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PHYSICAL CONDITIONS IN MOLECULAR CLOUDS

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RESUMEN. Los desarrollos recientes en el campo han complicado nuestra representación de las condiciones físicas en las nubes moleculares. Las observaciones obtenidas con el IRAS de emisión extendida en líneas de CO de alto J y la emisión en 12 μm han revelado la presencia de gas y polvo considerablemente más caliente de lo esperado cerca de las superficies de nubes moleculares. Estas componentes pueden complicar nuestra interpretación global de la nube de gas. Las relaciones comunmente supuestas entre la densidad de columna o densidad media y tamaño de la nube se ven puestas en duda por los resultados encontrados y por consideraciones de efectos de selección. Los análisis de densidad y estructura de densidad, por medio de excitación molecular, muestran que existen densidades muy altas (n $\geq$ 10^6 cm^{-3}) en regiones de formación estelar, pero la interpretación se complica por la existencia de estructuras sin resolver y por posibles efectos químicos. Las observaciones de alta resolución en infrarrojo lejano y en regiones submilimétricas brindan elementos complementarios y empiezan a dar pruebas acerca de las predicciones teóricas de los gradientes de densidad en las nubes.

ABSTRACT. Recent developments have complicated our picture of the physical conditions in molecular clouds. The discoveries of widespread emission from high-J lines of CD and 12μm IRAS emission have revealed the presence of considerably hotter gas and dust near the surfaces of molecular clouds. These components can complicate our interpretation of the bulk of the cloud gas. Commonly assumed relations between column density or mean density and cloud size are called into question by conflicting results and by consideration of selection effects. Analysis of density and density structure through molecular excitation has shown that very high densities (n $\geq$ 10^6 cm^{-3}) exist in star formation regions, but unresolved structure and possible chemical effects complicate the interpretation. High resolution far-infrared and submillimeter observations offer a complementary approach and are beginning to test theoretical predictions of density gradients in clouds.

Key words: **INTERSTELLAR-CLOUDS — INTERSTELLAR-MOLECULES — STARS-FORMATION**

I. INTRODUCTION

As the parent structures of massive stars and their consequent H II regions, molecular clouds are relevant to interpretation of H II region data. Indeed the study of the H II/molecular cloud interface is a rapidly developing field. At an earlier stage in stellar evolution, the stars are deeply embedded in the molecular cloud and the properties of the cloud control what observations of young stars are possible. At still earlier stages, the physical conditions in the cloud determine whether stars will form and, if so, what the nature of those stars will be. For these reasons and others, including the intrinsic interest of these objects, we are motivated to study the physical conditions in molecular clouds.

In discussing cloud properties, it is useful to distinguish "global" properties, which apply to the cloud as a whole, from local properties which may vary throughout the cloud. Examples of the former are the cloud size, shape, and mass, as well as its location and velocity in the galaxy. In discussing local properties we distinguish properties of the gas from those of the dust. We would like to know the gas kinetic temperature (T_K), density (n), the abundance of each species, i ($X_i \equiv n_i/n$), and the local velocity. The dust can be characterized by a temperature (T_D), size distribution ($n_d(a)$) and composition. In principle, T_D may depend on both size and composition of the individual grain, while a single T_K probably applies to all molecular constituents in a given volume element. More fundamentally, we can regard T_D as a measure of the internal energy for particles which are sufficiently large. The dividing line between large molecules and small grains is becoming increasingly blurred, but there is a size above which a particle can absorb a photon, redistribute the energy among its internal degrees of freedom, and slowly radiate the internal energy as photons of lower energy than the original photon (see Puget and Leger 1989). For particles not much bigger than this size limit, the grain temperature is a strong function of time, spiking after photon absorption, but the grain spends most of its time at very low temperature (Draine and Anderson 1985). In addition to the gas and dust properties, a complete specification of local cloud properties would include the magnetic field, cosmic ray ionization rate, and photon energy density.

