Stellar Winds and Dust Avalanches in the AU Mic Debris Disk

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Abstract

We explain the fast-moving, ripple-like features in the edge-on debris disk orbiting the young M dwarf AU Mic. The bright features are clouds of submicron dust repelled by the host star’s wind. The clouds are produced by avalanches: radial outflows of dust that gain exponentially more mass as they shatter background disk particles in collisional chain reactions. The avalanches are triggered from a region a few au across—the “avalanche zone”—located on AU Mic’s primary “birth” ring at a true distance of ~35 au from the star but at a projected distance more than a factor of 10 smaller: the avalanche zone sits directly along the line of sight to the star, on the side of the ring nearest Earth, launching clouds that disk rotation sends wholly to the southeast, as observed. The avalanche zone marks where the primary ring intersects a secondary ring of debris left by the catastrophic disruption of a progenitor up to Varuna in size, less than tens of thousands of years ago. Only where the rings intersect are particle collisions sufficiently violent to spawn the submicron dust needed to seed the avalanches. We show that this picture works quantitatively, reproducing the masses, sizes, and velocities of the observed escaping clouds. The Lorentz force exerted by the wind’s magnetic field, whose polarity reverses periodically according to the stellar magnetic cycle, promises to explain the observed vertical undulations. The timescale between avalanches, about 10 yr, might be set by time variability of the wind mass loss rate or, more speculatively, by some self-regulating limit cycle.

Key words: protoplanetary disks – stars: individual (AU Microscopii) – stars: winds, outflows – zodiacal dust

1. Introduction

Dust in debris disks originates from collisional cascades. The largest bodies, comprising the top of the cascade, have lifetimes against collisional disruption equal to the system age, tens of Myr or longer. They grind down into particles micron-sized or smaller at the bottom of the cascade. These tiny particulates are blown out of the system, typically by stellar radiation pressure, on orbital timescales of tens to thousands of years. For a general review of debris disks, see Matthews et al. (2014).

Quasi-steady cascades, in which the rate of mass erosion is constant from top to bottom (e.g., Dohnanyi 1969; Pan & Sari 2005; Wyatt et al. 2011), offer a ready framework for modeling debris disks on the longest of evolutionary timescales (e.g., Lühne et al. 2008; Wyatt 2008; Gáspár et al. 2013). At the same time, there are increasingly many observations demanding that we resolve our theories more finely, both in space and time, and accommodate more stochastic phenomena. Mid-infrared excesses that are unusually strong given the Gyr ages of their host stars are thought to signal recent catastrophic collisions or sudden comet showers (e.g., Beichman et al. 2005; Song et al. 2005; Wyatt et al. 2005; Weinberger et al. 2011; Kennedy & Wyatt 2013). Fast time variability in the infrared, on timescales of months to years, has been interpreted as tracing the immediate aftermath of a giant plume-inducing impact (Meng et al. 2014; see also, e.g., Kenyon & Bromley 2005; Melis et al. 2012; Kral et al. 2015).

Of all the short-timescale phenomena reported for debris disks, perhaps the most surprising and least understood is the discovery by the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) team of fast-moving features in the AU Mic edge-on debris disk (Boccaletti et al. 2015). The features appear as intensity variations at projected stellocentric separations of ~10–50 au and are seen only on the southeast ansa of the disk. They travel away from the star at projected speeds comparable to—and for the most distant features exceeding by a factor of ~2—the system escape velocity. The features also appear undulatory; the ones closest to the star are elevated by an au or so above the disk midplane (see also Schneider et al. 2014 and Wang et al. 2015).

Taken at face value, the faster-than-escape velocities and the trend of increasing velocity with increasing stellar separation suggest that the brightest features are coherent “clouds” of dust accelerated radially away from the star by a force stronger than the star’s gravity by a factor of 10 (Sezestre et al. 2017). We will adopt this simple interpretation. The fact that the clouds are seen to only one side of the star, together with the recognition that most of the mass in the underlying disk is concentrated in a “birth ring” of radius ~35 au (Augereau & Beust 2006; Strubbe & Chiang 2006), suggests that the clouds are launched from the birth ring—from the side of the ring nearest the observer, so as to appear bright in forward-scattered starlight—at a special azimuthal location lying directly along the observer’s line of sight to the star. Then the clouds simply inherit the orbital motion of the birth ring, whose near side must rotate from the northwest to the southeast to send the clouds to the southeast.

The host star’s wind can generate, for sufficiently small grains, the required radially outward force of magnitude $\beta_w$ relative to stellar gravity:

$$\beta_w \equiv \frac{3M_p v_{wind}}{16\pi G M_* \rho_p s}.$$  

$$\sim 4 \left( \frac{M_p}{10^3 M_\odot} \right) \left( \frac{v_{wind}}{400 \text{ km s}^{-1}} \right) \left( \frac{0.1 \mu\text{m}}{s} \right).$$  

(1)
where $G$ is the gravitational constant, $M_* = 0.6 \, M_\odot$ is the stellar mass (Boccaletti et al. 2015), grains are assumed spherical with internal bulk density $\rho_p \sim 1 \, \text{g cm}^{-3}$ and radius $a$, and $v_{\text{wind}}$ and $M_*$ are the stellar wind’s speed and mass loss rate, with the latter scaled to the solar mass loss rate $M_\odot = 2 \times 10^{-14} \, M_\odot \, \text{yr}^{-1}$ (Cohen 2011). Grain porosity in AU Mic (Graham et al. 2007; Shen et al. 2009) may boost $\beta_w$ by an extra factor on the order of 2. Augereau & Beust (2006; see also Schüppler et al. 2015) laid out the many reasons why the mass loss rate from this young, active M dwarf is orders of magnitude larger than the solar mass loss rate. See in particular their Figure 11, which attests that $\beta_w$ can be as large as $\sim 40$ when AU Mic flares.$^5$

We propose here an explanation for the escaping clouds in AU Mic. We posit that they are the outcome of dust avalanches: exponential rises in dust production caused by small grains moving on unbound trajectories and shattering bound disk material in their path (Artyomowicz 1997; Grigorieva et al. 2007). In an avalanche, submicron grains accelerated to high radial speeds (in this case by the powerful stellar wind) collide with larger parent bodies in the birth ring to create still more submicron grains; these collisional progeny are themselves brought up to high speed, leading to a collisional chain reaction and exponential amplification of the escaping dust column. We propose that each of the bright, fast-moving features observed by Boccaletti et al. (2015) results from an avalanche launched from a small region (a few au in size) in the birth ring lying directly along the line of the sight to the star (see above). Only in this localized region—what we call the “avalanche zone”—are submicron grains produced that can seed the avalanche. In our model, the avalanche zone marks where the birth ring is intersected by another structure: a secondary ring, much less massive than the primary, substantially inclined and/or eccentric and composed of debris from the catastrophic disruption of a planetesimal. Avalanches are triggered at the intersection point of these two rings, where collisions are especially violent.

