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STRIPPING A DEBRIS DISK BY GRAVITATIONAL INTERACTION WITH AN INNER PLANET

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Abstract. Debris disks are detected through scattered light or thermal emission of their dust, produced by collisions or erosion of planetesimals. The rate of collisions depends on the number density of planetesimals and on the dynamical excitation and geometry of the disk. We have studied a debris disk gravitationally perturbed by a single inner planet, by using a numerical integration over a large parameter space for both the orbital elements of the planet and the disk geometry. We discuss our findings in the context of observed orbital elements for exoplanets and plausible disk geometries.

We have studied whether or not a disk can be significantly disrupted, and stripped of its planetesimals, because of this interaction. We have focused on how the depletion of the disk depends on the masses of the central star and planet. We have found that this dependence is not monotonous, except for low mass stars.

Keywords: circumstellar disks, extrasolar planetary systems

1 Introduction

According to theory, a debris disk is made of planetesimals which are the left over of the processes that have formed planets, in the inner part of the system, during the first 10 Myrs. Afterwards, planets can dynamically excite the disk (Mustill & Wyatt 2009), or even can strip it of its planetesimals, as in the Nice model with Neptune and Uranus put on eccentric orbits when Jupiter and Saturn went through a MMR (Gomes et al. 2005). The fraction of planetesimals stripped off the disk depends on the planet orbital parameters (semi-major axis and eccentricity) and mass, as well as on the central star mass and disk properties (inner and outer radii, thickness, and radial distribution of planetesimals). We have undertaken a search of the parameter space of this problem.

A large variety of eccentricities and masses have been found among the ∼700 exoplanets discovered since 1995. For example, their eccentricities range from 0 to 0.97 (17% have high eccentricities > 0.4, see Fig. 1) and their masses ($m \sin i$) range from 3 Earth masses to more than 10 Jupiter masses. These planets are strongly biased toward small orbital radii because of the radial velocity technique and transit observations used for most of the discoveries. Hence, we use instead the Solar System as a guide for plausible orbital radii.

In this first report, we present our study on how the fraction of planetesimals stripped off a disk depends on the masses of the star and planet, non-monotonously according to our finding.

2 Methodology

We have numerically integrated the motion of planetesimals in the disk under the sole influence of the gravitational forces of the central star and the planet ; i.e. the restricted three body problem for the non self-gravitating disk. We use a leapfrog integration scheme. The time step (0.5 day) was adopted after various convergence tests.

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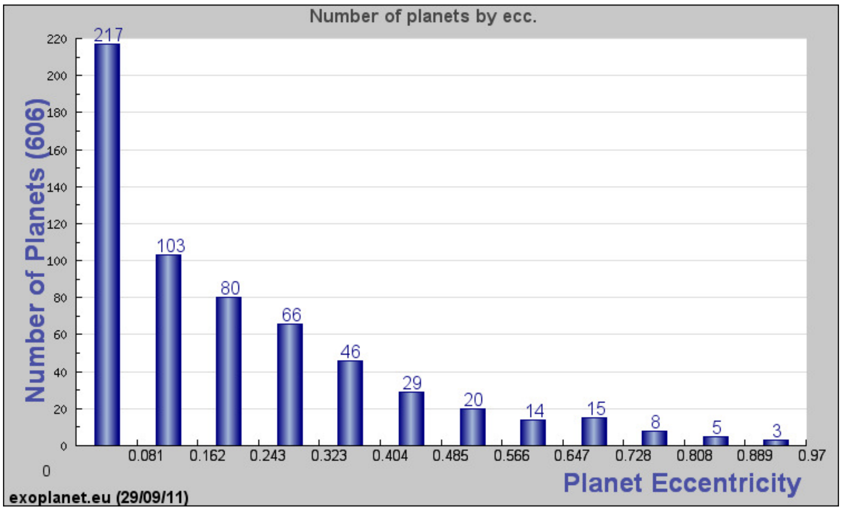

Fig. 1. Histogram of eccentricity of currently known exoplanets (`http://exoplanet.eu/`).