We are very far from a complete specification of the physical conditions in any real molecular cloud. One complication is that observations inevitably average over a finite beam and integrate along the line of sight through the cloud. This latter integration is explicitly recognized in such quantities as the extinction at a reference wavelength (e.g., A_V), the column density of a particular species (N_i), or the total column density $N \equiv \sum N_i$. A closely related quantity is the average density, $\langle n \rangle \equiv N/\text{size}$. Finally, our observational probe of the velocity field, integrated through the cloud, is the line shape, often characterized simply by the linewidth (ΔV) and the line center velocity. Since these quantities all involve an integration through the cloud, they are neither global nor local. We can think of them as hybrid properties: we can map them over the face of the cloud, but not along the line of sight.

Space does not permit a review of all these properties, so I will concentrate on only a few in which there have been some interesting recent developments. More complete discussions may be found in recent reviews of this subject including those by Goldsmith (1987), Myers (1987), Shu, Adams, and Lizano (1987), and Myers (1989).

II. TEMPERATURE

Let us first review the predictions of simple theories for molecular cloud energetics. In regions without significant star formation, the gas temperature should be established by a balance between heating through ionization by high energy cosmic rays and cooling by molecular transitions, primarily those of CO (Goldsmith and Langer 1978). Depending upon the exact ionization rate and the details of the molecular cooling, temperatures in a range around 10K are expected. These expectations are in fact confirmed by observations of low-J transitions of CO. The dust, on the other hand, should be heated by the photons of the general interstellar radiation field and reach temperatures ~ 10K, warmer on the outside and cooler on the inside of the cloud. This prediction also seems to be verified by submillimeter observations of isolated globules (Keene 1981). Note that while $T_K \sim T_D$ in these regions, that fact is purely a coincidence.

The situation is rather different in clouds where stars have formed recently. The photons from the young stars heat the surrounding dust; a collision with a molecule transfers the dust internal energy to the translational modes of the molecule. Analysis of this process by Goldreich and Kwan (1974) suggested that T_K will approach T_D for sufficiently high densities ($n \gtrsim 10^{4.5}$ cm^{-3}). A strong prediction of this picture is that T_K cannot exceed T_D. Observational tests of this picture using the lower J transitions of CO to measure T_K and the far-infrared fluxes to measure T_D have generally confirmed this picture (Evans 1981, Wu and Evans 1989). In regions of massive star formation, T_K and T_D, measured in this way, range from 10K up to ~ 100K. Note that most of these studies had spatial resolution of 1' - 2'.

I have been careful to specify the measurement technique for good reason; new measurements are giving very different results for T_K and T_D. It has long been known that a range of T_D must exist around new stars; indeed, $T_D \propto r^{-0.4}$ for optically thin clouds and a grain absorption efficiency $\propto \lambda^{-1}$. However, this behavior indicates that dust much hotter than ~ 100K will not be widely extended and hence cannot heat the regions usually probed by molecular line studes. As spatial resolution improved, evidence of regions of hotter gas associated with hotter dust began to emerge (e.g., the Orion "hot core"). More surprisingly, the IRAS 12 and 25 μm channels showed that there is a <u>pervasive</u> component of hotter dust extended over molecular clouds, not just near stars. This has been interpreted as small grains, perhaps polycyclic aromatic hydrocarbons (e.g., Puget, Leger, and Boulanger 1985) which are transiently heated by absorption of single photons from the general interstellar radiation field. If these small grains produce significant emission at wavelengths as long as 60μm, they will cause us to overestimate T_D of the larger grains from a comparison of 60 and 100μm emission (see Helou 1989). Also since the number of grains of radius a is thought to follow $n(a) \sim a^{-3.5}$ (Mathis, Rumpl, and Nordsieck 1977), most of the grain surface area should be in the smallest grains and these should then dominate the gas energetics. One might think that

collisions with these small grains would heat the gas, but in fact these grains spend most of the time between photon absorptions being very cold (T_D<5K) (Draine and Anderson 1985). If these grains exist in substantial numbers in the regions where the CO lines form , it is hard to see how the gas avoids being strongly *cooled* by them. (Wu and Evans 1989). Our neat picture begins to fray at the edges.