Most of the rest of this paper is devoted to reproducing the sizes, masses, and velocities of individual escaping clouds using avalanches. Regarding what sets the periodicity of the avalanches, we have less to say. To match the observations, the avalanche period must be the time between cloud ejections, i.e., the projected separation between clouds divided by their projected velocity. An approximate, characteristic value for the cycle period is

$$t_{\text{cycle}} \sim \frac{10 \, \text{au}}{5 \, \text{km s}^{-1}} \sim 10 \, \text{yr.}$$

We can imagine two mechanisms that can set this period. The first is time variability in the stellar mass loss rate. This proposal is admittedly somewhat ad hoc. Although AU Mic flares dramatically at ultraviolet and X-ray wavelengths (e.g., Robinson et al. 2001; Augereau & Beust 2006 and references therein), these bursts of high-energy radiation last mere minutes, whereas Equation (2) indicates that we are interested in modulating stellar activity on timescales of years. It is not clear whether the similarity between our required value for $t_{\text{cycle}}$ and the Sun’s 11 yr period for magnetic field reversals should be regarded as encouraging or irrelevant. An argument in favor of the latter is that the solar wind mass loss rate $M_\odot$ betrays no correlation with the solar magnetic cycle (Cohen 2011). By contrast, the rate of solar coronal mass ejections (CMEs) increases by an order of magnitude from solar minimum (when the CME rate is 0.5 day$^{-1}$) to solar maximum (when the rate is 6 day$^{-1}$; Gopalswamy et al. 2003). Magnetic activity cycles are just beginning to be photometrically detected for main-sequence stars en masse (Reinhold et al. 2017; there are rumors of a weak correlation between magnetic cycle period and stellar rotation period). For pre–main-sequence stars like AU Mic, there seem to be no useful data on magnetic cycles or the time evolution of their mass loss rates, although the situation may be changing with long-term monitoring by the Las Cumbres Observatory Global Telescope network (Brown et al. 2013).

An alternative idea is that the stellar wind blows strongly (as is demanded by the observations that point to large $\beta_w$) but steadily on year-to-decade timescales, and that the avalanches undergo some kind of self-regulating limit cycle. It takes time for avalanches to clear and for enough material to reseed them; this time could be identified with $t_{\text{cycle}}$. We will briefly attempt to make this identification at the end of this paper, after quantifying some of the avalanche dynamics in Section 2. We do not, however, provide an actual limit-cycle model; in particular, we do not answer the key question of why avalanches would not simply unfold in a steady fashion if the stellar wind were steady.

Since the idea of a self-regulating cycle is nothing more than a speculation at this point, we will assume throughout this paper that the avalanche period $t_{\text{cycle}}$ is set by the period of a variable stellar mass loss rate. Fortunately, many of the remaining elements of our proposal do not depend on this assumption. We flesh out our model in Section 2. A summary, including some predictions and a recapitulation of unresolved issues, is given in Section 3. In this first cut at a theory, we aim throughout for order-of-magnitude accuracy only.

2. Model

We present an order-of-magnitude understanding of the escaping clouds in the AU Mic system. We set the stage in Section 2.1 by estimating individual cloud masses and mass ejection rates: these are the observables that any theory must explain. The heart of our paper is Section 2.2, where we sketch our picture of dust avalanches, detailing quantitatively the creation of an avalanche zone from an ancient catastrophic collision, the current properties of the zone, and how the zone can give rise to the observed escaping clouds. In Section 2.3, we briefly consider magnetic levitation of grains in an attempt to explain the observed vertical displacements of the clouds. To illustrate and provide proof of concept of our ideas, we offer a numerical simulation in Section 2.4.

2.1. Cloud Mass and Mass Loss Rate

We estimate the mass of a given cloud using feature “B” (Boccaletti et al. 2015) as a fiducial. The V-band surface

$^5$ Strubbe & Chiang (2006) argued against high mass loss rates in AU Mic, relying instead on stellar radiation pressure to blow out grains. However, they idealized the grain cross section to radiation pressure as geometric; this is an overestimate given real-life optical constants (e.g., Figure 1 of Schüppler et al. 2015).
brightness of cloud B is comparable to that of the local disk, about $B \sim 16 \text{ mag arcsec}^{-2} \sim 0.5 \text{ erg}/(\text{cm}^2 \text{s sr})$ (Krist et al. 2005; Schneider et al. 2014). We take the line-of-sight column density of grains in the cloud to be $N$, the scattering cross section per grain to be $Q\pi a^2$, the relative power scattered per grain per steradian to be $P$ (normalized such that its integral over all solid angles equals unity), and $a$ to be the true (not projected) distance between the cloud and the star of luminosity $L_* \sim 0.1 L_\odot$. Then,

$$B \sim \frac{L_*}{4\pi a^2} NPQ\pi a^2. \quad (3)$$

The cloud mass is

$$M_{\text{cloud}} \sim \frac{4}{3} \pi \rho_p a^3 N A, \quad (4)$$

where $A \sim 4 \text{ au}$ (length) $\times 2 \text{ au}$ (height) is the projected area of the cloud. Combining Equations (3) and (4), we have

$$M_{\text{cloud}} \sim \frac{16\pi \rho_p B A s a^2}{3 Q P L_*} \sim 4 \times 10^{-7} M_* \left(\frac{s}{0.1 \mu\text{m}}\right) \left(\frac{0.3}{Q}\right) \times \left(\frac{2/4\pi}{P}\right) \left(\frac{a}{35 \text{ au}}\right)^2, \quad (5)$$

where we have placed the cloud near the birth ring at

$$a \sim 35 \text{ au} \quad (6)$$

and allowed for some forward scattering of starlight by assigning $P$ to be the isotropic scattering value $1/4\pi$ multiplied by a factor of 2. Throughout this paper, we adopt a nominal cloud grain size of

$$s \sim 0.1 \mu\text{m}, \quad (7)$$

small enough for grains to enjoy high acceleration (Equation (1)) but still large enough to scatter starlight with reasonable efficiency.

The implied mass loss rate from the debris disk—from clouds only—is

$$\dot{M}_{\text{cloud}} \sim \frac{M_{\text{cloud}}}{t_{\text{cycle}}} \sim 4 \times 10^{-8} M_* \text{ yr}^{-1}. \quad (8)$$

This is a large rate: it would take only $\sim 0.25$ Myr, or $\sim 1\%$ of the stellar age of $t_{\text{age}} \sim 23$ Myr (Mamajek & Bell 2014), to drain the disk of $\sim 0.01 M_\odot$, the total disk mass inferred from millimeter-wave observations (Matthews et al. 2015). This calculation suggests that the episodic ejections we are currently observing have not persisted for the system age but instead reflect a transient phase. We will provide additional support for this idea in Sections 2.2.4 and 2.2.7.

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**2.2. Avalanche Dynamics**

**2.2.1. The Azimuth of the Avalanche Zone, Where Clouds Are Launched**

We consider a $\beta_\omega$ avalanche composed of $0.1 \mu\text{m}$ grains accelerated radially across the birth ring. The avalanche occurs in a restricted region on the birth ring—the “avalanche zone”—that is fixed in inertial space. In other words, the azimuth of the zone does not rotate at Keplerian speed (Section 2.2.2 explains why).

Because (i) the birth ring has a radius of $\sim 35 \text{ au}$ while the cloud closest to the star (“A”) is located at a projected separation of $\sim 8 \text{ au}$ and (ii) all moving features are located on the southeast ansa and travel further southeast, we position the azimuth of the avalanche zone practically directly along the line of sight to the star, at a projected stellar separation $\ll 8 \text{ au}$, so that clouds launched from there can be delivered by disk rotation to the southeast. We also locate the avalanche zone on the half of the ring nearest the observer so that the dust clouds it produces appear bright in forward-scattered light.

