Vertical Structure of Debris Disks: Strengths of Bodies in the Collisional Cascade

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1 Scientific Justification

1.1 Scientific rationale: The Importance of Vertical Structure

The tenuous, dusty debris disks around main sequence stars indicate substantial reservoirs of large planetesimals. As these planetesimals grind down through collisions, they produce dust grains in a wide range of sizes observable at optical through radio wavelengths. Despite decades of successful imaging in scattered light and thermal emission, however, basic assumptions about the dynamical state of debris disks remain untested by observations. One fundamental concept in our understanding of debris disks is that of a collisional cascade, in which larger bodies collide and fragment into smaller bodies at such a rate as to replenish the loss of small particles from the system through radiation pressure. A central underlying assumption of the standard cascade and its resulting size distribution (Dohnanyi 1969) is that the collisional velocities are large and highly destructive. This assertion has never been tested outside the Solar System. The dynamical excitation of the debris disk is in turn directly related to the properties of massive bodies that perturb the orbits of nearby planetesimals (see, e.g., Pan & Schlichting 2012). In the absence of dynamical information, fundamental properties like the amount of dust locked up in planetesimals and the presence or absence of massive bodies sculpting the belts remain essentially unknown. In short, it is not yet clear whether the spectacular debris rings imaged on the sky represent a frenzy of catastrophic asteroid collisions whipped up by an ice giant, or gentle dust erosion stirred by nothing larger than a super-earth.

Vertical thickness is the most direct measure of the gravitational excitation of debris disk systems. Stirring by massive bodies can excite the eccentricities and inclinations of dust grains, increasing their out-of-plane velocity dispersion and thereby the disk thickness. Measuring the vertical scale height therefore allows the inference of two fundamental properties of the debris belt: (1) the velocity dispersion of particles and (2) the mass of the largest bodies stirring the planetesimal population (e.g., Artymowicz et al. 1997; Quillen et al. 2007). Such measurements have been achieved in the optical and near infrared (OIR) for a handful of nearby systems including the iconic edge-on disks around the nearby β Pic and AU Mic (Heap et al. 2000, Krist et al. 2005). However, theoretical work by Thebault (2009) has shown that simple radiation effects from starlight will increase the eccentricity and inclination of the small dust grains that emit the bulk of the radiation observed at OIR wavelengths, resulting in a substantial "natural" scale height consistent with the observations even in the absence of large bodies.

Millimeter-wavelength interferometry therefore has a key role to play: the macroscopic dust grains that dominate the emission in ALMA bands are large enough to be impervious to excitation by stellar radiation. Instead, they trace directly the gravitational excitation of the system. In ALMA Cycle 1, we were allocated "highest priority" time to resolve the vertical structure of the AU Mic debris disk in Band 6 (2012.1.00198.S, PI Hughes). The observations will provide the first measurement of velocity dispersion in a debris disk and measure the total mass of planetary bodies dynamically stirring the debris disk, down to a few-Earth-mass regime. But we can go farther. The velocity dispersion, and therefore the scale height, is predicted to be a function of particle size in the disk. The corresponding power law index encodes information about the internal strengths of the bodies in the collisional cascade, which is information that has never before been accessible through observation. Since different wavelengths are dominated by different particle sizes, measuring the scale height of a debris disk at two widely separated frequencies will allow us to measure the dependence of velocity dispersion on particle size for the first time, and thereby constrain the internal strengths of the bodies. Timely work by Pan & Schlichting (2012) represents the first theoretical calculation of steady-state, size-dependent velocity distributions in collisional cascades, providing a robust framework in which to interpret the observations. We are now in a position to solidify our understanding of the collisional cascades that represent a cornerstone of debris disk theory.

1.2 Immediate objectives: Mind your p's and q's

We propose to obtain high spatial resolution Band 9 observations of the debris disk around AU Mic. AU Mic hosts one of the closest (9.9 pc) and brightest (7.1 ± 0.2 mJy at 1.3 mm) edge-on debris disks. The only other comparable disk is β Pic, which has proven to have complicated millimeter structure in the Cycle 0 data (Dent et al. submitted), whereas AU Mic is remarkably regular and symmetric in Band 6 Cycle 0 observations (MacGregor et al. 2013; the angular resolution was too coarse to place interesting constraints on the vertical structure). The scale height measured in the OIR ($\sim$0.3") serves as an upper limit on the millimeter scale height since the puffing effect of starlight can only increase the OIR scale height above the dynamical height. With the proposed observations we can resolve scale heights up to a factor of 2.5$\times$ lower than the OIR scale height.

