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Final Report

Contract: NAG2-1060

Title: High Resolution Far-infrared studies...

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A summary of our work on this grant is presented here.

A. Observations

We have been obtained high-resolution data (20″ at 50 μm and 30″ at 100 μm) on the KAO using Paul Harvey's 2 ×10 element photometer in both scanning and nodding modes. The practical flux limit for scanning is about 100 Jy. For fainter sources, a nodding (beam-switching) mode, which spends more time on the source, is used. This technique has been used successfully on objects as faint as 10 Jy; the 1σ noise for a 1 hour integration is about 1 Jy. Although not as sensitive as space-based instruments, the higher spatial resolution afforded by the KAO is essential in studying the far-infrared emission associated with young stars; in several cases we have been able to distinguish emission from multiple sources which were blended in the IRAS beam. In addition, comparison of fluxes in the KAO beam to those in the much larger IRAS beam provides information on the extended low-level emission arising from the surrounding region.

The value of the KAO observations is exemplified by our study of Herbig Ae/Be stars. Using ground-based photometry, Hillenbrand et al. (1992) classified these stars according to their SED's: Group I stars had SED's consistent with circumstellar disks; Group II stars had such large far-infrared excesses that envelopes were invoked, in addition to disks; Group III stars had no significant infrared excesses. IRAS data adds a note of confusion because many Group I sources have far-infrared emission significantly in excess of that predicted by their disk model; however, the large IRAS beam makes it hard to know if that excess arose from nearby, more embedded sources, widespread, low-level emission from many sources, or a circumstellar envelope associated with the star under study.

Our previous work on far-infrared emission from Herbig Ae/Be stars confirmed that Group II stars indeed had evidence for circumstellar envelopes (Natta et al. 1992, 1993), as suggested by Hillenbrand et al. (1992). We have recently completed a far-infrared study of six Herbig Ae/Be stars in Group I (Di Francesco et al. 1994). Our results indicate that 5 of the 6 Group I stars observed show resolved far-infrared emission, closely centered on the star, ruling out a significant contribution from very extended emission or nearby sources. If the far-infrared emission were arising solely from a disk, it would not be resolved in our observations, regardless of the size of the disk, because the temperature in a disk drops rapidly with increasing radius. At a radius smaller than our beam size at these distances, disk temperatures fall below that required to produce significant far-infrared emission. Consequently, even very large disks cannot produce far-infrared emission which is extended on the scales observed (10″ to 100″) (Di Francesco et al. 1994).

Our discovery of extended far-infrared emission around Group I Herbig Ae/Be stars calls to question the use of far-infrared fluxes for determining circumstellar disk properties in these systems. Quite independently, Hartmann, Kenyon, and Calvet (1993) have questioned the use of near-infrared spectral energy distributions as probes of circumstellar disks.

They propose that the bulk of the near-infrared emission arises from aspherical envelopes associated with the central star or a nearby companion. In combination, these papers suggest a rather different picture from the one presented by Hillenbrand *et al.* (1992), in which the circumstellar accretion disk dominates the luminosity and infrared signature. Disks may still be present in these systems, but the disk is apparently not the only source of emission at infrared wavelengths. This means that estimates of the disk masses, disk sizes, accretion luminosities, and mass accretion rates need to be reexamined with more detailed modeling. In addition, the presence of envelopes around Group I sources blurs the dividing line between Groups I and II. If the envelopes around these Group I sources show steep density profiles characteristic of infall, it may make sense to categorize sources using the mass of the envelope. We have begun modeling the envelopes around Group I sources with a radiative transport code described below.

We have also observed some of the embedded stars which have luminosities similar to intermediate-mass pre-main-sequence stars. So far, the sources tend to show extended far-infrared emission, indicating extended envelopes (Di Francesco et al. 1995). We have further observations of this class of objects, and modeling of these data is still in progress.

