WHO STIRS THE POT? RESOLVING THE VERTICAL THICKNESS OF DEBRIS DISKS

2016.1.00878.S

ABSTRACT

The dusty debris disks around main sequence stars are hallmarks of substantial reservoirs of large planetesimals. Edge-on debris disks present a unique opportunity to characterize the dynamics of the collisional cascade, since the vertical scale height encodes the velocity dispersion and allows us to measure the total mass of any perturbing bodies "stirring" the planetesimal belt. Millimeter wavelengths are uniquely suited for revealing the dynamical state of debris disks, since the large grains are not subject to the excitatory effects of stellar radiation that puff up the vertical scale height at optical and infrared wavelengths. Here we propose to complement our recent high-resolution Band 6 observations that spatially resolved the scale height of the AU Mic disk for the first time by making the same measurement at Band 9. Resolving the vertical structure at two widely separated frequencies will allow us to constrain both the grain size distribution and the velocity dispersion as a function of particle size. For the first time, we will be able to distinguish the strengths of the bodies in the collisional cascade.

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ESTIMATED 12M TIME:	7.6 h	ESTIMATED ACA TIME:	0.0 h	ESTIMATED NON-STANDARD MODE TIME (12-M):	7.6 h
CO-PI NAME(S): (Large Proposals only)					
CO-INVESTIGATOR NAME(S):	Hilke Schlichting; Margaret Pan; Eugene Chiang; Meredith MacGregor; David Wilner; John Carpenter; Sean Andrews; Attila Moor; Kevin Flaherty				

EXECUTIVE SHARES[%]:	NA : EU : EA : CL : OTHER :	100 0 0 0 0	STUDENT PROJECT?	No
			RESUBMISSION OF	2015.1.00866.S

PREVIOUS PROPOSALS

CODE	TITLE	PI NAME	PUBLICATION STATUS

RELATED PROPOSALS

CODE	TITLE	PI NAME

REPRESENTATIVE SCIENCE GOALS (UP TO FIRST 30)

SCIENCE GOAL	POSITION	BAND	ANG.RES.(")	LAS.(")	ACA?	NON-STANDARD MODE
AU Mic Band 9	ICRS 20:45:09.5314, -31:20:27.242	9	0.280	2.000	N	Y
Total # Science Goals : 1						

SCHEDULING TIME CONSTRAINTS	NONE	TIME ESTIMATES OVERRIDDEN ?	No

Who Stirs the Pot? Resolving the Vertical Thickness of Debris Disks

1 Scientific Justification

1.1 Scientific rationale: The Importance of Vertical Structure

The tenuous debris disks around main sequence stars indicate reservoirs of large planetesimals. As these planetesimals grind down through collisions, they produce dust grains in a wide range of sizes. Despite decades of 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 disk around the nearby AU Mic (Krist et al. 2005). However, theoretical work by Thebault (2009) has shown that 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 insensitive to excitation by stellar radiation. Instead, they trace directly the gravitational excitation of the system. In Cycle 1, we were allocated time to observe the AU Mic debris disk in Band 6 (2012.1.00198.S, PI Hughes; Fig. 1, right panel). The data were delivered in August 2015, resolving the vertical structure of the disk at millimeter wavelengths for the first time. The preliminary measurement of the vertical FWHM of the outer disk (which exhibits none of the asymmetries of the scattered light observations) is 0.67±0.04 arcsec, implying a total mass of $5\,\mathrm{M_{Earth}}$ of solids in the outer belt – the first such measurement of the mass stirring the collisional cascade in a debris disk. 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. Since different wavelengths are dominated by different particle sizes, imaging 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 in the collisional cascade**. Work by co-Is 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 complementary 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. 2014), whereas AU Mic is remarkably symmetric in Band 6 (MacGregor et al. 2013; Hughes et al. in prep). The inclination of the AU Mic disk is well constrained from the OIR observations: $90 \pm 1°$ (Krist et al. 2005). The uncertainty in inclination translates into a scale height uncertainty of roughly $\Delta R \cos i$, or $\lesssim 10\%$ given the constraints on the ring width ΔR from spatially resolved SMA data (Wilner et al. 2012). Since we have already resolved the large-scale distribution of millimeter flux in this system, we have strong constraints on the radial flux distribution and can predict the sensitivity quite well. Given the strong concentration of flux in the ansae, disk warping should not introduce significant uncertainty into the scale height measurement (unlike at OIR wavelengths).