Meanwhile, the gas temperatures have been misbehaving as well. For some time, we have known that shocks can produce $T_K > T_D$, and $T_K \sim 2000$ K are revealed by studies of H_2 emission (e.g. Beckwith and Shull 1982). These regions comprise, however, only a small fraction of the molecular cloud mass. A more recent development has been the discovery that high J lines of CO are surprisingly widespread implying T_K of hundreds of degrees over substantial fractions of molecular clouds (see review by Jaffe in this volume). Some of this high J CO emission comes from the same shocks that power the H_2 emission, but increasingly this emission is seen where shocks cannot explain it. It is thought to arise from photodissociation regions (Tielens and Hollenbach 1985) where molecular clouds are exposed to strong external radiation fields. Since many of these regions are the same ones in which the Goldreich-Kwan energetics picture was checked, one wonders why the lower J CO lines did not reveal this hot gas. The most likely answer is that the hot gas is optically thin in these lines. So clearly there is a range in T_K and T_D along the line of sight through a cloud.

In summary, new observations have raised new questions about molecular cloud energetics. Our neat picture of a few years ago is seen to be extremely oversimplified. Future models of molecular clouds should take into account the effects of external radiation fields, small grains, and rather extreme variations in temperature along the line of sight.

III. COLUMN DENSITY AND MEAN DENSITY

A number of recent studies have suggested that the column density of clouds is independent of cloud size (e.g. Larson 1981; Solomon *et al.* 1987). Assuming that we are not preferentially observing sheet-like structures face-on, this result would imply that the mean density, $\langle n \rangle \propto D^{-1}$, where D is the cloud size. For example, Scoville *et al.* (1987) find $\langle n \rangle = 180\ cm^{-3}\ (D/40pc)^{-0.9}$ or $\langle n \rangle = 5000\ cm^{-3}\ (D/pc)^{-0.9}$. The normalization of this relation depends on the conversion from the tracer, N_i, to total column density, N. For example Myers (1989) finds $\langle n \rangle = 1800\ cm^{-3}\ (D/pc)^{-1}$. While this trend is often assumed to be well established, other studies get different results. Casoli *et al.* (1984) find constant density; Carr (1987) finds $\langle n \rangle = 220\ cm^{-3}\ (D/pc)^{-0.5}$ in Cepheus OB3, and Loren (1989) finds $\langle n \rangle \sim 4000\ cm^{-3}\ (D/pc)^{-0.18}$ in Ophiuchus. In addition, Scalo (1989) has pointed out that the tracers (mostly CO and ^{13}CO) which are used to establish these relations have a very limited dynamic range ($A_V \sim 0.5$-5 mag) and that the observations actually fill all the parameter space allowed to them. Further, studies using other tracers indicate much higher densities on small scales than would be predicted by these relations. Finally, studies of isolated small globules, show that within a single globule, one often finds that maps of $N(^{13}CO)$ are consistent with $n \sim r^{-2}$ (Arquilla and Goldsmith 1985).

The complications of the observational picture may be appreciated by noting that most estimates of the mean density in the largest clouds are lower than the local densities needed to excite the observed transitions, suggesting clumping with small volume filling factors (e.g., Myers *et al.* 1986). Other evidence for clumping and very complex cloud structure suggests that indiscriminate use of empirical relations for $\langle n \rangle$ as a function of r in cloud models may be a mistake. For example, Stutzki *et al.* (1988) find that some of the puzzling observations of photodissociation fronts can be understood if the clouds consists of numerous dense clumps. An idea of the complexity of molecular clouds may be had by examination of the CO map of the Taurus region (Ungerechts and Thaddeus 1987) and recalling that CO is the tracer least likely to show structure. In this situation, it is very tempting to try to bring order by naming structures like complexes, clouds, cores, clumps, etc. This natural human tendency to seek order in chaos should be tempered by a recognition of its perils, of which I will mention only one. Many of the "structures" are essentially defined by the observational methods used to find them and may not reflect any actual physical structure in the cloud (examples are "NH_3 cores").

