An asteroidal companion to the Earth

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Near-Earth asteroids range in size from a few metres to more than 30 km: in addition to playing an important role in past and present impact rates on the Earth, they might one day be exploited as bases for space exploration or as mineral resources. Many near-Earth asteroids move on orbits crossing that of the Earth, but none has hitherto been identified as a dynamical companion to the Earth. Here we show that the orbit of asteroid 3753 (1986 TO), when viewed in the reference frame centred on the Sun but orbiting with the Earth, has a distinctive shape characteristic of 'horseshoe' orbits. Although horseshoe orbits are a well-known feature of the gravitational three-body problem[1], the only other examples of objects moving on such orbits are the saturnian satellites Janus and Epimetheus[2]—and their behaviour is much less intricate than that of 3753. Moreover, the fact that 3753 exhibits such a dynamical relationship with the Earth shows that, although it is not a satellite of our planet *per se*, it is, apart from the Moon, the only known natural companion of the Earth.

Figure 1 shows a view of the inner Solar System projected onto the ecliptic plane in a frame which co-rotates with the Earth; in this frame, the Earth appears stationary. The path of asteroid 3753 over a little more than one year is indicated by the line with arrowheads. The path has roughly the shape of a kidney bean, owing simply to the eccentricity of the asteroid's orbit. As the asteroid's orbital period is currently slightly shorter than that of the Earth, its orbit does not close on itself but rather advances slightly each year: the asteroid thus spirals forward along the orbit of the Earth.

This behaviour is not unusual in itself. What distinguishes 3753 from other near-Earth asteroids (NEAs) is its behaviour as it approaches the Earth: our planet's gravitational pull acts to increase the asteroid's period from slightly below to slightly above one year. As a result, the asteroid begins to fall behind, and hence to move away from the Earth. A possible collision with our planet is avoided: the closest approach during this leg is indicated by the heavy line A in Fig. 1.

Having reversed its direction, the asteroid eventually approaches the Earth from the other side. In this case, however, the Earth acts to decrease the asteroid's period to its previous value slightly below one year, and 3753 begins moving away from the Earth again. At closest approach on this leg, the edge b of the 'kidney bean' trajectory coincides with the heavy line labelled B in Fig. 1. The cycle of reversals then goes on to repeat itself, the Earth effectively repelling the asteroid at each close approach. The previous two reversals occurred in approximately AD 1515 and 1900; the next two will occur in AD 2285 and 2680. The variation in semimajor axis of 3753 over the next 2,000 years is shown in Fig. 2, the reversals corresponding to transitions across the semimajor axis of the Earth (1 astronomical unit, AU, the average Earth–Sun distance).

It should be noted that reversals occur when edge a (not b; see Fig. 1) approaches the Earth. Owing to the inclination and orientation of the asteroid's orbit, edge b never approaches the Earth closely, despite its appearance when projected onto the ecliptic plane. Figure 3 presents a view of the inner Solar System from an ecliptic edge-on perspective, and the asteroid's high inclination (20°) is evident. The orientation of the asteroid's orbit allows edge b to overlap the position of the Earth in Fig. 1 with no danger of collision. The complete orbit of 3753 is thus an 'overlapping horseshoe' (the outer envelope of which is indicated by the heavy line in Fig. 1), a kind which has never been observed before, even in theoretical studies. The asteroid's significant inclination and eccentricity ($e \approx 0.5$) have evidently caused it to escape more intensive scrutiny since its discovery, as they serve effectively to obscure the nature of its trajectory.

The asteroid's orbit is chaotic, on a timescale of 150 years, but it remains a near-Earth object in our simulations for timescales of a million years. However, not all of this time is spent in a horseshoe orbit: the asteroid can switch between its current orbit and a non-horseshoe orbit with semimajor axis around 1.1 AU on timescales of a few hundred thousand years.

