EXCITATION ANALYSES OF INTERSTELLAR CLOUDS

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ABSTRACT

A review is given of our present knowledge of the physical characteristics of interstellar clouds and the methods used to derive parameters such as temperature and density. In particular, I discuss what can be learnt from excitation analyses of molecular clouds and compare results obtained using different molecular tracers.

1. INTRODUCTION

The interstellar gas is in a highly unrelaxed state. In fact,maps made in the 21 cm line of atomic hydrogen or in a variety of molecular lines show that much of the gas is in clumps, filaments, sheets, and in other contorted structures. A consequence is that both the dense gas (mainly molecular) and the diffuse gas (mainly atomic) is highly inhomogeneous. Much of the material is clearly in structures with densities quite different from the average smoothed-out value that one obtains, for example, from the column density of hydrogen along a given line of sight. Estimating the *local* (as opposed to the mean) density in an interstellar cloud is usually therefore done by means of an excitation analysis. That is to say; one examines the balance between collisional excitation and radiative decay for some atom, molecule, or ion with observable spectral lines and predicts their relative intensities. The observed relative intensities are then used to put constraints upon the density of the colliders - usually but not always hydrogen. Simultaneously, such analyses normally allow an estimate of the temperature and hence also of the thermal pressure in the clouds of interest. A determination of these parameters is important from the point of view of the cloud dynamics . It additionally allows an estimate to be made of the gas cooling rate and hence of the dissipation rate of the "non-thermal turbulence" which is often present in both atomic and molecular clouds.

Many reviews of molecular cloud characteristics are available[3),43),56)]. Atomic hydrogen clouds are discussed by Kulkarni and Heiles[30)]. The basic properties of giant molecular clouds (GMC's) are summarised by Solomon et al.[48)] and the characteristics of the dense cores often found associated with GMC's are considered by Myers[39),40)]. Recently also, some useful theoretical insights have come from the work of McKee[37)], of Elmegreen[16)], of de Boisanger et al.[4),5)] and of Wolfire et al.[58)]. Both the observational work and the theoretical studies rely upon excitation analyses of one sort or another. In this article, I will thus confine myself to summarising the techniques used to analyse level excitation in a variety of situations in the interstellar medium ranging from diffuse atomic hydrogen clouds to their denser molecular counterparts. I will also briefly discuss the estimates of the thermal pressure which one make in diffuse and molecular clouds and their consequences for our understanding of the processes taking place within them. I begin with a short summary of results for diffuse clouds (section 2) which are atomic in the sense that CO is a minority species. In section 3, I consider in turn the methods used and the results obtained for the diffuse molecular material seen in CO and ^{13}CO; for molecular absorption lines seen along the few lines of sight where such measurements are possible; for the "dense cores" seen in ammonia, CS and other high density tracers; and for regions of high mass star formation. Finally, in section 4, I discuss some possibilities for future studies.

2. PARAMETERS OF DIFFUSE CLOUDS

An excellent description of the properties of diffuse atomic gas in the galaxy has been given by Kulkarni and Heiles[30),29)] and readers interested in more than a superficial understanding are invited to examine that article. Analyses of optical and ultraviolet absorption lines towards stars in the solar neighbourhood have yielded a lot of information about the characteristics of diffuse clouds. A good example is the study by Jenkins et al.[28)] of the lines at 1138-1328 Angstroms of neutral atomic carbon. These authors have utilised the fact that the excited fine structure levels of CI are appreciably populated at the densities of diffuse clouds and that the ratio of excited state to ground state population is a sensitive function of the product of density and temperature or equivalently of pressure. They found thermal pressures p/k between 1000 and 10^4cm^{-3} K with a representative value being around 4000 cm^{-3} K. Kulkarni and Heiles[29)] also examined the possibility of using analogous data for ionized carbon (CII) for the same purpose and arrived at estimates for the thermal pressure a factor 2 higher than with CI. It seems in any case certain that the typical diffuse cloud pressure is below 10^4 cm^{-3} K.

