PHYSICAL AND CHEMICAL PARAMETERS IN DENSE CORES

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Abstract. The current state of our knowledge of the physical parameters and the chemical composition of dense cores in molecular clouds is discussed. In particular, I summarize what is known about the rate at which molecules condense out on grain surfaces. I discuss in turn : a) dense cores in nearby dust complexes such as Taurus, b) clumps in regions of massive star formation such as Orion and M17, c) hot dense cores near to newly formed O stars such as the Orion-KL hot core and d) the high density condensations which give rise to interstellar masers. Recent work on each of these categories is reviewed with emphasis on the chemical abundance determinations and estimates of the local density and temperature. Particular attention is given to recent work on OH, methanol, and ammonia masers.

Keywords : Molecular Clouds, Star Formation, Interstellar Chemistry, Masers, Clumps

1. Introduction

The physics of dense cores in nearby molecular clouds has been the subject of many reviews and it is doubtful whether it is useful to add to their number (but see e.g. Fuller and Myers 1987, Walmsley 1987, Shu et al. 1987, Wilson and Walmsley 1989). There is much less clarity about the chemical conditions and I therefore focus on this. Potentially, the observed molecular abundance distribution in molecular clouds can tell us a lot about local conditions and I discuss to what extent one can realise that potential. One of the questions which comes up in this regard is what fraction of the heavy elements are depleted out onto dust grain surfaces. I review briefly in section 2 what one expects theoretically and what is known from infrared studies. Section 3 deals with cold cloud cores and section 4 with the denser hotter clumps found in the neighbourhood of HII regions. In section 5, I give a very short discussion of hot core type regions and in section 6 I mention some new results for OH, methanol, and ammonia masers. Finally, in section 7, I give a very brief overview showing the range in temperature–density space covered by current observations.

2. Depletion onto dust grain surfaces

It has been realised for a long time that the timescale for a heavy atom or molecule hitting a dust grain and being removed from the gas phase is less than or of the same order as the timescale both for ion–molecule chemistry and for dynamical evolution of typical high density molecular cloud cores. Recent discussions of this problem are given by Walmsley (1985,1989) and by Williams(1990). One way of looking at the problem is to compare the free–fall timescale, which is an estimate of the time needed for dynamical evolution, with the time required for a large fraction of the molecules to deplete out on dust grains. The latter can be written as :

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$$t_d(yr) = 1.5\,10^5\,(10^4/n)\,(1/S)\,(2.1\,10^{-21}/\overline{\sigma_g}) \qquad 1$$

where n is the hydrogen density (cm^{-3}) , S is the sticking coefficient (i. e. the fraction of molecule collisions with grains which lead to adhesion of the molecule to the surface) and $\overline{\sigma_g}$ is the mean grain cross–section per hydrogen atom for which one normally assumes the value ($2.1\,10^{-21}cm^2$) which is derived from interstellar extinction measurements. Figure 1 shows the values of t_d derived from this formula for sticking coefficients of 0.1 and 1 plotted as a function of the hydrogen density. The free–fall time ($(3\pi/(32G\rho))^{0.5}$) is shown in figure 1 for comparison. For virialized clumps, this should in a statistical sense be a lower limit on the clump age. One sees that even for a sticking coefficient of 0.1, one expects a large fraction of the molecules to deplete out in one free–fall time at a density of 10^5 cm^{-3}. At higher densities, the "freeze–out" should occur in a fraction of a free–fall time. There have been a considerable number of theoretical investigations of sticking coefficients (e.g. Leitch–Devlin and Williams (1984)) which suggest that for realistic grain materials, a sticking coefficient of below 0.1 is unlikely. Hence, depletion of molecules onto dust grain surfaces seems probable at densities higher than 10^5 cm^{-3}. This poses at first sight a problem since most of the high density clumps in or near which star formation goes on appear to have densities of the order of 10^5 or greater.