The objective of the 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 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 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 radial 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., $p = 0$ and the Band 6 and Band 9 scale heights should be identical, 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 $\alpha_{\rm mm}$ ($F_\nu \propto \nu^{\alpha_{\rm mm}}$). 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 radius within the disk*. Such a map of q has never before been made in a debris disk, will allow us to study grain-size-dependent dynamics in debris disks for the first time, and is easily achievable independent of our ability to spatially resolve the vertical structure of the disk.

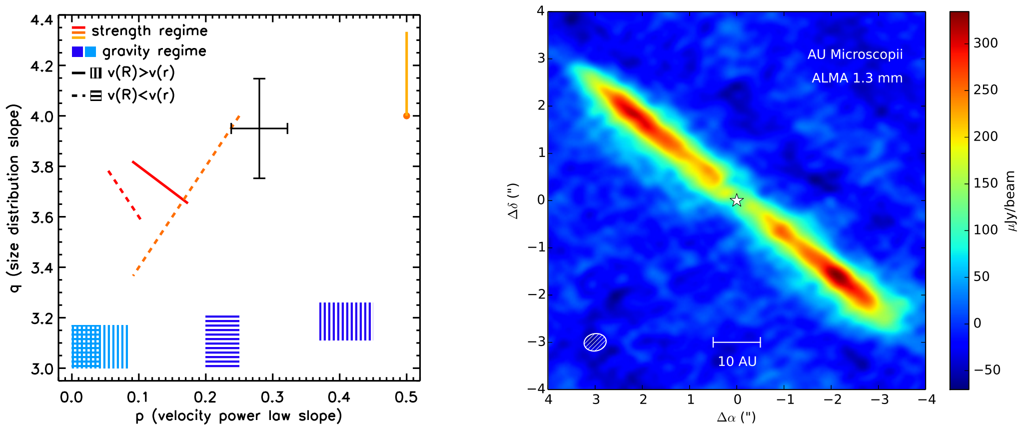

Figure 1: **Left:** *Illustration of how measuring the power law indices p and q constrains the physics of the collisional cascade, with different regimes indicated by different colored lines. Red-yellow colors indicate strength regime while blue indicates gravity regime. Darker colors (red in strength 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. This figure is 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).* **Right:** *New 0.3" resolution ALMA image of AU Mic at 1.3 mm wavelength. These data spatially resolve the scale height at millimeter wavelengths for the first time, and constrain the mass of the outer disk to be* $5\,M_{\rm Earth}$. *By measuring whether the scale height is identical or different in Band 9 we will measure the strengths of the bodies in the collisional cascade for the first time.*

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 new and fundamental characterization of the dynamical conditions in the disk. Fig. 2 shows two simulated observations representing two possible velocity dispersions. The combination of resolved observations at Band 6 and Band 9 allows us to measure 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.

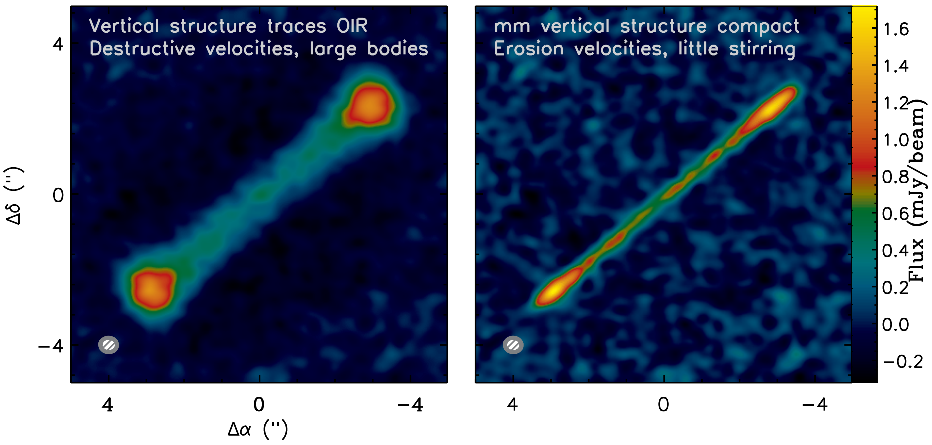

Figure 2: *Simulated Band 9 ALMA image of AU Mic with rms noise 150 μJy/beam. On the left, the vertical thickness of the millimeter emission is assumed to trace that observed in scattered light. Such a measurement would indicate destructive collisional velocities between particles, confirming a central 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, 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.*

2 References

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SG : 1 of 1 AU Mic Band 9 Band 9

Sub-arcsecond continuum imaging of AU Mic to measure its vertical scale height at Band 9.