It is worth noting that these estimates for the pressure are not greatly different from the thermal pressures found in the distributed ionized medium (sometimes known as WIM or Warm Ionized Medium) which is responsible for pulsar dispersion as well as the weak distributed Hα emission seen by Reynolds[42)]. Kulkarni and Heiles[29)] estimate for this component an electron density of 0.25cm^{-3} and a temperature of 8000 K corresponding to a pressure of 4000cm^{-3} K. This is close to the value derived for the cold clouds from CI data and suggests that rough pressure balance is maintained between the different phases in the diffuse atomic gas. On the other hand, this ignores the possible importance of magnetic and cosmic ray pressure. It also ignores pressure estimates based upon the scale height of local HI from 21 cm measurements (see Blitz's contribution) which suggest higher total pressures. Probably, the real truth is that all of the estimates discussed above have a factor of two uncertainty and, moreover, there are real pressure variations of this order also. In any case, these diffuse gas pressures are less than or of the same order as the molecular cloud pressures we discuss in the next section.

Before going on to this however, I note that at least *some* diffuse clouds appear to have relatively high thermal pressure (above $10^4 cm^{-3}K$) as evidenced by the detection of CS(2-1) emission at a very low level[14] towards 4 nearby stars. The interpretation is complicated by the fact that electron excitation becomes important in these regions but it is nevertheless interesting and a little surprising that CS emission is observable in this type of region. High thermal pressures are also estimated for the much studied cloud along the line of sight to ζOph[32]. Detailed models for this type of region have been computed by van Dishoeck and Black[51),52)].

3. MOLECULAR CLOUD PARAMETERS

The determination of densities and temperatures in molecular cloud regions has been reviewed by Walmsley[54] and by Cernicharo[8] among others. Briefly, one solves the statistical equilibrium equations for the level populations of a given molecule and uses an escape probability *ansatz* to correct for trapping in optically thick molecular lines. Rather doubtful assumptions about the geometry of the cloud, it's velocity field, and it's homogeneity are made in order to simplify the problem. A quick look at one of the many molecular line maps available in the literature suffices to see that the results of this procedure should be treated with some scepticism. On the other hand, more complex models are often not warranted.

In the following, we briefly review results from studies of this type for a variety of conditions. First, we consider observations of the "clumps" (for the purposes of this article, clumps are clouds with diameters of~ the order of roughly 1 parsec) which are commonly observed in regions such as Taurus and Ophiuchus.

3.1 Extended emission observed in CO isotopomers

Nature has decided that the most abundant interstellar molecule (apart from H_2) should have a small dipole moment which causes it to be excited in the relatively low density ($\sim 10^3 cm^{-3}$) parsec sized clumps out of which most molecular clouds appear to consist. This molecule is of course CO and it is interesting to speculate upon what masses might have been estimated for molecular clouds if CO had had a dipole moment of 1 rather than 0.1 debye. It is also of importance to realise that our estimates of the fraction of molecular cloud mass in structures with densities less than $10^3 cm^{-3}$ may be biased because in ^{13}CO and $C^{18}O$, even the J=1-0 transition is very sub-thermal.

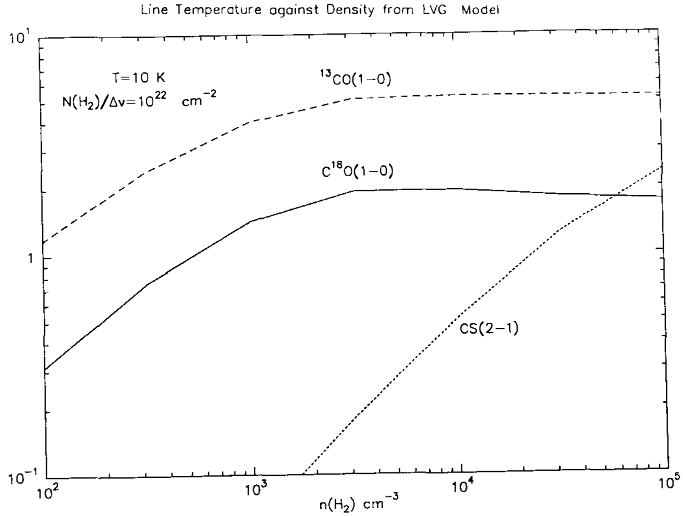

Figure 1: Predicted line temperatures of a model molecular clump of given hydrogen column density and temperature as a function of density for CS(2-1), $^{13}CO(1\text{-}0)$, and $C^{18}O(1\text{-}0)$. The temperature has been assumed to be 10K and the ratio of molecular hydrogen column density to linewidth has been taken to be $10^{22}cm^{-2}(kms^{-1})^{-1}$. The abundances relative to H_2 assumed for the various species are: 10^{-6} for ^{13}CO, 2 10^{-7} for $C^{18}O$, 3 10^{-9} for CS . Electron excitation is neglected.

