DENSE CORES AND YOUNG STARS IN DARK CLOUDS

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ABSTRACT. Dark clouds within a few hundred pc of the Sun contain hundreds of condensations with typical size 0.1 pc, density 10^4 molecules per cubic cm, mass 1 $M_{\odot}$, and temperature 10 K. These "dense cores" are defined by maps of molecular lines, such as the (J,K)=(1,1) line of ammonia at 1.3 cm wavelength. They are associated with regions of opaque visual obscuration, groups of T Tauri stars, and other cores. They are closely correlated with steep-spectrum, low-luminosity (1-10 $L_{\odot}$) IRAS sources: of about 60 cores with ammonia maps, half have an IRAS source within one map diameter. Thus cores form low-mass stars, which are probably precursors of T Tauri stars. Simple models indicate that time for a core to wait before collapsing, to collapse and form a star, and to disperse are each of order 10^5 yr. Cores with stars have broader lines and bigger velocity gradients than cores without stars, suggesting interaction between the star and the core due to gravity and/or outflow. Stars in cores have about 30 mag greater circumstellar extinction, and greater likelihood of CO outflow, than stars near, but not in, cores. Models of the 1-100 μm spectra of stars in cores suggest that inside of ∿100 A.U., the typical star suffers relatively little line-of-sight extinction but is accompanied by a source of significant luminosity at 5-25 μm. Models involving circumstellar disks provide good fits to the observed spectra.

1. INTRODUCTION

The work reported here is based on observations of molecular spectral line emission and circumstellar dust continuum emission from the nearest star-forming regions: dark cloud complexes in Taurus, Ophiuchus, Cygnus, and Cepheus. These complexes, each within a few hundred pc from Earth, contain hundreds of T Tauri stars with luminosity and mass comparable to those of the Sun. They are actively forming low-mass stars and are therefore well suited to the study of many tens of very young stars and star-forming condensations. The condensations ("dense cores") are easily identified by surveying spots of high apparent visual extinction in a molecular spectral line which requires relatively high gas density

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(about 10^4 molecules cm^{-3}) for collisional excitation. The young stars, while optically invisible, have been dramatically revealed by the 12-100 μm infrared observations of the IRAS satellite. The combination of these two techniques provides many interesting insights into the nature of low-mass star formation.

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2. DENSE CORES

2.1. Basic Physical Properties

The physical properties of dense cores summarized in Table I (Myers 1985a; Myers and Benson 1983) are derived from observations of the (J,K)=(1,1) and (2,2) lines of NH_3 at 1.3 cm wavelength. The typical size 0.1 pc should not be considered as necessarily characteristic of a

TABLE I. Dense Core Properties

FWHM map diameter (pc)	0.05-0.2
Log number density (cm^{-3})	4-5
Kinetic temperature (K)	9-12
FWHM line width (km s^{-1})	0.2-0.4
Gas mass within FWHM map contour ($M_\odot$)	0.3-10
Free-fall time (10^5 yr)	1-4

physical entity, but rather as the extent of core gas with mean density $\sim 3 \times 10^4$ cm^{-3}. The size at which a core loses its identity and cannot be distinguished from more extended cloud emission is probably closer to 0.5 pc, according to maps of ^{13}CO J=1-0 line emission. However, the quantities in Table I are of particular interest because the NH_3 maps on which they are based are highly correlated with young low-mass stars (Section 2.2) and the gas mass included by such a map is comparable to the included star mass. Thus, the properties in Table I can be considered typical of that portion of a condensation that is involved, or likely to become involved, in forming a low-mass star. Of particular interest is the line width, ~ 0.3 km s^{-1} -- among the smallest gas velocity dispersions measured in the interstellar medium.

The appearance of a typical core (TMC-2) on the Palomar Sky Survey is shown in Figure 1 (Myers 1985a). Such a core is evidently part of a larger complex and thus differs from the more isolated Bok globules. The NH_3 map contour encloses the most opaque part of the region, and several associated stars can be seen nearby (see also Jones and Herbig 1979, Figure 5).

