Dust Avalanches in Debris Disks

Collisions as an origin for asymmetric structures

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Introduction

Asymmetric structures & their origins:

The dust distribution in circumstellar disks is not always smooth & axisymmetric. Warps, clumps, spirals and other types of asymmetries are commonly observed. These morphological features can provide hints on important ongoing processes in the disks and improve our understanding of the evolution of circumstellar disks and of planetary formation.
The most popular explanation proposed for the observed structures is the perturbing influence of a bound (stellar or planetary) companion or of a stellar flyby. But is it the only possibility?
An alternative explanation for some asymmetries could be the catastrophic breakup of a large object(s) releasing a substantial amount of dust. Kenyon & Bromley (2005) published a detailed study on the possibility of detecting a catastrophic 2-body collision in debris disks. However only debris produced directly by the shattering event were taken into account. We re-examine the consequences of an isolated shattering impact taking into account the collisional evolution of the dust cloud after its release by the shattering event.

What is a collisional dust avalanche?

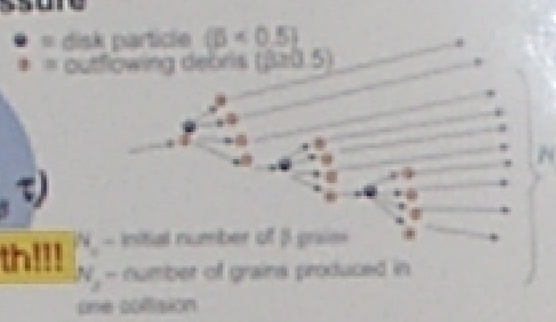
a chain reaction of outflowing debris striking particles creating even more debris accelerated by star's radiation pressure

Basic principal:

$dN = N_0 N_\beta d\tau$

$N_{tot} = N_0 \exp(N_\beta \tau)$

Exponential growth!!!

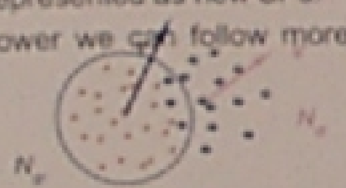


Method:

Resolution both in Space & Size

- We use a SuperParticle (SP) representation method
- Grains with similar parameters (sizes, spacial coordinates and velocities) are grouped in so-called SuperParticles.
- We follow the dynamical evolution of the SPs and calculate the collisional destruction rate of grains when SPs pass through each other.
- The newly created debris are represented as new SPs.
- With the current computing power we can follow more than 10^5 SPs.

Superparticles



Main model parameters:

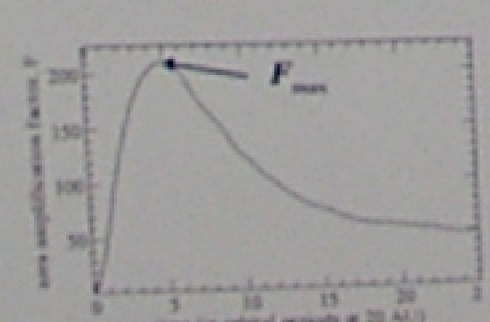
The disk:
β Pictoris disk is taken as a reference case for a dusty disk. Alternative dust distributions have also been explored. The results are nearly independent on a particular dust distribution if the midplane optical depth is the same.
The minimum size for the disk grains is 2µm and is restricted by the blown-out-cut-off. The maximum size is taken 1cm. Disk grains' size-frequency distribution is a single power law:
$dn = n(s/s_0)^p ds$ with $p = -3.5$ (Eq.1)
The radiation pressure forces are calculated in accordance with Mie theory using a code developed by Artymowicz (1988).

Cometary debris:
The initial source of an avalanche is a break-up of a cometary-like object. We do not perform a simulation of the break-up but just assume that M_0 (10^{20}g) of dust is released at a distance R_0. The fragments' size spectrum is a single power law (Eq.1) in the 1µm to 1cm range. The strength of an avalanche varies linearly with M_0.

Collisional outcomes:
For grains' collisional fragmentation we use the prescription from Petit & Farinella (1993) applied to a two-segment power law for the size-frequency debris distribution: $dn = n(m/m_0)q$ where $q = -1.5$ for $m < m_0$ and $q = -1.83$ for $m \geq m_0$. The threshold specific energy is a function of the gain size, $Q^* \sim s^{-0.2}$, and $Q^*(s=1cm) = 10^7$erg/g.

