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Debris Disks, Planetary Systems, and The Atacama Large Millimeter Array (ALMA)

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Abstract. The Atacama Large Millimeter Array, or ALMA, is an international telescope project which will be built over the coming decade in Northern Chile. With over 7000 m^2 of collecting area comprised of 64 12m antennas arrayed over baselines up to 14 km in extent, ALMA will provide images of unprecedented clarity and detail. One revolutionary feature of ALMA will be its ability to combine interferometric and single telescope data, providing complete flux recovery. ALMA will cover a spectral wavelength range from 7mm to <0.3 mm, providing astronomy with a detailed look at the structures which emit millimeter and submillimeter photons. The mapping of planetary debris disk systems will be among the most challenging projects for the ALMA array due to their large angular size (5-30$''$) and weak emission (less than 50 mJy at 345 GHz).

1. Introduction

Debris disks provide relic evidence to connect the genesis and growth of planetesimals around young stars with the process of their formation. Imaging debris disks details their structure, perhaps providing evidence for planets, differentiating confusing background objects and constraining disk orientation. With very little mass, debris disks are weak (typical masses provide less than 50 mJy at 345 GHz in the solar neighborhood). Because they must lie nearby to be detected, the flux will be spread over a large angular size (5-30$''$), requiring a sensitive system capable of recovering all of the disk flux. The simple detection of such systems is not too difficult: the rms continuum sensitivity under median weather conditions for ALMA in a 7 hour integration is expected to be 7 μJy at 345 GHz, corresponding to a gas+dust mass sensitivity of 4 x 10^{-4} Earth masses at a distance of 15 pc. However, this debris disk flux may spread over more than one $20''$ beam, requiring mosaic techniques and accurate total power measurement at low fluxes. If this challenge can be met, ALMA will determine the distribution of material and reveal signatures of planetary bodies.

Here we consider the capabilities of ALMA for studying debris disks through development of a simulated observation. A paradigm for the simulation is the nearby star 55 Cancri (ρ^1 Cnc), once thought to possess a debris disk. 55 Cancri lies at 12.53 pc as determined by Hipparcos; as a G8V star it approximates the Sun in age (~5 Gyr) and luminosity. The star has a companion (ρ^2 Cnc) about 1150 AU away. Butler et al (1997) noted that radial velocity variations suggest the presence of one or more planets. At least one of these companions has a mass (depending upon the unknown inclination i) M*sin i* of 0.84 Jovian masses in an orbit of 0.118 AU semi-major axis and a period of 14.66 days.

Dominik et al (1998) noted an excess of 60 micron emission detected by ISO, from which they inferred a debris disk with a radius of 50 AU. Trilling and Brown (1998), Trilling, Brown and Rivkin (2000), Jayawardhana et al. (2000) and Schneider et al. (2001) have sought evidence for this disk through scattered light; the latter two authors were unable to confirm the positive results presented by the first two, leaving the existence of the disk in doubt. Jayawardhana et al. (2000) used SCUBA on the JCMT to detect a submillimeter excess of 2.8 $\pm$ 0.5 mJy at 850 microns, and also an excess of 7.5 $\pm$ 4.2 mJy at 450 microns. Jayawardhana et al. (2002) repeated this observation, obtaining 7.1 hours of on-source observations of the region. Three peaks of emission at the 2.5 mJy level at 850 μm were detected, none coincident with the star. Hence, the peaks are likely unrelated background emission; the upper limit to the dust mass of the debris disk is 0.06 lunar masses, derived from the flux limit of 0.4 mJy within 100 AU of the star. Such a flux, somewhat above estimates for that of the Kuiper Belt, would be detected by ALMA in less than three minutes. Hence, ALMA will provide fast identification of debris disk systems and discriminate between disks and other confusing sources in addition to providing an idea of the inclination of the system through inspection of its image. Furthermore, ALMA will provide sensitive astrometry of the central star. The reflex motion induced by a companion might be measured, removing the uncertainty in inclination of the system and determining the companion mass.

2. ALMA Simulation

The simulation in these images represents a debris system with 1 Earth mass (gas+dust for a "normal" gas to dust ratio) of emitting material, developed by Lee Mundy. In terms of emitting dust mass alone, this corresponds to about 0.8 lunar masses of material. This amount of material is similar to that derived for the Fomalhaut system by Holland et al (1998). The model is described in Table 1. A feature of the model is that some rings have breaks with overdensities in the ring on each side. Such a feature may provide a signature of planets (Liou and Zook 1999). As a further test of ALMA imaging, the word ALMA is written in the lower part of the disk as a 50% overdensity and in the upper part of the disk as a 33% underdensity.