Part of the answer to this question is that infrared observations tell us unequivocally that depletion does occur in high density clumps. One observes directly in absorption towards embedded infrared sources bands of solid CO, water ice, and other species (see Tielens 1989,1990). However, the data presently available do not suggest that a large fraction (more than 50 percent) of the available heavy elements have been lost from the gas phase. In the first place there are lower limits of $5\,10^{-5}$ on the $[CO]/[H_2]$ abundance ratio towards deeply embedded IR sources in the NGC 2024 and NGC 2264 cloud cores (Black and Willner 1984, Black et al. 1990). These are high density lines of sight with CO column densities of order 10^{19} cm^{-2} and hydrogen densities at least 10^5 cm^{-3}. The data are much less equivocal than most radio observations in that one observes (in the 2-0 vibration–rotation band of CO) all rotation states of importance and in that one directly measures (or in this case puts limits upon) molecular hydrogen. These limits on $[CO]/[H_2]$ are very close to the values estimated on the basis of radio studies of nearby dust clouds (e.g. Dickman(1978)).

However, in regions such as the NGC 2024 molecular ridge which abuts upon an HII region, the dust temperatures may be sufficiently high that the more volatile components of the mantle such as CO can evaporate. Typical condensation temperatures for a sample of interstellar molecules are given by Nakagawa (1980) and a discussion of mantle evaporation is given by Léger et al. (1985). Above a dust temperature of 20 K, pure CO ice is likely to be evaporated but the reality is likely to be that the CO is in a matrix (see e.g. Tielens 1990) and in this case the fate of the mantle will probably be determined by less volatile species such as H_2O

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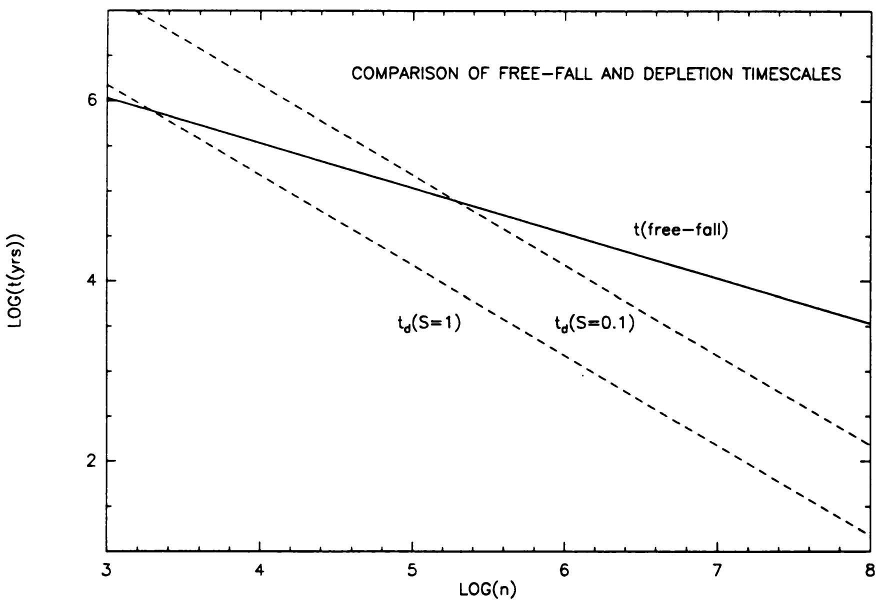

Fig. 1. The timescale for molecules condensing out on grain surfaces is plotted (dashed lines) as a function of the hydrogen density for two values of the sticking coefficient S. Equation 1 has been used with the normal diffuse gas value for grain surface area per hydrogen atom. The free fall time (full line) is shown for comparison

or CO_2 for which the corresponding condensation temperatures are 100 and 50 K respectively.

Direct evidence on the depletion question comes from the observations of the solid–state features of CO and H_2O towards infrared sources. In the sources examined by Lacy et al. (1984), the ratio of solid to gas phase CO varied between 0.02 and 0.3. Whittet et al. (1989) have observed 8 stars in the direction of the Taurus cloud and conclude that 30 percent of the available CO is in the solid form. On this basis, one might think that depletion is important but not overwhelming. However, it is conceivable that CO is processed upon grain surfaces and indeed d'Hendecourt and de Muizon have recently found solid CO_2 to have an abundance similiar to that of solid CO towards AFGL 961 and AFGL 989. This is in contrast to the gas phase where CO_2 is thought to be at least two orders of magnitude less abundant than CO (see Minh et al. 1988). It seems likely that the CO_2 has been made on the grain surface. Moreover, water ice is typically an order of magnitude more abundant on grain surfaces than CO (see Tielens 1989 for a summary of grain mantle abundances) and H_2O is probably formed on the grain surface. In fact, it seems reasonable to guess that water ice is the main repository of oxygen on the grain surface as is the case in comets. If this is so however, it implies that in the

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lines of sight examined to date, the column density of oxygen in the solid form is comparable to but not orders of magnitude greater than the column density of O in the gas phase (in all forms including CO).