The amplification factor F & F_{max}:

We quantify the strength of an avalanche by **an amplification factor, F, which is the ratio of the total cross-sectional area of avalanche grains within 500 AU from the star to the initial area of cometary debris released.**

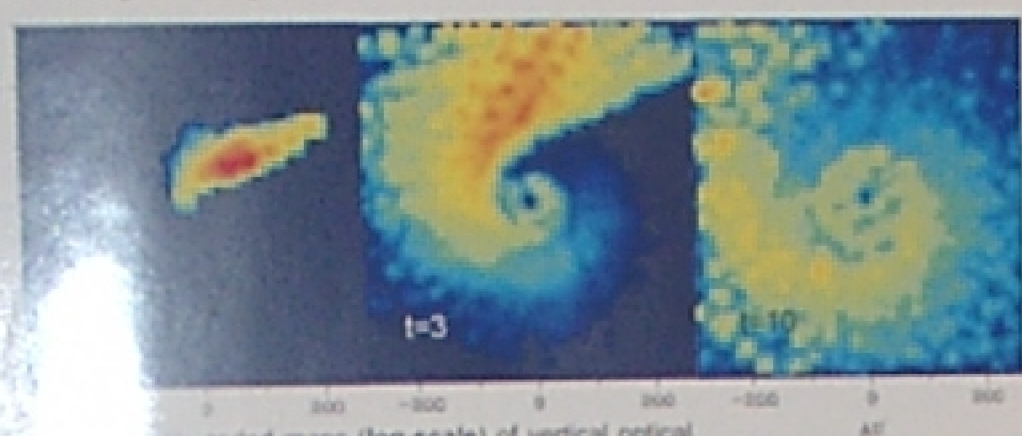


The amplification factor initially increases with time due to collisional dust production (Fig. 2) but then decreases as grains on unbound orbits leave the system despite of the ongoing collisions. The maximum value, F_{max}, is used to compare between different runs since in many cases the general avalanche shape is preserved.

Main Results I

Avalanche in a β Pic-like disk:

Successive stages of an avalanche propagation in β Pic disk (Fig.1). The cometary debris (10^{20}g) are released at R_0=20AU from the star (at t=0). If the system is viewed face-on the vertical optical thickness is about tree orders of magnitude less than that of the disk (see Fig.2). Time is in units of the orbital period at R_0=20AU (t_0~70 yrs).



...-coded maps (**log-scale**) of vertical optical ...valanche grains at different time stages. Only ... which have been created by collisions of ...rticles with disk grains are plotted.

Figure 2. Color-coded maps (**log-scale**) of the ratio of the avalanche vertical optical thickness to the disk optical thickness.

For observations in the visual domain (~0.5 µµ), dominated by scattered starlight, the ratio of the luminosity by the avalanche grains to the one by the "field" material can be taken as the ration of the respective optical thicknesses: $L_{av}/L_d = \tau_{av}/\tau_d$. Thus as can be seen from Fig. 1a, in the nominal case L_{av}/L_d never exceeds 10^{-2}. It means that this avalanche would probably be undetectable.
In order for an avalanche become visible in β Pic disk a 10-100 times bigger amount of dust should be released by the initial planetesimal break-up.

Probability of witnessing an avalanche (gas-free case):

The probability can be computed as : $P_{obs} = t_{av}/t_{shat}$, where t_{av} is the typical lifetime of an avalanche-induced pattern, and t_{shat} is an average time between two shatterings at which an amount of dust, required for an "observable" avalanche is released. The latter parameter is difficult to estimate, since for this we need to know the initial size of a planetesimal, which releases the required amount of dust, and how many such objects are present in the system. Assuming different power indexes (p=3.5-3.9) for the planetesimal debris distribution, we get that the initial size of the object needed for our nominal case can be in the range 50 - 500 km! **For β Pic disk we get that the probability can be in the range 10^{-4}-0.1.**
The dustier the system, the smaller the object size needed to produce an observable avalanche. And the probability increases significantly for such systems. In a disk which is just 2 times dustier than βPic the probability raises till 1.

Presence of gas:

Systems dustier than βPic are expected to be younger and contain more gas. Modeling of them may require inclusion of gas drag, which would change both the morphology & the strength of the avalanche.

The correct description of dust-gas coupling might require a full 2D or 3D treatment of gas (SPH or Hydrocodes). However one can get a simple estimate using an analytical prescription for the gaseous disk.

Gas friction damps the radial velocities of dust grains. This leads to a decrease of the grain relative velocities which makes the process of collisional dust destruction significantly less efficient.

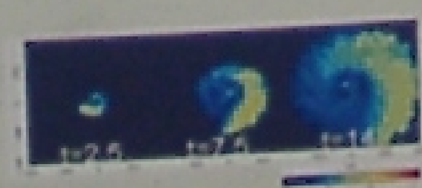


Figure 6. Color-coded maps (**log-scale**) of the vertical optical thickness of the avalanche grains in a system with $0.5M_\oplus$ of gas. The main parameters for the gas disk are taken from Takeuchi et al. (2001).

