38-201

Final Report: NASA-Ames Agreement

No. NAG 2-1060

Recd.
MAY 05 1999

CC 202A-3

CASI

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TITLE: High Resolution Far-Infrared Studies of Compact Regions in Star-forming Molecular Clouds

Work Accomplished Under Grant

This grant supported the acquisition, analysis and publication of high spatial resolution observations of the far-infrared emission from compact regions of star-forming molecular clouds using the Kuiper Airborne Observatory. We studied regions which are forming stars of low and intermediate mass. In analyzing the data, we utilized radiative transfer codes, incorporating disk models and envelopes, including departures from spherical symmetry. These data, along with data at other wavelengths, were used to probe the distribution of dust temperature and density around young stars and to test theoretical predictions about star formation. A substantial portion of this work represented the dissertation work of Mr. James Di Francesco. This work was done in collaboration with Dr. Neal J. Evans II of the University of Texas, who submitted an identical proposal separately.

The following is an overview of our work.

A. Results from Observations

We 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 were 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 provided 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 FIR 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 FIR 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 work on FIR 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 next 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 FIR emission, closely centered on the star, ruling out a significant contribution from very extended emission or nearby sources. If the FIR 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 FIR emission. Consequently, even very large disks cannot produce FIR emission which is extended on the scales observed (10" to 100") (Di Francesco et al. 1994).

Our discovery of extended FIR 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 modelled 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. These sources tend to show extended FIR emission, indicating extended envelopes (Di Francesco et al. 1995). In addition to the KAO observations, we obtained data at other wavelengths on the objects under study. We observed nine Herbig Ae/Be stars with the IRAM and BIMA mm-wavelength interferometers. These data indicate that much of the mm emission seen with single dishes is not coming from disks associated with the visible stars. In some cases, the mm 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 (Di Francesco et al 1994, 1995, 1997). These data constrain the contribution of disks in these systems.

B. Results from Modelling

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 FIR 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.

We have found that a surprising number of Herbig Ae/Be stars still have extended envelopes which appear to be responsible for most of the far-infrared emission. This result suggests that naked disk systems may be very rare but there is one significant caveat: so far, most of the observed stars have strong far-infrared emission. This choice may have bias our sample toward objects with envelopes. During our last flights, we made observations of a sample of Herbig Ae/Be stars with fainter FIR emission to investigate this possible bias. If the envelopes are still present in these systems, it may indicate a major difference in the formation of intermediate-mass stars and T Tauri stars, which are thought to include many naked-disk systems.

We also extended our observational sample of embedded stars of intermediate mass to include a total of 19 objects. Based on the new evolutionary calculations of Palla and Stahler, we focused on objects with luminosities between 200 and 5000 $L_\odot$, as the evolutionary precursors of stars with $4 < M_\odot < 8$. These objects were analyzed with the same techniques that we will use for the visible stars. Detailed analysis of the flux densities and positions from our maps suggest the FIR emission may not arise from the region immediately surround the Herbig Ae/Be stars in all cases. Instead, often the FIR emission from these objects originates from dust heated externally by the Ae/Be stars, or from dust heated internally by other sources. For the objects which are arguably surrounded by far-infrared emission, the emission has similar deconvolved sizes (0.10 to 0.15 pc) to the previous sources, suggesting that the emission may originate from an extended envelope or nearby cloud. The appearance of a far infrared object as either a Herbig Ae/Be star or an embedded IRAS source may often be a matter of viewing orientation rather than fundamental evolutionary status. This work is published in Di Francesco et al (1998).

This research on Herbig Ae/Be stars forms the core of the Ph.D. dissertation work of Mr. James Di Francesco at the University of Texas, Austin.

Publications resulting from this grant include the following.

"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.

Interferometric Observations of Herbig Ae/Be Stars at 2.73 mm" Di Francesco, J., Harvey, P.M., Evans, N.J. II, Mundy, L.G. AAS 185, 4814, 1994.

"Far-Infrared Maps of Intermediate-mass Young Stellar Objects", DiFrancesco, 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.

" Interferometric 2.7 mm Continuum Observations of the Herbig Ae/Be Star Elias 3-1" 'Di Francesco, J., Evans, N.J. II, Harvey, P.M., and Mundy, L.G., AAS 187, 10602, 1995.

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

"High Resolution Far-Infrared Observations of Intermediate-Mass Pre-Main-Sequence Objects", Di Francisco, J., Evan, N.J., Harvey, P.M., Mundy, L.G., and Butner, H., *ApJ*, 509, 324, 1998.