2.2. Cores Form Stars

The evidence that cores with properties in Table I form low-mass stars

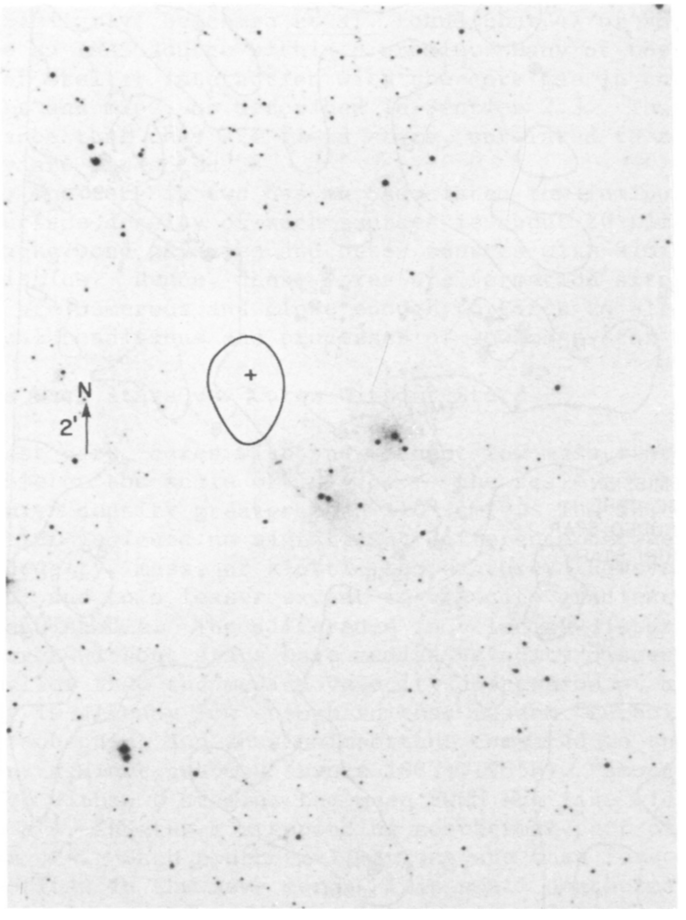

Figure 1. Reproduction of Palomar Sky Survey E print of the Barnard 18 region of the Taurus dark cloud complex. Emission in the (J,K)=(1,1) line of NH_3 at 1.3 cm is shown by a cross (peak) and a closed loop (FWHM contour). The contour is taken to define the "dense core" TMC-2. The linear dimension indicated by the arrow is 0.08 pc.

has become stronger as core positions and sizes have been compared with stellar data at optical, near-infrared, and far-infrared wavelengths. In Taurus-Auriga, T Tauri stars were found to be clustered in loose groupings 1-3 pc in size (Cohen and Kuhi 1979; Jones and Herbig 1979), and each of the seven groups studied was found to contain one or two cores in projection (Myers and Benson 1983; Figure 2). At 2 μm, a survey of 25 cores revealed six to have an associated star within one core map diameter of the map peak (Benson, Myers, and Wright 1984). Four of these six stars are optically invisible due to obscuration. At 12-100 μm, IRAS results indicate that 28 of 56 NH_3 cores have an

