Asteroids in retrograde resonance with Jupiter and Saturn

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ABSTRACT

We identify a set of asteroids among Centaurs and Damocloids, which orbit contrary to the common direction of motion in the Solar system and which enter into resonance with Jupiter and Saturn. Their orbits have inclinations $I > 140^\circ$ and semimajor axes $a < 15$ au. Two objects are currently in retrograde resonance with Jupiter: 2006 BZ8 in the 2/−5 resonance and 2008 SO218 in the 1/−2 resonance. One object, 2009 QY6, is currently in the 2/−3 retrograde resonance with Saturn. These are the first examples of Solar system objects in retrograde resonance. The present resonant configurations last for several thousand years. Brief captures in retrograde resonance with Saturn are also possible during the 20000 yr integration timespan, particularly in the 1/−1 resonance (2006 BZ8) and the 9/−7 resonance (1999 LE31).

Key words: celestial mechanics – comets: general – Kuiper belt: general – minor planets, asteroids: general – Oort Cloud.

1 INTRODUCTION

The discovery of exoplanets that revolve around their host stars in the opposite direction to stellar rotation has renewed interest in the dynamics of retrograde motion in N-body gravitational systems. In the Solar system, all major and most minor planets have prograde orbits around the Sun except for 50 small bodies known to orbit opposite the common direction (Minor Planet Center as of 2013 July 1). Such bodies are thought to originate mainly in the Oort Cloud comet reservoir (Jewitt 2005). However, numerical simulations have recently indicated that retrograde orbits in the inner Solar system may be produced through the gravitational excitation exerted by the gas giants (Greenstreet et al. 2012). Understanding the dynamics of retrograde minor bodies may provide clues to the mechanisms that reverse major and minor planets’ orbits alike. In this Letter, we seek to determine the dynamical states of the minor bodies that reside on retrograde orbits in the vicinity of Jupiter and Saturn. We show that some of the known minor bodies may be trapped temporarily in mean motion resonances with these planets where the ratios of their orbital periods are integer fractions.

Unlike a number of extrasolar multiplanet systems (~20 per cent), the Solar system’s planets are not in resonance even though the pairs Jupiter–Saturn and Neptune–Uranus are close to the 5/2 and 2/1 mean motion resonances, respectively. For minor bodies, the role of mean motion resonances is complex. For instance, the 3/1 mean motion resonance with Jupiter in the main asteroid belt is a known source of near-Earth asteroids (NEAs; Wisdom 1985; Morbidelli et al. 2002). On the other hand, the Hilda asteroid family resides stably at the 3/2 resonance with Jupiter (Nesvorny & Ferraz-Mello 1997). Mean motion resonances also protect objects on Neptune-crossing orbits in the Kuiper belt from disruptive close encounters with this planet (Morbidelli, Thomas & Moons 1995; Malhotra 1996). The existence of small bodies on retrograde orbits in resonance with the giant planets may provide another example of the dynamical diversity and the roles played by resonant excitation.

In Section 2, we recall the main features of retrograde mean motion resonances. In Section 3, we present our numerical simulations and identify the various observed dynamical states. Section 4 contains a summary and discussion of the significance of these findings.

2 RETROGRADE RESONANCE

In order to test whether a particular asteroid in retrograde motion around the Sun is in resonance with a planet, we need to identify the correct resonant terms of the standard Fourier expansion of the three-body problem’s disturbing function (Murray & Dermott 1999). Keeping with the usual definition of the osculating orbital elements where retrograde orbits are inclined by $I > 90^\circ$ and $\lambda > 0$, $\lambda' > 0$ where $\lambda$ and $\lambda'$ are the asteroid’s and the planet’s mean longitudes, respectively, we show elsewhere (Morais & Namouni 2013) that the resonant terms for the $p/−q$ resonance are of the form

$$\phi = q\lambda - px' - (p + q - 2k)\sigma + 2k\Omega,$$

where $p$, $q$, and $k$ are integers, $p + q \geq 2k$ and the longitude of pericentre is $\sigma = \omega - \Omega$, where $\omega$ and $\Omega$ are, respectively, the argument of pericentre and the longitude of ascending node. 1 To

1 When motion is retrograde, the usual ascending node becomes the descending node. To conserve the canonical nature of the longitude of pericentre,
The first object in Table 1 is near-Earth object 343158 (2009 HC82) an Apollo family member that always remains interior to Jupiter’s orbit. The other five objects cross Jupiter’s orbits and are sometimes referred to as Centaurs.\(^4\) Whereas 2005 VD has a pericentre just inside Jupiter’s orbit but does not cross Saturn’s orbit, 1999 LE31, 2008 SO218 and 2006 BZ8 cross both Jupiter’s and Saturn’s orbits, and 2009 QY6 also crosses Uranus’ orbit. These objects have high-eccentricity and/or high-inclination orbits, resembling Halley-type comet orbits. With a Tisserand parameter \(T < 2\), these objects may be part of the Damocloid population (Jewitt 2005) whose physical properties indicate that their likely source is the Oort Cloud similarly to Halley-type comets. The source of Centaurs with low to moderate inclinations is likely to be the Kuiper belt (Volk & Malhotra 2013).