The radio data relevant to the depletion problem are rather less clearcut than the infrared observations discussed above. I will mention some relevant measurements in the following sections and Mezger (this conference) will discuss the comparison of millimeter dust emission and molecular line maps. It is important to realise however that *it is not a valid assumption to suppose that molecular abundances are simply proportional to the depletion fraction.* With the exception of CO which is thought to be a major repository of gas phase carbon, the observed molecules (SiO is a special case also) contain trace amounts of the total gas phase heavy element content. As depletion progresses, their abundance may decrease more or less rapidly than the general loss of molecules. Ions such as HCO^+ , which are indirectly produced by cosmic ray ionization, may at first "not notice" the decrease in the CO abundance. Both the hydrocarbon radicals and deuterium fractionation can increase as a result of depletion (see the model calculations of Brown et al. 1988 ,Brown and Millar 1989, Brown and Charnley 1990). It is thus not possible to deduce that because, say, NH_3 decreases in abundance by a factor of a few close to a dust emission peak, that the molecules are being frozen out. The gas phase chemistry is just too complicated and too poorly understood for that and, incidentally, one knows of variations of the ammonia abundance in lower density regions where freeze–out is probably not the explanation (Olano et al. 1988). CO is different in this respect and its abundance should simply reflect the carbon depletion. In this sense, direct measurements of $[CO]/[H_2]$ such as those of Black et al. (1990) mentioned earlier are very important.

Having said all this, one sees from Figure 1 that depletion should occur on timescales short compared to free–fall for densities of 10^6 cm^{-3} or more. Moreover, the free–fall time is a minimum estimate for the lifetime of high density clumps and many scenarios have been envisioned where clumps are stabilised against collapse and exist for many free–fall times. Unfortunately, the abundance estimates discussed above refer mainly to regions between 10^4 and 10^6 cm^{-3}. In those regions which have been studied with densities above this limit, the dust temperature is typically of the order of 100 K or more and grain mantles can evaporate. These hot dust or "hot core" regions are very important in that they give us insight into the mantle composition. Nevertheless, the question remains of what happens in high density regions which are sufficiently far from a luminous infrared source that the dust is cold. One possibility of course is that the molecules do indeed *all* condense out. If this happens, it is interesting to note (Hartquist and Williams 1990) that a small fraction ($[CO]/[H_2]$ of order 10^{-7}) of molecules will remain in the gas phase due to photodesorbtion by Lyman photons secondary to cosmic ray ionization. This small quantity of CO may nevertheless be an important coolant for the gas and it is perhaps observable although confusion with surrounding CO makes this in practise difficult.

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It is useful therefore to summarize (see Williams(1990) for a more extensive discussion) the processes which might prevent rapid depletion in high density regions. One such process is grain coagulation leading to a reduction in the total grain surface area or, in terms of equation 1, to a reduction in $\overline{\sigma_g}$. Mathis (1990) has summarized evidence for a change in the grain size distribution between "diffuse" and "outer cloud" dust. Cardelli et al. (1989) find for example a reduction by a factor of 2 or more in the integrated UV extinction per hydrogen atom towards two nearby stars and attribute this to grain coagulation. These data refer to material at much lower densities than in the cores where star formation occurs and a large decrease in $\overline{\sigma_g}$ in high density regions is a distinct possibility. It is worth noting also that the reduction in UV extinction per hydrogen atom leads to an increase in the UV penetration of molecular clouds. This should cause greater photodesorption and photo–processing in the exterior regions of clouds and raises the question of whether exchange of material between cloud interior and exterior can lead to depletion being kept at moderate levels even in high density clumps (see Boland and de Jong 1982, Chièze and Pineau des Forêts 1989). This type of model can probably explain observed depletion levels at densities of 10^4 cm^{-3} and below but not at higher values. Another mechanism which seems to fail at high densities is desorption due to the passage of cosmic rays. Léger et al. (1985) have studied this and conclude that spot heating by cosmic rays can lead to thermal desorption at densities below 10^4 cm^{-3}. Perhaps the most promising possibility is that shocks in molecular clouds can be sufficiently violent to desorb the more volatile components in grain mantles. Williams and Hartquist (1984) proposed a mechanism of this type to explain the apparent presence of atomic carbon deep in molecular clouds where theory predicts that most gas phase carbon should be in the form of CO. Charnley et al. (1988,1990) have extended this model and studied a situation where matter is continually cycled between dense clumps and interclump material. In this picture, clumps are ablated by the stellar winds due to newly formed pre–main sequence stars. Shocks in the interclump material cause mantle–desorption and one finds that for clump lifetimes of $1 - 5\,10^6$ years that a reasonable fit can be found to observed abundances. Given the large number of outflow sources which have been recently found to be embedded in dense regions, this mechanism seems plausible. A consequence would seem to be that there should be abundance differences between clumps with and clumps without embedded infrared sources.

