NASA-CR-

INVESTIGATIONS OF THE DYNAMICAL EVOLUTION OF PROTOPLANETARY NEBULAE

NASA Grant NAGW-2306

Annual Status Report No. 1

For the period 1 November 1992 through 31 October 1993

Principal Investigator

Lee W. Hartmann

March 1994

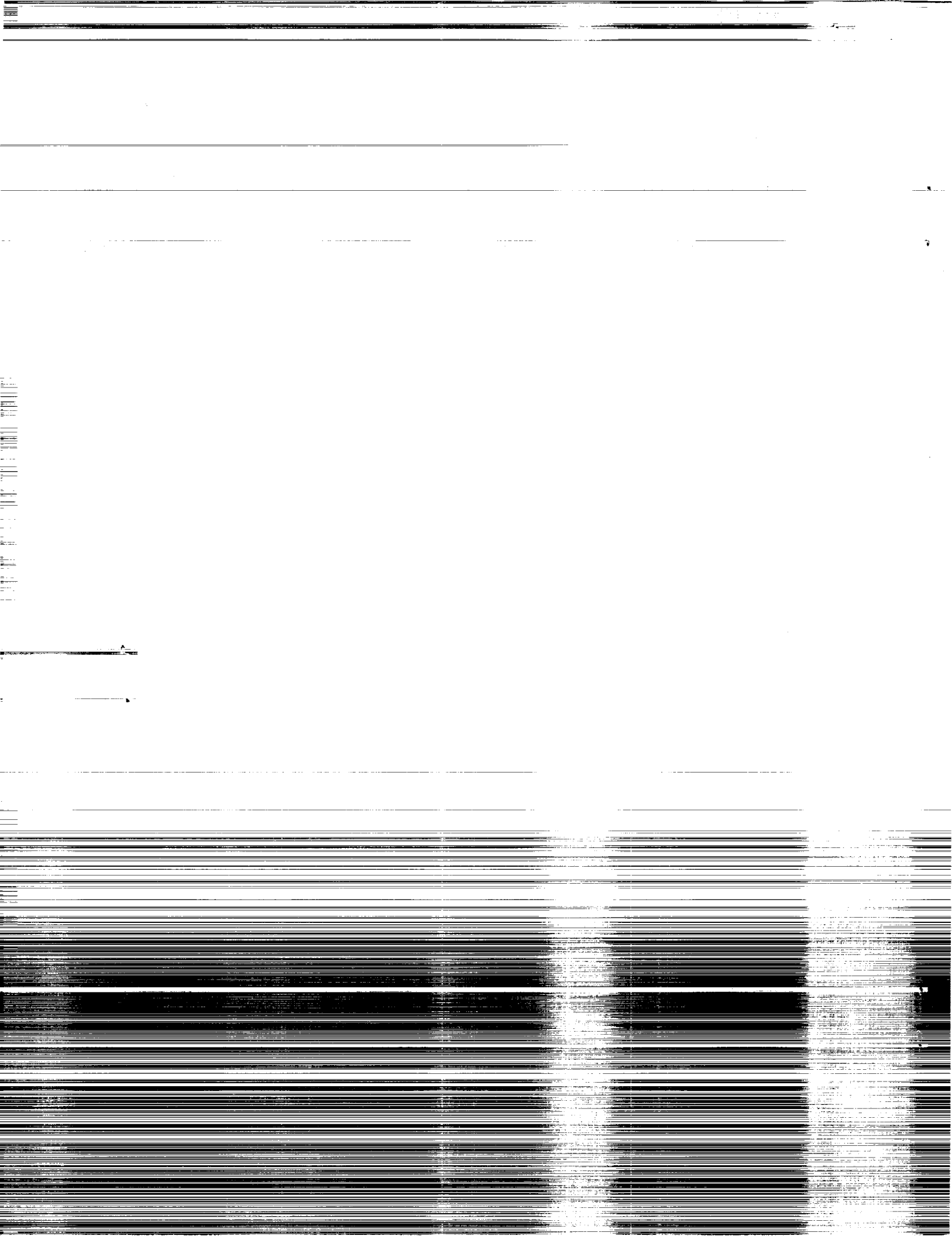Prepared for

National Aeronautics and Space Administration

Washington, D.C. 20546

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

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

The NASA Technical Officer for this Grant is Dr. Joseph A. Nuth, III, Code: SL, Headquarters, National Aeronautics and Space Administration, Washington, D.C. 20546