IV. DENSITY AND DENSITY STRUCTURE

In principle, it is possible to measure the local density, rather than the average along the line of sight, via analysis of molecular excitation. Of course, our observational measurements do represent averages along the line of sight and over the beam, but the average is weighted differently from that used to derive $\langle n \rangle$, and this difference may be used to study cloud structure. The method is basically the same as that used to study density in ionized regions, using forbidden lines, with some differences. The molecular lines are not forbidden, but their frequencies are so much lower than those of optical lines that the spontaneous emission rates are comparable to optical forbidden lines. Thus, collisons and radiation compete to establish the populations of excited states. The concept of a critical density ($n_c = A/\gamma$, where γ is the collision coefficient) is used in both fields, though with some amusing differences. Analysts of ionized regions are wont to say that lines are "quenched" if $n \sim n_c$, whereas molecular line workers often say that we need $n \sim n_c$ in order to see a line. Neither of these statements is in fact correct; they are based partly on the different observational techniques (forbidden lines get "quenched" relative to permitted lines which can be simultaneously measured in optical spectra, while molecular line types have trouble measuring lines with $n \ll n_c$ because of the importance of the cosmic background radiation at low frequencies), but also partly on the very different frequency range. Speaking the language of molecular line observations, we note that the excitation temperature (T_{ex}) varies between T_{bg} (the cosmic background temperature) and T_K according to the value of hν/k n/n_c. In the Rayleigh-Jeans limit,

$$T_{ex} = T_K \frac{T_{bg} + h\nu/k\ n/nc}{T_K + h\nu/k\ n/nc};$$

$$T_{ex} \to T_K \text{ if } n \to \infty;\ T_{ex} \to T_{bg} \text{ if } n \to 0.$$

The presence of hν/k reflects the importance of stimulated processes at low frequencies; thus if $h\nu/k << 1$, $n >> n_c$ before the transition is thermalized ($T_{ex} = T_K$). The NH_3 (J, K) = (1,1) transition, with ν = 23GHz, which has n_c=2 x 10^3, requires n > 10^5cm^{-3} before T_{ex}=0.90 T_K, while the CS J = 3→2 transition at 147 GHz has n_c = 1.5 x 10^6cm^{-3}, nearly three orders of magnitude larger than the NH_3 line but reaches T_{ex} = 0.9 T_K at 2 x 10^6 cm^{-3} (these examples are for T_K = 10K; see Figure 1). Thus n/n_c must be much larger to thermalize the low frequency radio lines that were first observed in the molecular line field, while submillimeter (and certainly optical) lines are essentially thermalized at n = n_c.