We numerically integrated massless objects with orbital elements from Table 1 using the Bulirsch–Stoer integrator of the package MERCURY (Chambers 1999) with an accuracy parameter \(10^{-12}\). The main eight planets were included and initial conditions (nominal orbits) for all bodies were obtained from JPL/HORIZONS at JD245 6400.5. We generated nine clones for each object with orbital elements sampled from a six-dimensional Gaussian distribution around the nominal orbit. The standard deviations \((1\sigma\) uncertainties) of the orbital elements were obtained from AstDyS (Knezevic & Milani 2012).\(^5\) We followed the nominal and clones’ orbits for \(\pm10000\) yr centred on JD245 6400.5.

2006 BZ8 (Fig. 2) is currently in the 2/−5 resonance with Jupiter (libration around 180°) while it is near the 1/−1 resonance with Saturn (circulation). All clones show similar behaviour with capture in the present configuration occurring at \(-8000\) yr and an exit at around 7000 yr. While the 2/−5 resonance with Jupiter lasts, the distance to Saturn remains larger than two Hill’s radii. The 2/−5 resonance with Jupiter protects the asteroids from close approaches to this planet for a while, despite the orbit’s large eccentricity. The distance to Jupiter remains larger than one Hill’s radius until around 7000 yr when very close encounters with this planet occur. As a consequence, the asteroid exits the 2/−5 resonance with Jupiter but a brief capture in the 1/−1 resonance with Saturn is possible (1/10 clones) as shown between 7000 and 10000 yr in this example.\(^6\) The argument of pericentre \(\omega\) remains close to 0, indicating a Kozai secular resonance.\(^7\)

2008 SO218 (Fig. 3) is currently in the 1/−2 resonance with Jupiter (libration around 0°) while it is near the 5/−4 resonance with Saturn. When the 1/−2 resonant angle librates around 0, the asteroid is protected from close approaches to Jupiter and the distance to this planet remains larger than two Hill’s radii, but it can experience close approaches with Saturn. Although all clones exhibit currently symmetric libration around 0, episodes of asymmetric libration in the 1/−2 resonance are also possible (6/10 clones) during which the asteroid can have close approaches to Jupiter, as shown between \(-10000\) and \(-5000\) yr in this example. All clones stay near the 1/−2 resonance with Jupiter during the integration timespan. The argument of pericentre \(\varpi\) remains near 0, indicating a Kozai secular resonance (see footnote 7).

1999 LE31 (Fig. 4) is currently near the 1/−2 resonance with Jupiter while it is near the 9/−7 resonance with Saturn. All clones show similar behaviour with present circulation of the 9/−7 resonant

\(^{4}\) A Centaur is a small body on a long-term unstable giant-planet-crossing orbit with 5.5 < \(a\) < 30.1 au as defined by JPL.\(^1\) The Minor Planet Center\(^2\) has a stricter definition such that the pericentre of a Centaur’s orbit must be exterior to Jupiter’s orbit.

\(^{5}\) http://hamilton.dm.unipi.it/astdys/

\(^{6}\) We note that we count the nominal orbit as one of the clones.

\(^{7}\) We confirmed libration of \(\omega\) with longer term integrations.

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3 NUMERICAL INTEGRATIONS OF OBJECTS IN RETROGRADE ORBITS

To identify retrograde mean motion resonances with Jupiter and Saturn, we searched the Minor Planet Center data base\(^2\) for objects in retrograde orbits with semimajor axes \(a < 15\) au and inclinations \(I \gtrsim 140\)° that were observed at multiple oppositions (uncertainty parameter \(\leq 2\)). The inclination constraint restricts the sample to nearly coplanar retrograde orbits thereby simplifying the identification of mean motion resonances. Fig. 1 shows the distributions of \((a, I)\) and \((a, e)\) for the selected objects. Table 1 shows their orbital elements at JD245 6400.5 obtained from JPL/HORIZONS (Giorgini et al. 1996).\(^3\)

The argument of pericentre \(\varpi\) remains close to 0, indicating a Kozai secular resonance.\(^7\)

\(^{1}\) http://www.minorplanetcenter.net/

\(^{2}\) http://sao.jpl.nasa.gov

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Figure 1. Distributions of \((a, I)\) and \((a, e)\) for our subset of retrograde asteroids.