**2.2.2. The Avalanche Zone Lies Where a Secondary Debris Ring Intersects the Birth Ring; Violent Collisions Here Produce Avalanche Seeds**

In our model, the avalanche zone is rooted where the birth ring—hereafter the “primary”—intersects a much less massive “secondary” ring composed of debris from a catastrophically disrupted body (we will place an upper bound on its mass in Section 2.2.4). The node where the rings intersect is stationary in inertial space (aside from an insignificant precession). A similar setup was considered in generic terms by Jackson et al. (2014); see also the “static” case of Sezestre et al. (2017) (neither of these studies considered avalanches, and the latter focused on matching the velocity profile of AU Mic’s escaping clouds, not their sizes and masses). See Figure 1 for a big-picture schematic.

We imagine the secondary ring to have a semimajor axis and therefore an orbital period comparable to that of the primary,

$$t_{\text{orb}} \sim 300 \text{ yr}, \quad (9)$$

and to be substantially inclined relative to the primary, reflecting the aftermath of a collision between a projectile in the primary ring and a target (the progenitor of the secondary ring) that once moved on an orbit inclined to the primary by $\sim 1$ rad. Alternatively, instead of a large mutual inclination, we could just as well posit a large eccentricity for the secondary progenitor. The secondary ring could then be nearly coplanar with the primary and so eccentric that it intersects the primary at the same special azimuthal location of the avalanche zone. The only real requirement on the relative ring geometry is that this “intersection region” be just a few au large, in order to match the observed sizes of the escaping clouds (we elaborate on these considerations of size in Section 2.2.3). We note that

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Equation (8) accounts for only the mass ejected in clouds (overdensities). There is also the mass ejected in intercloud regions, which we will account for in Section 2.2.7.
the shattering of the primary and secondary ring particles down acceleration by the stellar wind spanning just a few au.

secondary ring inclined relative to the primary, it need not be; an eccentric planetesimal less than a few hundred km in size. Although we have drawn the secondary ring is composed of debris from the catastrophic disruption of a / et al. by the curved arrow is pierced by a secondary ring fast enough to generate small 0.1 μm sizes suitable for strong radial erosion.

The large relative avalanche are generated from catastrophic collisions between secondary and primary particles in the intersection region includes the intersection region and can extend slightly further if the seeds have time to travel azimuthally before the stellar wind flushes them out of the system altogether (the direction of primary ring rotation is indicated by the curved arrow). The fast-moving bright features observed by Boccaletti et al. (2015) are clouds of dust launched from the avalanche zone. The ray from the star to the intersection region/avalanche zone points to Earth. The secondary ring is composed of debris from the catastrophic disruption of a planetesimal less than a few hundred km in size. Although we have drawn the secondary ring inclined relative to the primary, it need not be; an eccentric secondary ring is also possible, so long as it creates an intersection region spanning just a few au.

the asteroid and Kuiper belts, which are solar system analogs of debris disks, contain bodies commonly moving on highly inclined and eccentric orbits. Given either a large inclination or large eccentricity for the secondary ring, the relative velocities between secondary and primary particles in the intersection region are large,

\[ v_{\text{sec, pri}} \sim \frac{v_K}{2} \sim 2 \text{ km s}^{-1}, \]  

i.e., within a factor of a few of the local Keplerian velocity

\[ v_K \sim 4 \text{ km s}^{-1}. \]  

The intersection region is where 0.1 μm “seeds” for the avalanche are generated from catastrophic collisions between primary and secondary ring particles. The large relative velocities in the intersection region—which approach, if not exceed, the elastic wave speed in solid rock—readily lead to the shattering of the primary and secondary ring particles down to the small, ~0.1 μm sizes suitable for strong radial acceleration by the stellar wind (Equation (1)). We quantify these statements further in Section 2.2.5.

Outside the intersection region, in the rest of the primary ring, particle relative velocities are too low to generate submicron seeds. In the bulk of the primary, which is composed of bound and more nearly micron-sized particles (those dominating the primary’s optical depth), relative velocities are of order

\[ v_{\text{pri, pri}} \sim 100 \text{ m s}^{-1}, \]  

as judged from the observed vertical thickness of the ring (Strubbe & Chiang 2006). Collisions at such velocities will chip and erode but do not lead to catastrophic disruption, as they correspond to specific kinetic energies

\[ \frac{1}{2} v_{\text{pri, pri}}^2 \sim 5 \times 10^7 \text{ erg g}^{-1} \]  

that fall short of

\[ S^* \sim 2 \times 10^8 \text{ erg g}^{-1}, \]  

the threshold for catastrophic disruption of micron-sized, relatively flaw-free targets (Tielens et al. 1994; Grigorieva et al. 2007). Thus, in nonintersection regions, collisional cascades are not expected to proceed past past particle sizes for which \( \beta_w \sim 0.5 \), the minimum threshold for unbinding particle orbits. By contrast, the violence of collisions in the intersection region (Equation (10)) permits the creation of especially small grains attaining \( \beta_w \gg 1. \)

2.2.3. Sizes of the Intersection Region and Avalanche Zone

By definition, the avalanche zone comprises all regions where ~0.1 μm grains (accelerating projectiles) and primary ring particles (field targets that shatter into more projectiles) coexist. The avalanche zone includes the intersection region where ~0.1 μm seeds are created from collisions between primary and secondary ring particles. Avalanches can also extend beyond the intersection region because seeds can travel azimuthally (at the Keplerian speeds that they inherit at birth from their primary parents), out of the intersection region into the rest of the primary ring. Thus, the characteristic dimensions of the avalanche zone and intersection region obey (see Figure 1)

\[ \Delta l_{\text{avalanche}} > \Delta l_{\text{intersect}}. \]  

The size of the intersection region scales with the thickness of the secondary ring (really, a torus); that thickness, in turn, scales with the ejecta velocities \( v_{ej} \) of the catastrophic collision that gave birth to the secondary ring:

\[ \Delta l_{\text{sec}} \sim \frac{v_{ej}}{v_K} a \sim 4\left( \frac{v_{ej}}{400 \text{ m s}^{-1}} \right) \text{au} \]  

(the thickness scales with the dispersion of orbital elements of the secondary fragments, and that dispersion scales with the deviation of fragment orbital velocities from the progenitor’s Keplerian velocity). Ejecta velocities \( v_{ej} \) of ~200–400 m s\(^{-1}\) are realistic; see, e.g., modeling of the Haumea collisional family in the Kuiper Belt (Lykawka et al. 2012). Our nominal estimate for \( \Delta l_{\text{sec}} \) is comparable to the radial (\( \Delta r \)) and vertical (\( H \)) thicknesses of the primary ring, each of which is about 3 au (Augereau & Beust 2006; Strubbe & Chiang 2006). The intersection region between secondary and primary rings should be about \( \Delta l_{\text{sec}} \) large (lower if the originating collision occurred toward the margin of the primary and higher if the

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8 At the risk of belaboring the point, an analogy would be with high-energy collisions in a particle accelerator; the greater the energy of the collision, the smaller the constituent particles that are unleashed. See also Leinhardt & Stewart (2012).
inclination and/or eccentricity of the secondary ring is smaller; see Section 2.2.2):
\[ \Delta l_{\text{interact}} \sim \Delta l_{\text{sec}}. \]

An upper limit on \( \Delta l_{\text{avalanche}} \) is given by the distance that seeds travel azimuthally through the primary ring between avalanches (since a given avalanche triggered during the high phase of the stellar wind flushes the primary of all seeds):
\[ \Delta l_{\text{avalanche}} < \sqrt{ l_{\text{cycle}} \times \tau_{\text{cycle}} } \]
\[ < 8 \text{ au}. \]

The actual length \( \Delta l_{\text{avalanche}} \) will be smaller than this because, before the seeds have had a chance to cover an azimuthal distance of 8 au, the stellar wind (during its high phase) will have blown them radially out of the primary.