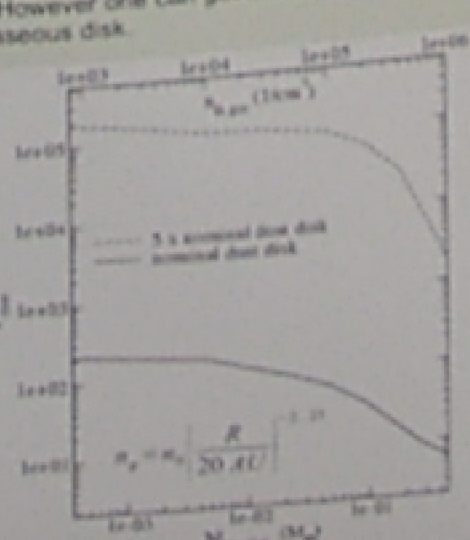


Figure 7. F_{max} as a function of the total amount of gas present in the system.

Main Results II

Avalanche-induced asymmetric structures:

Results for the disk, which is ~3 times dustier than β Pic

Azimuthal asymmetry

in pole-on orientation

Notice that we use here a linear brightness scale, and the avalanche looks more like a blob, not a spiral.

Two-sided asymmetry

in edge-on orientation

If the same system is viewed edge-on then a two-sided asymmetry can be observed, when one side of the disk becomes brighter than the other due to the contribution from the avalanche grains.

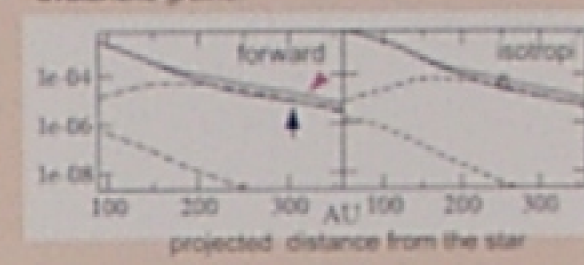


Fig.5 Midplane fluxes (arbitrary units) for the edge-on orientation. The solid lines indicate the the total fluxes for two sides of the system. The dashed lines show the avalanche contribution. Two different scattering functions were used.

How to get a powerful avalanche:

- **Large initial dust release:**

The most straightforward way of getting a more prominent avalanche is to start with a bigger amount of dust released in the initial planetesimal breakup. This can be achieved by e.g. a shattering of a bigger object. For the nominal, β Pic-like disk, we need ~10^{22}g of the planetesimal dust in order to have L_{av}/L_d~1.

- **Collisionally weak grains:**

Grains with lower specific energy values, Q*, can be easier disrupted, as a result an avalanche, developing in a system populated with such grains is stronger. For $Q^*(s_p=1cm)=10^6$erg/g (against 10^7erg/g for the nominal case) we get that $L_{av}/L_d = \tau_{av}/\tau_d$~0.5.

- **A brighter star:**

For the same disk configuration, avalanches are more powerful around more luminous stars. E.g. for a disk with $\tau_{mid}(R)$ dependence as in the nominal case, F_{max} depends on the central star luminosity as following:

Fomalhaut ($16L_\odot$)	650
HR4796A ($20L_\odot$)	1.5×10^3
Vega ($31L_\odot$)*	10^4

*However, since Vega disk has significantly lower optical thickness than our nominal case, we cannot expect powerful avalanches around Vega.

- **Denser dusty disk:**

The "dustiness" of the disk is the most important parameter for the avalanche propagation. The dependence is nearly exponential (see Fig.4).

The value of $\tau_\parallel$ depends on the total amount of dust in the system and the dust vertical distribution. Thus we can expect strong (detectable) avalanches in a disk (i) more dusty than β Pic **or** (ii) with similar amount of dust but distributed in a geometrically thinner disk.

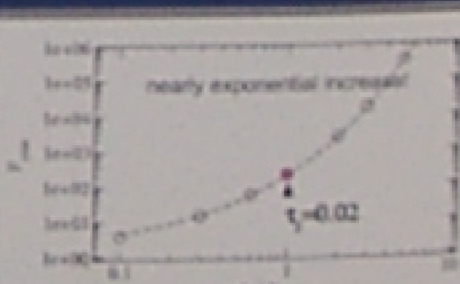


Fig. 4 Maximum amplification factor as a function of the optical depth in the disk midplane, $\tau_\parallel$. The red circle marks the nominal case.

Summary

- **First quantitative study of the avalanche mechanism,** (*Grigorieva, Artymowicz & Thébault, A&A, 2007*)
- **A powerful mechanism**: amplification factor >100, triggers significant **asymmetries.**
  The avalanches are most powerful *if*:
  i) they originate in the **innermost part** of the disk;
  ii) the system is **gas-free** with a relatively dense dust population;
  iii) the dusty grains experience higher radiation pressure or are **more easily disrupted** in collisions
- **Observability** strongly dependent on disk dustiness. Moderate collisional dust clouds suffice for observability in disks dustier than βPic. Otherwise larger impacting bodies are needed (but improbable!)
- Can be observed as **spirals or "blobs".**

References:
Artymowicz, P. 1988, ApJ, 335, L79
Kenyon, S. J. & Bromley, B. C. 2005, AJ, 130, 269
Petit, J.-M. & Farinella, P. 1993, CeMDA, 57, 1
Takeuchi, T. & Artymowicz, P. 2001, ApJ, 557, 990