen, K. (1997) In The Dynamical Behaviour of our Planetary System (Kluwer, Dordrecht, Holland) pp. 345-355. [5] Christou, A. A. (2000), *Icarus 144,* 1-20. [6] Minor Planet Center (2003), 2003 YN107. MPEC 2003-Y76. [7] J.E.Chambers (1999), *MNRAS 304,* 793-799. [8] Giorgini, J.D. et al. (1996), *BAAS 28*, 1158. [9] Stokes, G. H. et al. (2000), *Icarus 148*, 21-28. [10] JPL (2003), neo.jpl.nasa.gov [11] Ostro, S. et al (2003), *Icarus 166*, 271-275. [12] Valsecchi, G. B. and Perozzi, E. (1998), *Planet. Space Sci. 46*, 1623-1626. [13] Bottke, W. F. et al. (1996), *Icarus 122*, 406-427. [14] Margot, J. L. and Nicholson, P. D. (2003) *AAS DPS Mtg. 34*, #6.05 [15] Wiegert, P. et al. (2002) *Eos Trans. AGU*, *83*(47), #P11A-0352 [16] Morais and Morbidelli, (2002) *Icarus 160*, 1-9.