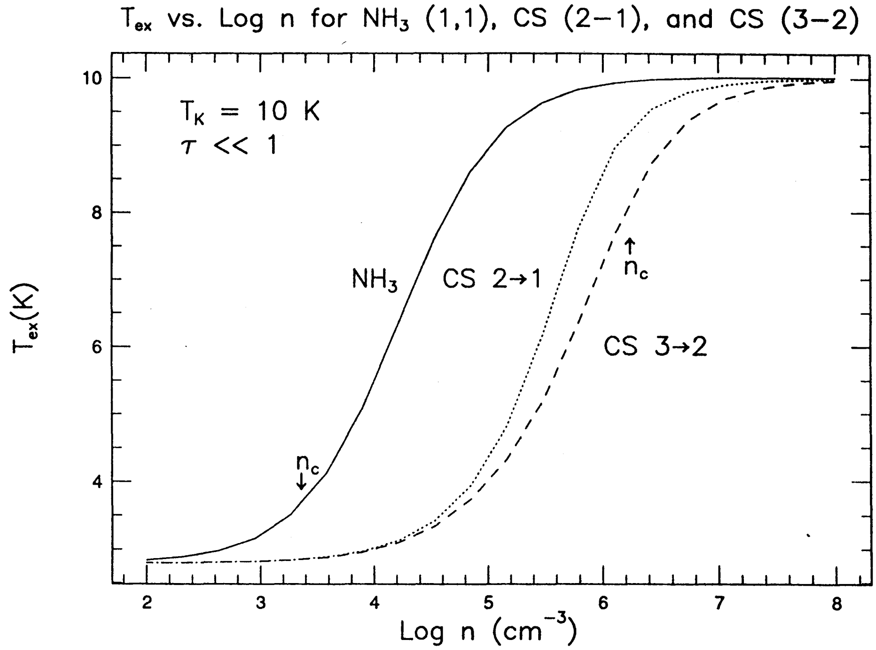

Figure 1 - The excitation temperature is plotted versus the density for the NH_3 (J,K) = (1,1) line and the CS J = 2-1 and 3-2 lines. The calculations were done for T_K = 10 K, with a multilevel statistical equilibrium code, with column densities sufficiently low to ensure negligible optical depth. The critical densities for the NH_3 line and the CS J = 3-2 line are indicated by arrows.

With this background in mind, let us re-examine the results of excitation analyses of molecular cloud densities. A decade ago, densities had been derived using pairs of lines (in order to separately determine T_{ex} and τ, two lines are needed) in various molecules. Our distressing discovery was that different molecules gave different answers in the case of clouds with massive star formation and that each pair of lines tended to return a value of n comparable to n_c of the more easily excited line of the pair (hence the idea that seeing a given line means that n ~ n_c) (Evans 1980). A natural way to reconcile all these measurements was to assume that they were all correct: each density did exist along the line of sight and was probed by the appropriate transitions. Thus a physical model (a cloud with a density gradient) and an observational program for studying it (use a series of lines with different n_c) were simultaneously suggested.

This program was pursued by Mundy and collaborators using 4 transitions of CS (Snell *et al.* 1984), 3 transitions of $C^{34}S$ (Mundy *et al.* 1986) and 6 transitions of H_2CO (Mundy *et al.* 1987). With a range of critical densities spanning 6 x 10^5 - 1.3 x 10^7 cm^{-3}, these studies were well equipped to find density variations in relatively dense gas. Perversely, the lines proved to be reasonably consistent with a single density model in most cases. Furthermore, maps of the three sources studied (M17, S140, and NGC2024) showed little change in n over a region where the line intensities varied substantially. Contrary to expectations, a map of a hard-to-excite transition proved not to be a map of density, but of some combination of molecular column density and filling factor. For a variety of reasons, we suggested that filling factors were the primary variable and that the regions of high density (n ~ 10^6 cm^{-3}) in these clouds would prove to be composed of small, dense clumps.

Recent studies with higher spatial resolution have confirmed this suggestion by observing the clumps (e.g., Mezger *et al.* 1988 and Moore *et al.* 1989 in NGC2024 and Stutzki *et al.* 1989 in M 17). Improved resolution is needed to distinguish the individual clumps which are forming individual (single or binary) stars rather than observing the ensemble of many fragments. With the new generation of higher resolution telescopes and sensitive high frequency receivers, the technique of analyzing the excitation of multiple transitions of a molecule should find new application.

A new attempt at using multitransition analysis to search for density grandients is also motivated by recent theoretical work predicting specific density laws for gas which is in the process of forming stars (Shu, Adams, and Lizano 1987; Lizano and Shu 1989). Before reporting some initially encouraging work on testing the predicted density distributions, let me add one more cautionary example. An observational result which has played an important role in shaping theoretical work on low mass star formation, such as that of Lizano and Shu (1989), has been the NH_3 core. These cores are revealed by the detection of NH_3 (J,K) = (1,1) emission in nearby molecular clouds and have been interpreted as tracing densities of n ~ 10^4 cm^{-3} in regions of very low turbulence (Myers and Benson 1983). However a recent study of CS J = 2→1 and 3→2 lines, which should trace higher densities than