The lowest order in eccentricity \((e)\) and inclination \((I)\), the corresponding force amplitude is proportional to \(\cos^{2k}(I/2)e^{p+q-2}\). When the inclination is close to 180° (nearly coplanar retrograde motion), the dominant resonant term has \(k = 0\) and amplitude proportional to \(e^{p+q}\). This reflects the fact that a \(p/-q\) retrograde resonance is weaker than its \(p/q\) prograde counterpart (whose force is proportional to \(e^{p-q}\)) as an encounter of an asteroid and a planet orbiting in opposite directions around the Sun occurs at a higher relative velocity during a shorter time than in a prograde configuration. We note that the definition of the \(p/-q\) resonant angle may be expressed using orbital angle variables that assume a retrograde longitude (e.g. \(\lambda > 0\), \(\lambda' < 0\)) along with an inclination \(I < 90°\) (Morais & Giuppone 2012). We prefer the use of \((1)\) as we have developed a simple approach to identify analytical resonant amplitudes from the classical expression of the disturbing function for prograde orbits (see Morais & Namouni 2013). Ultimately, resonance is independent of the coordinates’ choice as long as they are obtained through a suitable canonical transformation from the usual orbital elements.
Table 1. Nominal orbital elements and Tisserand parameter of the selected retrograde asteroids at JD245 6400.5, taken from HORIZONS with AstDyS 1σ uncertainties (in parentheses) on the last significant decimal place.

|                | a (au)   | e      | I (°)  | M (°)   | ω (°)   | Ω (°)   | T       |
|----------------|----------|--------|--------|---------|---------|---------|---------|
| 343158 (2009 HC82) | 2.527 7835(3) | 0.807 4783(2) | 154.497 16(2) | 38.93235(5) | 298.515 11(7) | 294.933 44(8) | 1.317 |
| 2005 VD         | 6.760 19(8)     | 0.250 215(8)     | 172.8732(1)    | 147.325(4)   | 79.080(3)   | 173.2478(3)  | 1.395 |
| 1999 LE31       | 8.1212(6)       | 0.468 242(2)     | 151.806 72(4)  | 223.18(1)    | 32.3232(2)  | 291.9924(2)  | 1.314 |
| 330759 (2008 SO218) | 8.134 97(2)     | 0.564 005(1)    | 170.359 62(1)  | 51.1362(2)   | 354.590 79(9) | 348.107 64(9) | 1.396 |
| 2006 BZ8        | 9.606 67(6)     | 0.800 88(1)      | 165.299 92(1)  | 82.298(8)    | 62.321(5)   | 183.6132(8)  | 1.032 |
| 2009 QY6        | 12.541(1)       | 0.834 73(1)      | 137.759 83(6)  | 28.649(4)    | 195.0817(2) | 197.622 43(4) | 0.851 |

Figure 2. Nominal orbit of 2006 BZ8 (from top to lower panel): semimajor axis $a$ and location of $p_1/q_1$ resonance with inner planet (Jupiter); $φ_2$ is the angle of $p_2/q_2$ resonance with outer planet (Saturn); $φ_1$ is the angle of $p_1/q_1$ resonance with inner planet (Jupiter); eccentricity $e$ (lower curve in black) and inclination $inc$ divided by 180° (upper curve in blue); argument of pericentre $ω$ (black thick curve) and difference in nodal longitudes between asteroid and Jupiter (red curve) or Saturn (green curve); encounters with Jupiter (red plus), Saturn (green filled square) and Uranus (blue open square) in units of Hill’s radii of these planets.

angle with Saturn but brief libration is possible (9/10 clones) as shown between 7000 and 9000 yr in this example. Close approaches to Saturn at around ~8000 yr brought the asteroid to the vicinity of the 9/7 resonance with this planet. The distance to Jupiter remains larger than one Hill’s radius. The argument of pericentre $ω$ executes a Kozai libration around 0 (see footnote 7).

2005 VD (Fig. 5) has its current pericentre very close to Jupiter’s orbit, while its apocentre is close to Saturn’s orbit. It is also the retrograde asteroid closest to the Solar system’s median plane with a largest inclination ($I = 172.9°$). It therefore suffers repeated close encounters with Jupiter and Saturn, making its orbit very chaotic as can be seen through the fast semimajor axis drift. Accordingly, the clones’ dynamical behaviour varies widely and any resonance capture is short lived. In this example, the asteroid passes the 7/11, 9/13, 7/11 and finally the 2/3 resonances with Jupiter.