In practise however, it turns out that ^{13}CO and $C^{18}O$ are excited at densities above $100cm^{-3}$ while high dipole moment species such as CS require much higher densities in order to produce observable emission. This is demonstrated in figure 1 which compares the results of statistical equilibrium calculations for the three species. The LVG computation carried out here assumes a molecular hydrogen column density of $10^{22}cm^{-2}$ and "typical" abundances (CS/H_2 =3 10^{-9}, $^{13}CO/H_2=10^{-6}$, $C^{18}O/H_2=2$ 10^{-7}). One sees that CS(2-1) becomes easily observable only above 10^4cm^{-3}. An implication of this is that one expects maps made in CS and in ^{13}CO (say) to look very different from one another as long as there is a considerable fraction of the molecular cloud material in low density gas (below 10^4cm^{-3}). In fact, the available observations[31)] do confirm this implying that the high density cores contain a small fraction of the total molecular cloud mass.

Can one make useful density estimates on the basis of the CO isotopcmer measurements alone? Figure 2 shows some sample results of an LVG calculation which has been carried out for $C^{18}O$. An abundance ratio $[C^{18}O]/[H_2]$ of 2 10^{-7} has been assumed and the calculations were carried out for temperatures of 10 and 20K.

One sees that the (2-1)/(1-0) ratio saturates above a density of $10^4 cm^{-3}$ and that it is most sensitive in the range $1000-10^4$. One sees also that a knowledge of or at least bounds upon the temperature are needed to use $C^{18}O$ (2-1)/(1-0) or $C^{18}O$ (3-2)/(2-1) as a density indicator.

Observationally, there has been rather little work studying the $C^{18}O$ (2-1)/(1-0) ratio. However, Young et al.[53)] have carried out a detailed study of the B5 cloud and use calculations similiar to those whose results are shown in figure 2 to derive a density of $4000 cm^{-3}$ for the central part of this cloud. Significantly, their study of ^{13}CO suggests smaller densities suggesting that density gradients are present. The "onion-skin" model of Gierens et al.[22)] offers one approach to solving such discrepancies. In the same spirit, large scale ^{13}CO and $C^{18}O$ maps[6)15)] towards the Orion A cloud have been used to "map" the local density. These authors find clumps with densities in the range 3000-1.5 $10^4 cm^{-3}$ and masses 1-20 solar masses. It will be interesting to compare these results with those from other tracers such as NH_3 and CS. Finally, Falgarone et al.[17] have examined the ^{13}CO (2-1)/(1-0) ratio in areas of low ^{13}CO brightness and conclude rather surprisingly that much of the matter is in rather high density clumps (above $10^4 cm^{-3}$). This however concerns regions which are non self-gravitating.

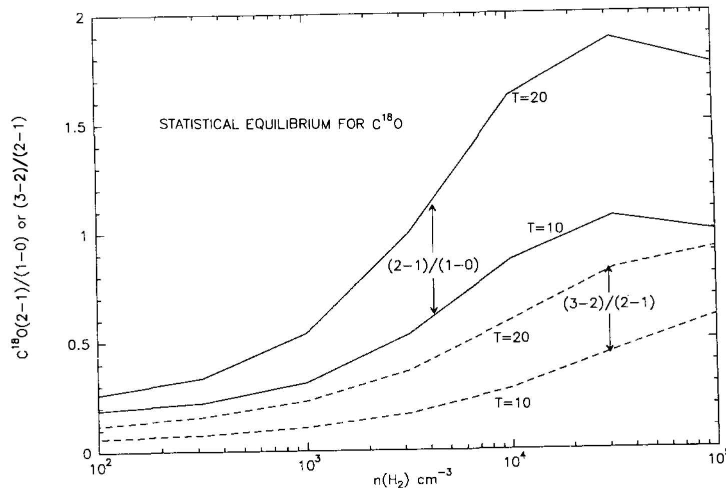

Figure 2: Results of LVG calculations similiar to those used for fig. 1 which show predictions for the $C^{18}O$ (2-1)/(1-0) line intensity ratio as a function of density. Calculations have been carried out for temperatures of 10 and 20K.