The objective of the new Band 9 observation is to constrain, for the first time, the grain-size-dependent (and therefore wavelength-dependent) physics of the collisional cascade in debris disks. A theoretical description of the physics of the collisional cascade in a debris disk essentially relies on specifying two power law indices, p and q. Fig. 1a presents a graphical depiction of the different predicted physical regimes specified by these variables. The index p describes how the velocity dispersion changes with particle size: $v(a) \propto a^{-p}$, where a is the grain size and v is the velocity dispersion. The index q describes the grain size distribution: $dN/da \propto a^{-q}$, where N is the number of grains in a size bin. As shown in Fig. 1a, the measurement of q essentially distinguishes between the strength regime, in which collisions between particles at the measured velocity dispersions actually break apart rock (red, orange, and yellow lines), and the gravity regime, in which gravitational forces dominate the physics of the collisions between bodies (blue filled regions). The value of q can be constrained on a global scale by existing single-dish photometry, but our data will be the first to search for point-to-point variations within the disk. The proposed measurement of p is totally unique – no such measurement has been previously attempted. For the first time we will determine whether there is any damping in the collisional cascade (the typical assumption is no, i.e., $p = 0$, but this assumption has never been tested observationally), and if there *is* damping, whether that damping is due to catastrophic collisions or collisions between particles of similar (or smaller) size. There is a vast literature in the field of planetary science investigating the physics of impact and cratering in these various regimes, and such an understanding is a critical input to models of the collisional evolution of the Solar System (e.g., Wetherill & Stewart 1993, Kenyon & Luu 1999, Stewart & Leinhardt 2009).

Measuring the grain size distribution: q — By measuring the flux of the disk at two widely separated frequencies we can calculate the millimeter spectral index $\alpha_{\rm mm}$ ($F_\nu \propto \nu^{\alpha_{\rm mm}}$), which can be related to the power-law index of the grain size distribution q through the power law index β that describes how mass opacity κ varies with frequency ν ($\kappa_\nu \propto \nu^\beta$). Since the frequency dependence of the flux is determined by the product of the Planck function and the mass opacity, q can be written as $(\alpha_{\rm mm} - \alpha_{\rm Planck})/\beta_s + 3$, where $\alpha_{\rm Planck}$ is 2 in the Rayleigh-Jeans limit and β_s is empirically determined to have a value 1.8 ± 0.2 (Draine 2006). Conceptually, this means that measuring the flux as a function of frequency tells us the number of dust grains as a function of grain size. Given the expected signal-to-noise ratio and the anticipated systematic flux calibration uncertainties of 20% at Band 9 and 10% at Band 6, we anticipate being able to constrain q and therefore the grain size distribution to within 5% *as a function of position within the disk.*