In addition to the KAO observations, we are continuing to obtain data at other wavelengths on the objects under study. We have observed nine Herbig Ae/Be stars with the IRAM and BIMA millimeter-wavelength interferometers. These data indicate that much of the millimeter emission seen with single dishes is not coming from disks associated with the visible stars. In some cases, the millimeter emission is entirely resolved out. In other cases, the emission is compact, but it appears to come from a nearby, more embedded object, rather than the visible Herbig Ae/Be star. We reported on our initial observations of these objects (Evans and Di Francesco 1995) and we present an analysis of these data which constrains the emission contributions from disks in these systems in Di Francesco et al (1997).

These additional observations are supported by other grants, but they contribute to the analysis of the KAO data.

B. Analysis

We have developed a number of codes for producing model intensity distributions. One is a disk code which uses a parametric power law formulation for the radial dependence of the dust temperature and column density (Beckwith et al. 1990). Another code models a spherical envelope, also using the parametric formulation for the density and temperature (Wilking *et al.* 1993). The advantage of these two codes is that they are simple and computationally cheap, hence good for exploration of parameter space.

The main analysis code used in our work is a modified version of the code described by Egan, Leung, and Spagna (1988) which solves the radiation transport problem self-consistently. The code calculates the dust temperature distribution which is consistent with the input density distribution, the assumed dust properties, and the radiation from a central source. The central source can be either a stellar blackbody or a star plus disk system. The radiation from the central source is propagated through the spherical envelope to produce a model intensity distribution, including the star, disk, and envelope contributions. Since essentially all theories of collapse produce power-law density distributions (e.g., Larson 1969; Shu 1977), we assume this form: $[n(r) = n_i(r/r_i)^{-\alpha}]$, where n_i is the density at the inner radius of the envelope, r_i.

The output from these models is compared to the data by simulated observation of the model intensity distribution. For more compact and isolated emission sources, it is usually best to conduct the analysis at the level of the scan. A scan across the source can be compared to models by convolving the intensity distribution from a model with the response of our system to a point source. By scanning the intensity predicted by models with different parameters, we can determine which values of α, n_i, and r_i most successfully reproduce the far-infrared data.

To include observations at other wavelengths into the picture, our code also computes the model spectral energy distribution by convolving the surface brightness distribution with the beam pattern used in the individual observations. Comparison of these model flux densities with the actual observations provides more constraints on the models than are available from the far-infrared observations alone. In addition, we have developed a code which can calculate the visibility function of a model for comparison to data from interferometers. These codes have been used in the works discussed above and the publications listed below.

In collaboration with N. Calvet and L. Hartmann, we have begun to use a two-dimensional radiative transport code to allow us to consider departures from spherical symmetry. With this new code, we will be able to model the Group I sources more consistently.

C. Publications

"Far-Infrared Maps of Intermediate-mass Young Stellar Objects", Di Francesco, J., Evans, N.J.II, Harvey, P.M., Mundy, L.G., and Butner, H.M. in Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust, v. 73, p. 267, 1995.

"Constraining Circumstellar Environments - Far-Infrared Observations of Herbig Ae/Be Stars", Di Francesco, J., Evans, N. J., Harvey, P. M., Mundy, L. G., and Butner, H. M., *Ap.J.*, 432, 710, 1994.

"Photon Heating of Envelopes around Young Stellar Objects: An Explanation for CO J=6-5 Emission", Spaans, M., Hogerheijde, M.R., Mundy, L.G., and van Dishoeck, E.F., *ApJL.*, 455, L167, 1995.

"On Turbulent Pressure Confinement of Ultra-Compact HII Regions", Xie, T., Mundy, L.G., Vogel, S.N., and Hofner, P., *ApJL*, 473, L131, 1996.

"Millimeter Interferometry of Herbig Ae/Be Stars", Di Francisco, J., Evans, N.J., Harvey, P.M., Mundy, L.G., and Guilloteau, S., *ApJ*,482, 482, 1997.