Equations (15)–(18) constrain \( \Delta l_{\text{avalanche}} \) to be several au. This is the right order of magnitude: Boccaletti et al. (2015) observed that the bright, fast-moving features are \( \Delta l_{\text{cloud}} \sim 4 \text{ au} \) in length. Computing \( \Delta l_{\text{cloud}} \) from first principles, starting from the considerations outlined here, requires that we fold in the detailed time history of the stellar wind and resultant avalanches—this is what we do in the numerical model of Section 2.4, where we find that, because of strong radial outflows and projection effects, the intersection region practically single-handedly determines the observed cloud size (i.e., \( \Delta l_{\text{cloud}} \sim \Delta l_{\text{avalanche}} \sim \Delta l_{\text{interact}} \)).

Our main takeaway point for this subsection is that, putting aside the various order-unity details, a secondary ring of debris created from a catastrophic collision has the right thickness, namely a few au (Equation (16)), to be relevant for the observations by Boccaletti et al. (2015).

### 2.2.4. The Secondary Ring: Lifetime and Upper Mass Limit

The ejecta velocities of the originating collision place an upper limit on the surface escape velocity of the progenitor: \( v_{ej} \sim 400 \text{ m s}^{-1} \) implies a progenitor radius \( \lesssim 400 \text{ km} \) or, equivalently, a progenitor mass
\[ M_{\text{sec}} \lesssim 10^{-4} M_{\oplus}. \]

where we have assumed a progenitor bulk density of \( \sim 2 \text{ g cm}^{-3} \) (only for Equation (19)); elsewhere, for less compressed grains, we adopt \( \rho_{c} \sim 1 \text{ g cm}^{-3} \). A progenitor radius of \( \sim 400 \text{ km} \) is comparable to those of large asteroids (e.g., Vesta) and Kuiper Belt objects (e.g., Varuna).

The secondary ring has a finite life span because its particles are destroyed by collisions with the primary ring. Every time a secondary ring particle executes an orbit, it has a probability of colliding with a primary particle equal to \( \tau_{\text{pri}} \), the optical depth traversed through the primary ring. That optical depth is on the order of
\[ \tau_{\text{pri}} \sim 0.01 \]

based on detailed models derived from scattered-light images (Augereau & Beust 2006; Strubbe & Chiang 2006). Then, the secondary ring disintegrates on a timescale
\[ t_{\text{sec}} \sim t_{\text{orb}} / \tau_{\text{pri}} \]
\[ \sim 3 \times 10^{4} \text{ yr} \left( \frac{0.01}{\tau_{\text{pri}}} \right). \]

By “disintegrate,” we refer only to those secondary ring particles small enough to be shattered by the \( \mu \text{m}-\text{ sized} \) particles comprising the bulk of the primary’s optical depth. Such secondary ring particles are likely to have sizes smaller than several \( \mu \text{m} \). Despite their restriction in size, such particles may still carry a fair fraction of the mass of the secondary progenitor, for two reasons. The first is that in the immediate aftermath of the progenitor’s destruction, ejecta mass is expected to be distributed equitably across logarithmic intervals in fragment size. This expectation arises from the “crushing” law for catastrophic single collisions (Takasawa et al. 2011; Leinhardt & Stewart 2012; Kral et al. 2015). Second, as secondary ring bodies collide with one another and establish an equilibrium cascade, particles near the bottom of the cascade—i.e., \( \mu \text{m}-\text{ sized} \) particles on marginally bound orbits—grow enormously in population because they spend much of their time at the apoastra of orbits made highly eccentric by the stellar wind, away from destructive collisions in the secondary ring (see Figure 3 of Strubbe & Chiang 2006). Thus, our estimate of the total secondary ring mass \( M_{\text{sec}} \) may not be that much greater than the mass in \( \mu \text{m}-\text{ sized} \) secondary ring particles; we will assume in what follows that they are within an order of magnitude of one another.

Qualified to refer only to secondary particles small enough to be susceptible to disruption, the lifetime of the secondary ring \( t_{\text{sec}} \) (which notably does not depend on the secondary ring mass) is some three orders of magnitude shorter than the system age. This aligns with our earlier suspicion (Section 2.1) that the phenomenon of escaping dust seen today is transient. In fact, the avalanches may not even last as long as \( t_{\text{sec}} \)—see Section 2.2.7 for the reason why.

### 2.2.5. Seed Mass and Avalanche Mass

Within the intersection region, primary and secondary ring particles destroy each other to produce 0.1 \( \mu \text{m} \) avalanche seeds at a rate
\[ M_{\text{seed}} \sim \frac{M_{\text{sec}}}{t_{\text{sec}}}. \]

A couple of comments regarding this estimate: first, although Equation (22) appears superficially to account only for the destruction of secondary ring particles, it actually accounts for the destruction of primary ring particles as well, by symmetry (\( M_{\text{seed}} \sim M_{\text{sec}} / t_{\text{sec}} \times M_{\text{sec}} \tau_{\text{pri}} \times M_{\text{sec}} M_{\text{pri}} \), where \( M_{\text{pri}} \sim 0.01 M_{\odot} \) is the primary ring mass). Second, underlying Equation (22) is the assumption that when primary and secondary ring particles shatter each other, they invest an order-unity fraction of their mass into 0.1 \( \mu \text{m} \) grains. Here again we appeal to the crushing law for catastrophic single collisions, which tends to distribute mass logarithmically uniformly across particle sizes; we do not appeal to any equilibrium cascade law like Dohnanyi’s (see the discussion in the penultimate paragraph of Section 2.2.4).

The 0.1 \( \mu \text{m} \) avalanche seeds are accelerated radially outward by the stellar wind over some fraction of \( t_{\text{cycle}} \). If the “high”
phase of the stellar wind lasts
\[ t_{\text{high}} \sim \frac{t_{\text{cycle}}}{4}, \]
then the seeds attain a radial velocity
\[ v_\beta \sim \beta_{\text{w,high}} \frac{GM_*}{a^2} t_{\text{high}} \]
\[ \sim v_K \left( \frac{\beta_{\text{w,high}}}{20} \right) \frac{t_{\text{high}}}{t_{\text{cycle}}/4} \] (24)

Other values for \( t_{\text{high}} \) and \( \beta_{\text{w,high}} \) are possible: only their product matters in Equation (24). (Of course, the product cannot be so high that the larger bodies comprising the primary and secondary rings also become unbound.)

