KINEMATICS AND DYNAMICS OF DENSE CLOUDS

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1. INTRODUCTION

Star formation is widely considered as resulting from the collapse of interstellar molecular clouds. The purpose of this paper is to review the observational evidences for collapse in dense clouds, and also for the factors which can play against collapse (turbulence, rotation, magnetic field). We shall also examine to which extent the maser sources (OH, H_2O, SiO) can be related to star formation. An overlap with the review papers given by P. Thaddeus, P.G. Mezger, and to some extent by C.G. Wynn-Williams and L. Mestel appears unavoidable.

It should be noted from the beginning that the lack of spatial resolution of the present millimeter wave observations prevents us to see individual stellar-mass fragments in molecular clouds. Thus observations, even if they give direct information on the behaviour of large clouds, still tell us very little about their fragmentation and the collapse of the fragments which are likely to end-up as individual stars. Only the observations of interstellar masers can reach an appropriate resolution, but we shall see that the interpretation of those observations in terms of star formation are still far from clear. We apologize for unavoidably not doing justice to all the recent contributors to this vast field.

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2. ORDERS OF MAGNITUDE FOR GRAVITATIONAL INSTABILITY AND COLLAPSE ; PREDICTIONS OF LINE PROFILES.

We recall here a few expressions of interest for comparison with observations, and some relevant comments.

2.1 Jeans Length (gravitational collapse is possible if cloud dimensions $R > \lambda_J$).

$$- \qquad \lambda_J = (\pi\ k\ T_K/4\ G\ \mu\ \rho)^{1/2} = 1.6\ \{T_{(K)}\ R^3_{(pc)}\ /\ M_{(\odot)}\}^{1/2}\ \mathrm{pc}$$

(k = Boltzman's constant, G = constant of gravitation, T_K = kinetic temperature, ρ = density, μ = mean molecular weight, R = radius of the cloud and M = mass of the cloud).

Usually the dimensions of molecular clouds are larger than λ_J and they can collapse. One should remember that the Jean's criterion is not the only criterion of instability. Jura (1976) gives numerical values of critical masses above which clouds can collapse when submitted to an external pressure, and shows that spiral density shock waves can trigger the collapse of clouds with $M > 1000\ M_\odot$, and supernova shock waves the collapse of clouds with $M \gtrsim 1\ M_\odot$. Thermal-chemical instabilities due to CO and H_2O formation-destruction (Glassgold and Langer, 1976a and 1976b) or to H_2 formation-destruction (Hutchins, 1976) can also play an important role at various phases of cloud evolution (see Glassgold, 1976).

2.2 Critical rotation velocity (for stabilizing the cloud against gravity).

For a spherical uniform cloud, uniformly rotating,

$$(3/5)\ (GM^2/R) = 0.5\ I\ \omega^2_{crit} = 0.2\ M\ (V_{crit})^2$$

I being the moment of inertia, ω_{crit} the critical angular velocity and V_{crit} the critical rotation velocity at the equator.

Hence :

$$V_{crit} = (3\ G\ M\ /\ R\ )^{1/2} = 0.11\ \{\ M_{(\odot)}\ /\ R_{(pc)}\ \}^{1/2}\ \mathrm{km\ s}^{-1}$$

Usually cloud rotation is too small to stabilize it. Note that even if so collapse is still possible along the rotation axis, yielding a disk.

2.3 Critical magnetic field (for stabilizing the cloud)

By writing that magnetic energy is equal to gravitational energy, one finds for a uniform spherical cloud :

$$B_{crit} = 0.2\ M_{(\odot)}\ /\ R^2{}_{(pc)}\ \text{microgauss.}$$

Direct measurements of B in interstellar clouds are very few. If the field is frozen into the gas during the formation and collapse of the cloud one expects to have, at density n, for an isotropic collapse :

$B \simeq (n\ /10\ cm^{-3})^{2/3} \times 3$ microgauss, which could seem somewhat larger than the critical field for usual molecular clouds ; however the few measurements seem to indicate somewhat smaller fields, and the problem is unsettled. Note $E_{mag} \propto E_{gravit}$ during collapse so that a field initially unable to prevent collapse continues to do so in later stages.

2.4 Free-fall velocity at cloud edge

$$V_{ff} = (2\ G\ M\ /\ R)^{1/2} = 0.1\ (M_{(\odot)}\ /\ R_{(pc)})^{1/2}\ km\ s^{-1}$$

Usually, the widths of the molecular lines emitted by dense clouds are of the order of V_{ff}, suggesting that collapse is not an unlikely hypothesis in many cases. This will be discussed in more details later. However this problem deserves a more careful comparison between observation and realistic collapsing cloud models.