3.2 Low density gas seen in absorption

Centimeter wavelength molecular lines have been known for a long time to show absorption towards galactic continuum sources. It was rather more surprising to find absorption at millimeter wavelengths because continuum sources are relatively much weaker. However, it has been known for more than a decade that several ground state transitions can be observed in absorption towards sources such as SgrB2 and W49[33,41,24]. These lines are found to have excitation temperatures very close to that of the 3K microwave background suggesting densities of a few thousand cm^{-3} at most. It is significant that absorption is seen in transitions such as HCN(1-0) and HCO^{+}(1-0) but not in ^{13}CO or $C^{18}O$. The simplest conclusion is that the densities are such that $C^{18}O$ and ^{13}CO are excited whereas the high dipole moment species are not and, as one sees from figure 1, this implies densities in the range 10^{3}-$10^{4}cm^{-3}$.

Some temperature estimates for the absorption features are available from ammonia measurements. For the Cas A clouds, Batrla et al. [1] find a temperature of 20K and a pressure of $10^{5}cm^{-3}K$. This seems consistent with recent ^{13}CO measurements by Wilson et al.[57]. For the v=40 cloud towards W49, ammonia measurements by Mauersberger (priv.comm) suggest temperatures below 15K and the C_3H_2 measurements of Cox et al.[12] put an upper limit to the density of $5000cm^{-3}$. This translates into an upper limit on the thermal pressure of 7.5 $10^{4}cm^{-3}$. Thus the absorption line measurements ,which presumably sample random regions in molecular clouds, suggest that typical thermal pressures in molecular clouds are a factor of 20 at most above the diffuse cloud thermal pressures found in tracers such as CI.

Some work of this type has been carried out towards extragalactic continuum sources. These objects are in general at higher galactic latitudes than the regions mentioned above and hence relatively nearby clouds are observed. A recent survey by Liszt and Wilson[34] summarizes recent CO studies. One result of considerable interest is the detection of CO absorption towards BL Lac by Marscher et al.[36] using the Owens Valley Interferometer. Here, it is significant than the linewidth measured in *absorption* by the Interferometer is comparable to that measured in *emission* using a single dish. Thus the measured supersonic linewidth does not appear to be due to averaging velocity variations within the beam.

3.3 Parameters of dense cores

Many excitation analyses have been carried out of the dense "cores"found embedded in molecular clouds with densities of $10^4 cm^{-3}$ or more[8]. These cores are typically found using ammonia or CS as tracers of the dense gas. Figure 1 demonstrates why CS is appropriate for this purpose. Often, one finds associated with such cores infrared (IRAS) sources which appear to be young stars which are still embedded in a dust cocoon of stellar or interstellar nature.

Characteristics of the dense cores and their relevance for star formation are summarized in a series of articles by Myers and associates[39,40,20]. The basic conclusion is that these regions, which can easily be picked out in maps of the NH_3(1,1) line, have typical dimensions 0.1 parsec and mass of the order of a few solar masses. There is strong evidence[11] for a correlation between ammonia cores and cool IRAS sources with color temperatures between 60 and 100 microns of order 40K. There is also a general correlation between ammonia cores and the positions of T.Tauri stars in well studied regions such as Taurus. Hence, there is good reason to believe that low mass star formation is taking place in dense cores.

The ammonia observations yield temperatures and limits upon the density[27,50,2]. Typical temperatures are in the range 10-20K if one restricts consideration to cores either without associated infrared sources or those associated with low luminosity IRAS sources. A curious feature of the data is that there appear to be differences between the cores embedded in different molecular clouds. Thus while Taurus dense cores have uniformly a temperature of around 10K, cores embedded in larger molecular clouds such as the Orion clouds (L1630 and L1641) have temperatures which average around 15K[10,25]. The cause of this difference is obscure. It seems to be related to the fact that measured line widths are also in general larger in the Orion clouds than in Taurus. This is also seen in the CS(1-0) survey of Tatematsu et al.[49]. One obvious difference between the Orion and Taurus regions is the presence of large OB associations in Orion. The supernova explosions and stellar winds associated with the presence of these young stars may be at the origin of the increased turbulence in the Orion cloud.

