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An efficient, low-velocity, resonant mechanism for capture of satellites by a protoplanet

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Abstract

Numerical simulations of the gravitational scattering of planetesimals by a protoplanet reveal that a significant fraction of scattered planetesimals can become trapped as so-called quasi-satellites in heliocentric 1:1 co-orbital resonance with the protoplanet. While trapped, these resonant planetesimals can have deep low-velocity encounters with the protoplanet that result in temporary or permanent capture onto highly eccentric prograde or retrograde circumplanetary orbits. The simulations include solar nebula gas drag and use planetesimals with diameters ranging from ∼1 to ∼1000 km. Initial protoplanet eccentricities range from $e_p = 0$ to 0.15 and protoplanet masses range from 300 Earth-masses ($M_\oplus$) down to $0.1M_\oplus$. This mass range effectively covers the final masses of all planets currently thought to be in possession of captured satellites—Jupiter, Saturn, Neptune, Uranus, and Mars. For protoplanets on moderately eccentric orbits ($e_p \geqslant 0.1$) most simulations show from 5–20% of all scattered planetesimals becoming temporarily trapped in the quasi-satellite co-orbital resonance. Typically, 20–30% of the temporarily trapped quasi-satellites of all sizes came within half the Hill radius of the protoplanet while trapped in the resonance. The efficiency of the resonance trapping combined with the subsequent low-velocity circumplanetary capture suggests that this trapped-to-captured transition may be important not only for the origin of captured satellites but also for continued growth of protoplanets.

Keywords: Accretion; Planetary formation; Planetesimals; Resonances; Satellites

1. Introduction

The four giant planets of our Solar System each possess populations of satellites that follow highly inclined and elongated orbits (Gladman et al., 1998, 2000, 2001; Sheppard et al., 2001; Kavelaars et al., 2004). These so-called irregular satellites revolve around their respective planets at distances well outside the nearly circular co-planar orbits of regular satellites such as Io, Europa, Ganymede, and Callisto in the jovian system. Many of the irregular satellites orbit their planet in the retrograde sense—opposite both the rotational motion of the planet and the orbital motion exhibited by regular satellites. Orbital characteristics of irregular satellites suggest that they were heliocentric planetesimals captured during the final stages of giant planet formation (Peale, 1999), although there is currently no consensus as to what mechanism was responsible for the energy dissipation required for capture to occur. One theory suggests capture could have occurred during passage of planetesimals through an extended gaseous envelope surrounding a young protoplanet (Pollack et al., 1979). An alternative is collisions between small bodies near enough a planet to be temporarily dominated by its gravitational field, thus allowing some low-velocity fragments to be captured (Colombo and Franklin, 1971). Yet another mechanism involves a rapidly increasing protoplanetary mass that gravitationally attracts nearby planetesimals—a "pull down" capture (Heppenheimer and Porco, 1977).

The resonant configuration of some irregular satellites suggests they may have undergone some degree of post-capture orbital decay due to aerodynamic drag from ex-

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tended protoplanetary atmospheres (Whipple and Shelus, 1993; Saha and Tremaine, 1993). This lends support to the theory of planetesimal capture by circumplanetary nebular drag. However, there is a long-standing fundamental problem with this mechanism. Planetesimals on typical randomized protoplanet-crossing orbits will encounter the protoplanet at hyperbolic velocities with respect to the protoplanet. This requires the planetesimals to penetrate deep into the circumplanetary nebula where gas densities are high enough to bleed away enough excess energy to make capture possible. Such deep initial passages then doom the new satellites to rapid post-capture orbital decay, causing them to spiral down to the protoplanet's surface in just a few orbits. Captured planetesimals could delay their fate by having more distant initial encounters through the nebula where gas densities are low and circumplanetary orbits would not decay as rapidly. However, these distant initial encounters are unlikely to dissipate enough energy to reduce hyperbolic velocities below the protoplanet's escape velocity.

