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Apsidal alignment in migrating dust - Crescent features caused by eccentric planets

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Abstract. Circumstellar discs are known to exist in great variety, from gas-rich discs around the youngest stars to evolved debris discs such as the solar system's zodiacal cloud. Through gravitational interaction, exoplanets embedded in these discs can generate density variations, imposing potentially observable structural features on the disc such as rings or gaps. Here we report on a mirrored double crescent pattern arising in simulations of discs harbouring a small, moderately eccentric planet - such as Mars. We show that the structure is a result of a directed apsidal precession occurring in particles that migrate the planet's orbital region under Poynting-Robertson drag. We further analyze the strength of this effect with respect to planet and particle parameters.

Keywords. Circumstellar matter, meteoroids, celestial mechanics

1. Overview

The zodiacal cloud, a circumsolar disc of dust, has long been known to pervade the space inhabited by the planets. Constantly replenished by comets and asteroids, dust grains from 10s to 100s of microns in size slowly migrate inward under Poynting-Robertson drag, until being destroyed in the vicinity of the Sun. As the dust moves inward, its spatial distribution is shaped by the gravitational interaction with the planets, whose orbital regions it traverses. The emerging structures, known to exists not only in our own solar system but also around distant stars, can act as signatures of planets and have been subject of numerical as well as observational studies (e.g. Jackson and Zook (1989); Wyatt et al. (1999); Stark and Kuchner (2008)). A recent numerical study primarily concerned with resonant structures arising in the zodiacal cloud hinted at a further feature forming mechanism associated with the planet Mars, which embodied as a mirror-inverted double crescent pattern, locked to the apseline of the planet (Sommer et al. 2020).

In this follow-up, we revisit the structure's formation principle and analyse the strength of this effect with respect to planet, as well as particle parameters. Figure 1 shows the simulated surface density of a disc made up of particles of one discrete size harbouring a Mars-like planet, posing an example of the aforementioned structure. The effect of the planet on the disc manifests as a crescent with increased particle density, roughly spanning the inbound—that is from apocentre to pericentre—half of the planet orbit, and a mirrored but density-wise inverted crescent, spanning the outbound half of the

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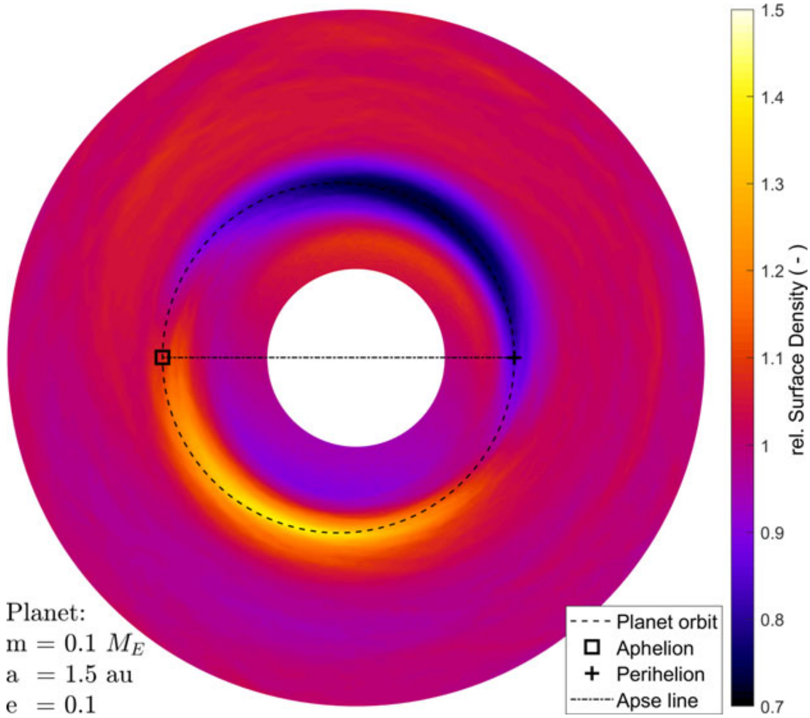

Figure 1. Exemplary surface density arising in a system with a Mars-like planet. The density distribution is normalized to the one produced by a simulation without planet but otherwise unchanged parameters. The orbital elements of the initial particle population are uniformely distributed in: 2.1 au $\leqslant q \leqslant$ 2.4 au, $0 \leqslant e \leqslant 0.5$, and $0^\circ \leqslant i \leqslant 20^\circ$. ($q$: pericentre distance, e: eccentricity, i: inclination). Ratio of forces acting on particles resulting from central star radiation pressure and central star gravity used here is: $\beta = F_{r\star}/F_{g\star} = 0.002$.

