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A Resolved Millimeter Emission Belt in the AU Mic Debris Disk

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Abstract. Imaging debris disks at millimeter wavelengths is important, because emission at these long wavelengths is dominated by large grains with dynamics similar to the population of dust-producing planetesimals. We have used the SMA and ALMA to make 1.3 millimeter observations of the debris disk surrounding the nearby (9.9 pc), ∼10 Myr-old, M-type flare star AU Microscopii. We characterize the disk by implementing Markov Chain Monte Carlo methods to fit parametric models to the visibilities. The millimeter observations reveal a belt of dust emission that peaks at a radius of 40 AU. This outer size scale agrees with predictions for a reservoir of planetesimals (a "birth ring") based on the shape of the midplane scattered light profile. We do not find any significant asymmetries in the structure or the centroid position of the emission belt. The ALMA observations with a resolution of 0.6 arcsec (6 AU) also reveal a previously unknown central emission peak, ∼6 times brighter than the stellar photosphere at these wavelengths. This central component remains unresolved and could be explained by stellar activity or an inner planetesimal belt located $\lesssim 3$ AU from the star and containing roughly 1% the mass of the outer belt. Future observations with higher angular resolution will be able to distinguish between these possibilities.

Keywords. circumstellar matter, stars: planetary systems, submillimeter

1. The AU Microscopii Debris Disk

AU Microscopii is a nearby (9.91 ± 0.13 pc) M-type flare star located within the β Pictoris moving group (Zuckerman *et al.*, 2001) with the young age 12^{+8}_{-4} Myr. The star is surrounded by an edge-on ($i > 89.5°$) debris disk that was first detected in coronagraphic images of scattered starlight (Kalas *et al.* 2004). Optical observations reveal that the midplane surface brightness profile of this disk steepens dramatically in the outer regions, and is best described by a broken power law, r^{α}, with $\alpha \sim 1-2$ in the inner regions and $\alpha \sim 4-5$ in the outer regions (Liu 2004). This same structure is seen in the surface brightness profile of the β Pictoris disk and has led to the development of a uniform framework for understanding debris disks based on the presence of a localized belt of planetesimals undergoing a collisional cascade, often termed a 'birth ring' (Augereau *et al.* 2001; Augereau & Beust 2006; Strubbe & Chiang 2006).

Within this framework, larger planetesimals located within the birth ring collide and are ground down to produce dust with a range of sizes. This birth ring remains hidden at optical and near-infrared wavelengths, where scattered light is dominated by the smaller grains populating an extended halo of small dust grains. We can probe this proposed framework by turning to submillimeter wavelengths, which highlight thermal emission from larger grains that trace best the location of these dust-producing planetesimals.

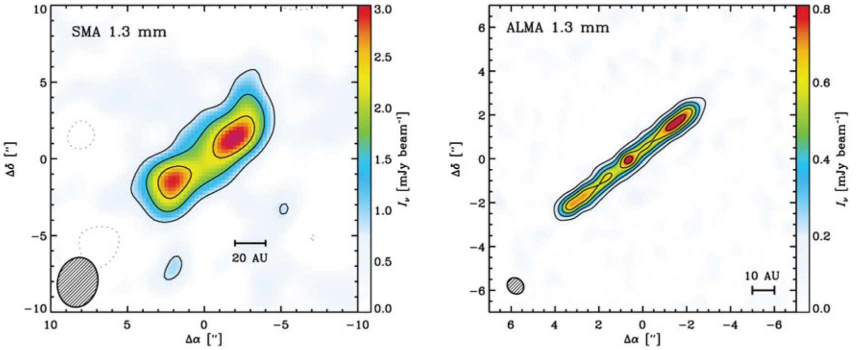

Figure 1. Images of the 1.3 millimeter continuum emission using *(left)* the SMA (Wilner *et al* 2012) and *(right)* ALMA in Cycle 0 (MacGregor *et al.* 2013). The contour levels are -2, 2, 4, 6, ... × the rms noise level of 0.4 mJy for the SMA and -5, 5, 10, 15, ... × 30 μJy for ALMA. The ellipses in the lower left corners represent the respective beams.

2. SMA Observations and Results

We set out to explore the millimeter emission structure of the AU Mic debris disk by using the SMA to resolve the disk. These observations, at a wavelength of 1.3 millimeters, obtained an rms sensitivity of 0.4 mJy and a beam size of $\sim 3''$ (30 AU). The emission structure reveals two peaks located symmetrically on either side of the star that are characteristic of a belt of thermal emission with the same edge-on geometry seen in optical observations of the more extended scattered light disk (Figure 1, left panel).