The disk is made of 1000 massless particles, sufficient in number to properly estimate the fraction of planetesimals that leave the system on unbound orbits. Our result below is based on integrations over 100 Myrs. A few integrations were run over 200 Myrs and 500 Myrs to probe the longer term evolution which is not significant except for low mass planets (see Fig 2).

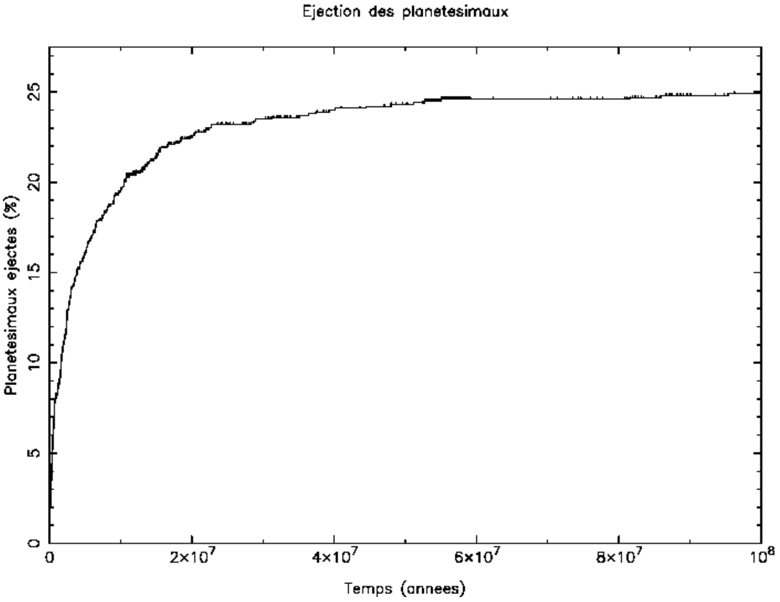

Fig. 2. Ejection fraction of planetesimals, according to time, for a disk surrounding a solar mass star and a Jupiter mass planet orbiting at $a = 20$ AU with $e = 0.5$ ($m_{pl}/m_* = 10^{-3}$). For lower ratio m_{pl}/m_*, the curve saturates less rapidly over 100 Myrs and may underestimate the final ejection fraction by 10-20%.

The initial edges of the disk are set at 30 and 80 AU. Integrations are carried out in a three-dimensional space : the thickness of the initial disk is 1 AU at the inner edge, and 2.8 AU at the outer edge (opening angle $= 2°$). The planetesimals in the disk are initially set on circular orbits. The surface density of planetesimals decreases as $1/r$.

