RESONANT CAPTURE OF IRREGULAR SATELLITES BY A PROTOPLANET.

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Numerical simulations of the gravitational scattering of planetesimals by a protoplanet reveal that a significant fraction of scattered planetesimals can become trapped very near the protoplanet in an unusual co-orbital resonance [1]. The simulations include solar nebula gas drag and use planetesimals with diameters ranging from ∼1 to ∼1000 km. Protoplanet masses range from 2 to 15 Earth-masses ($M_\oplus$), effectively covering both the range of likely core masses for Jupiter and Saturn, as well as the full masses of Uranus and Neptune. Protoplanet eccentricities range from $e_p = 0$ to 0.15. For protoplanets on moderately eccentric orbits ($e_p \geq 0.1$) most simulations show from 5-25% of all scattered planetesimals can become temporarily trapped in the resonance. While trapped, these resonant planetesimals can subsequently have deep low-velocity encounters with the protoplanet that result in temporary or permanent capture onto highly eccentric prograde or retrograde circumplanetary orbits.

We used N-body simulations to model the combined effects of solar nebula gas drag and gravitational scattering of planetesimals by a protoplanet. None of the initial orbits were in co-orbital resonance with the protoplanets. In the N-body simulations, planetesimals were treated as massless test particles that had no mutual gravitational interactions nor any gravitational effect on the protoplanets. We used a v^2 gas drag force [2], where v velocity of the planetesimal's motion with respect to the gas.

Our initial simulations used 2 $M_\oplus$ protoplanets and 0.5 km diameter planetesimals (assuming $\rho = 1\,\mathrm{g\,cm^{-3}}$). During a period of 50,000 years, out of 1000 planetesimals gravitationally scattered by the inner protoplanet about 10% became temporarily or permanently trapped in an unusual co-orbital resonance, where the protoplanet and planetesimal orbited the sun with the same period (Fig. 1). This class of co-orbital resonance is similar to that found by Jackson [3] and is sometimes referred to as a quasi-satellite resonance [4,5].

The equilibrium configuration shown in Fig. 1 results from the balance between resonant gravitational excitation of the planetesimal's orbit and damping of this excitation by solar nebula gas drag. Only a narrow range of planetesimal diameter allowed for this equilibrium. For larger sizes, equilibrium was never achieved and trapping was only temporary. One reasonable way to demonstrate the effect of non-equilibrium evolution is to slowly increase the mass of the protoplanet or slowly decrease the solar nebula gas density (Figs. 2 & 3).

The examples shown in Figs. 2 and 3 illustrate that both prograde and retrograde captures may be possible with this mechanism, although deep retrograde encounters are somewhat more common. Numerous interesting cases were observed, including resonant planetesimals impacting the protoplanet or being captured into long-lived circumplanetary orbits extending out to about R_H (e.g., Fig. B & C). None of the simulations described here included the effects of a circumplanetary nebula, which likely would have increased the capture rate.

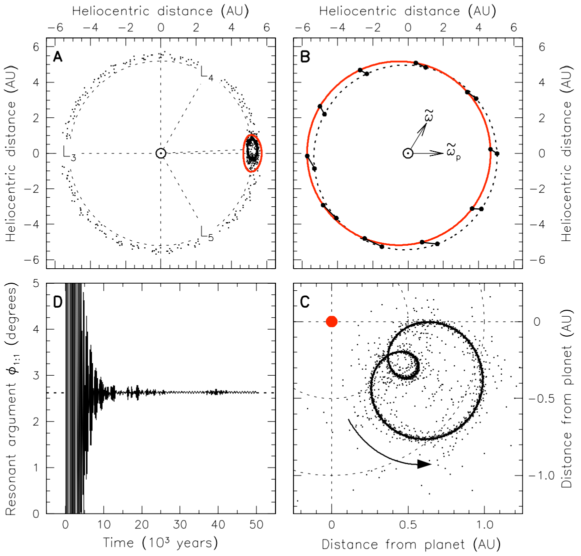

Figure 1: The orbits of a 2 $M_\oplus$ proto-Jupiter and a ∼0.5 km diameter planetesimal are shown projected onto the X-Y plane in three different reference frames; (A) a sun-centered frame rotating with the mean orbital motion of the protoplanet, (B) a sun-centered fixed frame, and (C) a protoplanet-centered frame with the inertial orientation of the X and Y axes preserved. In all three frames the X-axis is aligned with the protoplanet's projected longitude of pericenter ($\tilde{\omega}_\mathrm{p}$). The resonant planetesimal's longitude of pericenter ($\tilde{\omega}$) is offset by about 60°. In A, the protoplanet's orbital eccentricity (0.1) causes it to follow the red elliptical path. Three of the traditional Lagrange equilibrium points, L_3, L_4 and L_5, are indicated. Black points mark the position of the planetesimal every 10 years for 50,000 years (for clarity, some points were omitted near the Lagrange points). In B, 10 synchronized points along the protoplanet and trapped planetesimal's orbits (red and dashed, respectively) are connected to indicate relative positions of the bodies at specific times. In C, the trapped planetesimal quickly evolves onto the looping path, moving counter-clockwise (indicated by arrow). Panel D shows the evolution of the resonant argument, $\phi_{1:1} = \lambda - \lambda_\mathrm{p}$, the difference between the mean longitudes of the planetesimal (λ) and protoplanet (λ_p). The equilibrium value of 2.6° is the magnitude of the offset between the elliptical paths of the protoplanet and the trapped planetesimal seen in A above.