3. Dark Cloud Cores and their Chemistry

Rightly or wrongly, it is generally accepted that dense clumps embedded in molecular clouds are the starting points for star formation. In nearby clouds such as Taurus, there is evidence for this in the form of the spatial correlations which have been found between infrared (IRAS) sources embedded in molecular clouds and high density molecular condensations observed in tracers such as NH_3 and CS. (e.g. Myers 1987, Fuller and Myers 1987). The masses of such clumps are typically

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only a few solar masses and it is natural to guess that they are in some sense "proto–protostars".

In order to verify such statements, one needs to estimate the physical parameters in the high density clumps. The ammonia data itself shows that 10 K is a reasonable estimate for the kinetic temperature in the nearby clouds seen in Taurus and similiar complexes. It is interesting however that in the clumps so far examined in the nearest GMC, Orion, temperatures are higher than in Taurus and linewidths also (Wouterloot et al. 1988). A very recent study (Harju et al. 1990 and this conference) suggests that the diameters of the Orion clumps are a factor of two larger than in Taurus. The local density is rather more debatable and studies to date have used tracers such as CS , HC_3N , NH_3 and C_3H_2. (see Cox et al. 1989, Walmsley and Wilson (1985), E.Lada (this conference), Zhou et al. 1989 and references therein). There is some disagreement between these different probes and also evidence that the spatial distribution of different species is not identical. For instance, clumps mapped in CS have a larger angular extent than in NH_3 (Zhou et al. 1989) suggesting that NH_3 is relatively less abundant in the lower density extended component. This is consistent with the fact that $NH_3(1,1)$ shows no signs of "self–absorbed" profiles. Other differences in the spatial distributions have been discussed by Swade (1989) and by Olano et al. (1988).

One potentially useful tracer of cloud history is the abundance of carbon rich molecules such as HC_3N in particular and the cyanopolyynes in general. There appears to be no obvious *physical* difference between the clumps where the cyanopolyynes are abundant and those where they are absent. It is possible that the important parameter is age and that the observed abundance distribution contains coded information about the dynamical history of the cloud. For example, given that current chemical models (e.g. Herbst and Leung 1989) predict that carbon–rich species should be abundant at "early times", it seems reasonable to conclude that the clumps where HC_3N and other cyanopolyynes are abundant are younger than the majority of "ammonia" clumps. Thus TMC1 should be younger than L183 and the majority of NH_3 cores (although why then the variations within TMC1 ?). If this is the case, one can use the relative abundance of the different members of the cyanopolyyne family as a "clock" (for a variant on this idea see Stahler 1984). Of course, older clumps should also show higher degrees of depletion onto dust grain surfaces and hence one might expect that high cyanopolyyne concentrations should correlate with low depletion. It is worth noting here that depletion of CO, H_2O and other species is expected to lead to increased deuterium fractionation (see e.g. Dalgarno and Lepp 1984). Hence, a comparison of cyanopolyyne abundances and deuterated ratios in several dense core sources might be useful. One can already compare the DCO^+/HCO^+ ratios found by Guélin et al.(1982) for L183 (relatively low cyanopolyyne abundance) with those for TMC1 (high cyanopolyyne abundance). These authors find an increase by a factor of 2 in the integrated intensity ratio of DCO^+ relative to $H^{13}CO^+$ between the TMC1 cyanopolyyne peak and L183. This is qualitatively what one expects but the effect is sufficiently small

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that it may not be significant. Unfortunately, there are considerable uncertainties in the detailed models for deuterium fractionation. (Brown and Millar 1989).