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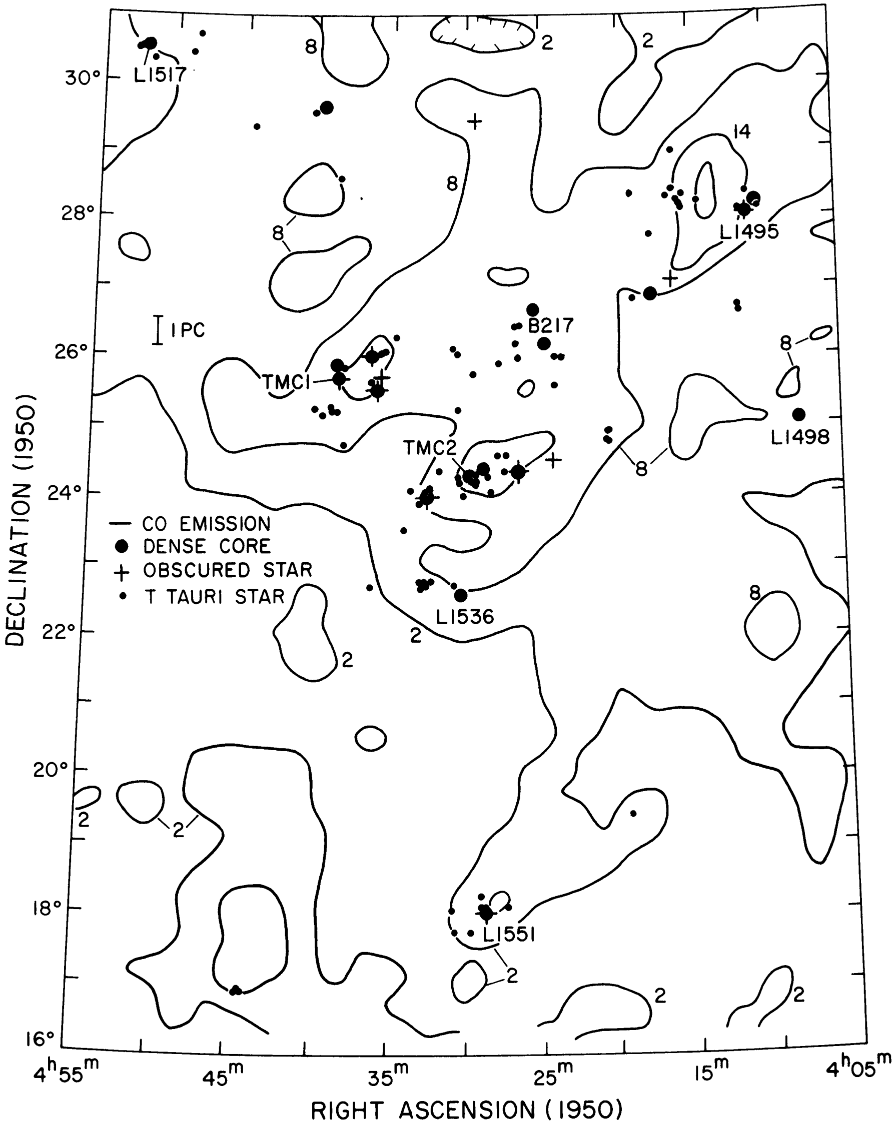

Figure 2. Summary of the distributions of low-density molecular gas (CO emission, Ungerechts and Thaddeus 1986; contours in K km s^{-1}); dense cores (NH_3 emission, Myers and Benson 1983 plus recent unpublished results; large filled circles); highly obscured stars (Beichman et al. 1986, Myers et al. 1986b; crosses); and T Tauri stars (Cohen and Kuhi 1979, Jones and Herbig 1979; small filled circles) in Taurus-Auriga. Names refer to prominent dark clouds.

IRAS source within one NH_3 map diameter of the map peak. Such IRAS sources were selected according to the criteria of Beichman et al. (1986). Similarly, Beichman et al. found that 47 of 95 NH_3 or $C^{18}O$ cores have an IRAS source within 6 arcmin. Many of these cores have evidence of stellar interaction with the core gas in the molecular line widths and maps, as described in Section 2.3. Thus, there is little chance that they are field stars, unrelated to the cores on which they are projected.

Thus, one core in two has an associated low-luminosity IRAS source, and the surface density of such sources is about 20 times greater than that of background galaxies and other sources with similar spectral characteristics. Hence, dense cores are formation sites of low-mass stars and are numerous and close enough to Earth to allow studies of the physical conditions and processes of low-mass star formation.

