A New Millimeter Look at the HD 15115 Debris Disk

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Abstract

We have used the Submillimeter Array (SMA) to make 1.3 millimeter observations of the debris disk surrounding HD 15115, an F-type star located in the 12 Myr-old β Pictoris moving group. This nearly edge-on debris disk (the "Blue Needle") has been previously well-resolved in optical scattered light and displays an extreme asymmetry. Unlike scattered light that reflects tiny grains that are blown out by stellar radiation and swept by the interstellar medium, the thermal emission from large grains that dominate at millimeter wavelengths closely traces the locations of the dust-producing parent planetesimals. These SMA observations reveal a circumstellar belt of thermal dust emission that extends to a radius ~113 AU, coincident with the outer edge of the ``birth ring'' of planetesimals hypothesized to explain the midplane scattered light profiles. The detection of this cold belt strengthens the kinship between the debris disks around its moving group sister stars, AU Mic and β Pic. Additionally, the continuum emission shows a ~3σ feature coincident with the western extension along the disk axis previously seen in scattered light observations. This feature is plausibly explained by secular perturbations to grain orbits introduced by neutral gas drag. However, future multi-wavelength observations are needed to reveal the true origin and structure of this potential disk asymmetry.

An Introduction to HD 15115

HD 15115 is an F2V star at 45 ± 1 pc (van Leeuwen 2007) whose space motions suggest membership in the ~ 12 Myr-old β Pictoris moving group (Moór et al. 2011), which includes the well-studied β Pic and AU Mic debris disk systems. Scattered light imaging from HST, Keck, and LBT have resolved a remarkable edge-on circumstellar disk (Kalas et al. 2007; Debes et al. 2008; Rodigas et al. 2012). In optical scattered light, the HD 15115 debris disk shows an extreme asymmetry (Kalas et al. 2007): the east side of the disk extends to ~ 7'' (315 AU), while the west side reaches 12.38'' (>550 AU).

Disk Modeling

In order to characterize the millimeter emission, we use the method described by MacGregor et al. (2013) that employs Markov Chain Monte Carlo (MCMC) methods to fit a simple parametric disk model to the observed visibilities and estimate the parameter uncertainties. We assume that the millimeter emission arises from a geometrically thin, axisymmetric belt. By fitting the visibility data directly, we are not sensitive to the non-linear effects of deconvolution, and take full advantage of the complete range of spatial frequencies sampled by the observations. Figure 2 shows the output of ~10^4 MCMC trials and the table to the right lists the best-fit model parameter values and their 68% uncertainties. Figure 3 shows a comparison between the data and best-fit model in the image plane, including the imaged residuals in the rightmost panel. Overall, this simple, symmetric disk model reproduces the bulk of the millimeter emission well. However, the residual image shows a ~3σ feature coincident with the western extension of the scattered light along the disk axis.

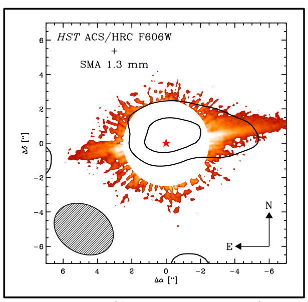

Figure 1- SMA image of the 1.3 mm continuum emission from HD 15115, overlaid on an image of optical scattered light from the *Hubble Space Telescope* (Kalas et al. 2007). The contour levels re in steps of 2 x 0.3 mJy, the rms noise level. The ellipse in the lower left corner indicates the 3.0''x 2.1'' (FWHM) synthesized beam size. The star symbol marks the position of the stellar photosphere, very close to the millimeter emission peak.

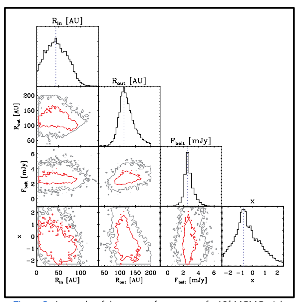

Figure 2- A sample of the output from a run of ~10^4 MCMC trials for the 4 main model parameters (R_{in}, R_{out}, F_{belt}, and x). The diagonal panels show the 1D histogram for each parameter marginalized over all other parameters considered in the model. The remaining panels show contour plots of the 1σ (red) and 2σ (gray) regions for each pair of parameters.