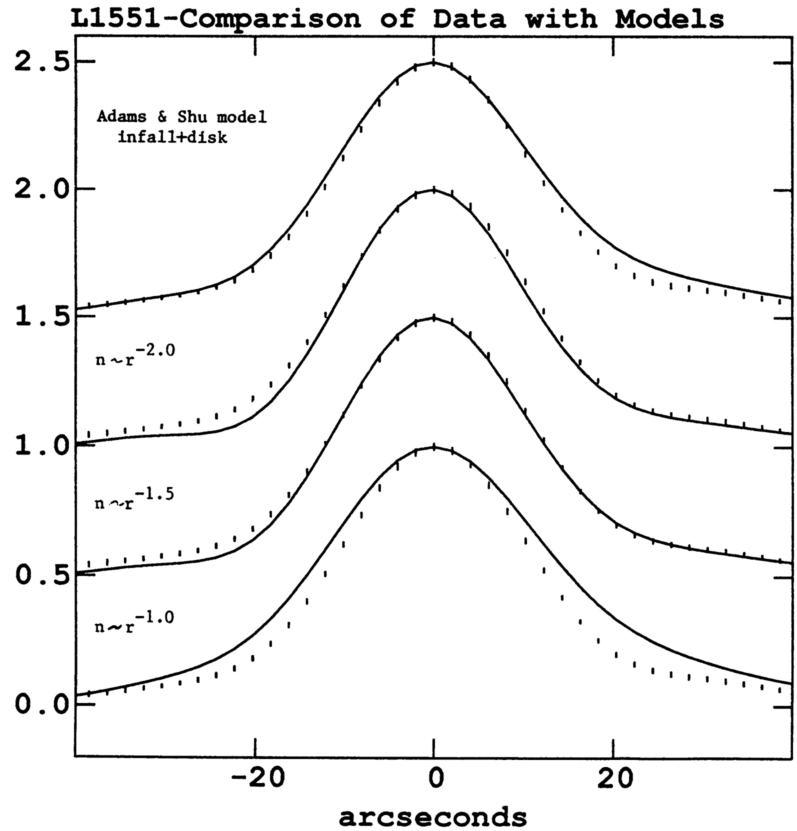

Figure 2 - The 100μm relative intensity is plotted versus the positional offset from the L1551 peak. The data and uncertainties are indicated by the vertical error bars and the model predictions are indicated by the lines. The assumed model is indicated above and to the left of the line. In all models except that of Adams and Shu, the temperature distribution was assumed to be $T_D \propto r^{-0.4}$. The predicted intensities were used for the Adams and Shu model.

those of NH_3 (see Figure 1) present some puzzling results (Zhou *et al.* 1989). Our naive expectations were that the CS would be confined to a smaller region and have still narrower linewidths (since $\Delta V_{th} \sim m^{-1/2}$, $\Delta V(CS)/\Delta V(NH_3) = 0.62$ for purely thermal broadening). Indeed, the CS lines do indicate densities higher than those indicated by NH_3. Unfortunately, the CS maps are more extensive than those of NH_3 and the CS linewidth is larger, not smaller than $\Delta V(NH_3)$, both contrary to expectations. While we are exploring possible interpretational flaws in both the CS and NH_3 data, it seems likely now that chemical effects are also involved. For unknown reasons, it seems that NH_3 preferentially exists in regions of especially low turbulence. Since one possible outcome of this puzzle is that the densities and masses are considerably higher than those inferred from the NH_3 analysis, caution is recommended in comparing theoretical models with the NH_3 results.