We used a simple parametric model of an axisymmetric belt to constrain the basic properties of the observed emission: the radius of the belt center; the belt width; and the total flux. By fitting the model directly to the visibility data, we avoid being sensitive to any of the nonlinearities associated with the process of imaging and deconvolution. The best-fit belt center radius is $R = 36^{+7}_{-16}$ AU and belt width is $\Delta R = 10^{+13}_{-8}$ AU. The position of this millimeter emission belt agrees closely with the $\sim$ 43 AU location of the break in the midplane optical surface brightness profile thought to mark the outer edge of the dust-producing planetesimals hypothesized in the birth ring framework.

3. ALMA Observations and Results

Following the SMA study, we obtained ALMA Cycle 0 observations of AU Mic at 1.3 millimeters. These observations were made over four two hour-long “scheduling blocks” (SBs) between April and June 2012. The 16-20 operational 12-m antennas were arranged to span baselines ranging from 21 to 402 m, resulting in a beam size of 0.”80 × 0.”69 (8 × 7 AU) and an rms noise level of 30 μJy beam^{-1}, an improvement over the SMA observations by more than an order of magnitude. An image shows clear peaks near both extrema of the disk and in the middle of the structure (Figure 1, right panel). We interpret the observed millimeter continuum emission using a model with two distinct components: (1) an edge-on belt with a power-law radial emission profile and (2) an unresolved central feature described by a circular Gaussian.

With these new data, we are able to better characterize the properties of the millimeter emission and to make more detailed comparisons with the scattered light disk structure. Building on the phenomenological methodology of Wilner *et al.* (2012), we developed Bayesian tools that employ Markov Chain Monte Carlo (MCMC) methods to estimate

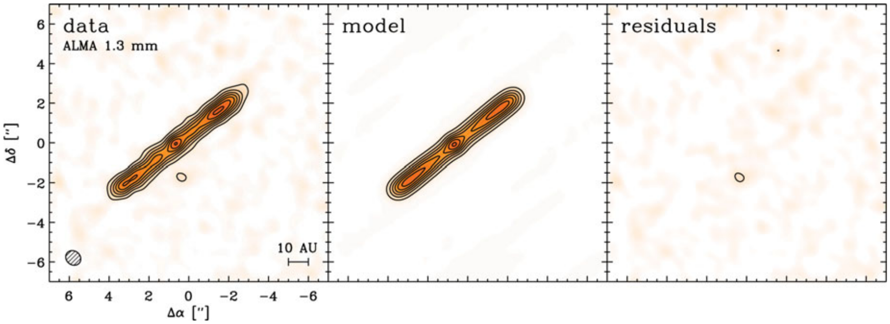

Figure 2. *Left*: the 1.3 mm continuum emission from AU Mic observed with ALMA. *Center*: the best-fit model (see Section 3 for a description of the modeling formalism). *Right*: the imaged residuals. The contour levels are at 4σ (120 μJy beam^{-1}) intervals in all panels.

parameters and uncertainties. These tools allowed us to explore models with a large number of free parameters.

The position of the far edge of the belt is well-constrained at 40 AU, in good agreement with both the earlier SMA observations and the predicted outer edge of the hypothesized birth ring. Within the ∼6 AU resolution limit, this outer edge appears to be sharp, reminiscent of the truncated classical Kuiper Belt. The millimeter belt has a rising emission profile that is best described by a radial power law of the form $I(r) \propto r^{2.3\pm0.3}$. Assuming that the temperature profile of the belt falls off as $r^{-0.5}$, approximating radiative equilibrium, this result implies that the radial surface density profile *rises* as $r^{2.8}$. This radial gradient could be produced in a "self-stirred" disk where planet formation is ongoing (Kennedy & Wyatt 2010). However, the timescale thought to be required to assemble Pluto-sized bodies at 40 AU to stir the disk is longer than the ∼10 Myr age of the system. Interestingly, these new observations reveal no detectable asymmetries or substructure that might indicate gravitational perturbations resulting from a planet within the disk.