This difference in temperature is reflected in figure 3 which shows a comparison of the thermal pressures found in the nearby ($<$300pc) cores of the Benson Myers[2] sample(triangles) with the analogous results for the Orion cores of Harju et al.[25], open squares). While, for the reasons discussed below, the individual density determinations (and hence also pressure) are suspect, the trends seen in figure 3 are probably reliable. One can draw the general conclusion that, while there is no clear difference in density between Orion and local cores, the Orion GMC cores do have slightly higher pressure. One notes also that all of the cores have thermal pressures considerably in excess of the typical diffuse atomic clouds discussed in section 2.

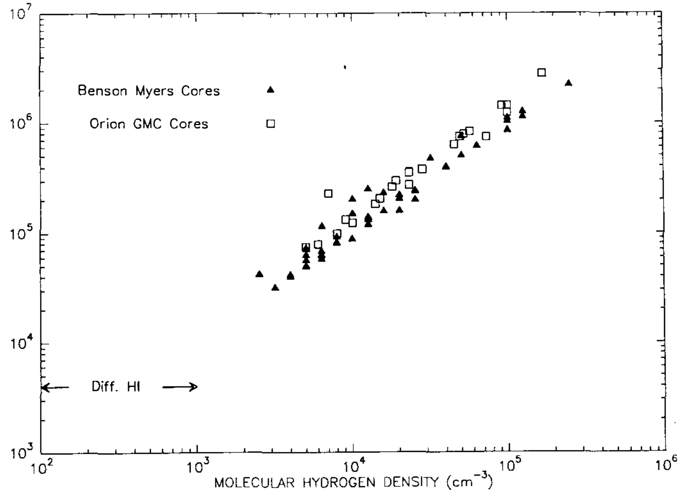

Figure 3: The thermal pressure and density derived from the ammonia data of Benson and Myers[2)] for nearby clouds (triangles) are compared with similiar results for cores in the Orion GMC obtained by Harju et al.[25)], open squares). For comparison, the typical density and pressure of interstellar HI clouds is shown at the lower left.

In the Orion cores, "turbulence" makes the main contribution to the observed line width. By contrast, in some of the nearby cores, the line widths are so small that the effects of thermal broadening are directly measurable. A recent multi-molecular study by Fiebig and Güsten[19,18)] examines the variation of linewidth as a function of molecular mass for three NH_3 cores (L1498, L1512, TMC1-C) and derives kinetic temperatures which (in two of the three cases) are completely consistent with the numbers obtained from the ammonia excitation analysis. The non-thermal line broadening in these objects has almost disappeared. A consequence of this is that thermal pressure plays an important role in the dynamics of the region and in fact thermal pressure and gravitation are roughly in balance in these cores. Magnetic field pressure and rotational energy seem incidentally to be negligible.

Comparisons of this sort often depend upon the density derived from the ammonia (1,1) excitation temperature. This method will be affected by clumping within the beam which causes one to underestimate the molecular hydrogen density. One clearly therefore needs to compare ammonia results with estimates based upon other molecules. A study of this type has been carried out by Zhou et al.[59)] who observed several CS and $C^{34}S$ transitions towards a sample of low mass cores. They derive higher densities from their CS measurements than from NH_3 which at first suggests that clumping is affecting the ammonia results. However, for the three sources studied by Fiebig[18], one can compare the 100-m NH_3 measurements taken with a 40" HPBW with the Haystack-Greenbank results of Benson and Myers[2] taken with beams roughly double the size. The results show that for one source (L1512), the density derived by Fiebig is a factor 8 smaller than by Benson and Myers whereas for L1498, the 100-m observations suggest a density 2 times larger than the results from Haystack and Greenbank. For TMC1-C, the different telescopes give results consistent within a factor 2. All of these sources have high NH_3 (1,1) optical depths and the above differences suggest that the combination of calibration errors together with the difficulty of making a precise trapping correction make densities derived from the estimated NH_3(1,1) excitation temperature very suspect. Probably, the only safe statement on the basis of the ammonia measurements is that the densities in all of these sources is above $10^4 cm^{-3}$.