4. Cores in regions of massive star formation

In regions of massive star formation, densities and temperatures are typically higher than in the relatively low mass cores discussed in the previous section. Ammonia has been used as a "thermometer" by several groups (e.g. Batrla et al. 1983, Güsten and Fiebig 1988). The dense gas clumps bordering HII regions typically have temperatures in the range 20-50 K. Multi–transition observations of CS and H_2CO towards three HII regions have been carried out by Snell et al. (1984) and by Mundy et al. (1986,1987). These studies are relatively consistent with one another and suggest that the regions are clumped with local densities in the range $3\,10^5$ to 10^6 cm^{-3}. What is between the clumps remains something of a mystery. However, VLA maps of the clumps north of Orion-KL in the 2 cm K-doublet transition of formaldehyde (Wilson and Johnston 1989) seem to confirm the general picture by directly imaging the clumps. One of the observations, which any model of these regions must explain, is the presence of considerable amounts of warm CO (e.g. Schmid–Burgk et al. 1989, Stutzki (this proceedings)). Tauber and Goldsmith(1990) have developed a radiative transport model for such a clumpy cloud which gives a qualitative agreement with observation.

The "fragments" seen north of Orion-KL with the VLA (Wilson and Johnston 1989) have densities varying from $8\,10^5$ to $3\,10^7$ cm^{-3}, masses between 1 and 150 $M_\odot$ and temperatures of order 30 K. Thus the thermal pressure is of order 10^8 cm^{-3}K or roughly 10^4 times the general interstellar medium value. The pressures are not however greatly different from those pertaining in the HII region and this suggests that the ionized gas contributes directly or indirectly to the confinement of the clumps.

The molecular abundances in such high density clumps is a matter of interest for the same reasons as discussed above for the cold cores. At densities of 10^6 cm^{-3} , the freeze out timescale in such regions is of order 1000 years and thus considerably less than the dynamical timescale of order $r_c/\Delta v$ or roughly 10^4 years where r_c is the clump radius and Δv the line width. There have not been many abundance determinations in this type of high density core. However, in the clumps north of Orion-KL discussed above, both the ammonia abundance (see Batrla et al. 1983) and the methanol abundance (Menten et al. 1988a) are of order 10^{-8} relative to H_2 which is approximately the value observed in cold dust clouds (see Irvine et al. 1987). Moreover, in the high density region of M17, where the conditions seem to be quite similiar to those found in the Orion clumps, Stutzki and Güsten (1990) find that their CS data is comparable with an abundance of $2.5\,10^{-9}$. This is a "normal" dark cloud value and the M17 ammonia abundance (Güsten and Fiebig 1988) seems to be within a factor of 2-3 of that in Orion. Hence, while detailed abundance studies would certainly be useful, there is no evidence for generalised

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depletion of molecules onto grain surfaces in this type of high density region (Stutzki and Güsten find that the temperature is of order 50 K and the density 10^6 cm^{-3} in the M17 clumps).

5. Hot Core regions

Still hotter and denser are the so–called "hot core" regions which are found close to very luminous infrared sources. These clumps are observationally characterised by the fact that they show up on VLA ammonia maps (see e.g. Migenes et al. 1989, Genzel et al. 1982, Pauls et al. 1983). The temperature in such regions can be deduced both from the observed line brightness temperatures (the metastable ammonia lines are highly optically thick and thermalized) and from multi–line analyses. In the Orion-KL hot core, Hermsen et al. (1988) have derived a temperature of 160 K from their ammonia measurements. On the other hand, Loren and Mundy (1984) derive 275 K from their methyl cyanide measurements. It seems likely that this reflects different spatial distributions of the two species. The Migenes et al. maps show that there is considerable structure within the hot core region. Presumably, the clump is being battered by the wind blowing from the nearby luminous infrared object Irc2. In view of this structure, one can expect a considerable range in local densities. From the millimeter dust emission, the average Orion hot core density has been estimated to be $3\,10^7$ cm^{-3} and the mass of the region to be 45 $M_\odot$ (Mundy et al. 1988).

