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Extreme, variable debris disks produced by giant impacts during terrestrial planet formation

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Abstract

Giant impacts between planetary scale bodies release large quantities of debris into their host systems. This debris, especially vapour condensates, may be extremely bright and optically thick. The variation in the shape of the dust cloud as it orbits the star, and undergoes Keplerian shear, can lead to large variations in the optical thickness, and consequent large variations in the observed flux, producing complex light-curves. By studying the light-curves of these extreme debris disks we can gain a powerful probe into the properties of the forming planets in the system.

1. Introduction

Debris discs are traditionally taken to be low density, optically thin environments, however in the case of debris discs produced as the result of a giant impact between planetary scale bodies this may not be the case.

The collision of two planetary scale bodies is inherently a rather violent event. The material of the bodies will be subject to powerful shocks, which can be sufficient to vaporise the material. Even for a comparatively 'gentle' giant impact like the canonical Moon-forming scenario vaporises 10-30 per cent of the material (Canup, 2008).

Once material has been vaporised and launched into planetary or heliocentric orbit it will expand and cool, rapidly condensing into mm-cm scale droplets (Johnson & Melosh, 2012). One per cent of an Earth mass in mm-size particles has a total surface area of around 3 AU^2 (absorbing area of 0.75 AU^2). With such an enormous absorbing area it is clear that optical thickness will play a significant role.

We present a framework for the optical thickness of debris released in giant impact events and use simple models to discuss the observational effects on the resulting disks, particularly focusing on the appearance of variability in the very early stages. We discuss the application of our work to the newly discovered class of extreme (and variable) debris disks, as exemplified by ID8 (Meng et al., 2014), and to the giant impact stripping of the Mercurian mantle, and illustrate how this can allow us to gain new insights into forming systems of terrestrial planets.

2. Modelling approach

We adopt the formalism of Jackson et al. (2014) and describe the debris release in terms of the scaled velocity dispersion $\sigma_v = \Delta v / v_k$, where Δv is the (Gaussian) width of the velocity distribution, and v_k is the circular Keplerian speed at the collision-point. We expect σ_v to scale approximately as the escape velocity of the progenitor body (Leinhardt & Stewart, 2012, e.g.), and so σ_v can be used as a proxy for mass. Similarly the Keplerian speed is a proxy for orbital distance ($v_k \propto a^{-1/2}$), and thus the behaviour of giant impact debris depends on both the mass of the progenitor and on the orbital distance at which the impact occurs.

To track the dynamics of the debris we use the Mercury N-body integrator (Chambers, 1999) with at least 10^5 particles per simulation. Since these N-body integrations are computationally expensive, using σ_v / v_k as the primary variable determining the dynamics of the debris allows us to explore a wider range of progenitor masses and orbital distances.

Optical thickness is tracked by assigning N-body particles a cross-sectional area and projecting them onto a surface to determine overlap between them.

3. Discussion

There are two sources of optical thickness in observations of a debris disk, 'internal' and 'line-of-sight'. Internal optical thickness is intrinsic to the disk and arises when the disk is optically thick to the light from the central star. Internal optical thickness will be higher if the debris is more spatially concentrated, either azimuthally in a clump or small arc, or vertically in a very thin structure. Line-of-sight optical thickness on the other hand arises as a result of our viewing geometry meaning that certain sight lines pass through

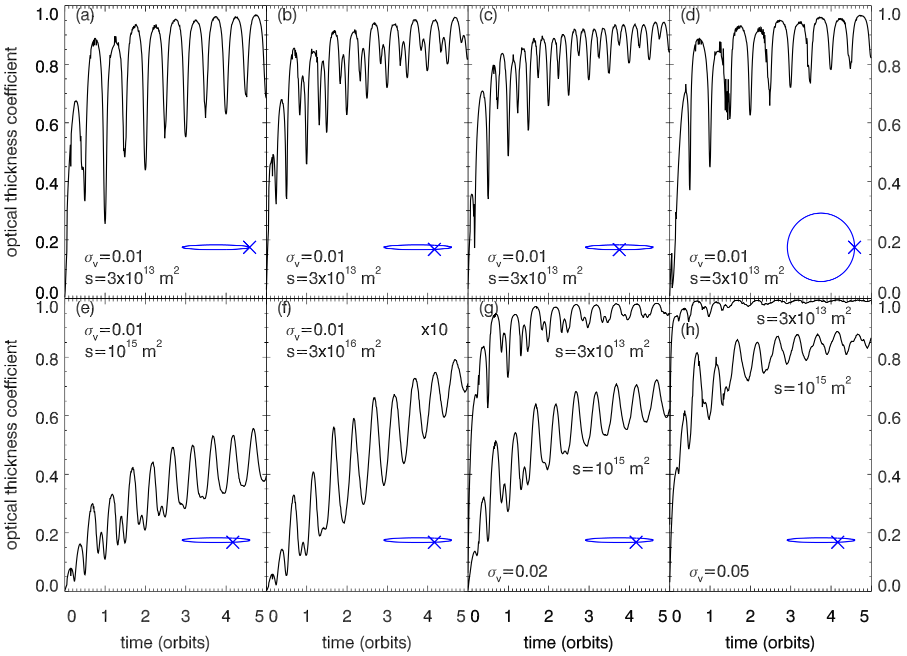

Figure 1: Variation of the optical thickness coefficient over time for a selection of different system parameters. The optical thickness coefficient is the visible emitting area divided by the total surface area of the cascade, s (indicated in each panel, and below each curve in panels (g) and (h)). Time is measured in orbits since the initial impact. The scaled width of the velocity dispersion, σ_v, is also given in each panel. The viewing orientation of the system is shown in blue in the lower right of each panel, where the cross shows the location of the collision-point. Note that the curve in panel (f) has been scaled up by a factor of 10, as indicated in the top right of the panel.

a sufficient column density of material to be optically thick. Line-of-sight optical thickness is clearly most likely to occur in an edge-on viewing geometry.

It is entirely possible for a disk to have a large internal optical thickness while being optically thin along the line-of-sight (e.g. a razor-thin disk viewed face-on), or to be optically thin internally but optically thick along the line-of-sight (e.g. a vertically puffy disk viewed edge-on), or anywhere in between.

As the cloud of dust released in the initial impact travels around the orbit and changes shape due to passage through the collision-point (site of the original impact) and the anti-collision line (the opposing node), and over longer timescales is sheared by differential rotation, the optical thickness of the cloud can undergo large variations. Large variations in optical thickness correspond to large variations in the absorbing and emitting area of the cloud and so to large variations in the observed flux. The interplay between internal and line-of-sight optical thickness can lead to complex light-curves including apparently bi-periodic oscillations, as illustrated in Fig. 1.

By conducting detailed studies of the light curves of extreme, variable debris disks produced by giant impacts we can gain access to the properties of the progenitor bodies.

References

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