References: [1] Kortenkamp, *Icarus* (submitted); [2] Adachi *et al. Proc. Theor. Phys.* **56**, 1756–1771 (1976); [3] Jackson, *MNRAS* **74**, 62–82 (1913); [4] Naoumi, *Icarus* **137**,293–314 (1999); [5] Weigert *et al. AJ* **119**, 1978–1984 (2000).

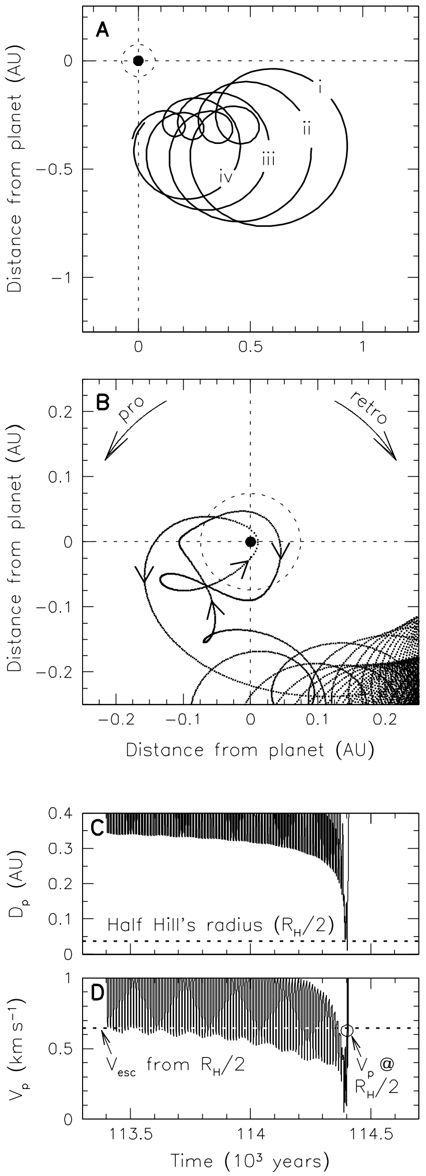

Figure 3: The fate of the resonant planetesimal in Fig. 1 is shown here in a simulation where the protoplanet's mass grows linearly from 2 to $10\,\mathrm{M}_\oplus$ over 10^6 years. Panels A and B use the same planet-centered reference frame as used in Fig. 1C, and the dashed circle in each panel indicates the approximate size of the Hill radius (R_H) for the protoplanet. The four orbits shown in A indicate the path of the planetesimal as it is attracted to the growing protoplanet, with output at 10 kyr (i), 113 kyr (ii), 114.2 kyr (iii), and 114.3 kyr (iv). Panel B is a high resolution plot of the ultimate encounter. The retrograde and prograde orbital directions are indicated on the plot. Panels C and D show the planetesimal's distance and velocity with respect to the protoplanet (D_p and V_p) for $\sim$1000 years preceding the ultimate encounter. The dashed lines represent $R_H/2$ and the pure 2-body escape velocity (V_{esc}) from $R_H/2$. The planetesimal's velocity as it crosses the threshold $R_H/2$ is highlighted by the open circle.

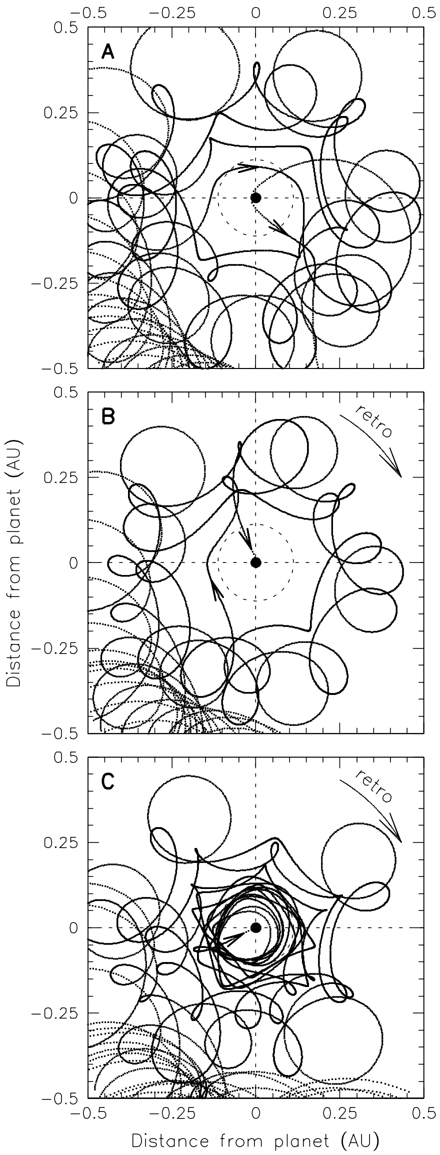

Figure 4: Three examples demonstrating some common fates of resonant quasi-satellites. In all three panels the protoplanet is $10\,\mathrm{M}_\oplus$ and the quasi-satellite is initially trapped in the 1:1 resonance. In panel A the protoplanet grows by just 3% and yet upsets the balance between solar nebula gas drag and resonant perturbations. The quasi-satellite eventually has two close-encounters with the protoplanet inside the Hill radius (dashed circle) before escaping to a free heliocentric orbit. In panels B and C the protoplanets have constant mass but the solar nebula gas slightly dissipates, which also upsets the resonant balance. In B the first encounter inside the Hill radius results in impact with the protoplanet. In C the quasi-satellite becomes temporarily captured as a true retrograde satellite before solar perturbations lead to impact with the protoplanet. Note that there is no circumplanetary gas drag in any of these simulations.