4. The Nature of the Central Millimeter Emission Component

In addition to clarifying our view of the outer dust belt, these new observations have revealed a central emission peak whose origin remains undetermined. A NextGen stellar model (Hauschildt *et al.* 1999) that matches optical photometry of AU Mic predicts a flux from the stellar photosphere of 52 μJy at 1.3 mm, ∼6× fainter than the observed flux of 320 μJy for the central peak. AU Mic is known to be an active flare star (Bower *et al.* 2009), but this millimeter peak persists in all four ALMA SBs with no indication of variability on timescales of hours to months. We are left with two plausible explanations for the origin of this emission: (1) a hot stellar corona and (2) an unresolved inner planetesimal belt within 3 AU of the star. Coronal models with realistic parameter values are consistent with all of the existing measurements (Cranmer *et al.*, 2013), but more sensitive observations of the source radio spectrum are needed to provide a stringent test of this mechanism. The properties of a potential inner dust belt are constrained by the lack of excess emission in the AU Mic spectral energy distribution at $\lambda \leqslant 25\mu$m. Rough modeling shows that a belt of large grains located at a radius of a few AU from star is compatible with this constraint.

The unprecedented observations from ALMA provide a clearer view of the structure of the debris disk surrounding AU Mic. However, the need for observations with even better spatial resolution and spectral extent are apparent. A simulation of ALMA

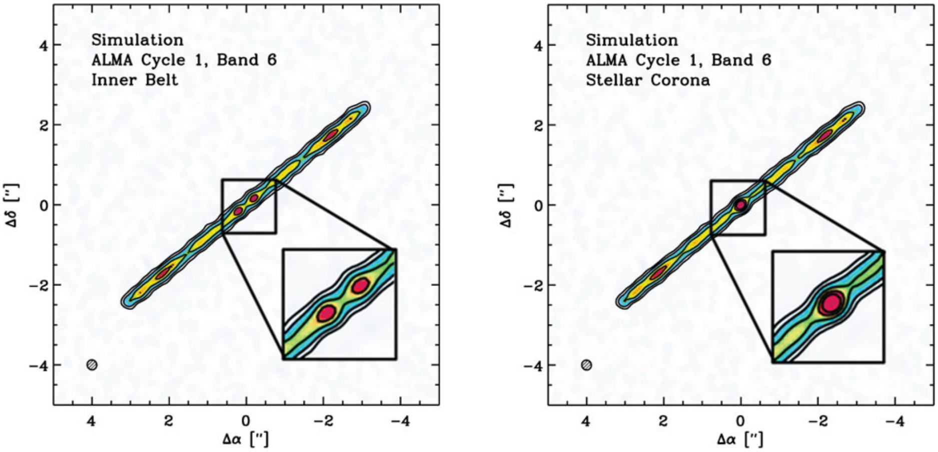

Figure 3. Simulations of the AU Mic outer disk with *(left)* an inner dust belt from 2 to 3 AU and *(right)* an unresolved stellar corona. It is clear that even ALMA Cycle 1 observations can easily resolve an inner belt and distinguish between these mechanisms for the central emission component.

Cycle 1 observations using the `SIMOBSERVE` task in the `CASA` software package of a disk model that includes an inner dust belt (from 2 to 3 AU) in addition to the already resolved outer belt shows that this inner belt structure can be easily resolved (Figure 3, left panel). A simulation of a model that instead includes a still unresolved peak from a hot stellar corona can be easily distinguished (Figure 3, right panel).

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Discussion

Liu: Substructure in AU Mic has been robustly detected in optical/near-IR scattered light. What are the implications for the nature of the clumps given that your ALMA observations did not detect any substructure?

MacGregor: It may be that any such features at millimeter wavelengths are erased by collisions over the lifetime of the system. Kuchner & Stark (2010) show that grain-grain collisions erase any signs of azimuthal asymmetry within the Kuiper Belt. As a result, any observer looking at the Kuiper Belt at millimeter wavelengths would see only a symmetric ring.

Booth: We saw from Sam Lawler's talk that although a significant proportion of Kuiper Belt Objects are in resonant orbits, these resonant structures are not obvious from the mass distribution. Therefore, it is perhaps not surprising that the sub-mm observations do not show structures seen in scattered light.

MacGregor: Very true. The detectability of any resonant population must depend on the relative contributions of dust producing objects located in and out of resonances. That, coupled with the role of collisions at higher optical depths, means that there is no guarantee that resonant populations will have visible signatures in millimeter images.

Graham: What are the prospects for resolving the vertical structure in the disk at mm-wavelengths?

MacGregor: ALMA Project 2012.1.00198.S (PI Meredith Hughes) aims to do just that.