The Embedded Young Stars in the Taurus-Auriga Molecular Cloud:
Models for Spectral Energy Distributions

In this paper, which appeared in Kenyon *et al.* (1993a), we extended the pioneering work of Adams *et al.* (1987) to model the spectral energy distributions (SEDs) of all of the known Class I (protostellar) sources in the Taurus molecular cloud. The key ingredient of the models which produces reasonable fits rotation, which causes material to fall directly onto the disk, not the star, reducing the extinction in the inner envelope and allowing more short-wavelength light to escape. We adopted the Terebey, Shu, & Cassen (1984 = TSC) density distribution for a rotating, infalling envelope. At large distances, the TSC model is in essentially spherical steady free-fall, with a density distribution $\rho \approx r^{-3/2}$. On small scales rotation becomes important, and most of the material lands on a disk rather than directly onto the star. The centrifugal radius R_c denotes the maximum radius to which infalling material lands on the disk at a given instant. The basic TSC model is defined by four parameters: the density at a reference level ρ_1, the centrifugal radius R_c, the total system luminosity L, and the inclination i of the polar (rotational) axis to the line of sight.

We calculated the radiative equilibrium temperature distribution from the *spherical* average of the TSC density distribution (Adams & Shu 1986). The resulting spherically-symmetric temperature distribution then provides the source function to obtain the emergent spectrum at a given inclination angle i from the formal solution of the transfer equation, using the exact density (opacity) distribution, which is axisymmetric but not spherically-symmetric. We assume that the luminosity originates entirely in the central source, which radiates isotropically. To minimize the number of parameters we adopt the standard Draine & Lee (1984) dust opacities and assume that dust is destroyed at temperatures $\gtrsim 1600$ K.

Our results showed that the SEDs of the protostar candidates in Taurus can be reproduced with TSC models having infall rates close to the values predicted by the theory of isothermal cloud collapse (e.g., Shu 1977). We also found that the cloud angular momenta had to be such as to produce infall to disks with $R_c \sim 100$ A.U. This result is plausible, since the typical estimated sizes of T Tauri disks are of this order. However, the results indicated that most of the protostar candidates had large R_c envelopes, which is not predicted by the TSC model. In addition, the model results formally indicated a tendency to observe Class I sources more pole-on, but this was probably due to our neglect of bipolar outflow cavities in the model, as suggested by scattered light calculations (Kenyon *et al.* 1993b).

Flat Spectrum T Tauri Stars: The Case for Infall

We showed that the mid- to far-infrared fluxes of "flat spectrum" T Tauri stars can be explained by radiative equilibrium emission from infalling dusty envelopes. Infall eliminates the need for accretion disks with non-standard temperature distributions. The simplicity and power of this explanation indicates that models employing "active" disks, in which the temperature distribution is a parameterized power law, should be invoked with caution. Infall also naturally explains the scattered light nebulae detected around many flat-spectrum sources. To match the observed spectra, material must fall onto a disk rather than the central star, as expected for collapse of a rotating molecular cloud. It may be necessary to invoke cavities in the envelopes to explain the strength of optical and near-infrared emission; these cavities could be produced by the powerful bipolar outflows commonly observed from young stars. If viewed along the cavity, a source may be lightly extincted at visual wavelengths, while still accreting substantial amounts of material from the envelope. Infall may also be needed to explain the infrared-bright companions of many optical T Tauri stars. This picture suggests that many of the flat spectrum sources are "protostars" - young stellar objects surrounded by dusty infalling envelopes of substantial mass.

Our results showed that the SEDs of the protostar candidates in Taurus can be reproduced with TSC models having infall rates close to the values predicted by the theory of isothermal cloud collapse (e.g., Shu 1977). We also found that the cloud angular momenta had to be such as to produce infall to disks with $R_c \sim 100$ A.U. This result is plausible, since the typical estimated sizes of T Tauri disks are of this order. However, the results indicated that most of the protostar candidates had large R_c envelopes, which is not predicted by the TSC model. In addition, the model results formally indicated a tendency to observe Class I sources more pole-on, but this was probably due to our neglect of bipolar outflow cavities in the model, as suggested by scattered light calculations (Kenyon *et al.* 1993b).

This paper has been submitted to The Astrophysical Journal.