The 0.1 \( \mu m \) seeds slam into more typically \( \mu m \)-sized primary parent bodies, creating more 0.1 \( \mu m \) grains in an exponentially amplifying avalanche. By the time the avalanche has propagated across the radial width of the primary ring, it has traversed an optical depth \( \tau_{\text{pri}} \) and acquired a mass
\[ M_{\text{avalanche}} \sim M_{\text{seed}} \exp(\eta \tau_{\text{pri}}) \] (25)
(see, e.g., the order-of-magnitude description of avalanches by Grigorieva et al. 2007). Here \( \eta \) is the number of fragments produced per catastrophic collision,
\[ \eta \sim \left( \frac{1/2}{S} \frac{m_{\text{frag}}}{S} \right)^2 \sim \frac{v_\beta^2}{2S^*}, \] (26)
where the projectile mass \( m_{\text{proj}} \) and the individual fragment mass \( m_{\text{frag}} \) are assumed comparable and both are imagined to correspond to 0.1 \( \mu m \) grains. Inserting Equation (24) into Equation (26) yields
\[ \eta \sim 400. \] (27)
An upper limit on \( \eta \) can be estimated by noting that the catastrophic disruption of a 1 \( \mu m \) primary parent particle can yield no more than \( \eta_{\text{max}} = 1000 \) fragments, each of size 0.1 \( \mu m \).

The seed mass underlying a given cloud is that generated during the high phase of the stellar wind (seeds generated during the low phase give rise to the intercloud emission; see Section 2.2.7):
\[ M_{\text{seed}} \sim M_{\text{seed}} \times t_{\text{high}} \]
\[ \sim 10^{-8}M_* \left[ \frac{M_{\text{sec}}}{10^{-4}M_*} \right] \left( \frac{\tau_{\text{pri}}}{0.01} \right) \left( \frac{t_{\text{high}}}{t_{\text{cycle}}/4} \right). \] (28)

Putting Equations (25), (27), and (28) together, we derive a single-avalanche mass of
\[ M_{\text{avalanche}} \sim 5 \times 10^{-7}M_* \left[ \exp(\eta \tau_{\text{pri}}) \right] \left[ \frac{M_{\text{sec}}}{10^{-4}M_*} \right]. \] (29)

which is a remarkably good match to the observationally inferred cloud mass \( M_{\text{cloud}} \sim 4 \times 10^{-7}M_* \) (Equation (5)), considering that we have not fine-tuned any of the input parameters.

Of course, uncertainties in \( \eta \) and \( \tau_{\text{pri}} \) will be exponentially amplified in the avalanche gain factor \( \exp(\eta \tau_{\text{pri}}) \). Increasing the gain factor would require that we reduce the secondary ring mass \( M_{\text{sec}} \) to maintain the agreement between \( M_{\text{avalanche}} \) and \( M_{\text{cloud}} \). Thus, we can do no better than to restate our upper bound of \( M_{\text{sec}} \lesssim 10^{-4}M_* \) (Equation (19)), which in turn implies that avalanche gain factors \( \exp(\eta \tau_{\text{pri}}) \gtrsim 50 \).

Although Equation (25) oversimplifies the avalanche dynamics (among other errors, it neglects the finite acceleration times and differing velocities of grains), our conclusions do not depend on the specific implementation of a simple exponential to describe avalanches. Stripped to its essentials, our reasoning can be recapitulated as follows: the mass of an individual cloud is \( M_{\text{cloud}} \sim 4 \times 10^{-7}M_* \) by Equation (5); generically, the mass unleashed in an avalanche is \( M_{\text{avalanche}} \sim M_{\text{seed}} \times \text{Gain} \), where \( \text{Gain} \gtrsim 1 \) need not take the form of a simple exponential; \( M_{\text{seed}} \lesssim 10^{-8}M_* \) by Equations (28) and (19); then, for \( M_{\text{avalanche}} \) to match \( M_{\text{cloud}} \), we need \( \text{Gain} \gtrsim 40 \). Numerical simulations of avalanches by Q. Kral & P. Thébault (2017, personal communication; see also Grigorieva et al. 2007) indicate that such gain factors are possible, even though they are not described by the simplistic exponential in Equation (25).

2.2.6. Avalanche Propagation Time

The timescale for the avalanche to propagate radially across the zone (whose size is comparable to the radial width of the primary ring; see Section 2.2.3) is
\[ t_{\text{rad,esc}} \sim \frac{\Delta l_{\text{avalanche}}}{v_\beta} \]
\[ \sim 5 \text{ yr} \left( \frac{\Delta l_{\text{avalanche}}}{4 \text{ au}} \right) \left( \frac{20}{\beta_{\text{w,high}}} \right), \] (30)
which is both shorter than \( t_{\text{cycle}} \sim 10 \text{ yr} \), implying that only one avalanche occurs per stellar cycle, and longer than our assumed acceleration time of \( t_{\text{cycle}}/4 \sim 2.5 \text{ yr} \), as required for consistency.

2.2.7. Total Mass Budget: Cloud + Intercloud Regions and Starving the Avalanche

That we can reproduce the observed \( M_{\text{cloud}} \) (Equation (5)) using our theory for \( M_{\text{avalanche}} \) (Equation (29)) is encouraging to us. The theory relies on a variety of estimates, several of which were made a priori, and it is heartening that the numbers hang together as well as they do.

Here is another check on our work. Suppose (just for the sake of making this check; we will see at the end of this subsection why this supposition is probably not realistic) that avalanches continue for the entire lifetime of the secondary ring at their current pace and magnitude. Then, the total mass lost from the system should equal the mass of the secondary ring multiplied by the avalanche gain factor:
\[ \max M_{\text{total,1}} \sim M_{\text{sec}} \exp(\eta \tau_{\text{pri}}) \sim 0.005M_* \] (31)
(See the caveats regarding our use of \( M_{\text{sec}} \) in Section 2.2.4.) We want to check whether this (maximum) mass matches that inferred more directly from observations of mass loss (i.e., Boccaletti et al. 2015). To make this accounting complete, we must include not only the mass lost in clouds (\( M_{\text{cloud}} \) from Equation (8), multiplied by the secondary ring lifetime \( t_{\text{sec}} \) from Equation (21)) but also the mass lost from intercloud regions. We appeal to our model to account for the latter. The intercloud regions represent avalanches from seeds produced during the “low” phase of the stellar wind. Because the duration of the low
phase is much less than the orbital time (the system dynamical time), these seeds are not accelerated much beyond their Keplerian speeds during the low phase, and so they stay roughly within the primary ring during this time. Our numerical simulation in Section 2.4 confirms this point: the low-phase seeds are distributed along streams that are longer azimuthally than radially. They do not escape radially until the stellar wind attains its high phase, at which time they undergo their own avalanche. Thus, while intercloud regions are produced from seeds generated during the low phase lasting an assumed $3t_{cycle}/4$, and clouds are produced from seeds generated during the high phase lasting $t_{cycle}/4$, both sets of seeds are amplified by about the same avalanche gain factor, because avalanches only occur when the wind is in its high phase. Since the seed production rate is constant (Equation (22)), the mass loss rate from intercloud regions must be $3 \times$ the mass loss rate from clouds; the total must be $4 \times$ the latter. Hence, for our second estimate of the total mass lost from the system, we have

$$\max M_{\text{total},2} \sim 4M_{\text{cloud}}t_{\sec} \sim 0.005M_\odot.$$  

(32)

The match between $\max M_{\text{total},1}$ and $\max M_{\text{total},2}$ is better agreement than we probably deserve.