Close to newly formed massive stars, dust particles become sufficiently hot that icy dust mantles can evaporate. Because of the long timescales for gas phase chemistry, the newly ejected mantle material is not immediately destroyed and one can use observations of the abundance distribution in hot core regions to draw conclusions about the composition of the mantle. In this context, an interesting characteristic of the Orion hot core is the relatively high abundance of deuterated molecules in general and HDO in particular (Plambeck and Wright 1987, Jacq et al. 1990). This can be shown to be quite consistent with the idea that the hot core gas is to a large degree evaporated mantle material (Brown and Millar 1989). Also relevant is the general trend that saturated molecules are present in the hot core while radicals and ions are not (see Irvine et al. 1987 for a summary of abundance estimates). Some questions are however left open by all these studies. It is in particular frustrating that one still does not know in what form most of the hot core oxygen and nitrogen is present. The Jacq et al. study suggests that only a few percent of the oxygen is in the form of gas phase water (see also Knacke et al. 1988). One concludes then that either oxygen condenses out in some other form than water ice (e.g. O_2) or else complete heavy element depletion did *not* occur prior to the switch on of the luminous IR source IRc2 (which is presumed to heat the dust). In any case, one of the fundamental questions left in this field is "where is the O and N ?".

Another open question relates to methanol whose abundance also appears to jump in hot regions close to where massive stars are forming. CH_3OH is estimated

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to have an abundance of 10^{-6} in Orion-KL as compared to $3\,10^{-9}$ in the more extended ridge gas (Menten et al. 1988a). The latter value is similiar to that found in dark clouds (Friberg et al. 1988). It is tempting to relate the rise in the methanol abundance in high temperature regions to grain evaporation also. There is evidence (Tielens 1989,1990) that methanol is very abundant in mantle material but how this CH_3OH is produced is not clear. Also the CH_3OH spatial distribution in Orion-KL differs from the classical hot core distribution as seen say in NH_3 (Wilson et al. 1989). Partly as a consequence of this, Blake et al. (1987) have proposed that the methanol gets produced as a consequence of the mixing in of water–rich material from the Orion-IRc2 wind with surrounding ion–rich gas. Then, radiative association of H_2O and CH_3^+ can give rise to protonated methanol which in turn can recombine to CH_3OH. A recent study by Millar and Herbst (1990) suggests however that this scheme will not work in the original form.

6. Maser Regions

Interstellar masers allow us to study structures with sizes as low as a few astronomical units. They are important for a variety of reasons but in particular because they allow us to study detailed kinematics of star–forming regions. Good reviews of the subject are available from Reid and Moran (1981), Elitzur (1982), Genzel (1986) and Cohen (1989) among others. In this discussion, I confine myself to a few recent results concerning OH, methanol and ammonia masers.

6. 1. OH MASERS

The regions giving rise to OH masers may in fact be sub–structures of clumps which from the point of view of their physical parameters are similiar to the Orion hot core. OH masers tend to be found in the close vicinity of ultra–compact HII (UCHII) regions and it is natural to ask why this should be. Elitzur and de Jong (1978) for example put forward the idea that the OH abundance was enhanced due to photodissociation of water molecules which in turn were produced in the shock running ahead of the HII region ionization front. Andresen (1986) has suggested that the OH pump is basically chemical and also caused by water photo–dissociation which directly inverts the OH Λ-doublets. In principle, these two mechanisms could support one another although the chemical pump appears to be too inefficient (at most one maser photon per OH formation) to supply the observed flux. One of the difficulties in judging the Elitzur-de Jong proposal is that the OH abundance in "normal" gas clumps is poorly known and hence it is unclear whether an abundance enhancement is necessary. An interesting new suggestion (Hartquist and Sternberg 1990) is that the UV photons from the HII region can heat the dense gas close to the ionization front sufficiently (above 1000 K) that gas phase OH production mechanisms ($O+H_2$) can proceed efficiently.