planet orbit. This can be explained by the evolution of longitude of pericentres, ϖ, of particles as they migrate the planet's orbital region, driven by Poynting-Robertson drag. As displayed in Fig. 2 (a), upon droping inside the planet orbit, the orbit of a typical particle starts to experience an apsidal drift that is maintained until it revolves entirely within the planet orbit. Effectively, the orbit dacay is accelerated in the region that the pericentre rotates towards and halted in the region that the apocentre rotates towards, apparent in the varying gap width between the *before* and *after* orbits (indicated in blue color in Fig. 2 (a)). Due to the asymmetric decay, the cumulated particle dwell time is lengthened in the region of halted decay, and shortened in the other. Thus, the opposed depletion-enhancement zones are consequential, if all particles experience an apsidal drift with a preferred final apse line orientation relative to that of the planet. This is evident in Fig. 2 (b), showing the relative frequency distribution of ϖ for all particles making up the synthetic disc over bins of their semi-major axes. When still distant from the planet, at semi-major axes larger than 2 au, particle pericentres start off distributed uniformely. However, once particle's semi-major axes decrease below the planet's aphelion distance, an alignment of their apselines occurs, with ϖ reaching a relative frequency of a factor of 3 over that of the uniform distribution, at a longitude around 60° to 80° ahead of the planet pericentre. This aggregation of particle pericentres along the outbound half of the planet orbit (corresponding to positive longitudes in Fig. 2 (b)) confirms the asymmetric orbit decay within the whole particle population, thus generating the opposed depletion-enhacement structure.

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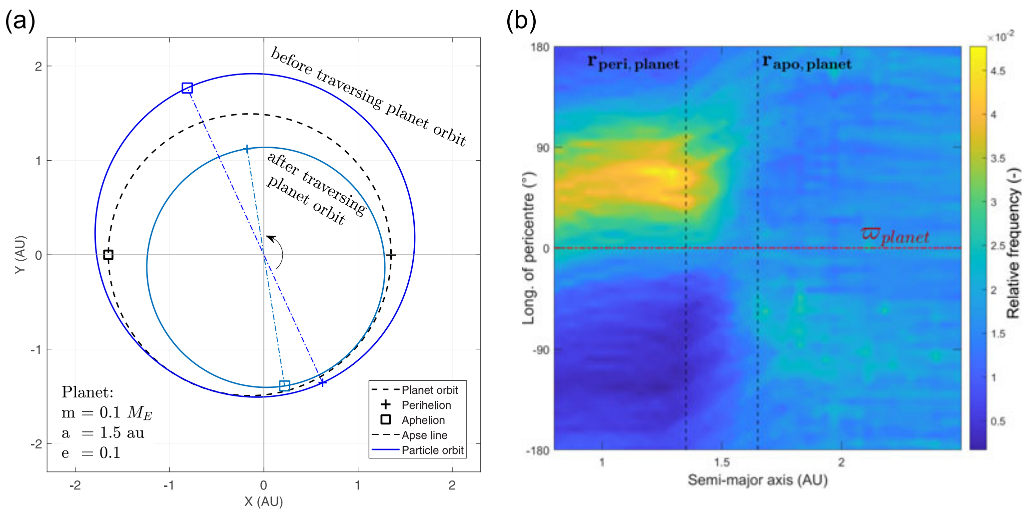

Figure 2. (a) Apsidal precession of an exemplary particle ($\beta = 0.002$, $i = 7°$, no close enctounter with the planet occurred) as it traverses the orbital region of a Mars-like planet under PR-drag. The particle's orbit is shown before and after crossing the planet orbit. (b) Evolution of the distribution of ϖ in a migrating particle population (same as that used in Fig. 1). Relative frequency of ϖ is recorded at semi-major axis bins of 0.035 au and is normailized for each bin.

2. Conclusions

We have run simulations with a multitude of planet and particle population parameters (with mass of the central star fixed at 1 solar mass). We conclude that the effect favours particles less influenced by radiation ($\beta < 0.01$), as well as moderate particle eccentricities ($e < 0.4$) and inclinations ($i < 20°$). The formation of these crescents most strongly occurs in the presence of low-mass (0.1 to 0.3 Earth-masses) planets of moderate eccentricity ($0.1 \leqslant e \leqslant 0.2$) and with a semi-major axis of 1.5 au to 5 au. For heavier planets and/or planets further out, the crescents disappear in favour of enhacements caused by resonant trapping or distant secular perturbation (akin to Wyatt et al. (1999)), as the planets' capacity to influence particles outside their orbital region increases. The fact that these features are readily produced by sub-Earth-mass planets, which are incapable of clearing a gap in the vicinity of their orbit or produce a meaningful resonant enhancement is especially noteworthy. In light of ongoing advances in observational astronomy and our increasing capability to resolve structures in exozodiacal clouds, these findings may become relevant in tracking down exoplanets in a planet-mass regime hardly accessible through other methods.

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