NASA-CR-204638

June 5, 1997

Attn: Barrie Caldwell
NASA Ames Research Center

Dear Barrie,

You recently requested a copy of the Final Report for a grant that I obtained through the Airborne Astronomy Program. This grant, NAG 2-959, was through the Department of Terrestrial Magnetism, Carnegie Institution of Washington. The Carnegie Institution will have already sent you the Final Cash Report. I enclose the final Technical Report. My apologies for not getting this to you sooner, but I was unaware that it was required.

To complicate matters, I recently moved from DTM-Carnegie to Steward Observatory.

My phone number is 520-626-5216 (office) and my fax number is (520)-621-5554, should you have any questions. I will be unavailable for the next few weeks due to my impending marriage and honeymoon.

Sincerely yours,

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Final Technical Report: Airborne Astronomy Program (NRA2-36449 (BXM) Grant NAG 2-959

The Circumstellar Environment of Low Mass Star Forming Regions

Harold M. Butner Principal Investigator

I. Introduction

Since the 1980's, our understanding about the inter-relationship between the collapsing cloud envelope and the disk has been greatly altered. While the dominant star formation models invoke free fall collapse and a $r^{-1.5}$ density profile, other star formation models are possible. These models invoke either different cloud starting conditions or the mediating effects of magnetic fields to alter the cloud geometry during collapse. To test these models, it is necessary to understand the envelope's physical structure. However, the presence of a disk complicates the interpretation of the envelope's size, shape, and temperature profile. The disk has emerged as an important component in its own right. Many models predict that disks should be a common feature of the star formation process. Disks also are of great interest as a potential planet forming region. Observationally, a number of disk "signposts", such as millimeter emission from optically visible T Tauri stars, were detected. Yet, in many cases, the information we derive about disk properties depends implicitly on the assumed envelope properties. Thus, a key problem is how to separate the two components from each other.

A high spatial resolution program, undertaken over a variety of wavelengths, offers us the opportunity to model the two components, disk and envelope, in detail. Both the disk and envelope will contribute different amounts of flux at different wavelengths. The spatial scale of the disk emission and envelope emission will also be very different. By combining high resolution multiwavelength data with radiative transfer models, one can assess the likely contribution of both the disk and the envelope. The envelope contribution dominates the far-infrared emission, with as much as 80% of the total flux coming from the cool dust found in the outer portions of the envelope. This emission can be detected and mapped with high resolution observations, such as the Yerkes Far-InfraRed (FIR) Camera on board the Kuiper Airborne Observatory(KAO). We obtained far-infrared (60, 100, 160, 200 micron) images for a number of young stellar objects (YSOs) with the KAO prior to the KAO's shutdown.

In the proposal covered by the grant (NAG-2-959), we proposed to analyze the data, acquire additional data for models, and to develope source models for the YSOs under study. Based on the results of these models, we hope to define the range of physical conditions that are expected in young stellar systems of different ages and masses. We received funding from the Airborne Astronomy program to pursue these goals. Through the resources provided by the Airborne Astronomy program, we were able to accomplish many of our project goals.

II. Observational Data Acquired for Source Models

Far-Infrared Images: In FY 93 and FY95, we were awarded two flights each year to study the envelope arounds low mass protostars in Taurus. Working with the Yerkes FIR camera, we obtained data on a total of 13 sources. Table 1 summarizes the far-infrared data that we have available. The Yerkes FIR camera contained an 60 element array. Our standard observing method was to dither the array around the desired source position, and to take a series of images for later coadding. Initial data reduction indicated that most of the sources were compact, as would be expected for low luminosity protostars surrounded by an infalling envelope. Such objects will not tend to heat up a lot of the envelope, and what dust is heated will be concentrated towards the center. However, two sources (L1527 and L1551NE) appeared to show extended emission. This was particularily interesting since these objects may be the the youngest objects in the sample. The claim of youth is based on their spectral energy distributions (SEDs). which are peaked very strongly in the FIR. Such a peak implies that the object is still deeply enshrouded in dust.

Our initial data reduction was based on smoothing the data with a relatively broad smoothing function (i.e. a Gaussian beam). The smoothing resulted in the data being far from the diffraction limit. To address this situation, we undertook (with the Yerkes group) to re-reduce the data using improved convolution methods. These methods took considerable time to develope at Yerkes Observatory, due to the desire to achieve the true diffraction limit in our maps. The data reduction was recently completed and we have begun the final set of models.

To supplement the KAO data, we obtained observations at related wavelengths for a number of the sources in our KAO dataset.

Mid-Infrared spectra: Building upon the original 10 μm Cohen and Witteborn (1985) survey of T Tauri stars, we have obtained R=200 spectra for several of the T Tauri stars (DG Tau, T Tau, GG Tau). (Wooden *et al.* 1997). The spectra show 9.8 μm silicate emission, indicating the presence of optically thin silicate dust.