The OH maser regions have also the characteristic that the masers in low lying states are often associated with absorption lines in highly excited states (see Baudry

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et al. 1981, Guilloteau et al. 1985, Wilson et al. 1990). The excitation requirements for the masers (typical densities 10^7 cm^{-3} and temperatures 100 K) are not greatly different from those for the absorption lines and indeed similiar to the hot core characteristics discussed in the previous section. Hence, the question is raised of whether the absorption lines and the masers form in essentially the same regions. In a recent study of OH maser emission towards W3(OH) for example, Cesaroni and Walmsley conclude that one can fit both ground and excited state data with a model which has temperature 150 K and density of order 10^7 cm^{-3}. In other words, the OH lines form in a hot core which is 3 kpc distant and which happens to contain an embedded compact HII region. The masing transitions can amplify the background continuum radiation and one observes emission or absorption lines depending upon the relative populations in the upper and lower states of the relevant transitions. The OH abundance in these models is $2\,10^{-7}$ which is comparable to that estimated in TMC1 (Irvine et al. 1987).

6. 2. METHANOL MASERS

Methanol masers in a series of transitions at 25 GHz were originally reported in Orion A by Barrett et al. (1971). More than ten years later, it was found that maser action can be observed in several other methanol transitions as well (Wilson et al. 1984,1985, Morimoto et al. 1984). It was also found that the strongest methanol masers are those found in the 12.1 GHz 2_0-3_{-1} E-type lines towards many compact HII regions (Batrla et al. 1988). Interferometric images of the 12 GHz sources show that the line brightness temperature can reach 10^{10} K (Menten et al. 1988b) and that individual maser spots have sizes of a few astronomical units.

It has also become apparent that there are in fact two "families" of methanol masers. Type 1 (or A) masers are found in the general neighbourhood of HII regions and other tracers of high mass star formation but, rather surprisingly, they are not coincident with known infrared objects, radio sources, or other types of masers. This poses a puzzle because, irrespective of the precise pump mechanism, one expects observable radiation to emerge at other wavelengths from these regions. There is some evidence that the type 1 methanol masers are found at or close to regions which emit strongly in the vibrationally excited lines of molecular hydrogen (Plambeck and Menten 1990, Johnston et al. 1990). If so, this would suggest that the methanol is produced in shocks caused when stellar winds emanating from young stellar objects impact upon surrounding gas clumps. The mechanism for population inversion appears to be collisional (Menten et al. 1990) and theoretical studies suggest that the type 1 masers are quenched at densities much higher than 10^7 cm^{-3} .

The 12.1 GHz masers as well as several other transitions with similiar characteristics (Type 2 or B methanol masers) are found , as are OH masers, close to ultra-compact HII regions from which they presumably derive their power. Collisions anti-invert the 12.1 GHz line and hence the pump mechanism is quite different from that operating in the class 1 methanol masers discussed above. It seems likely

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that a far infrared pump is operating but a detailed model is lacking. An interesting feature is that the available maps (e.g. Menten et al. 1988b) of the 12.1 GHz line show the masers to be lined up as if they delineated a front.

6. 3. AMMONIA MASERS

Several high gain masers have been found in the (9,6) transition of NH_3 which is 1090 K above ground (Madden et al. 1986). The excitation of this maser is a puzzle. Neighbouring ammonia transitions (e.g. (8,6)) appear to be "normal". While the (9,6) maser is found towards W51 and other "hot core–type" regions, it behaves "normally" in Orion-KL. Interferometric measurements would be useful for the understanding of this phenomenon. The (6,3) line is also an "occasional" maser (Madden et al.) and various other transitions may be inverted (Wilson and Henkel 1988) towards the northern compact source in W51. Hot core type conditions seem to be a necessary but not sufficient condition for maser action in these transitions.

Another region which may be a hot core "silhouetted" against a background continuum source is the region seen in ammonia towards the ultra–compact HII region NGC7538. The source is unusual partly because of the $^{15}NH_3(3,3)$ masers which are observed in a region approximately 10^{16} cm in size towards the ultra–compact HII region NGC7538-IRS1(Johnston et al. 1989). Also, Schilke et al. (1990) have observed what appears to be a line of vibrationally excited ammonia in absorption towards the same source. Finally, there is a formaldehyde maser coincident within the errors with the $^{15}NH_3(3,3)$ (Rots et al. 1981). The interpretation of this is unclear but at least one can say that the bulk of the ammonia is at a temperature of around 150 K and the column density of NH_3 is estimated to be $5\,10^{18}$ cm^{-2}. An educated guess at the hydrogen column density is 10^{24} cm^{-2} which would put the $[NH_3]/[H_2]$ ratio at $3\,10^{-6}$. This certainly is very remniscent of the Orion hot core. More recent 100-m data (Schilke, this conference) suggest that the $^{15}NH_3(4,3)$ and (4,4) lines are also masers and can be interpreted in a model where the maser inversion occurs due to pumping via the excited vibrational state. This makes the coincidence of the vibrationally excited absorption line and the $^{15}NH_3$ masers comprehensible. However, as far as the $^{15}NH_3(3,3)$ maser is concerned, there is another interpretation (Flower et al. 1990) which requires an overabundance of para-H_2 in the region where the maser forms. This implies relatively low temperatures and densities (say 100 K and 10^5 cm^{-3}) and an overabundance of para-H_2 relative to that expected in thermal equilibrium.