The maximum total mass lost, $\max M_{\text{total},1}$, is still less than what the primary ring contains, $M_{\text{pr1}} \sim 0.01M_\odot$, but only by about a factor of 2. The prospect of losing an order-unity fraction of the total disk mass over a small fraction of the stellar age highlights the destructive power of avalanches. But there is good reason to believe that avalanches will not continue unabated for the full life span of the secondary ring. If avalanche targets are strictly those at the bottom of a conventional cascade in the primary ring ($\sim \mu$m-sized particles in our simple model, i.e., those dominating the primary ring’s optical depth $\tau_{opt}$), then avalanches could be “starved” if the primary cascade does not supply such small targets at a fast enough rate. The primary cascade rate might only be $M_{\text{pr1}}/t_{\age} \sim 0.01M_\odot/(20 \text{ Myr})$, much lower than the current avalanche mass loss rate $M_{\text{total}}/t_{\sec} \sim 0.005M_\odot/(0.03 \text{ Myr})$. Conceivably, avalanches weaken before $t_{\sec}$ elapses as the population of $\mu$m-sized targets in the primary ring dwindles. Forecasting the long-term evolution of avalanches is left for future work.

2.3. Vertical Oscillations Driven by the Magnetized Stellar Wind

The stellar wind, moving with a radial velocity $v_{\text{wind}}\hat{r}$ and carrying a magnetic field $B$, exerts a Lorentz force on dust grains of charge $q$ and velocity $\mathbf{v}$:

$$F_\mathbf{v} = \frac{q}{c} [(\mathbf{v} - v_{\text{wind}}\hat{r}) \times \mathbf{B}],$$  

(33)

where $c$ is the speed of light.$^{10}$ At the large stellocentric distances of interest to us, well outside the wind’s Alfvén point, the magnetic field is tightly wrapped and primarily azimuthal: $B \simeq B_\phi \hat{r}$ (Weber & Davis 1967). The field strength around AU Mic is unknown, but we expect it to be larger than in the solar system, as AU Mic is a rapidly rotating, strongly convective, active young star—properties that all point to a strong stellar magnetic field. For reference, in the solar system, $B_\odot \sim 40 \mu G (a/\text{au})^{-1}$ (e.g., Weber & Davis 1967; Schwenn 2000). Thus, we expect that for the AU Mic system at $a \sim 35 \text{ au}$, $B_\odot > 1 \mu G$.

Given that the field is dominated by its azimuthal component and that grain velocities $|\mathbf{v}|$ are much smaller than $v_{\text{wind}} \sim 400 \text{ km s}^{-1}$, the Lorentz force is dominated by the term proportional to $-v_{\text{wind}}\mathbf{F} \times \mathbf{B}_\phi = -v_{\text{wind}}B_\phi \hat{z}$. This term is equivalent to a vertical electric field $E \hat{z} = -(v_{\text{wind}}/c)B_\phi \hat{z}$ (the electric field seen by a grain when a magnetic field moves past it). We explore in this subsection how we might use this vertical electric field to generate the cloud vertical offsets observed by Boccaletti et al. (2015). We state at the outset that our Lorentz force model will be found wanting in a few respects when confronted with observations (Section 2.3.2).

In a simple conception of a stellar magnetic cycle, the magnetic field varies sinusoidally with period $t_{\mag} = 2\pi/\omega_{\mag}$.

$$B_\phi = B_{\phi,0} \cos(\omega_{\mag}t).$$  

(34)

The vertical equation of motion for a grain of mass $m$ reads

$$z = \frac{qE_{\phi,0}}{m} \cos(\omega_{\mag}t)$$  

(35)

$$= -\frac{qv_{\text{wind}}B_{\phi,0}}{mc} \cos(\omega_{\mag}t).$$  

(36)

The solution for the displacement $z$ is oscillatory with a phase that depends on initial conditions, in particular the phase in the magnetic cycle at which the grain is born. A grain born with $z = z_0$ at $t = 0$ (when the field $B_\phi$ is strongest with magnitude $B_{\phi,0}$) is displaced according to

$$z(t \geq 0) = -\frac{qv_{\text{wind}}B_{\phi,0}}{mcw_{\mag}^2} [1 - \cos(\omega_{\mag}t)];$$  

(37)

it oscillates vertically on one side of the disk, never crossing the midplane to the other side. At the other extreme, a grain born with $z = z_0 = 0$ at $t = \pi/\omega_{\mag}$ (when $B_\phi$ is strongest with the opposite polarity $-B_{\phi,0}$) obeys

$$z(t \geq \pi/\omega_{\mag}) = +\frac{qv_{\text{wind}}B_{\phi,0}}{mcw_{\mag}^2} [1 + \cos(\omega_{\mag}t)]$$  

(38)

and oscillates on the other side. Intermediate cases cross the midplane.

2.3.1. Magnitude of Vertical Displacements and Parameter Constraints

The maximum vertical displacement is given by

$$z_{\text{max}} = \left| \frac{(q/m)B_{\phi,0}v_{\text{wind}}^2 t_{\mag}^2}{2\pi c} \right|$$

$$= 2 \text{ au} \left( \frac{v_{\text{wind}}}{400 \text{ km s}^{-1}} \right) \left( \frac{q/m}{5 \times 10^{-8} e/m_p} \right) \times \left( \frac{B_{\phi,0}}{30 \mu G} \right) \left( \frac{t_{\mag}}{\text{yr}} \right)^2,$$

(39)

where the charge-to-mass ratio $q/m$ is scaled to the proton value $e/m_p$, and we have chosen all input parameters to yield a vertical offset $z_{\text{max}}$ similar to that observed for feature “A” by Boccaletti et al. (2015). We can relate $q/m$ to the grain surface

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10 Working in cgs units, in which electric and magnetic fields have the same units and the electrical capacitance of a spherical grain equals its radius $r$. 
potential $\Phi$:

$$\frac{q}{m} = \frac{s\Phi}{4\pi \rho_s s^3/3} \sim 5 \times 10^{-8} \frac{e}{m_p} \left( \frac{2 \text{ volt}}{0.1 \mu \text{m/s}} \right)^2. \quad (40)$$

Grains are charged positively by ultraviolet (UV) photoelectric emission; the grain charge equilibrates when the rate at which photoelectrons are ejected (a process that becomes less efficient as the grain increases its positive charge) balances the rate at which ambient stellar wind electrons are absorbed. A surface potential of 2 volts (SI units; equivalent to 2/300 statvolts in cgs) would be comparable to potentials for solar system grains (Kimura & Mann 1998) and would suggest that, when scaling from the solar system to AU Mic, the increased number of electrons from the stronger stellar wind nearly balances the heightened UV radiation field. A first-principles calculation of $q/m$ is reserved for future work.

Grains are “picked up” by the magnetized wind to reach stellar wind velocities if they are allowed to complete a magnetic gyration. Since the features are observed to move with velocities much less than $v_{\text{wind}}$, pickup must not have occurred (or at least not fully developed; cf. Section 2.4). This constrains

$$1 > \frac{q}{m} \frac{2\pi^2 v_{\text{wind}}^2}{\omega_{\text{gyro}} t_{\text{mag}}} > \frac{q B_{\text{wind}}}{m c} t_{\text{mag}}, \quad (41)$$

which, rewritten in terms of Equation (39), states that

$$\frac{2\pi^2 v_{\text{wind}}^2 z_{\text{max}}}{\omega_{\text{gyro}} t_{\text{mag}}} < 1$$

$$0.5 \left( \frac{2 \text{ au}}{\text{yr}} \right) \left( \frac{400 \text{ km s}^{-1}}{v_{\text{wind}}} \right) < 1,$$  

implying $t_{\text{mag}} > 1$ yr.