2009 QY6 (Fig. 6) is currently in the 2/3 resonance with Saturn (large-amplitude asymmetric libration) while it is near the 2/1 resonance with Uranus. The 2/3 resonance configuration can last the entire integration timespan (2/10 clones) or at least half the

Only minor planet 2013 LA2’s uncertain orbit exceeds such an inclination with $I = 175°$ (MPC uncertainty parameter =6).
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Figure 4. Nominal orbit of 1999 LE31. Plotted quantities are those of Fig. 2.

Figure 5. Nominal orbit of 2005 VD. Plotted quantities are those of Fig. 2.

Figure 6. Nominal orbit of 2009 QY6. Plotted quantities are those of Fig. 2 but the inner planet is Saturn and the outer planet is Uranus. Also shown is the difference in nodal longitudes with Saturn (green) or Uranus (blue).

integration timespan (7/10 clones). Passage through the 2/−3 resonance with Saturn near the current time (without capture) is also possible (1/10 clones). The distance to Jupiter and Saturn remains larger than about seven Hill's radii. The orbit is moderately chaotic due to close encounters with Uranus. The argument of pericentre $\omega$ executes a Kozai libration around 180° (see footnote 7).

2009 HC82 (Fig. 7) is currently located near the 3/−1 resonance with Jupiter (the resonant argument circulates) and has very regular behaviour despite experiencing close encounters with Venus, Earth and Mars. The parameter $h = (1 - e^2) \cos^2 I = 0.28$; hence, the orbit’s evolution is probably dominated by the Kozai secular resonance with Jupiter (Kinoshita & Nakai 2007) that forces the slow circulation of the argument of pericentre $\omega$. The origin of this asteroid is likely to be related to its proximity to the 3/1 resonance with Jupiter as numerical integrations by Greenstreet et al. (2012) indicate that this resonance can be a source of retrograde NEAs.

4 CONCLUSION

This analysis is to our knowledge the first identification of Centaurs and Damocloids currently in retrograde resonance with the giant planets. Although long-lived Centaurs are known to hop between prograde resonances with the planets (Bailey & Malhotra 2009), there was no previous report of retrograde resonant capture. The relevant resonances observed in this Letter are the 2/−5 resonance with Jupiter for 2006 BZ8 (libration around 180°), 1/−2...
resonance with Jupiter for 2008 SO218 (libration around 0) and the 2/−3 resonance with Saturn for 2009 QY6 (asymmetric libration). The present resonant configurations last for several thousand years. Moreover, retrograde resonant capture with Saturn is possible within the 20000 yr integration timespan for 2006 BZ8 (1/−1) and 1999 LE31 (9/−7). The identified resonant configurations are temporary as the minor planets experience close encounters with the giant planets. This is akin to the temporary capture of NEAs in the (prograde) 1/1 with the terrestrial planets resonance (Namouni, Christou & Murray 1999; Christou 2000) and that of Centaurs in the same resonance with Uranus and Neptune (de la Fuente Marcos & de la Fuente Marcos 2012, 2013; Alexandersen et al. 2013).

As our studied asteroids may be termed as Damocloids (Tisserand parameter \( T < 2 \)), they too are likely to originate in the Oort Cloud as nuclei of dead comets. This conclusion was reached by Jewitt (2005) based on the physical study of 20 such objects. However, with the exception of 1999 LE31 (Jewitt 2005) and 2005 VD (Pinilla-Alonso et al. 2013), the physical properties of our asteroid sample have not been studied so far. A possible lack of ultrared matter, rich organic material that cannot survive in the inner Solar system, must await photometric analysis of the asteroids in resonance to confirm their similarity or lack thereof with the known Damocloid population (Sheppard 2010). If such objects are indeed the nuclei of dead comets that entered the giant planet region on initially retrograde orbits, then their semimajor axis drift rate in that region must be particularly small in order to be trapped in retrograde resonances. The reason is that retrograde resonances are much weaker than their prograde counterparts as physical encounters occur at larger velocities during a shorter time (Morais & Namouni 2013). The strongest retrograde resonance is the co-orbital 1/−1 resonance (of order 2 in eccentricity) yet it did not dominate resonant capture in our sample. This indicates that the dynamics of retrograde resonant capture may be more complex and could involve an interplay of retrograde mean motion resonances with the secular Kozai resonance (Gomes et al. 2005; Gallardo, Hugo & Pais 2012) as observed for 2006 BZ8, 2008 SO218, 1999 LE31 and 2009 QY6. Another interesting possibility is given by the recent numerical integrations of Greenstreet et al. (2012), who observed an orbital inversion in the inner Solar system. That work indicates that the 3/1 prograde mean motion resonances may produce large-inclination NEAs like 2009 HC82. It is not yet clear whether the prograde resonance may provide a preferential path to retrograde resonance capture. Further dynamical and physical study of the minor planets identified in this Letter will help discriminate between the possible origins of retrograde resonance capture.

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