On this basis, one might think that the CS results are preferable. However, one finds observationally[59] that the observed CS emission has typically larger linewidth and comes from a larger region than does NH_3. This suggests that chemical differences between the two species are confusing the issue with CS being relatively more abundant in the low density envelope surrounding the core with density above $10^4 cm^{-3}$. One can imagine then that the radiative transfer for CS is analogous to that for HCO^+ [7,23]. The scattering envelope redistributes the photons emitted by the core both spatially and in velocity. NH_3 (which seems to be thin in the envelope) gives a truer representation of the core characteristics. If this is generally true, one needs to measure an optically thin tracer such as $C^{34}S$ in order to derive reliable core densities. Another possibility is C_3H_2 [13].

The above discussion also suggests that homogeneous models are often not an appropriate approach to modelling dense cores. Some work has also been carried out assuming density distributions appropriate to star forming cores. Thus, Zhou et al.[60] suggest that their formaldehyde and CS data towards B335 can be explained by a model which, outside an inner core of radius 0.03 parsec, has an envelope with a $1/r^2$ density profile. In such a situation, higher angular resolution observations detect higher densities, which causes the simple LVG homogeneous models often used in this sort of analysis to be of doubtful value.

Nevertheless, the simple LVG models give an estimate of the density on the scale size of the beams used and hence of the local pressure. The Benson and Myers[2] ammonia data suggest that the pressure in their cores varies between $10^{4.7}$ and

$10^{6.1}$cm^{-3}K with a median value of $10^{5.2}$cm^{-3}K. In the smaller sample of Zhou et al.[59] observed in CS, the derived pressure varies between $10^{5.3}$ and $10^{6.7}$ with a median of $10^{6.1}$cm^{-3}K.

3.4 Physical Parameters of Regions of High Mass Star Formation

The techniques discussed earlier have found their greatest application in regions where O-B stars are currently forming. A pioneering work in this field was that of Snell et al.[47] who used CS observations to derive the molecular hydrogen density in the regions M17, S140, and NGC 2024. These authors observed CS(2-1),(3-2), (5-4), and (6-5) with an angular resolution of roughly 1 arc minute. They thus sampled a considerable range in "critical density " (i.e the density for which the collision rate n(H_2), σv is equal to the transition Einstein A-value). They nevertheless managed to get single density solutions in a considerable number of positions and concluded that the CS emission arises in clumps of density between 4 and 9 10^5cm^{-3}. Their results were later confirmed by the subsequent $C^{34}S$ study of Mundy et al.[38]. More recent work with higher angular resolution (Ref.44) has directly demonstrated the existence of such clumps in the M17 cloud and confirmed that their densities are of order 10^6cm^{-3}. The most recent development is the extension of this work to the submm range with the CS(10-9) detections of Hauschildt et al.[26]. This transition has a critical density, above 10^7cm^{-3} and one would naively think it should trace extremely high density regions. This may be the case but it seems likely that in the sources where CS(10-9) has been detected, infrared pumping via the vibrational transition at 7.9μm is competitive with collisions.

Another possible tracer is formaldehyde. A very recent study by Mangum and Wootten[61] shows that one can exploit the fact that H_2CO is a slightly asymmetric top molecule in order to derive both density and temperature. The consequence of being slightly asymmetric is that there are several transitions at neighbouring frequencies whose intensity ratios are sensitive to temperature and relatively independent of density. Mangum and Wootten derive temperatures of 50-300K and densities of 10^5 to 10^7cm^{-3} for several regions of high mass star formation.

A number of detailed studies have also been made of the high density gas surrounding the Orion-KL region[35,45]. Over a region roughly 0.5 parsec in size, the 2cm ($2_{1,1}$-$2_{1,2}$) line of formaldehyde is found to be in emission (see Wilson and Johnston[55]) and this implies densities of at least 3 10^5cm^{-3}. In this case, the pressures are probably influenced by the nearby HII region and are probably above 10^7cm^{-3}K. The more distant regions in the inner galaxy studied by Cesaroni et al.[9] probably have similiar characteristics to the Orion ridge gas.