2.3.2. Unresolved Issues with Vertical Deflections

While our little Lorentz force model predicts an oscillatory vertical motion that recalls the “wavy” structure seen in images of AU Mic (Schneider et al. 2014; Boccaletti et al. 2015), the details of this model do not fit the observations. A key unknown is the period of the magnetic cycle, $t_{\text{mag}}$. One hypothesis sets $t_{\text{mag}} = 2 t_{\text{cycle}} = 20$ yr, in the belief that if the stellar mass loss rate varies with time—which it would with period $t_{\text{cycle}}$ by definition—then it would peak twice per magnetic cycle. In other words, it is imagined that dust avalanches are launched at $t = n \pi / \omega_{\text{mag}}$ for integer $n$, when the stellar field is strongest irrespective of polarity. The hypothesis that $t_{\text{mag}} = 20$ yr runs into the immediate difficulty that the images of AU Mic, spaced in time by significant fractions of $t_{\text{mag}}$ (they were taken in 2010 July, 2011 August, and 2014 August), betray no vertical motion for features A and B; these clouds appear to float at a practically constant height of $\sim 2$ au above the midplane at three separate epochs.

Faced with this phasing problem, we might hypothesize instead that $t_{\text{mag}} \sim 1$ yr, i.e., the observations just happen to catch the clouds at the same phase. A magnetic cycle period as short as $\sim 1$ yr marginally satisfies Equation (42). It is not obviously compatible with a stellar mass loss period as long as $\sim 10$ yr (but then again, the stellar mass loss rate might not vary with this period in the first place; see Sections 1 and 3).

Other mysteries include the observed lack of moving features below the midplane and the observation that the vertical offsets appear smaller for the most distant clouds. The expected $1/a$ decay in the azimuthal magnetic field strength helps to explain this drop-off but might not be sufficient.

These problems notwithstanding, Lorentz forces still appear to be the most natural way of explaining the observed vertical undulations. There is no doubt that the stellar wind is magnetized, emanating as it does from a low-mass star, just as there is no doubt that submicron grains are charged, bathed as they are in a relatively intense stellar UV radiation field. Moreover, the sign of this field must periodically reverse; if it did not, the magnetized wind would eventually pick up grains and accelerate them to speeds and heights far exceeding those observed. What we seem to be missing is an understanding of the detailed time history of the field and how it is phased with the avalanche history.

2.4. Numerical Simulations

We construct numerical simulations to illustrate our ideas, omitting magnetic fields for simplicity. We simulate particles that represent packets of 0.1 $\mu$m grains produced in the intersection region and amplified by avalanches. In cylindrical coordinates centered on the star, the particle equations of motion read

$$\ddot{r} = -\frac{GM_\odot (1 - \beta_w)}{r^2 + z^2} \frac{r}{r^3} + \dot{I}_{\phi,z} \hat{z},$$

where $M_\odot = 0.6 M_\odot$ and $l = r^2 \dot{\phi}$ is the specific angular momentum, conserved because there are no azimuthal forces (torques). The force ratio $\beta_w$ cycles in a step-function manner between a high value $\beta_{w,\text{high}} = 20(40)$ lasting $t_{\text{high}} = t_{\text{cycle}}/4 = 2.5$ yr and a low value $\beta_{w,\text{low}} = \beta_{w,\text{high}}/10 = 2(4)$ lasting $t_{\text{low}} = 3 t_{\text{cycle}}/4 = 7.5$ yr. All of the numerical parameters of our simulation are inspired by the various estimates made in Section 2.2.

The simulation particles are initialized as seeds freshly produced in the intersection region. They begin their trajectories at $r = r_0 = 35$ au, moving at circular Keplerian speed. Their spatial density in the $(\phi, z)$ plane follows a two-dimensional Gaussian representing the intersection region,

$$I_{\phi,z} \propto \exp \left[ -\frac{r^2 (\phi - \phi_0)^2 + z^2}{2\sigma^2} \right].$$
The projected velocities of the simulation particles for both $\beta_{w,\text{high}} = 20$ and 40 are plotted in Figure 4, together with observational data from Figure 4 of Boccaletti et al. (2015). The agreement is good for observed features A, B, and C and less good for D and E (note that feature E as identified by Boccaletti et al. 2015 is not a bright cloud but an intercloud region). Feature D in particular appears to be something of an outlier, not much helped by increasing $\beta_{w,\text{high}}$. To improve the fit, we might look to (i) decreasing the launch radius $r_l$ (thereby increasing our model velocities), (ii) incorporating Lorentz forces from the stellar wind (perhaps we are seeing the onset of magnetic pickup; see the last paragraph of Section 2.3.1), and (iii) independent remeasurement of feature velocities and reanalysis of the uncertainties (see Figure 2 of Sezestre et al. 2017, which reports a new and relatively large error bar on the velocity of feature D).

3. Summary and Discussion

We have interpreted the fast-moving features observed in the AU Mic system as coherent clouds of dust produced by periodic avalanches. The clouds are composed of $\sim 0.1 \mu m$ grains, small enough to experience a radially outward ram pressure force from the stellar wind up to $\sim 20 \times$ stronger than stellar gravity. The clouds are launched from a region a few au across—the “avalanche zone”—situated on the primary ring encircling the star at $\sim 35$ au and lying at an orbital azimuth directly along the line of sight to the star. The avalanche zone marks where a body of radius $\lesssim 400$ km and mass $\lesssim 10^{-4} M_\odot$ was catastrophically disrupted less than $\sim 3 \times 10^4$ yr ago. The debris from that event, now strewn along a secondary ring that intersects the primary ring at the location of the avalanche zone, continues to collide with primary ring particles at km s$^{-1}$ speeds, generating the submicron grains that seed the avalanche.

This picture can reproduce the individual feature sizes (a few astronomical units) and masses ($\sim 4 \times 10^{-7} M_\odot$) inferred from the SPHERE and Hubble Space Telescope observations using standard collision parameters (e.g., specific energies $\sim 2 \times 10^6$ erg g$^{-1}$ for catastrophic disruption of competent targets and ejecta velocities of a few hundred m s$^{-1}$) and ring parameters validated by previous modeling of the AU Mic disk (e.g., primary ring optical depths on the order of $0.01$). Avalanche amplification factors exceed $\exp(4) \sim 50$. If avalanches of the kind seen today continue unchecked over the $\sim 3 \times 10^4$ yr lifetime of the secondary ring, then a total mass of $\sim 0.005 M_\odot$, roughly half the total mass of the primary ring, would be blown out. In reality, the avalanches may weaken substantially well before the secondary ring disintegrates, as the number of available targets for disruption ($\sim \mu$m-sized parents) in the primary ring drops. The rate at which mass is lost through avalanches may eventually asymptote to the rate at which the primary ring erodes mass through a conventional cascade.