Flattened Infalling Envelope Models

Evidence is mounting that many young stars have dusty flattened envelopes around them, with sizes of a few thousand A.U. For example, the T Tauri star HL Tau has been found to have such an envelope in ^{13}CO radio interferometry. Sargent & Beckwith (1991) interpreted this structure as a rotating flattened disk, but Hayashi *et al.* (1993) argued that the motions of this material are more consistent with infall than rotation. Hayashi *et al.* suggest that this structure is a "psuedodisk" of the type predicted by Galli & Shu (1993a,b; see also Fiedler & Mouschovias 1993). In the Galli-Shu model, even if magnetic

fields are not of sufficient strength to prevent collapse, they can deflect infalling material into a "pseudodisk" which is not rotationally supported and then must continue falling in.

Some further thought suggests that pseudodisks might be a common occurence in star formation even without the presence of magnetic fields. If collapse is initiated in a flattened, rather than spherical cloud, it is likely that the flattening will be enhanced during collapse rather than suppressed. That such flattening might be general is indicated by the studies of star-forming molecular cloud cores which by Myers *et al.* (1991), which indicated average aspect ratios $\sim 2 : 1$. Beyond this, the idea that stars form from clouds fragmenting from molecular cloud sheets or filaments (Larson 1985) has gained increasing interest and support (e.g., Bonnell & Bastien 1992). It is likely that a fragmenting sheet could also collapse to form a pseudodisk-type of infalling envelope.

To examine this possibility further, we are collaborating with Dr. Alan Boss of the Carnegie Institution (DTM). Dr. Boss is calculating the collapse of a fragmenting sheet configuration with his time-dependent hydrodynamics code. For initial explorations isothermal collapse should be an adequate assuption. The dynamical models have been calculated to many free-fall times already for one set of initial conditions. An analytic approximation to the infall has been developed which reproduces many of the main features of the collapse models, and we are using this approximation to modify the radiative transfer solutions to investigate the qualitative effects expected. Ultimately we will use the density structures calculated by Dr. Boss at specific snapshots in time as the input for the radiative transfer models. The resulting predictions will be compared with observations in the optical, near-infrared, and far-infrared spectral regions.

The collapse of the flat layer produces somewhat different results from the model of Terebey *et al.* (1984), which begins with an initially spherical cloud. We tend not to get an "inside-out" collapse initially, even though we have specified the location of the central mass by the assumption of axial symmetry. The outer layers react to the growth of the central perturbation before an expansion wave can arrive there because the gravity changes are felt immediately, unlike the spherical case. More importantly, the infall rate now depends not only on the sound speed (or gas temperature) but on the surface density as well, since for a given sound speed one may have a wide range of surface densities.