3 Results and discussion

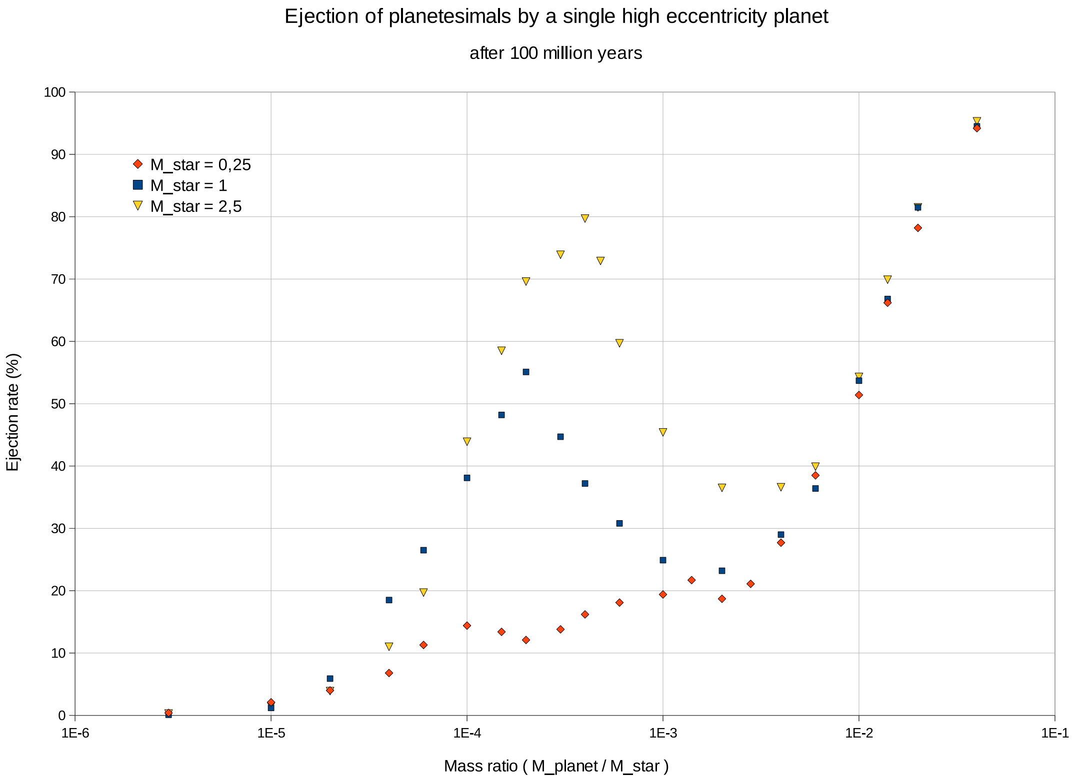

Fig. 3. Fractions of planetesimals stripped off a disk versus the ratio of planet and star masses, after 100 Myrs, by a single planet at $a = 20$ AU and with $e = 0.5$. The apoapsis of the planet is located at 30 AU of the star, which corresponds to the inner edge of the disk. The outer edge is placed at 80 AU. Three star masses are adopted : 2.5, 1. and 0.25 solar mass (spectral types : A, G and M). Each point corresponds to a full integration of 100 Myrs.

Current results are shown on Fig. 3. For each of the three star masses (A, G, M spectral types), the points delineate three regions :

1. for low mass ratios ($m_{pl}/m_* < 2.10^{-5}$), the ejection fraction asymptotically vanishes, as expected because the low planet mass cannot perturb the disk sufficiently.
2. for high mass ratios ($m_{pl}/m_* > 6.10^{-3}$), the ejection fraction depends solely on the mass ratio, and the disk can be completely stripped for the most massive planets.
3. for the intermediate range $2.10^{-5} < m_{pl}/m_* < 6.10^{-3}$, the ejection fraction depends on the masses of the star and planet, independently. In this range, there is an enhancement of the stripping which is counter-intuitive ; for example, a Jupiter mass planet strips the disk more efficiently around an A star (peaking at ~80%) than around a G or a M star (~25%). Similarly, a six Jupiter mass planet around an A star ejects less planetesimals than a one Jupiter mass planet around the same star (36% vs 80%). In this intermediate range, for the same mass ratio, the higher the star mass is, the higher the ejection fraction is.

4 Conclusion and perspectives

We have shown that the ejection fraction in a debris disk perturbed by an inner eccentric ($e = 0.5$) planet is clearly not monotonous as a function of m_{pl}/m_*. The enhanced ejection fraction of planetesimals for relatively low m_{pl}/m_* could make debris disks around A star less frequently observable. Current observational data show the opposite trend (∼30% of A stars have observable disks, ∼15% for F, G and K stars, and 5% for M stars), however this trend is not corrected for observational bias (it is easier to detect "cold" dust in disks around A stars, than "very cold" dust in disks around M stars).

We are currently in the process of studying the analytical justification (mean motion resonances, orbit precession, . . .) for this numerical result.

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References

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