2.3. Cores With Stars vs. Cores Without Stars

For the most part, cores with and without low-mass stars are not distinguishable on the scale of 10^{17} cm -- the scale set by the extent of core gas with density greater than $\sim 10^4$ cm^{-3}. The NH_3 observations cited earlier indicate no significant difference between the two groups in size, density, mass, or kinetic temperature. However, in velocity dispersion, and to a lesser extent in velocity gradient, the groups are distinguishable. The difference in velocity dispersion is notable because cores without stars have median velocity dispersion significantly smaller than the median velocity dispersion of all cores, and the latter is already low enough so that random "turbulent" motions are primarily subsonic, and thus unimportant compared to thermal motions for support against gravity (Myers 1983, 1985b). Among cores with no IRAS source within 6 arcmin, the mean FWHM NH_3 line width is 0.26 km s^{-1} $\pm$ 0.01 km s^{-1}, and the corresponding nonthermal part of the line width is 0.20 km s^{-1}. Such nonthermal motions are then less than half of the thermal motions in the same core. This small nonthermal contribution makes the low-mass cores discussed here unusual compared to more extended portions of their parent clouds, or compared to cores that form more massive stars. It has therefore been suggested that such reduction in nonthermal motions may be a characteristic, or perhaps necessary, feature in the beginning stages of core collapse (Myers 1983).

If cores without stars and cores with stars differ only in evolutionary state, then the detection rate of stars in cores cited above, ~ 0.5, implies that the "waiting time" until a starless, detectable core begins to collapse to form a star is of the same order as the core free-fall time, $\sim 2 \times 10^5$ yr (Myers 1985b). Therefore, some starless cores may be in the early stages of collapse. The low velocity dispersions observed in starless cores are consistent with early collapse, but the angular resolution of the presently available data is too coarse to allow any decisive conclusion. To estimate the relevant scales of angular and velocity extent, we use the singular isothermal sphere model of a dense core (Shu 1977; Boss and Black 1982). When such a centrally condensed structure collapses, the spherical surface ("expansion wave") between the collapsing interior and static exterior propagates outward and has radius $r_c = at$, where a is the sound speed (0.19 km s^{-1} for the usual gas of H_2 molecules and He atoms at 10 K), and t is the time since collapse begins. At the same time, the mass M_* of the accreting star-disk system increases according to $M_* = a^3t/G$. Consequently, the linear and velocity extents of the collapsing region can be expressed in terms of M_*. Allowance for the difference between line-of-sight and radial components of velocity leads to a reduction by a factor ∿2 in the apparent linear extent of the collapsing region, projected on the plane of the sky. Accordingly, over a region of diameter $\Delta\rho$ less than or equal to

$$\Delta\rho_c = \frac{M_* G}{a^2} = 0.12\ \frac{M_*}{M_\odot}\ \mathrm{pc} = 180\ \frac{M_*}{M_\odot}\ \mathrm{arcsec}\ , \qquad (1)$$

the expected FWHM of the distribution of line-of-sight velocity due to collapse is

$$\Delta v \approx 2a\left(\frac{\Delta\rho}{\Delta\rho_c}\right)^{-\frac{1}{2}} = 0.13\left(\frac{M_*}{M_\odot}\right)^{\frac{1}{2}}\left(\frac{\Delta\rho}{\mathrm{pc}}\right)^{-\frac{1}{2}}\ \mathrm{km\ s^{-1}}$$

$$= 5.2\left(\frac{M_*}{M_\odot}\right)^{\frac{1}{2}}\left(\frac{\Delta\rho}{\mathrm{arcsec}}\right)^{-\frac{1}{2}}\ \mathrm{km\ s^{-1}}\ , \qquad (2)$$

where sound speed 0.19 km s^{-1} and source distance 140 pc have been assumed. These expressions show that a "starless" core (e.g., $M_* \leq 0.1\ M_\odot$) will have a collapsing region no greater than about 18 arcsec wide in Taurus. Thus, present-day molecular line observations made with FWHM beam width ∿1 arcmin will have beam dilution of the collapsing region by a factor $\gtrsim$10, so collapse effects are probably invisible in this case. Consequently, the aforementioned nonthermal broadening ∿0.20 km s^{-1} typical of starless cores is not likely to arise from collapse motions, but probably represents more extended and more complicated "turbulent" motions. Detection of collapse motions, if present, requires higher angular resolution in a suitable molecular line.