This picture of a collapsing "thick disk" or toroid may also explain the infalling envelope of HL Tau on size scales $\sim 1000 - 2000$ A.U. The models also suggest that the infalling envelope will become increasingly flattened as the collapse proceeds (see Figure 1). At long times the density distributions are reminiscent of the "flared disks" invoked by Kenyon & Hartmann (1987) to explain the far-infrared excesses of many T Tauri stars. It is conceivable that such relatively thick infalling structures could explain the infrared emission in excess of that expected from a flat, steady disk.
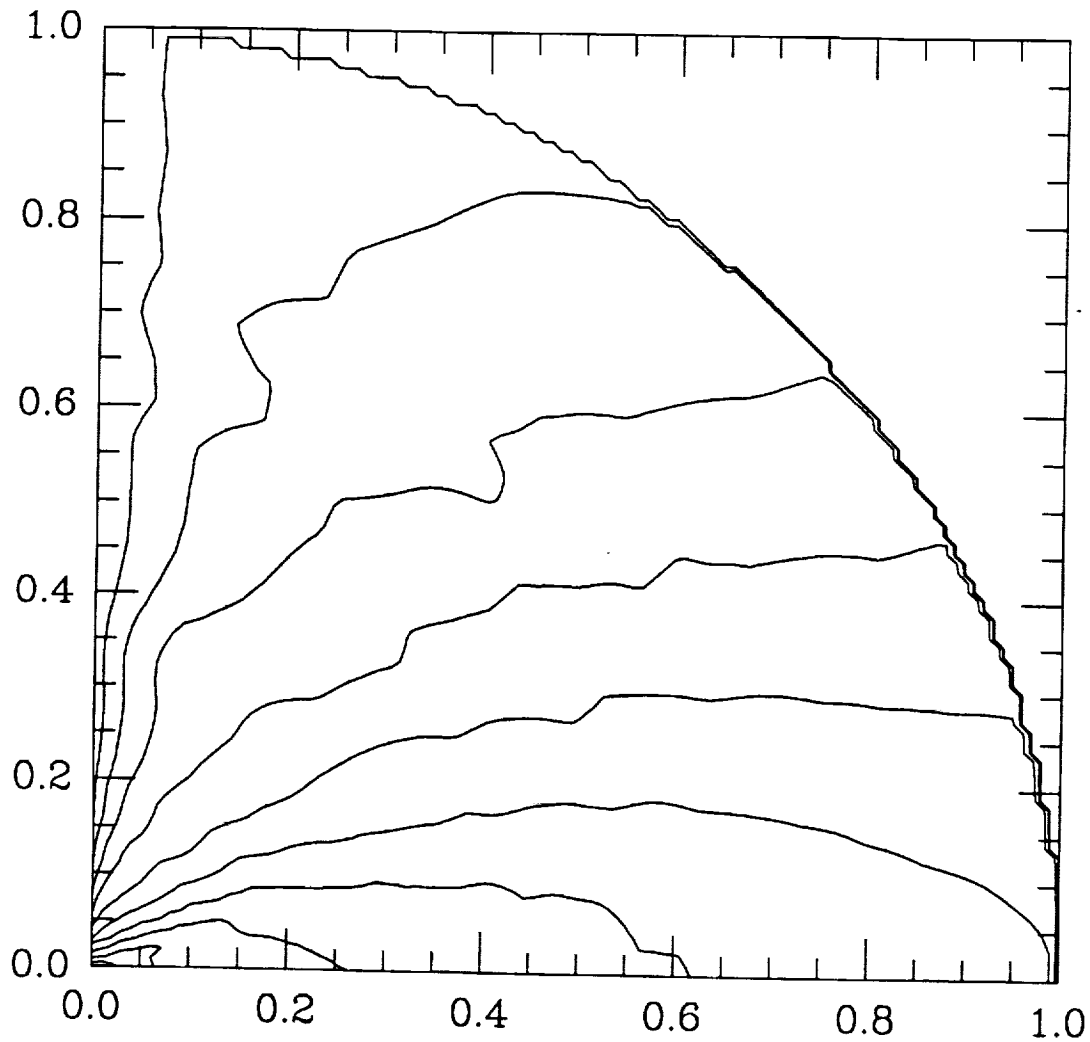
Figure 1 - density distribution in the meridional plane for the collapse model described in the text, at a time approximately 7 free-fall times after the start of the calculation. Each contour is a factor of two different than its neighbor, with the highest densities along the horizontal (equatorial) axis. The calculation shows the tendency for a flattened infalling envelope to develop, along with an axial hole in the envelope.

References

Adams, F.C., Lada, C.J., & Shu, F.H. 1987, ApJ, 312, 788 (ALS I)

Adams, F.C. & Shu, F.H. 1986, ApJ, 308, 836

Bonnell, I., & Bastien, P. 1992, ApJ, 401, 654

Draine, B.T., and Lee, H.M. 1984, ApJ, 285, 89

Galli, D., & Shu, F.H. 1993a, ApJ, 417, 220

Galli, D., & Shu, F.H. 1993b, ApJ, 417, 243

Hayashi, M., Ohashi, N., & Miyama, S.M. 1993, ApJL, 418, L71

Kenyon, S. J., Calvet, N., & Hartmann, L. 1993a, ApJ, 414, 676

Kenyon, S.J., & Hartmann, L. 1987, ApJ, 323, 714

Kenyon, S. J., Whitney, B.A., Gomez, M., & Hartmann, L. 1993b, ApJ, 414, 773

Larson, R.B. 1985, M.N.R.A.S., 214, 379

Myers, P.C., Fuller, G.A., Goodman, A.A., & Benson, P.J. 1991, ApJ, 376, 561

Sargent, A.I., & Beckwith, S. 1991, ApJ, 382, L31

Shu, F.H. 1977, ApJ, 214, 488

Terebey, S., Shu, F.H. & Cassen, P. 1984, ApJ, 286, 529

Publications

1993 The Embedded Young Stars in the Taurus-Auriga Molecular Cloud. I. Models for Spectral Energy Distributions, S.J. Kenyon, N. Calvet, & L. Hartmann, ApJ, 414, 676

1994 Flat Spectrum T Tauri Stars: The Case for Infall, N. Calvet, L. Hartmann, S. J. Kenyon, and B. A. Whitney, submitted to Ap J.