Science Goal Parameters

Ang.Res.	LAS	Requested RMS	RMS Bandwidth	Rep.Freq.	Cont. RMS	Cont. Bandwidth	Poln.Prod.	Non-standard mode
0.28"	2.0"	260 µJy, 8.7 mK	3296.838 km/s, 7.5 GHz	682.000000 GHz	257.68 µJy, 8.6 mK	7.500 GHz	XX,YY	Yes

Use of 12m Array (40 antennas)

t_total(all configs)	t_science(C40-3)	t_total()	Imaged area	#12m pointing	12m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate
7.6 h	3.7 h	0.0 h	2.8 "	3	offset	8.5 "	4535.8 s	67.1 GB	2.5 MB/s

Use of ACA 7m Array (10 antennas) and TP Array

t_total(ACA)	t_total(7m)	t_total(TP)	Imaged area	#7m pointing	7m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate

Spectral Setup : Single Continuum

Center Freq (Sky)	Center Freqs. SPWs	Eff #Ch p.p.	Bandwidth	Resolution	Vel. Bandwidth	Vel. Resolution	RMS
679.000000	676.000000	128	1875.00 MHz	15.625 MHz	831.5 km/s	13.859 km/s	509.68 µJy, 17.4 mK
	678.000000	128	1875.00 MHz	15.625 MHz	829.1 km/s	13.818 km/s	499.45 µJy, 16.9 mK
	680.000000	128	1875.00 MHz	15.625 MHz	826.6 km/s	13.777 km/s	509.1 µJy, 17.2 mK
	682.000000	128	1875.00 MHz	15.625 MHz	824.2 km/s	13.737 km/s	520 µJy, 17.4 mK

1 Target

No.	Target	Ra,Dec (ICRS)	V,def,frame --OR--z
1	1-AU_Mic	20:45:09, -31:20:27	-4.50 km/s,hel,RELATIVISTIC

Expected Source Properties

	Peak Flux	SNR	Pol.	Pol. SNR	Linewidth	RMS (over 1/3 linewidth)	linewidth / bandwidth used for sensitivity
Line	0.00 uJy	0.0	0.0%	0.0	0 km/s		
Continuum	1.50 mJy	5.8	0.0%	0.0			

Dynamic range (cont flux/line rms): N/A

Justification for requested RMS and resulting S/N (and for spectral lines the bandwidth selected) for the sen...

Sensitivity: The total 1.3 mm flux in the AU Mic debris ring measured by ALMA Cycle 0 observations (MacGregor et al. 2013) is 7.14 +/- 0.2 mJy, concentrated into a ring with the region of greatest surface brightness roughly 2" in radial width. Assuming a spectral index of 2.5, this implies roughly 90 mJy of flux in Band 9. Since the primary purpose of the experiment is to determine the spatial distribution of the flux, we make a conservative estimate based on the lowest surface brightness allowed by existing observational constraints. In a worst-case scenario, the millimeter flux fc AU Mic might be distributed over several arcseconds in radius (concentrated into the ~2"-wide ansae) and up to ~0.6" FWHM vertically across the disk midplane (equivalent to the height measured in scattered light). As a gross estimation, assuming that the flux is spread uniformly into two 2x1 arcsec squares (one at each ansa) and resolved into 0.3" beams, this implies a required flux sensitivity of 260 uJy/beam to achieve a signal-to-noise ratio of 10 per beam in Band 9.

Justification of the chosen angular resolution and largest angular scale for the source(s) in this Science Goal.

The diameter of the debris ring is ~9", which requires mosaicking at Band 9. We have specified a 3-point mosaic along the disk plane (using the precise PA measurement of 128.4 +/- 0.1 degrees from Cycle 0 data analyzed by MacGregor et al. 2013). The edge-on orientation of the disk concentrates flux along the midplane, which is advantageous for imaging. The simulations in Fig. 2 of the proposal text utilize the C40-3 configuration; with the shortest baselines in that configuration, corresponding to a largest angular scale of <4", more than 95% of the flux is recovered, which indicates that we do not require ACA for imaging. A scale of ~2" is crucial for the observations, since that is roughly the width of the ansae in the Cycle 0 observations. The required angular resolution is chosen to most closely match the Band 6 observations (0.25" resolution) and to resolve substantially below the OIR scale height (0.6" FHWM) while requiring only a single configuration that also includes the necessary short baselines. The spatial resolution of ~0.3" will allow us to measure the FWHM even if it is substantially smaller than the Band 6 FWHM of 0.67 +/- 0.04 arcsec.

Justification of the correlator set-up with particular reference to the number of spectral resolution element...

This is a continuum project, so we request maximum bandwidth (7.5 GHz per polarization). We do not include any line observations since the Band 6 data returned an extremely low upper limit on the CO mass in the disk, and CO is likely to be the most abundant molecule so we do not expect other lines to occur in the spectrum.