7. Overview

The regions discussed in this review span several orders of magnitude in density and pressure. In order to visualize this, I show in figures 2a and b the parameters derived for thermal pressure, density, and temperature in a variety of molecular cores. Median values for the derived local density have been taken from the studies of Cox et al. (1989), Harju et al. (1990), and Mundy et al.(1986). The choice of

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objects plotted in this diagram is arbitrary and the aim is merely to show what range in parameter space is covered. One sees interestingly that there is no evidence for cold (10 K) high density (10^6) regions although ρ Oph B is only a factor of 2 hotter than this. It is possible that the paucity of cold dense regions is due to selection but it may also be the case that high pressures (and by inference high densities) are caused by the proximity of newly formed O-B stars and HII regions which heat and compress their surroundings. Then, high pressure regions will only occur where O-B stars are forming and in such regions the temperature will also be high due to interaction with hot dust. On the other hand, one certainly cannot exclude the possibility that cold high density regions are not observed simply because molecules have been frozen out in such regions. As one sees in figure 2, the best approximation to a cold high density region seems to be the ρ Oph B core (Wadiak et al. 1985) which is unusual in that it shows emission in the 2 cm line of formaldehyde. This region stands out on figure 2 and is certainly worth further study. On the basis of presently available data, it seems to be exceptional.

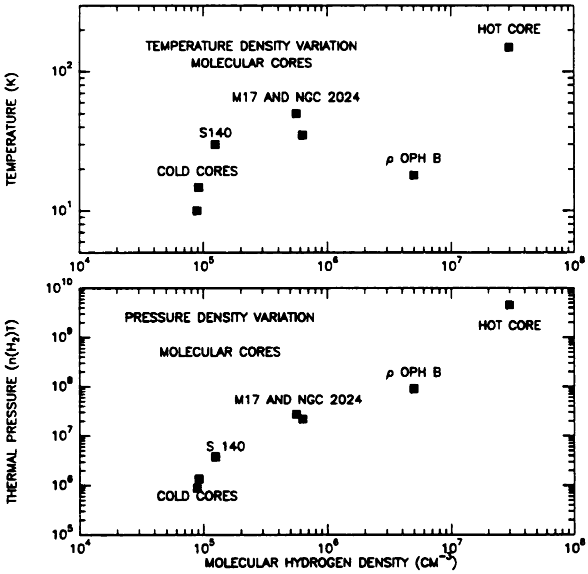

Fig. 2. Thermal pressure and Temperature as a function of molecular hydrogen density for a sample of the molecular cloud cores discussed in the text. The cold core data is taken from Cox et al. (1989) and Harju et al. (1990, Orion cores). The data for M17, NGC 2024 and S140 is from Mundy et al. (1986) and for ρ Oph B from Wadiak et al. (1985).

On the basis of equation 1, one has a "freeze–out" time for ρ Oph B of 3000 years even assuming an "extreme" value for the sticking coefficient of 0.1. This compares with a free fall time of $2\,10^4$ years and hence one concludes that the

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grain surface area ($\overline{\sigma_g}$) must be an order of magnitude larger (at least) in this region than in the diffuse interstellar medium. Perhaps this is not as surprising as it might appear. It does seem worth carrying out in regions of this type extensive abundance analyses aimed at determining whether indications for partial depletion of the type discussed in section 2 (e.g. large D fractionation) can be observed. On the other hand, it might be useful to examine the consequences for the dust emission properties of a surface area reduction as discussed here.

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