Asteroid 3753 passes from inside to outside the Earth's orbit, but its minimum yearly approach distance is usually quite large. During the closest approaches, which happen only every 385 years, the asteroid passes within 0.1 AU (roughly 40 times the Earth–Moon distance) of our planet, the last such approach having occurred about 100 years ago. Over the next year, the closest approach will be only to within 0.31 AU. The relative proximity of 3753 to the Earth during recent times presumably aided in its discovery by Waldron in October 1986[3,4]. Asteroid 3753 has an absolute visual magnitude of 15.1 (ref. 5), brighter than typical of NEAs, and from which one can estimate a diameter of 5 km (refs 6, 7).

Asteroid 3753 crosses the orbits of Venus and Mars as well as that of the Earth. Though its orbit does not currently intersect that of any planet, the asteroid's argument of perihelion precesses at a rate of roughly $\dot{\omega} \approx +0.6°$ per century. As a result, its orbit will intersect that of the Earth in 2,750 years, and (if it survives this crossing) that of Venus in about 8,000 years. Similarly, the asteroid's orbit intersected Mars's roughly 2,500 years ago. These results suggest that the asteroid's current horseshoe orbit may not be stable for arbitrarily long times, unless there is some dynamical 'safety mechanism' which preserves it against close planetary encounters. At this point, the existence of such a safety mechanism seems unlikely, and yet the very low a priori probability of an object being injected

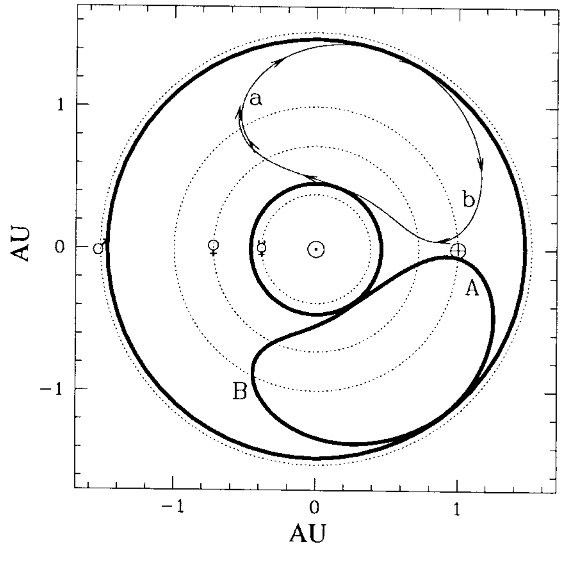

Figure 1 A view of the inner Solar System projected onto the ecliptic plane in a frame which co-rotates with the Earth; in this frame, the Earth appears stationary and is located at the symbol ⊕. The average distances of the planets Mercury, Venus, Earth and Mars from the Sun are indicated by dotted circles. The path of asteroid 3753 over slightly more than a year, beginning approximately in AD 2000, is shown by the line with arrowheads, with the outer envelope of the horseshoe indicated by the heavy lines. Reversals occur when a coincides with A, and when b coincides with B (see text).

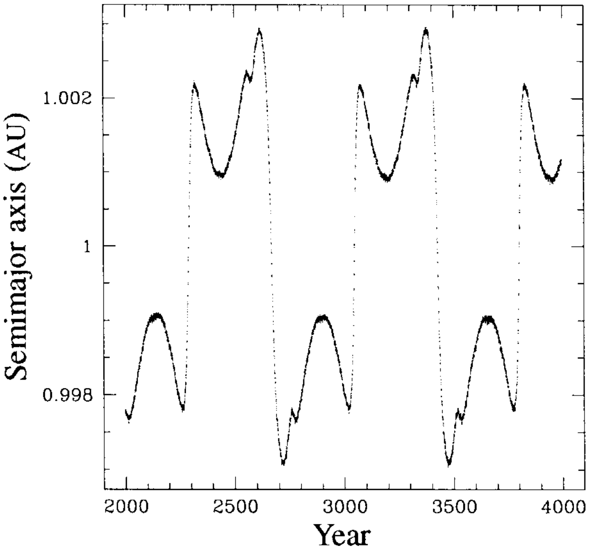

Figure 2 The heliocentric semimajor axis a of asteroid 3753 (1986 TO) over the next 2,000 years. As the asteroid's orbital period is proportional to $a^{3/2}$, transitions from $a > 1$ AU to $a < 1$ AU or vice versa correspond to reversals of the asteroid's direction within the horseshoe.