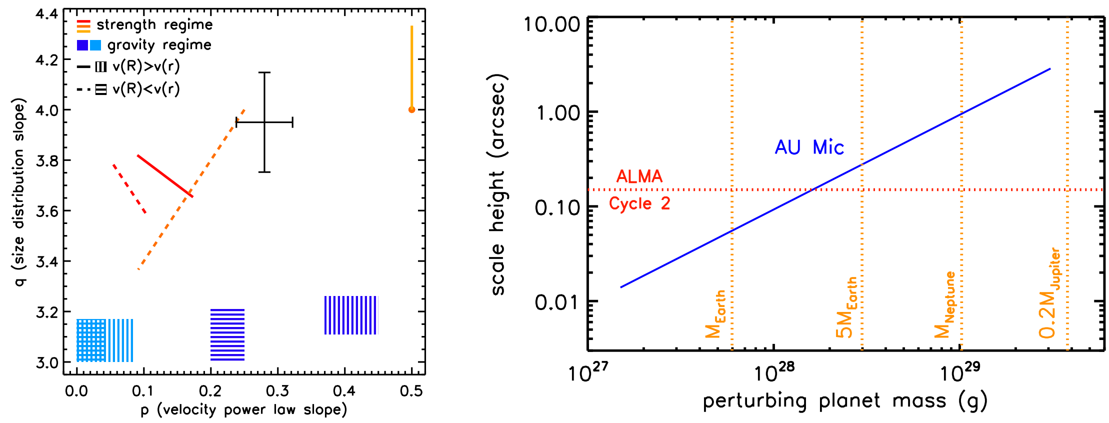

Figure 1: **Left:** *Illustration of how measuring the power law indices p and q constrains the physics of the collisional cascade, with different regimes indicated by different colored lines. Red-yellow colors indicate strength regime while blue indicates gravity regime. Darker colors (red in strength regime, dark blue in gravity regime) indicate damping by catastrophic collisions, while lighter colors (orange in strength regime, light blue in gravity regime) indicate damping by collisions between particles of similar size, and yellow represents damping by collisions with small bodies. The black cross represents the size of the error bars on the anticipated ALMA measurement, which will be the first to meaningfully distinguish between these various physical regimes. In particular, models currently assume $p = 0$, which has never been tested observationally.* **Right:** *Dependence of measured scale height on the total mass of the perturbing bodies in the debris disk. Note that since we resolve both the top and bottom halves of the disk, we can measure a scale height (HWHM) of roughly half the spatial resolution (FWHM) of the observations. These figures are based on calculations of steady-state, size-dependent velocity distributions in collisional cascades from Pan & Schlichting (2012), with dust mass measurements from Liu et al. (2004) and Nilsson et al. (2010).*

Measuring velocity dispersion as a function of grain size: p — Based on the work presented in Pan & Schlichting (2012), we can robustly connect the scale height measurement to the velocity dispersion in the disk and thereby the total mass of the largest bodies in the system, which dominate the dynamical stirring of the disk. While there is some degeneracy involved in the interpretation (with a single measurement it is not simple to distinguish between, say, a single Neptune-mass perturber or two super-Earths), such a total mass measurement would nevertheless represent a fundamental characterization of the dynamical conditions in the disk. Fig. 1b plots the dependence of the measured scale height on the total mass of the perturbing bodies, while Fig. 2 shows two simulated observations representing two possible velocity dispersions. *The truly unique information provided by the combination of resolved observations at Band 6 and Band 9 is the frequency dependence of scale height*, which is a sensitive function of the strength of the colliding dust grains (Pan & Schlichting 2012). The scale height is directly proportional to the velocity dispersion, and the wavelength of observation is proportional to the grain size that dominates the opacity of the observation. By measuring the scale height at both Band 6 and Band 9, we can measure p to within 14%, given the anticipated signal-to-noise and resolution of the data. As indicated in Figure 1a, such a measurement would allow us to meaningfully distinguish between destructive and erosive velocities in the collisional cascade, and would represent the first such characterization of the physics of the collisional cascade.

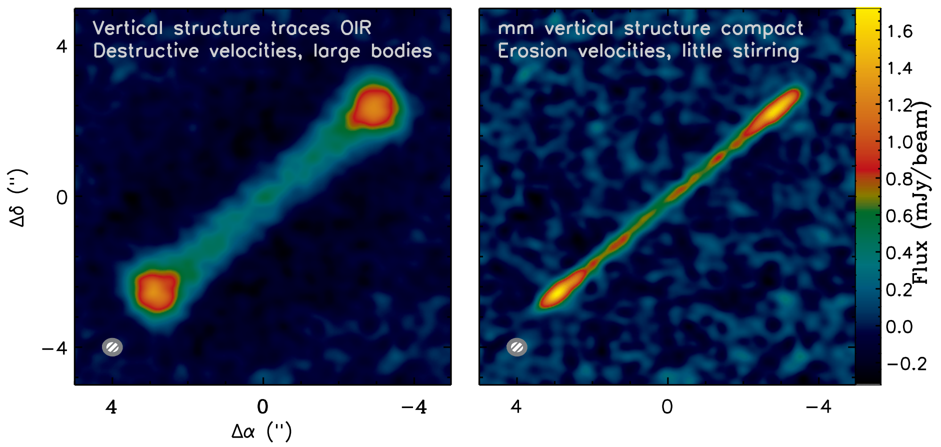

Figure 2: *Simulated Band 9 ALMA image of AU Mic with rms noise 150 μJy/beam that resolves the vertical scale height of the disk. The beam size is indicated in the lower left of each panel. On the left, the vertical thickness of the millimeter emission is assumed to trace that observed in scattered light. Such a measurement would indicate destructive collisional velocities between particles, confirming a central paradigm in the theory of debris disk structure. It would also indicate stirring by large bodies with a total mass of at least 0.1* M_{Jup}. *If instead, as on the right, the millimeter emission is substantially more compact in the vertical dimension than the scattered light, the velocity dispersion would be far smaller. This would indicate very small collision velocities, requiring more mass in planetesimals than has been previously inferred to sustain the observed small dust grain population. It would also require that the total mass of the largest bodies stirring the belt be no larger than 2* $M_{\rm Earth}$.

2 Potential for Publicity

The proposed observations will produce spectacular images an iconic nearby debris disk, achieving spatial resolution comparable to the existing *HST* images; a multiwavelength montage would present an extremely appealing image for publicity. Furthermore, the science enabled by these observations probes the dynamics of planetary systems, always a topic that engenders keen public interest.

3 References

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