In cores with stars, the typical nonthermal broadening observed with present-day instruments has a better chance of arising from collapsing motions. In 16 cores with stars, the nonthermal FWHM of the NH_3 line is 0.40 ± 0.04 km s^{-1} (mean ± standard error of the mean). For a 0.5 $M_\odot$ star, typical of T Tauri stars in Taurus, the collapse extent expected from eq. (1) is ∿90 arcsec, about one NH_3 beamwidth, and the line broadening expected from eq. (2) is then 0.4 km s^{-1}, as observed. However, two reservations must be noted. The gravitational line broadening should be confined to the ∿90" region centered on the star, and the observed line width should be significantly less at surrounding positions. This pattern has not yet been demonstrated, and a few well studied cores with stars show no such regional variation in NH_3 line width (Walmsley and Wilson 1985). Also, about one core in three with an embedded star has evidence of CO outflow (Myers _et al._ 1986a). It appears plausible that such outflow motions and/or winds may couple enough mechanical energy into the dense gas where the NH_3

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line is formed to broaden the NH_3 line to the observed 0.4 km s^{-1}, but detailed estimates of this process have not yet been made.

A second point of difference between cores with and without stars concerns the magnitude of velocity gradients. An examination of some 20 NH_3 line maps of low-mass cores for linear velocity gradients indicates that cores without stars have significantly smaller gradients than cores with stars (Myers, Goodman, and Benson 1986). Eight cores with stars have median gradient $\sim$5 km s^{-1} pc^{-1} while nine cores without stars have median gradient less than 2 km s^{-1} pc^{-1}. This difference in gradient may be related to the difference in line width, noted above: The shift in line velocity across a cloud (i.e., cloud size times velocity gradient) is correlated with, but usually less than, the cloud line width. This latter relationship appears to suggest that in low-mass cores the mechanical energy in simple rotation tends to be less than that in more complicated, "turbulent" motions.

3. STARS IN AND NEAR CORES

3.1. Stars in Cores vs. Stars Near Cores

To distinguish these two groups, we consider a star to be a point source detected by IRAS at 25 μm, or at both 60 and 100 μm (Beichman et al. 1986). A star "in" a core lies within one NH_3 map diameter of the NH_3 map peak, while a star "near" a core lies between one and a few such diameters from the map peak. These two groups have significantly different properties, as described by Beichman et al. (1986), who studied 47 such stars observed by IRAS, and by Myers et al. (1986b), who studied 30 such stars observed by IRAS and by ground-based telescopes at 1-20 μm.

Stars in cores tend to be invisible on the Palomar Sky Survey red print, as expected from the selection criteria for cores. Stars near cores tend to be visible, and most with identifications are T Tauri stars. Stars in cores tend to have steeper spectral slope between 1 and 100 μm than stars near cores, as illustrated in Figure 3. The typical obscured star has weaker flux density at 1-5 μm and stronger flux density at 5-100 μm than the typical visible star. These differences in the near-infrared (1-5 μm) can be accounted for by a simple model in which the spectrum arises from a stellar blackbody attenuated by a layer of absorbing grains. Then stars near cores typically have extinction $A_V \sim$ few mag, in agreement with values obtained from spectral type and B-V color excess. Stars in cores typically have $A_V \sim 30$ mag, and a histogram of A_V or spectral slope has a well-defined gap between the two groups, occurring at about 15 mag. In bolometric luminosity, stars in cores and stars near cores are indistinguishable, with typical luminosity 1-2 $L_\odot$ in each case.