Mid-Infrared images: Using the MIRAC2 (Mid-Infrared Array Camera), we have imaged several of the embedded YSOs at 10 μm. These observations provide high sensitivity high spatial observations of the circumstellar environment on size scales of 150 AU. Our initial data analysis suggests that the emission is very compact, consistent with the emission as arising from either the disk or the innermost edge of an envelope. We have yet to apply MEM techiques, as Marsh *et al.* (1995) did for AB Aur, so we may yet find examples of slight extended emission among this group. Extended emission is possible, since we found several examples in related studies of Herbig Ae/Be stars. However, if found, it is likely to reflect the presence of small, hot grains. The stars are generally too cool to provide much heating of classical dust grains in the extended envelope. In addition, we obtained 10 and 20 μm images of the Trapezium cluster, with its proplyds, which we are currently analyzing to provide a comparison with our isolated stars.

Submillimeter/millimeter photometry: This has been a very active area in the star formation field. A number of surveys have been completed for Herbig Ae/Be stars, T Tauri stars, and embedded YSOs. Our attention has focused on two groups within our sample: the Taurus embedded YSOS and the Vega-like stars. In the case of the Taurus sources, we have obtained a complete survey of the 450-2000 μm emission using the JCMT 15 meter telescope. For the Vega-like stars, we used the CSO 10m and IRAM 30m telescopes to get 800 and 1300 μm photometry. The data is currently being written up in two papers.

Submillimeter/Millimeter Interferometry: A number of our sample stars have data already available in the literature. However, a large fraction of the stars remained to be observed. To fill that void, we recently obtained 1.3 mm interferometry data for the brightest 16 YSOs in our Taurus sample. These observations extended a previous survey we had done. We detected 14/16 sources (Wannier *et al.* 1997 in prep). Of particular interest, we discovered evidence for a couple of binaries in our sample (L1551NE). This dataset will be combined with published interferometer 2.7 mm data reported in several surveys. We also were awarded time to study a sample of Taurus YSOs with the JCMT-CSO Single-Beam-Interferometer, and got data on DG Tau. Other observations were weathered out but we have resubmitted the proposal, and hope to establish a sample of ten stars with high resolution observations.

Summary: We have obtained the complete SED from 10 microns out to 1.3mm for all of our sources. We have the FIR imaging data, processed to reveal the maximum angular resolution possible, which allows us to model the disk. To model the disk, we have the high resolution millimeter interferometry data.

Table 1: Observed Sources

IRAS	ID	R.A.(1950)	Dec.(1950)	$F_{100\mu m}$ Jy	$F_{800\mu m}$ Jy	L_{IRAS} $L_\odot$	CO Outflow?	λ Obs.?
Embedded Stars in Taurus								
04016+2610	L1489IRS	$4^h01^m40.6^s$	26°10'49"	55.69	0.58	2.9	Y	100,200
04287+1801	L1551IRS5	4 28 40.2	18 01 41	457.91	8.05	19.	Y	60,100,160,200
	L1551NE	4 28 50.5	18 02 10	130.	2.30	3.8	Y	60,100,200
04325+2402	L1535	4 32 33.5	24 02 15	22.35	0.30	0.6	Y	100
04365+2535	TMC 1A	4 36 31.2	25 35 56	39.25	1.01	1.7	Y	100,200
04368+2557	L1527	4 36 49.8	25 57 21	73.26	1.52	1.0	Y	100,160,200
T Tauri Stars								
04190+1924	T Tau	4 19 04.2	19 25 05	98.07	1.216	7.6	Y	60,100,200
04240+2559	DG Tau	4 24 01.0	25 59 36	45.98	1.23	3.6	Y	60,100,160,200
04296+1725	GG Tau	4 29 37.1	17 25 22	5.16	1.11	0.4	N	100
04328+2248	HP Tau	4 32 52.9	22 48 18	16.54	0.21	0.8	Y	100
Low Mass Cores								
21106+4712	B361	21 10 40.9	47 12 01	38.00		4.7		
	L1031B	21 45 27.9	47 18 12					60,100,200
23238+7401	L1262A	23 23 48.7	74 01 08	14.00		0.9		60,100,200

Notes to Table 1: Taurus objects taken Moriarty-Schieven, Wannier, Keene, and Tamura (1994), see references within; Low Mass cores taken from Benson and Myers (1989).

III. Modeling Techniques Developed for Source Models

At the start of the project, we had one primary modeling technique: a 1-D radiative transfer code that allowed us to explore a variety of density gradients and grain properties. We also had a way of including disk emission within the envelope. With these models, we could explore a wide range of disk/envelope models. We have continued to refine our modeling techniques as the dataset expanded. In addition to the 1-D radiative transfer code, we have added another code that allows us to explore the importance of Polycyclic Aromatic Hydrocarbons (PAHs) and small grain heating for the models. This code, developed by Siebenmorgen, Krugel, and Mathis (1992), allows us to do spatial models of the PAH emission and small grain emission. Such effects are critical to understanding the emission from a number of the Herbig Ae/Be stars we have under study.

More recently, we have gained accessed to a fast 2-D code which will allow us to more fully explore the effects of disks on the source models. This code is being supplied to us by Dr. Men'shchikov. It can handle both deeply embedded sources as well as visible disks. Thus, we will be able to study the range of disk-envelope systems for which we have data. This work is expected to continue in the future.