4. DISCUSSION

The molecular cloud physical parameters derived from excitation analyses are important in at least two respects. In the first place, they allow us to check cloud mass estimates and indeed mean densities derived from a tracer such as CO or dust. These latter estimates usually make an assumption (see Genzel[21]) for a discussion) about the abundance of the relevant tracer as well as about it's excitation temperature (temperature and emissivity in the case of dust). The excitation analyses do not require such assumptions and indeed provide a check upon their validity. It is thus only via excitation analyses that we are able to measure molecular hydrogen as opposed to something representing molecular hydrogen. On the other hand, the excitation analyses have also their weaknesses and one concludes that the two approaches to determining molecular cloud masses (from excitation and from column density) are complementary.

Secondly, the thermal pressure one derives from density and temperature measurements should also provide useful constraints upon molecular cloud models. Thermal pressure is certainly important dynamically in those dense "ammonia" cores where thermal broadening is larger than the non-thermal contribution to the linewidth. In this case, it appears that thermal pressure dominates magnetic and turbulent pressure. It seems reasonable to believe that these regions[46]) are a reasonable approximation to a hydrostatic isothermal sphere and the mass accretion rate of an embedded object is then simply a function of the temperature. Tests of this hypothesis on the lines of the study of Zhou et al.[60]) seem a reasonable way to go forward. In regions such as the Orion cloud cores where "non-thermal" turbulence dominates the line broadening, there is evidence[25]) that temperatures are higher than in the narrow line cores. Understanding the reason for this as well as understanding the nature of the non-thermal broadening is an important goal for the future. The proposals put forward by Chièze at this conference offer one approach to solving these problems theoretically.

The fraction of molecular cloud gas in high density material (above $10^4 cm^{-3}$) is still a controversial quantity. The excitation studies discussed in this article should be capable of providing a partial answer to this problem. In particular (see Fig.1), the comparison of maps of high density tracers such as CS with maps of ^{13}CO or $C^{18}O$ should allow crude estimates to be made. A start in this direction has been made by Lada et al.[31]) who have mapped a large fraction of the L1630 cloud in

CS(2-1). They detected CS emission over 10 percent of the region surveyed and conclude that less than 19 percent of the cloud mass is in cores with density above 10^4cm^{-3}. The absorption line measurements discussed earlier in this article (section 3.2) are broadly consistent with this result and suggest that the bulk of GMC material is in clumps with density of a few thousand per cubi centimeter or less. However, clearly the vastly improved data sets one can expect in the future (see Fukui's contribution) will provide new answers to this question.

As discussed in the Introduction, the origin of the non-thermal turbulence observed in most molecular clouds is not presently understood. One result which may help to find a resolution of this question is the observation (section 3.3 and fig.3) that there are marked differences between dense cores embedded in different molecular clouds. These differences appear to be in the sense that cores embedded in more massive clouds (10^5 solar masses or more) have higher pressure (both thermal and total) than cores associated with low mass aggregates such as Taurus[25]. One possible explanation (see section II of Ref.37 and in particular equation 2.17) may be related to the higher pressures expected in massive clouds with high mean extinction. Here, the idea is that the pressure contrast between cloud edge and center should reflect the depth of the gravitational potential well.

Finally, I note that one fundamental problem with most of the excitation studies discussed in this article is that the clouds, clumps, and cores under consideration are far from being homogeneous entities. Hence, as with forbidden line studies of HII regions, one can have the problem that since each tracer is sensitive in a limited density range (for example 1000-10^4cm^{-3} in the case of $C^{18}O$ - see fig.2), the result of excitation studies tends to be that one always derives a value corresponding to the critical density of the tracer under consideration. This criticism is certainly partially valid and in many cases, explains the discrepancies between density estimates derived using different tracers. However, one should also be aware that excitation studies using several molecular lines of differing critical densities have been carried out and one does often find an unique density within observational errors[38,61]. Moreover, even when excitation studies do not yield unique densities, the derived limits can be significant. For example, the absorption line studies discussed in section 3.2 yield upper limits to the density whereas most emission line studies give lower limits. Combining the two can rather tightly constrain the density in the region under consideration. One should therefore not be too pessimistic about the possibility of learning something from excitation.

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