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Chaos in the inert Oort cloud

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Abstract

We investigate the orbital dynamics of small bodies in the intermediate regime between the Kuiper belt and the Oort cloud, i.e. where the planetary perturbations and the galactic tides have the same order of magnitude. We show that this region is far less inert than it could appear at first sight, despite very weak orbital perturbations.

1. Introduction

The orbits of distant trans-Neptunian objects are subject to internal perturbations from the planets, and external perturbations from the galactic tides. A distinction is generally made between the Kuiper belt and the Oort cloud, which are thought to have been initially populated through distinct mechanisms (see e.g. the recent review by [4]). However, there is no dynamical boundary between the two populations, and numerical simulations show a continuous transfer of objects in both ways (see e.g. [2]). This means that objects initially perturbed mostly by the planets are driven into a region where the galactic tides dominate, and vice versa.

There actually exists a transitional region, called here the "inert Oort cloud", where both kinds of perturbations are weak but have the same order of magnitude. Strong orbital perturbations could only have occurred there in the early evolutionary stages of the solar system. Therefore, it contains objects that are "fossilised" (or "detached"), like Sedna [1], 2012 VP_{113} [7] or 2015 TG_{387} [6].

However, a clear understanding of where the transition occurs is still missing, as well as the behaviour of small bodies when they cross the limit. Our aim is to characterise the long-term dynamics of the inert Oort cloud, driven by the perturbations from both the galactic tides and the giant planets. In particular, we will draw a quantitative picture of the timescales at play in this region.

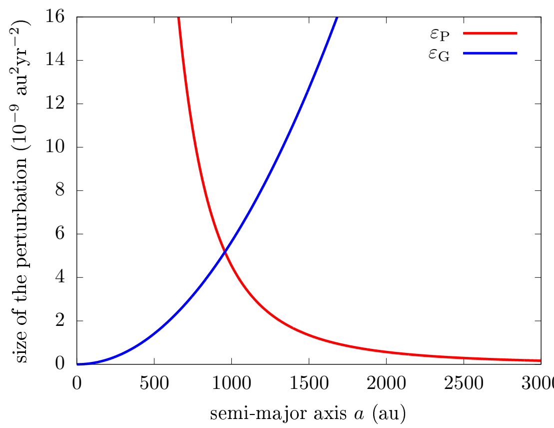

Figure 1: Size of the small parameters appearing in the Hamiltonian function (Eq. 1) with respect to the semi-major axis of the small body. The red curve represents the planetary perturbations, and the blue curve represents the galactic tides.

2. Overview of the dynamics

The Hamiltonian function governing the long-term orbital dynamics of a small body subject to both planetary and galactic perturbations can be written as

$$\mathcal{H} = \varepsilon_P \mathcal{H}_P + \varepsilon_G \mathcal{H}_G \,, \tag{1}$$

where the index P refers to the planetary perturbations and the index G refers to the galactic tides. Using suitable expansions of the perturbing terms, the small parameters ε_P and ε_G can be expressed as functions of the semi-majox axis a of the small body.

Figure 1 shows that at about 1000 au the two kinds of perturbations have the same order of magnitude. Much below this limit, the planetary perturbations dominate, and much beyond this limit, the galactic tides dominate. The dynamics in these two extreme regimes is well known [3, 5] and can be modelled by on-degree-of-freedom integrable systems. In the intermediate regime, the dynamics have two degrees of freedom. As illustrated in Fig. 2, Poincaré sections

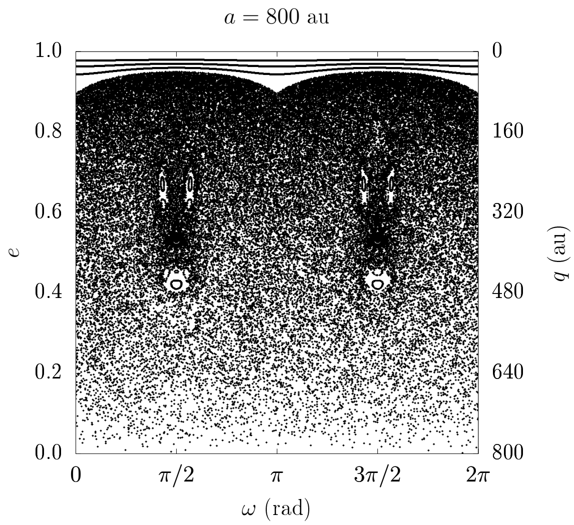

Figure 2: Example of Poincaré section obtained for $a = 800$ au, represented in the plane of the argument of perihelion ω, and the eccentricity e. Continuous lines are regular trajectories, and small dots are chaotic regions.

reveal very large chaotic zones. Based on a systematic exploration of the parameter space, we will describe their locations, compute the associated diffusion timescales, and investigate the implications for large samples of small bodies, including the known distant trans-Neptunian objects.

3. Summary and conclusion

We study the long-term orbital dynamics of the inert Oort cloud, i.e. the region where both the planetary perturbations and the galactic tides are weak, but have the same order of magnitude. The dynamics is integrable when one kind of perturbation or the other is set to zero, but highly chaotic in the intermediate regime, between about 700 and 1200 au. The diffusion timescale of the perihelion distance decreases with the semi-major axis. This diffusion can lead to large orbital changes in a few billion years for semi-major axes as small as 800 au. Even though frozen orbital regions do exist (this is the case for Sedna and 2012 VP_{113}), we conclude that this region is far from being "inert", contrary to what one could expect from the weakness of the perturbations. Hence, we advocate including the galactic tides in any numerical simulation of trans-Neptunian objects with semi-major axes larger than 500 au.

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