Now I would like to mention some preliminary results of a rather different technique for measuring density distributions around young stars. Since these stars heat the surrounding dust, the dust distribution (and by inference, the gas distribution) can be probed by high resolution measurements in the far-infrared and submillimeter. In particular, we have been using the Kuiper Airborne Observatory to make diffraction-limited-resolution scans of the 50 and 100 µm emission around young stars (see Lester *et al.* 1986 for a description of the technique). The observations can be compared with computed scans across model clouds to see which model density distributions are consistent with the data (Campbell *et al.* 1989). We have applied this analysis to L1551 and find that a density gradient of $n \sim r^{-1.5}$ provides the best match to the observations (Butner *et al.* 1989; Figure 2). This law is expected for free-fall collapse in a cloud which had previously relaxed to a $n \sim r^{-2}$ distribution by slow contraction (as in the models of Lizano and Shu 1989). We have assumed $T_D \sim r^{-0.4}$, the optically thin approximation, in our simple models, but initial tests with a dust radiative transport code suggests that this law is reasonably correct in the regions where most of the far-infrared emission is produced. Also, we have compared our data with the predictions of the much more detailed model of Adams, Lada, and Shu (1987) and find an equally good fit, not surprisingly since $n \sim r^{-1.5}$ in the outer parts of their model.

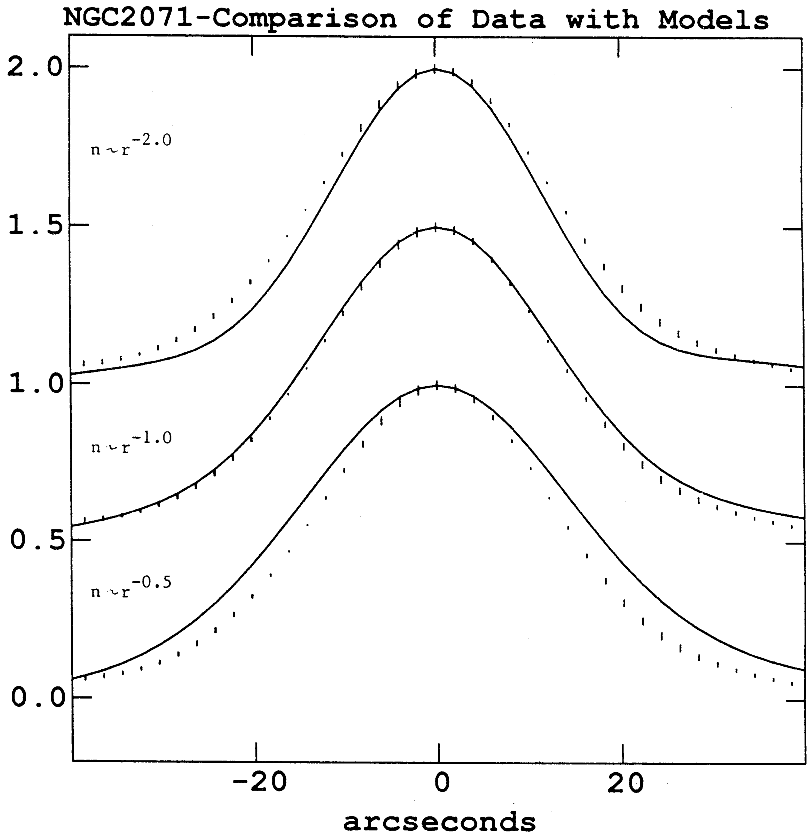

Figure 3 - The same as Figure 2, but for NGC 2071.

We plan to apply this analysis to a number of other stars, including a range of stellar masses, since a recent study by Churchwell *et al.* (1989) suggested roughly constant densities around very massive stars. Our preliminary work on NGC2071, an intermediate mass star, suggests $n \sim r^{-1}$ (see Figure 3), tempting one to speculate on a possible connection between the density distribution and the mass of the star that forms.

This technique avoids the possible problems of chemical effects and other complications of molecular line studies, but it is subject to uncertainties in the dust properties. In particular, the dependence of the grain emission efficiency on wavelength is poorly known (see Helou 1989 for a recent review). Ultimately, we plan to apply high resolution multitransition molecular line excitation methods to the same regions. If the conclusions of the dust analysis are consistent with those of the molecular line analysis, we will have more confidence in the results.

V. PARTING HOMILY

Recent developments have led us to question our simple interpretations of cloud temperatures and densities. It may fairly be said that we know less now than we thought we knew a few years ago. Perhaps we can console ourselves with the Socratic wisdom that better understanding must be preceded by a more profound appreciation of our ignorance.

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