HIGH RESOLUTION IMAGING OF CIRCUMSTELLAR DISKS AT MILLIMETER WAVELENGTHS

Grant NAG5-11777

Annual Report

For the period 1 March 2002 through 28 February 2003

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January 2003

Prepared for

National Aeronautics and Space Administration
Goddard Space Flight Center, Greenbelt, MD

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The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

January 10, 2003

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Our program uses the techniques of millimeter interferometry to make high resolution observations of dust continuum emission to study the structure of protoplanetary disks and debris disks around nearby stars. Observations of dust emission at these wavelengths are advantageous because the dust emission is generally optically thin and directly proportional to mass, and contrast with stellar photospheres is not a problem. We are using of several observational facilities, including (1) the Very Large Array (VLA) of the National Radio Astronomy Observatories, (2) the Plateau de Bure Interferometer (PdBI) of the Institut de RadioAstronomie Millimetrique, and (3) the Submillimeter Array (SMA), now under construction by the Smithsonian Astrophysical Observatory and Academia Sinica (Taiwan).

In the past year, we have accomplished the following (more details below):

1. We continued work on our "low resolution" VLA survey of disks in Herbig Ae star and binary systems, primarily to identify candidates for higher resolution follow-up. We have submitted a paper for publication on the detailed analysis of the structure of the disk around CQ Tauri.
2. We completed analysis of our PdBI observations of the debris disk around Vega (Wilner et al. 2002), and we presented these results at (1) the 199th AAS meeting in Washington, DC, and (2) a symposium in memory of Fred Gillett on Debris Disks and the Formation of Planets, in Tucson, AZ.
3. We continue commissioning observations with the SMA, which include the first ever interferometric images in the 850 μm wavelength band, in preparation for eventually imaging debris disks.

1. VLA Observations of Herbig Ae Stars and Binaries

The VLA 7 mm observations now take advantage of the maturity of the system, which now includes receivers on nearly all of the antennas (25 of 27) and very efficient observing modes. The disks around pre-main-sequence stars of 1.5 to 3 $M_{\odot}$ are the precursors of the much older debris disk systems. Recent observations show surprisingly flat spectral indices at millimeter wavelengths for some of these stars, which require either a massive disk with dust particles grown to centimeter sizes or physically small disks of high opacity. These models can be distinguished using millimeter observations that obtain sufficient angular resolution. We have started a survey a small sample of Herbig Ae stars to obtain reliable interferometric determinations of spectral indices between 1.3 mm and 7 mm. We successfully detected five targets using the VLA in the D configuration, and we resolved one of them with observations in the C configuration. The detailed analysis of this star, CQ Tau, has been submitted for publication. We have successfully proposed to observe additional Herbig Ae stars with the VLA in the C configuration.

We also surveyed a small sample of multiple star systems in with the VLA in D configuration. Much of this observing time was lost to poor weather, though some of these data were OK. More interesting has been follow-up in the high resolution A configuration (50 mas resolution) of the embedded protostellar source IRAS04368+2557 in the Taurus cloud. These 7 mm observations resolve a compact binary system of dust condensations with a projected separation of 25 AU, one of which has a disk morphology. Possibly the disk is truncated by tidal interactions. Comparison of the new data with VLA 7 mm observations made 6 years earlier show the proper motion of the Taurus cloud ($\sim$ 20 mas/yr) and residuals that are most readily interpreted as orbital motion of the binary ($\sim$ 4 mas/yr). The paper by Loinard et al. (2002) provides more details.

2. IRAM PdBI Observations of Debris Disks

Until recently, little was known about structure in the dust emission nearby main-sequence stars surrounded by dusty debris. Imaging and photometry now suggest that these systems frequently contain clouds of dust shaped like disks or rings, which hints at clearing by planets. We used the PdBI to image the 1.3 mm dust emission from Vega, one of the most nearby examples. Figure 1 summarizes the results. The PdBI image is consistent with earlier inferences of a clumpy disk viewed pole-on. These data also show that the dust emission is largely concentrated to two peaks. The simultaneous detection of the stellar photosphere allows for excellent relative astrometry; the peaks are not exactly at the same distances from the star, and they are not exactly co-linear with the star. Our numerical simulations show that the observed asymmetries in the peak positions may be naturally explained by the dynamical influence of an unseen planet in an eccentric orbit, which traps dust in principal mean motion resonances. The lower left panel of Figure 1 shows a simulated 1.3 mm emission image made by numerically integrating the orbits of test particles under the influence of gravity from Vega and a 3 Jupiter-mass planet, together with radiation pressure and Poynting-Robertson drag. The lower right panel of Figure 1 shows the result of imaging the model brightness distribution using the visibility sampling of the PdBI observations, which captures the main features of the data. Wilner et al. (2002) provide more details. We are working on another paper on the dynamical theory that explains the strength of the resonances. The Vega results were the subject of a press release at the 199th AAS meeting in Washington, DC that resulted in substantial media coverage, both local (Harvard Gazette) and national (Science News cover story).