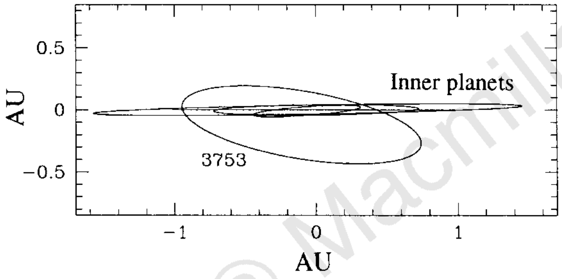

Figure 3 The orbits of the inner planets Mercury, Venus, Earth and Mars, along with that of asteroid 3753 when seen from the direction of the vernal equinox. The orbits of the inner planets are hard to distinguish, but the relatively high inclination of 3753 is apparent. The Sun is at the origin.

into such an unusual orbit makes a recent origin seem equally unlikely. As for the asteroid's future, though prediction is problematic owing to 3753's short chaotic timescale, a collision with the Earth seems very improbable. A strong gravitational interaction with Venus in 8,000 years seems quite likely, though the possibility of a collision with that planet at that time remains remote. On balance therefore, the origin of this object remains an enigma. More detailed investigation of this object is clearly required; even the direct exploration of 3753 by spacecraft is presumably well within the reach of current technology. ☐

Methods

The numerical simulations of asteroid 3753 presented here were performed with the Wisdom–Holman[8] integrator, in a model Solar System which included all the planets except Pluto. It should be noted however that the Earth–Moon barycentre was used for the Earth, an approximation which is valid because the Earth–asteroid distance is always much larger than the Earth–Moon distance. The heliocentric orbital elements of 3753 used were[5]: semimajor axis $a = 0.99778030$ AU, eccentricity $e = 0.51478431$, inclination $i = 19.812285°$, longitude of the ascending node $\Omega = 126.373212°$, argument of perihelion $\omega = 43.640637°$, and mean anomaly $M = 40.048932°$; these elements were calculated for epoch JD 2450500.5 and the equinox of J2000.0.

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A silicon/iron-disilicide light-emitting diode operating at a wavelength of 1.5 μm

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Although silicon has long been the material of choice for most microelectronic applications, it is a poor emitter of light (a consequence of having an 'indirect' bandgap), so hampering the development of integrated silicon optoelectronic devices. This problem has motivated numerous attempts to develop silicon-based structures with good light-emission characteristics[1], particularly at wavelengths (~1.5 μm) relevant to optical fibre communication. For example, silicon–germanium superlattice structures[2] can result in a material with a pseudo-direct bandgap that emits at ~1.5 μm, and doping silicon with erbium[3] introduces an internal optical transition having a similar emission wavelength, although neither approach has led to practical devices. In this context, β-iron disilicide has attracted recent interest[4–12] as an optically active, direct-bandgap material that might be compatible with existing silicon processing technology. Here we report the realization of a light-emitting device operating at 1.5 μm that incorporates β-$FeSi_2$ into a conventional silicon bipolar junction. We argue that this result demonstrates the potential of β-$FeSi_2$ as an important candidate for a silicon-based optoelectronic technology.

There has been interest for some time in the semiconducting β-phase of iron disilicide as a possible route to optically active structures compatible with silicon technology. However, experimental investigations into this material have been limited and even its basic properties, such as the value of the bandgap energy and the type (that is, the directness), have been controversial[4–12]. Photoluminescence has also been observed but its origin has been disputed and has been attributed by some[13,14] to defects in the surrounding silicon. Recent work[15,16] has shown that β-iron disilicide, β-$FeSi_2$ (produced by ion implantation into device-quality (100) silicon followed by suitable annealing) is direct-gap. Photoluminescence at a wavelength of 1.5 μm has been observed in this material and has been shown conclusively to be band-edge-related luminescence from the β-iron disilicide[17].

Efficient semiconducting electroluminescent sources such as high-intensity light-emitting diodes (LEDs) and particularly injection lasers are made from direct-gap semiconductors, as these provide an efficient and fast radiative route. It is also necessary to incorporate heterojunctions to provide good carrier and optical