The free-fall time is :

$$t_{ff} = \{\ 3\ \pi\ /\ (32\ G\ \rho)\ \}^{1/2} = 1.65 \times 10^7\ \{R^3_{(pc)}/M_{(\odot)}\}^{1/2}\ \text{years}$$

for a uniform spherical cloud (of course pressure-free).

2.5 Models of internal structure of collapsing clouds

In a free-fall pressure-free spherical cloud it can easily be shown that, if the number density n (r) varies with radius r as :

$$n(r) \propto r^{-x}$$

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then the collapse velocity V(r) varies as :

$$V(r) \propto r^{(2-x)/2} \quad (x < 3),$$

This kind of model is often used for comparing with observation. For example Goldreich and Kwan (1974 a) study a model with n (r) = cst, V (r) $\propto$ r (x = 0).

Larson (1969, 1972) has built more sophisticated hydrodynamical models. His isothermal model gives, in most of the cloud, some time after the onset of collapse :

$$n(r) \propto r^{-2}$$

$$V(r) \propto cst$$

also similar to a special case (x = 2) of the free-fall model. However, non-isothermal models rather give

$$n(r) \propto r^{-3/2}$$

$$V(r) \propto r^{-1/2}$$

A free-fall model with a large central density would also give

$$V(r) \propto r^{-1/2}$$

Theory is rather unable at present to predict the thermal structure inside a collapsing cloud because of our poor knowledge of the heating and cooling mechanisms (in particular there are inside many molecular clouds stars formed in earlier generations which are efficient sources of heating). However numerical experiments show that V(r) and n(r) are not extremely sensitive in most of the cloud to the thermal structure, which can thus be chosen more or less independently for comparing with observations (see e.g. Mestdagh, 1975).

In view of the difficulty of this comparison with observations, it does not seem necessary for our purpose to go into more refinements in the cloud models.

2.6 Predicted line widths and shapes.

Observations of line profiles and comparison with theoretical models provides an obvious way of testing collapse models for interstellar clouds. The CO lines are the most interesting for the purpose, since they are excited even for total densities as low as a few $10^2 cm^{-3}$, contrary to the other molecular lines which give access only to denser parts of the clouds. However the ^{12}CO line, and even sometimes the ^{13}CO line, is saturated and the profile has to be calculated by solving the coupled equations for the populations of the CO levels and for the transfer of radiation. This has been done however in a variety of cases, as summarized in Table 1.

Table 1

Calculations of CO-line profiles in various cloud models.

V(r)	n(r)	$T_K(r)$	microturbulence	geometry		Note
0	cst	cst	yes	plane-parallel	a	
$\propto r$	cst	cst	no and yes	spherical	b	1,2
$\propto r$	cst	cst	no	spherical	c	
					d	
					e	3
cst	$\propto r^{-2}$	cst	no	spherical	e	3,4
$\propto r$	$\propto r^{-2}$	cst	no	spherical	f	
$\propto r^{-1/2}$	$\propto r^{-2}$	$\propto r^{-0.1}$	no and yes	spherical	g	1

Notes to Table 1 :

1 The program works for any distribution V(r), n(r), $T_K(r)$

2 At the cloud center

3 Integrated over the surface of the cloud

4 Not valid at cloud center

References to Table 1 : a : Lucas (1974) ; b : Lucas (1975) ; c : Goldreich and Kwan (1974 a) ; d : Scoville and Solomon (1974) ; e : de Jong et al (1975) ; f : Gerola and Sofia (1975) ; g : Snell and Loren (1976).

3. COMPARISON OF CLOUD MODELS WITH OBSERVATIONS

3.1 Are line widths due to "turbulence" or large-scale motions ?

The widths of molecular lines from interstellar clouds are usually quite large. According to Penzias (1975) (see also data in Milman et al, 1975), the ^{12}CO line widths at half intensity are in

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the range 3-10 km s^{-1}, sometimes larger (e.g. Sgr B2) and always >1 km s^{-1}, while the lines of the isotopic molecule ^{13}CO have 1/2 to 2/3 the width of the ^{12}CO lines ; the lines of $C^{18}O$ have similar widths to those of ^{13}CO, but are sometimes slightly narrover.

It is quite clear that this width cannot be purely thermal. The kinetic temperature in molecular clouds is generally much smaller than 100 K (from an analysis of saturated lines), corresponding to a thermal width of 0.4 km s^{-1} for CO. Saturation cannot account for the observed widths either : an optical depth of 60 typical of ^{12}CO lines would increase the thermal width by a factor 2.5 only, quite insufficient for explaining the observations.