Stars in cores tend to have CO outflow with greater frequency than stars near cores or than visible T Tauri stars generally. Of about 30 NH_3 cores with stars mapped in a search for CO outflow, 9 have evidence of monopolar (1), bipolar (7), or more complex (1) CO outflow (Myers et al. 1986a). In contrast, a survey of a similar number (28) of

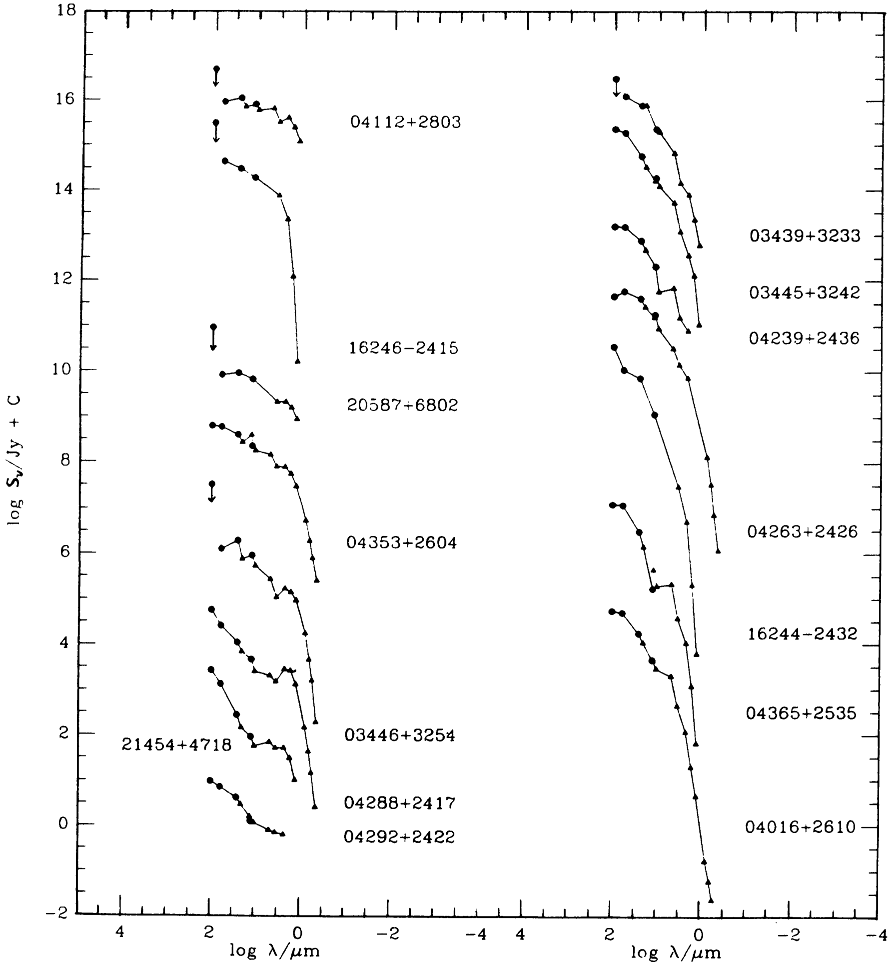

Figure 3. 1-100 μm spectra of IRAS sources near (left) and in (right) dense cores. The 12-100 μm IRAS data are combined with ground-based data (Myers et al. 1986b). The sources near cores are primarily T Tauri stars. The sources in cores have steeper spectra that imply typical circumstellar extinction $A_V \sim 30$ mag.

T Tauri stars revealed three with CO outflow (Edwards and Snell 1982). Such stars with CO outflow, or which excite Herbig-Haro objects, tend to have significantly higher luminosity than otherwise similar stars without outflow (Levreault 1985; Myers et al. 1986a). Each of these properties may be useful in ranking the evolutionary states of young stars.