Table 1. Model Debris Disk Characteristics

Feature	Amplitude	Radius (AU)	Width (AU)	PA (deg)
Dark Ring	1.0	7	2	
Dark Ring	2.0	16	4	
Planet Debris	1.5	40	5	45
Planet Debris	3.0	60	9	155

Notes: T_{dust}=350 K at 1 AU; $T_{dust} \propto r^{-0.45}$; $\Sigma_{dust} \propto r^{-1.3}$; Inclination = 45°; r_{inner}=3AU; r_{outer}=125AU

As is evident in the images, lower resolution images are needed to bring out the large scale structure of the disk; higher resolution can be used to probe the warmer and higher surface density inner regions of the system.

The planetary induced breaks in the outer two rings are detectable in the simulated observations. If this type of model for dust-planet interaction is correct it may be possible to indirectly detect and track the orbits of planets in some debris systems.

One major advantage of millimeter and submillimeter wavelengths in the mapping of debris systems is the modest dynamic range needed to separate the stellar and disk emission. In this simulation, the solar-type star is a 250μJy point source at the center of disk; the disk has total flux of 10 mJy. At $0.11''$ resolution (1.7 AU resolution at 15 pc), the emission from the inner portion of the disk (in mJy/beam) is 2-3 times that from the stellar photosphere.

Simulations of ALMA's performance have been performed in several software packages, all showing similar results. Even in its most compact configuration, ALMA will be able to image structure in the outer debris disk in only a few hours of observation with nearly perfect imaging characteristics. Although the debris disk approaches the size of the ALMA primary beam, no flux will be lost, as total power observations are a feature of ALMA imaging. Thus, the total mass of the disk is well-constrained by the ALMA observations, which may be performed at several frequencies. ALMA's resolution changes as the antennas are deployed over the Chajnantor plain. In a configuration of diameter 450m, several rings in the model are resolved in the paradigm 4 hour integration; the inclination of the system is also measured. Radial velocity techniques imprecisely explore the possible existence of planets in this extended region; dust rings, indicative of the presence of such planets, can be imaged by ALMA in a single transit. In larger configurations, the central star and features near it (but not the planet) could be imaged, testing hypotheses about the size of the central hole, of the dust temperature distribution in debris disk systems, and of the existence of closer planets in the system.

3. ALMA Astrometry

ALMA could also constrain the mass of planets in the system through astrometry. McGrath et al. (2002) cite Hipparcos data which suggest that ρ^1 Cancri has a reflex motion with a radius of 1.15 mas, implying that its companion is an M dwarf with the mass of 126 Jupiters. Using the Hubble Space Telescope Fine Guidance Sensor and a novel observing technique they found no reflex motion

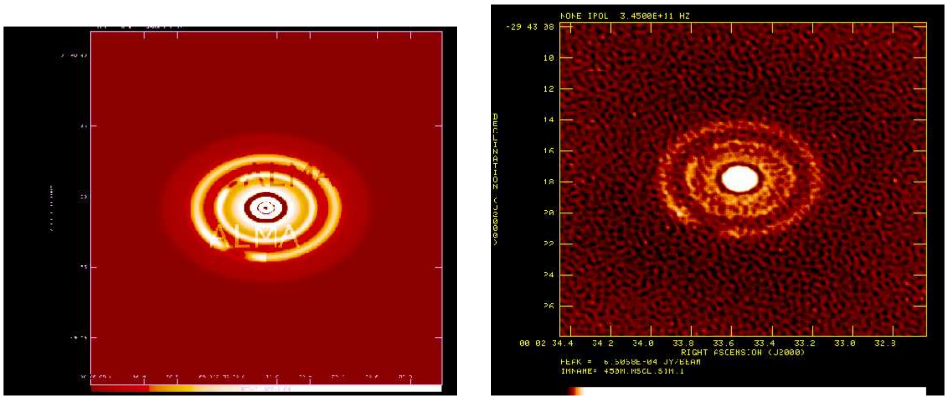

Figure 1. Simulations of an ALMA observation of the debris disk using multi-scale CLEAN in the aips++ package. On the left, a representation of the model described in Table 1. On the right, a 4 hour observation with the 450m array, which achieves moderate (0.4″) resolution. Thermal noise limits sensitivity. A combination of images in multiple arrays would afford the best representation of the original image. Clearly, in one transit ALMA would be able to constrain 1) the photospheric flux of the central star (not resolved from inner dust in these compact configurations), 2) the general structure of the disksuggesting the presence of planets and 3) the total dust mass of the disk, as all of the flux is recovered in the image.

above 0.3 mas, putting the mass below 30 Jupter masses and well within the brown dwarf range. The 240 μJy flux of ρ^1 Cancri could be detected at 30 σ in the extended 14 km configuration of ALMA with a 13 mas beam in a five hour track at 850μm. The position of the star relative to nearby stars (ρ^2 Cancri is within the ALMA beam) should be measurable to better than 20 mas. A few observations spread over several months should be sufficient to determine the reflex motion quite well.

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