Figure 2 plots the face-on column density of particles from our simulation using $\beta_{w,\text{high}} = 20$. The particles trace a zigzag path as they flow out of the primary ring. The radial segments (zigs) correspond to seeds (and their subsequent avalanche products) born during the stellar wind’s low state: these particles exited the intersection region moving primarily azimuthally. Each initially azimuthal segment was then blown outward when the stellar wind later entered a high state, retaining their azimuthal orientation for subsequent wind cycles (once a zig, always a zig). Conversely, radially oriented segments (zags) contain seeds (and their subsequent avalanche products) born during the stellar wind’s high state: these particles exited the intersection region moving primarily radially and remained nearly radial in their orientation as they were blown outward, aside from a small rotational shear (once a zag, always a zag).

Remarkably and encouragingly, Figure 3 shows that the radial segments appear as clouds when viewed edge-on. The radial segments have greater line-of-sight column densities than the azimuthal segments do; thus, the radial segments appear as bright clouds, while the azimuthal segments represent the intercloud regions. We label our brightest clouds A, B, C, and D; they seem to compare well with features A through D identified in Figure 2 of Boccaletti et al. (2015). In particular, the projected separations between our simulated clouds agree with observations.

We integrate the equations of motion using a second-order leapfrog scheme with a fixed time step of $t_{\text{cycle}}/500 = 0.02$ yr. New particles (seeds) are generated in the intersection region at a constant rate of $\sim 15,000$ particles yr$^{-1}$. When constructing surface brightness maps of the disk viewed edge-on, we employ a Henyey–Greenstein scattering phase function with an asymmetry parameter $g = 0.25$.

2.4.1. Simulation Results

Figure 2 plots the face-on column density of particles from our simulation using $\beta_{w,\text{high}} = 20$. The primary ring rotates such that its northwest ansa at $x > 0$ approaches the observer and its southeast ansa at $x < 0$ recedes. When the wind is weakest (when $\beta_w = \beta_{w,\text{low}} = 2$), grains emanate from the primary ring on more nearly azimuthal trajectories; these azimuthal segments retain their orientation as they are blown outward from the star. The radial segments, emerging from the primary ring when the wind blows strongest ($\beta_w = \beta_{w,\text{high}} = 20$) and labeled A to D, align with the observer’s line of sight; when viewed edge-on (Figure 3), the radial segments have greater projected column densities and appear as bright clouds.

Remarkably and encouragingly, Figure 3 shows that the radial segments appear as clouds when viewed edge-on. The time of 5 yr represents the finite propagation time of the avalanche across the primary ring.

This picture can reproduce the individual feature sizes (a few astronomical units) and masses ($\sim 4 \times 10^{-7} M_\odot$) inferred from the SPHERE and Hubble Space Telescope observations using standard collision parameters (e.g., specific energies $\sim 2 \times 10^6$ erg g$^{-1}$ for catastrophic disruption of competent targets and ejecta velocities of a few hundred m s$^{-1}$) and ring parameters validated by previous modeling of the AU Mic disk (e.g., primary ring optical depths on the order of $0.01$). Avalanche amplification factors exceed $\exp(4) \sim 50$. If avalanches of the kind seen today continue unchecked over the $\sim 3 \times 10^4$ yr lifetime of the secondary ring, then a total mass of $\sim 0.005 M_\odot$, roughly half the total mass of the primary ring, would be blown out. In reality, the avalanches may weaken substantially well before the secondary ring disintegrates, as the number of available targets for disruption ($\sim \mu$m-sized parents) in the primary ring drops. The rate at which mass is lost through avalanches may eventually asymptote to the rate at which the primary ring erodes mass through a conventional cascade.
We have not specified with confidence the mechanism regulating the avalanche period $t_{\text{cycle}}$ (Equation (2)). We have supposed that it could set by the time variability of the host stellar wind. Certainly AU Mic’s wind is known to be at least some two orders of magnitude stronger than the solar wind, as judged by the star’s flaring activity and from detailed models of the primary ring that point to significant sculpting by the wind (Augereau & Beust 2006; Schüppler et al. 2015). But to explain how the dust avalanches turn on and off, the wind would need to sustain ~yearlong gusts every ~10 yr, causing the star to lose mass at peak rates several thousand times larger than the solar mass loss rate. Whether such extreme and sustained episodes of stellar mass loss are actually realized, and whether we can reconcile the stellar mass loss cycle with the stellar magnetic cycle (as traced by the cloud vertical displacements; see above), are outstanding issues.

We wonder whether we might dispense with the need for decadal-timescale variability in the stellar mass loss rate by instead positing some kind of limit-cycle instability in the avalanche zone. The order-of-magnitude similarity between the required cycle period ($\sim 10$ yr) and the time it takes for the avalanche to propagate radially across the parent ring ($\sim 5$ yr from Equation (30)) suggests that perhaps the avalanche zone regulates itself—that avalanches are triggered when some threshold condition is periodically satisfied in the intersection region. It must be some condition on the seed optical depth. Conceivably, the avalanche evacuates the zone so thoroughly of seeds that the system needs time to refill. Avalanches are characterized by exponential amplification, and with exponentials there is extreme sensitivity to environmental conditions. At the moment we are unable to say more than this, but the possibility of a self-regulating limit cycle (and a stellar wind that is steady but that still needs to blow strongly to achieve the large force ratios $\beta_w \sim 10$ implied by the observed cloud velocities) seems deserving of more thought. Note that while distinct clouds are created from line-of-sight projection effects in our time-variable stellar wind model (Section 2.4), they would be created instead by time variability in the avalanche dust production rate in the limit-cycle picture.

Regardless of what drives the time variability, the avalanche zone from which dust clouds are launched remains fixed in inertial space. By contrast, orbiting sources of escaping dust (e.g., a planet, putting aside the separate problem of how a planet could be a source of dust in the first place) tend to follow the dust that they eject, since the observed velocities of the features are comparable to orbital velocities at ~35 au. This
similarity of velocities leads to immediate difficulties in using a moving source to reproduce the observed spacing between features; the resultant clouds will be too closely spaced if launched from a moving source near the primary ring at \( \sim 35 \) au. Our model avoids this problem altogether because the dust launch zone is located at the intersection of two rings; this node does not move, aside from a negligible precession.

Although our proposal contains significant room for improvement, it points to a few observational predictions. (i) The escaping cloud grains should have smaller sizes (the better to be accelerated outward and electrically charged) than their counterparts bound to the primary and secondary rings; the size difference could be confirmed by measuring color differences between the fast-moving features and the rest of the disk (a pioneering attempt to spatially resolve color differences has been made using the Hubble Space Telescope by Lomax et al. 2017). (ii) Assuming that there is only a single avalanche zone (i.e., a single intersection point between the primary and secondary rings) located directly along the line of sight to the star, all escaping clouds will always be seen on the primary and secondary rings; the size difference could be confirmed by measuring color differences between the fast-moving features and the rest of the disk (a pioneering attempt to spatially resolve color differences has been made using the Hubble Space Telescope by Lomax et al. 2017). (iii) The primary ring should rotate such that the northwest ansa approaches the Earth while the southeast ansa recedes from it. This sense of rotation is not a crucial detail of our model but is preferred because it situates the avalanche zone on the side of the primary ring nearest the observer, so that the clouds launched from there are seen more easily in forward-scattered than in backscattered starlight. Spectral line observations in CO gas can test our expectation. (iv) The secondary ring has a mass \(< 1\%\) of that of the primary and might be distinguished from the primary (this is admittedly ambitious) in ultra-deep exposures if the rings are mutually inclined. (v) What goes up should come down: the features should be observed to vary their vertical positions according to the stellar magnetic cycle.

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