3.2. Evolution of Stars in Cores

The obscured stars in cores are found near T Tauri stars, as is evident in Figure 2; and they have luminosity similar to that of T Tauri stars, as noted above. It is therefore possible that as a group the obscured stars are predecessors to T Tauri stars. If so, an estimate of the typical duration of their high obscuration can be made from the number of obscured stars in a region, the number of T Tauri stars, and the ages of the T Tauri stars. Such an estimate has been made for Taurus-Auriga, where $\sim$10 highly obscured stars and $\sim$100 visible T Tauri stars are known, the latter with ages $\sim 10^5$ to 10^7 yr deduced from position on the Hertzsprung-Russell diagram (Cohen and Kuhi 1979). The typical obscuration time is then 3-8 x 10^4 yr, depending on differing assumptions about stellar birthrate and zero-point of stellar age (Myers et al. 1986b). This interval is significantly less than the typical core free-fall time, suggesting that the heavily obscured stars are among the youngest known, and are still accreting -- perhaps even while their obscuration is being dispersed. The interval is also similar to the dynamical time of outflows from low-mass stars (Goldsmith et al. 1984), consistent with the well-known idea that such outflows may be the dominant agent of dispersal.

3.3. Structure of Circumstellar Obscuration

When the extinction of a highly obscured star (typically A_V = 30 mag) is combined with the usual relation between A_V and gas column density N, the resulting circumstellar column density is typically N $\sim$ 3 x 10^{22} molecules cm^{-2}. When this column density is compared with the associated core radius R (typically 0.05 pc) and mean gas density within R, $\langle n \rangle_R$ (typically 3 x 10^4 cm^{-3}), one can estimate the inner radius r_1 of the circumstellar extinction for a particular density law n(r). For $n \propto r^{-1.5}$,

$$r_1 = R[N/\langle n \rangle_R R + 1]^{-2} \approx 170 \text{ A.U.} \tag{3}$$

This radius greatly exceeds the grain-melting radius, of order 1 A.U. for a 1-$L_\odot$ star. Estimates of r_1 have been made for a wide range of density power laws $n \propto r^{-p}$, with the result that only for p = 1.0 to 1.2 does r_1 agree, within uncertainties, with 1 A.U. Shallower density laws (p < 1.0) yield values of r_1 much smaller than 1 A.U., and are thus unlikely to be realistic because of grain melting. Steeper density laws (p > 1.2) give r_1 $\sim$ few hundred A.U. (Myers et al. 1986b). Unless the power-law exponent lies in a narrow range, these results imply that some highly obscured stars have some sort of circumstellar cavity a few hundred A.U. in size, within which the gas and dust density are sharply reduced. It is noteworthy that this size is also comparable to that of some circumstellar disklike structures, in HL Tau (Grasdalen et al.

1984) and β Pic (Smith and Terille 1984).

The circumstellar extinction ~30 mag implied by near-infrared photometry of obscured stars in cores absorbs a significant fraction of the stellar luminosity and reradiates it at longer wavelengths. This emission has been modelled for collapsing cores without rotation (Adams and Shu 1985) and with rotation (Adams and Shu 1986) and for cores that have density laws other than $n \propto r^{-1.5}$ expected for collapse (Myers et al. 1986b). The main result is that a model of star and circumstellar shell can account for observed near-infrared (1-5 μm) flux, and observed far-infrared (25-100 μm) flux, but is much too weak in the mid-infrared (5-25 μm). The "missing" luminosity is about one-third of the total. The rotating core model of Adams and Shu (1986) includes a circumstellar disk and uses an inner radius of the circumstellar shell much greater than the grain-melting radius. The inner radius is determined by the "centrifugal barrier" at which the core makes a transition from spherical symmetry to a collapsed star-disk system. These two changes -- addition of a disk emitting in the mid-infrared, and increasing the inner radius to ~100 A.U. -- lead to much better agreement between model and observation (see Shu, Lizano, and Adams in this volume).

3.4. Acknowledgments

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