Evidence for A ``Birth Ring''

HST imaging of HD 15115 (Debes et al. 2008) shows that the surface brightness profile of the western side of the disk falls as $r^{-1.4\pm0.1}$ between 0.7'' (32 AU) and 1.8 (80 AU), and then steepens to fall as $r^{-3.5\pm0.06}$ beyond 1.8''. Additional scattered light observations from the LBT (Rodigas et al. 2012) show a coincident break in the western surface brightness profile near ~2'' (~90 AU). The inferred location of the outer edge of the millimeter emission belt, $R_{out} \approx 110$ is consistent within the uncertainties to both of these previous measurements. The observations of Rodigas et al. (2012) additionally show a drop in the surface brightness of the disk's western lobe *interior* to 1'' (45 AU), marking the inner edge of the belt. This estimation of the inner disk edge matches well with our determined inner radius of R_{in} = 43±28 AU. Thus, despite the modest signal-to-noise ratio and the presence of the residual extension, this model fitting exercise yields constraints on the inner and outer radii of the disk that are consistent with previous scattered light observations and compatible with the ``birth ring'' model of debris disks.

Submillimeter Array Observations

We observed HD 15115 in the fall of 2013 with the Submillimeter Array (Ho et al. 2004) on Mauna Kea, Hawaii at a wavelength of 1.3 mm using both the compact and extended configurations of the array (baseline lengths ranging from 6 to 182 m). Typically six (or fewer) of the eight array antennas were available during the five tracks, though the weather conditions were generally very good for this wavelength band. The phase center was located at α = $02^h26^m16.25^s$, δ = +06°17'33.19'' (J2000), the position of the star uncorrected for its proper motion of (86.31, -49.97) mas yr^{-1}.

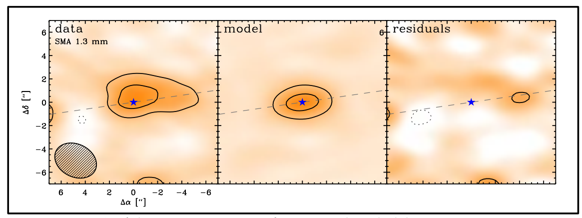

Figure 3- *Left*: the 1.3 mm continuum emission from HD 15115 observed with the SMA, as in Figure 1. *Center*: the best-fit symmetric disk model. *Right*: the image residuals. The contour levels are at 2σ (0.6 mJy $beam^{-1}$) intervals in all three panels.

Parameter	Description	Best-Fit	68% Confidence Interval
F_{belt}	Belt flux density (mJy)	2.56	+0.50, -0.83
R_{in}	Belt inner radius (AU)	43.	+28., -28.
R_{out}	Belt outer radius (AU)	110.	+31., -22.
x	Belt radial power law index	-0.75	+1.37, -0.87
Δα	R.A. offset of belt center ('')	1.26	+0.07, -0.05
Δδ	Decl. offset of belt center ('')	-0.78	+0.09, -0.05

What Causes Disk Asymmetries?

Peculiar scattered light debris disk morphologies have been observed previously, notably in HD 32297 (Currie et al. 2012; Debes et al. 2009; Boccaletti et al. 2012) and HD 61005 (Hines et al. 2007; Maness et al. 2009). While all of these disks demonstrate unique features, similar physical mechanisms should apply to shaping the dust belt in all three cases. Using these data, we are exploring several potential mechanisms for creating asymmetric disk structures like what is seen in HD 15115 and consider whether or not they can plausibly explain these unique morphologies.

Interactions with the ISM

1. **Ram Pressure Stripping of Disk Grains**
   Ram pressure from interstellar gas can remove bound and unbound grains from a disk.
2. **Ram Pressure Stripping of Disk Gas**
   Disk grains are swept away when they become entrained in outflowing gas.
3. **Neutral Gas Drag**
   Neutral gas drag introduces secular perturbations to the orbits of bound grains.

Interactions with External Perturbers

4. **Planetary Induced Resonance**
   Planets within the system produce dust-trapping resonances that create clumpy, wavelength-dependent grain distributions.
5. **Stellar Flyby**
   Interaction with a second moving group member (possibly HIP 12545) truncates one side of the disk.