One traditional way out of this dilemma is to assume that the circumplanetary nebula dispersed or collapsed on a time scale shorter than the orbital decay time scale of captured planetesimals, thus leaving the last few captured objects in stable circumplanetary orbits. It seems unlikely that circumplanetary nebula dispersal/collapse time scales would be similarly rapid for planets as diverse as gas giants Jupiter and Saturn, ice giants Uranus and Neptune, and small rocky Mars. It may be possible to avoid the necessity for timely and rapid circumplanetary nebula dispersal if capture was more independent of the circumplanetary nebula and if the process was efficient enough to continuously supply new satellites to compensate for those lost to orbital decay. In this way, whenever and however nebular dispersal occurred, it would simply leave behind the freshest captured objects after a prolonged period of the planet accreting such objects. Unfortunately, conventional theories appear to lack the capture efficiency needed to produce such a continuous supply of planetesimals (Peale, 1999).

All previous models of satellite capture mechanisms (e.g., See, 1909; Brown, 1911; Colombo and Franklin, 1971; Heppenheimer and Porco, 1977; Pollack et al., 1979; Ćuk and Burns, 2004) have assumed that the primordial orbits of the giant planets were similar to their present day nearly circular orbits. However, in the early history of our Solar System, an era of higher orbital eccentricities of the giant planets may be required to explain features such as the main asteroid belt (Chambers and Wetherill, 2001) and the distant orbits of Uranus and Neptune (Thommes et al., 1999). In addition, more than three quarters of all known giant planets have orbital eccentricities greater than 0.1 and about one fifth have eccentricities greater than 0.5 (see http://www.obspm.fr/encycl/catalog.html). These recent developments encourage an examination of dynamical effects that become more efficient at moderate to high planetary orbital eccentricities. Using numerical modeling we have been exploring these effects and have identified a resonant mechanism that may be capable of delivering a substantial quantity of planetesimals to a protoplanet at low relative velocity. This resonant mechanism is distinct from earlier capture theories in that we invoke solar nebula gas drag in a *heliocentric* disk to account for most or all of the energy dissipation required for capture. This solar nebula drag force, when combined with resonant perturbations from the protoplanet, forces trapped planetesimals onto nearly the same orbit as the protoplanet prior to their ultimate capture.[2]

2. Method and results

We used N-body simulations to model the combined effects of solar nebula gas drag and gravitational scattering of planetesimals by a protoplanet. All our simulations included two protoplanets on orbits similar to those of Jupiter and Saturn with the exception that different initial orbital eccentricities were used, ranging from 0 to 0.15. Primordial eccentricities at or above 0.1 for Jupiter are in better agreement with those found in asteroid belt formation models (Chambers and Wetherill, 2001). Protoplanet masses ranged from a large Jupiter-like body with 300 Earth-masses ($M_\oplus$) down to a small Mars-like body with $0.1M_\oplus$. In most simulations the second protoplanet at Saturn's orbital distance was identical in mass to the first protoplanet at Jupiter's distance. However, the mass of the second protoplanet was capped at a Saturn-like $100M_\oplus$. By using such a cap, the simulations with the largest protoplanets ($300M_\oplus$ at 5.2 AU and $100M_\oplus$ at 9.5 AU) became crude approximations to the current Solar System (with Jupiter at $318M_\oplus$ and Saturn at $95M_\oplus$). For simulations with small protoplanet masses the second protoplanet likely played no significant dynamical role in resonance trapping but it was nonetheless included for the sake of consistency and continuity. Qualitatively, the second protoplanet serves to justify three-dimensional simulations with non-zero mutual inclinations between the protoplanets, planetesimals, and midplane of the solar nebula. As in the real Solar System, the protoplanets in these simulations interact with each other and force secular changes in their orbits.

Planetesimals were initially placed on free heliocentric orbits with random uniform distributions in semi-major axes a between 5.5 and 5.8 AU. These initial orbits are outside the extent of the 1:1 resonance region found by Holman and Wisdom (1993) for a full-size Jupiter and well outside the 1:1 region for smaller protoplanets. We set initial planetesimal eccentricities to $e = 0.05$ and inclinations to half that value in radians. Mean longitudes and longitudes of pericenter and ascending node were randomly distributed between 0° and 360°. None of the initial orbits were in co-orbital resonance with the protoplanets. In the N-body simulations,

[2] Note that in this paper *trapped* and *captured* have distinct meanings. A planetesimal is first *trapped* in heliocentric 1:1 co-orbital resonance with the protoplanet and later *captured* into circumplanetary orbit.