Encouraged by the Vega results, we proposed to use the PdBI to make a similar study of the 1.3 mm dust emission around ϵ Eridani, the closest (3.22 pc) main sequence star surrounded by a substantial debris disk, and the only one where precision radial velocity measurements indicate the presence of a planet. We hope to image the inner region of the disk, where 850 μm images show an unresolved enhancement in the dust emission, possibly due to dynamical interactions with the planet. Our proposal received the highest rating from the IRAM Programme Committee. The observations are extremely difficult and will require excellent weather. Data taking began in late 2002, and the these data have been reduced, showing the expected noise level. However, much more data will be required to detect an interesting signal, and it is unclear if these observations will be made.

3. Preparation for SMA observations of Debris Disks

We remain on track to use the SMA, a unique submillimeter interferometer now under construction on Mauna Kea, for observations of debris disks during the last year of this grant. The dust emission in the submillimeter is stronger than at longer wavelengths, which will allow for sensitive observations of debris disk structure, including the possible signatures of planets. As of this writing, half of the eight SMA antennas are operational, and the rest are expected to be operational before the end of 2003. Preliminary SMA observations have resulted in the first ever interferometric images made in the 850 μm and 450 μm atmospheric windows. The PI (Wilner) and Co-I (Ho) expect to continue their active participation in SMA commissioning and early science observations.

REFERENCES

Wilner, D.J., Holman, M.J., Kuchner, M.J., Ho, P.T.P. 2002, "Structure in the Dusty Debris around Vega", ApJ, 569, L115

Loinard, L., Rodriguez, L.-F., Wilner, D.J., Ho, P.T.P. 2002, "Orbital Proper Motions in the Protobinary System L1527", ApJ, 518, L109

Testi, L., Natta, A., Shepherd, D.S. and Wilner, D.J. 2004, "Large Grains in the disk of CQ Tau", A&A, submitted

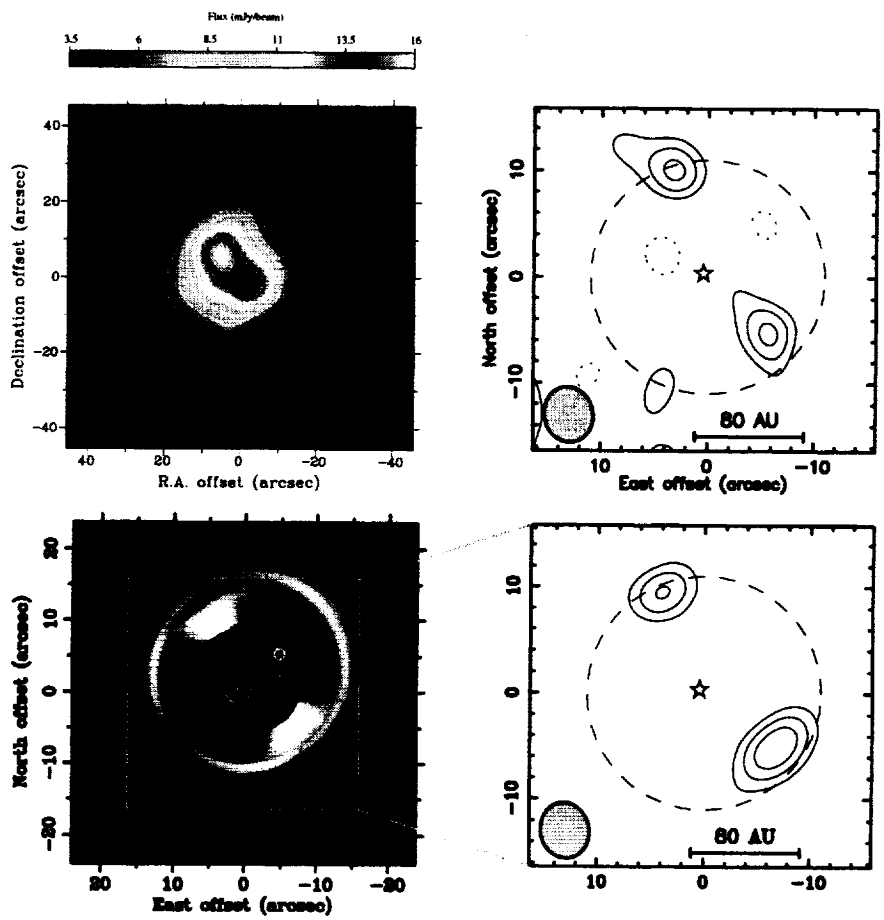

Fig. 1.— **(upper left)** JCMT 850 μm image of the dust disk surrounding Vega, from Holland et al. (1998). **(upper right)** IRAM PdBI 1.3 mm image of Vega, with the stellar photosphere subtracted (1.7 mJy). Contour levels are $\pm 2, 3, 4 \times 0.5$ mJy. **(lower left)** A simulation of 1.3 mm emission from orbital dynamics that includes a 3 Jupiter-mass planet, radiation pressure, and Poynting-Robertson drag. The dust becomes temporarily entrained in mean motion resonances associated with the planet. The ellipse represents the planet's orbit, and the circle marks the planet's position. **(lower right)** Simulated observation of the numerical model, taking account of the IRAM PdBI response for the Vega observations.

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