Overall, there are three important parameters we are exploring with our models:

1) The envelope geometry and temperature structure.

To model this requires the use of the overall SED and spatially resolved data at a couple of different wavelengths. Experience with the models reveals that the best wavelengths are typically the far-infrared and submillimeter.

2) The disk geometry and temperature structure.

The SED is required, plus some very high resolution data at either millimeter or mid-infrared wavelengths. The latter is critical if one wishes to investigate the role that small grains or PAHs might play in the dusty disk.

3) The dust properties in both the envelope and the disk.

These dust properties are best probed by the mid-infrared spectral line data and careful comparison of specific dust model predictions with the observed spatial extent. In the models, we have found that we can trade off between assumed dust properties and the model disk/envelope structure to a limited degree when reproducing the observations.

IV. Results to date

Several major results have already emerged from our project:

1) Most but not all of the Taurus YSOs are compact at 100 microns, and are consistent with models that either are disk-dominated (GG Tau is an example) or envelopes that are infalling ($r^{-1.5}$).

2) Based on the submillimeter and millimeter photometry, we can assess the success of some published source models. For example, the envelope models of Hartmann *et al.* (1993) for Taurus sources are very successful matching the overall SED. These models make use of an infalling envelope as prescribed in the standard Shu type collapse models. However, in a number of cases, they are clearly missing a component in their models. Disk emission plays an important role and must be considered when predicting the overall emission. (Butner *et al.* 1997c(in preparation)).

3) We find one example of variability in the submm flux of a disk. GG Tau appeared to under a change in the disk emission (particularily around 800 microns) over a span of 3 years. These results, published in Moriarty-Schieven and Butner (1997), are one of only two examples for disk variability at such long wavelengths. Our far-infrared data unfortunately is not likely to address the variability issue due to the difficulties of proper flux calibration.

4) In the two cases where we seem to have extended emission, we have to investigate other possible source models than a Shu collapse. For example, Hartmann *et al.* (1995) proposed collapse models for flat sheets as an alternative to the spherical collapse of the standard model. Such models should also fit our typical YSOs in Taurus.

V. Future Work

We are currently doing the modeling for the revised FIR maps, and anticipate having two or three papers done by the end of the year. These papers will present our data and the complete set of parameter space that we explore. In particular, we wish to assess the role of flat sheet collapse models (see point 4 above) in explaining our Taurus FIR data.

VI. Papers in Preparation or Published

The following papers were supported in part by the Airborne Astronomy Grant NAG 2-959. The support provided salary, travel funds, or equipment used for data reduction and analysis.

Refereed Articles

H. J. Walker, V. Tsikoudi, C. A. Clayton, T. Geballe, D. H. Wooden, & H. M. Butner, "The Nature of the unusual source IRAS 18530+0817," 1997, *A&A*, accepted.

H. M. Butner, H. J. Walker, D. H. Wooden, & F. C. Witteborn, "1997," Examples of Comet-Like Spectra Among β Pic-Like Stars, in *Astronomical and Biochemical Origins and the Search for Life in the Universe*, ed. C. B. Cosmovici, S. Bowyer, & D. Werthimer (Bologna: Editrice Compositori), p.149.

G. H. Moriarty-Schieven & H. M. Butner, "A Sub-Millimeter-Wave 'Flare' From GG Tau?," 1997, *Ap. J.*, **474**, 768.

H. M. Butner, "Far-Infrared Spatial Observations of Herbig Ae/Be Stars and Low Mass Stars," 1996, in *The Role of Dust in the Formation of Stars*, ed. H. U. Käufl and R. Siebenmorgen (Berlin: Springer-Verlag), p.149.

G. H. Moriarty-Schieven, H. M. Butner, & Peter Wannier, "The L1551NE Molecular Outflow," 1995, *Ap. J.(Letters)*, **445**, L55.

H. M. Butner, A. Natta, & N. J. Evans II, "'Spherical Disks': Moving Towards a Unified Source Model for L1551," 1994, *Ap. J.*, **420**, 326.

Selected Unrefereed Articles

A. Natta, & H. Butner, "Resolving Disks in YSOs," 1996, in *Infrared Space Interferometry*, ed. A. Alberdi, T. de Graauw, C. Eiroa, C. J. Schalinski, and H. Thronson (Space Science Reviews), in press.

H. M. Butner, G. H. Moriarty-Schieven, M. E. Ressler, & M. W. Werner, "Modeling Far-Infrared Observations of Young Stellar Objects," 1995, in *Circumstellar Matter 1994*, ed. G. D. Watt (Kluwer: Dordrecht), p.77.

Abstracts

H. M. Butner, G. H. Moriarty-Schieven, & P. G. Wannier, "The Spectral Energy Distributions of Low Mass Protostars in Taurus," 1994, *BAAS*, **26**, 1449.

G. H. Moriarty-Schieven, & H. M. Butner, "A Sub-millimeter 'Flare' from GG Tau?," 1994, *BAAS*, 26, 1470.