In principle, microturbulence (with scale smaller than the mean free path of a CO-line photon) could account for the observed widths : however, the sound velocity being equal to $0,6(\frac{T}{100K})^{1/2}$ km s^{-1} in molecular clouds, turbulence would be highly supersonic and dissipated within a short time-scale. Another difficulty with a turbulent model is that there is no good fit between the observed and calculated ratio of the widths of the ^{12}CO and ^{13}CO lines. For typical thicknesses $\tau_{^{12}CO} \simeq 40$ and $\tau_{^{13}CO} \simeq 1$ (Penzias, 1975) the calculated ratio $\Delta V_{^{13}CO}/\Delta V_{^{12}CO}$ should be $\lesssim 1/2$ if both molecules are thermalized, a ratio smaller than observed. One might think (see e.g. Milman et al, 1975) that if they are not thermalized and their excitation temperature is governed mainly by radiation trapping this difficulty might be alleviated ; however the calculations by Lucas (1974) show that this effect is not very significant.

A major difficulty with microturbulent models is that the ^{12}CO optical depth towards the center of the cloud is so large that it cannot be seen but in the wings of the line ; however the hot core of the Orion cloud is obviously seen in the center of the ^{12}CO line, which peaks in the K-L object region.

An interesting suggestion has been made by Arons and Max (1975) who propose that hydromagnetic waves could provide the observed velocity dispersion.

However the wavelengths they predict are large and correspond to global motions of the cloud rather than "turbulence". This mechanism requires in practice $B \gtrsim 40\ \mu G$ in most cases, which does not seem unreasonable, but one should check that this field could not have impeded the formation of the dense cloud, and that at least some clouds are able to contract for forming stars ! The energy output is reasonably small and can come from an HII region inside or at the border of the cloud. This theory must be considered seriously, although it certainly does not apply to clouds with very large line profiles like the Sgr B2 cloud. An interesting suggestion of wave-like motions in the Orion molecular cloud is the spiral pattern observed by Phillips et al (1975).

Another possibility to avoid collapse (or expansion) models is to imagine that the clouds are made of relatively small emitting elements moving at high velocities in largely empty surroundings ; these elements must have narrow lines (if not, one would be back to the previous problem). This model has been proposed by Zuckerman and Evans (1974) (see also Morris et al, 1974), on the following arguments : (i) collapse models predict a rate of star formation too high by a factor > 10 (ii) H_2CO absorption lines at 2 and 6 cm and CO emission lines have the same velocity, a feature not expected in collapse or expansion models if the H_2CO lines are formed by absorption of the continuous radiation of a central HII region (iii) it is often difficult to define the "center" of a cloud, even in the case of Orion (the Trapezium would have been it 3×10^5 years ago) (iv) the uniform widths of the lines often observed over an extended cloud do not suggest collapse.

Argument (ii) appears the most serious (argument (i) could be turned down simply by noting that by far not all the material contained in a molecular cloud is used for forming stars) ; however we have no proof that the HII regions often associated with molecular clouds are located inside ; moreover the smaller width of the H_2CO lines suggests that they are not formed in the main cloud but perhaps in cooler regions outside the cloud at the same mean velocity (Penzias, 1975). It is true that by a suitable choice of the parameters such a model can meet the main requirements : seeing the center of the cloud and reproducing the line width: see Baker (1976). However the necessity (from the observation that the ^{12}CO brightness temperatures are often equal to the grain temperatures) that the beam be essentially filled by cloudlets at each frequency in the line requires a large number of cloudlets, suffering many collisions during the life time of the cloud ; moreover, their relatively low density and small dimensions are such that they must be stabilized by a hot (10^4K) gas which is not observed. Thus it seems likely that the cloudlets would be dissipated into a more uniform cloud considered above (Penzias 1975), and this is a major difficulty for this kind of model. As an alternative, one may consider the cloud as macroturbulent, the cloudlets being the largest turbulent cells and then being replaced continuously (Baker, 1976) ; however the energy requirements to maintain the turbulence are quite large (700 $L_{\odot}$ for a 10^5 $M_{\odot}$ cloud). A possible mechanism has been described by Baker.

It thus seems that the line widths are most often caused by large-scale motions, as suggested by many authors (apparently first by Heiles, 1973 and in more detail by Goldreich and Kwan, 1974a). We shall now review the evidences for collapse or other kinds of ordered motions.

3.2 Evidence for collapse or ordered motions.

The various collapse models discussed in Section 2 yield theoretical line shapes with the following characteristics :

1) If the collapse velocities are much larger than turbulent velocities (which is probably the case) the line width is dominated by the collapse velocities and the differences in width between lines formed in the same regions (e.g. ^{12}CO and ^{13}CO) are not as large as in the turbulent models, and in better agreement with observation.

2) In a cloud with uniform density and kinetic temperature predicted self absorption of the profiles is not important : efficient self absorption requires that two regions of the line of sight have the same radial velocity and that the one at the front is colder. This obviously cannot occur in models where V(r) increases with r (like Goldreich and Kwan's free-fall model), but can occur in models where V(r) decreases with r.

3) Whatever the law of variation of V(r) with r, the line width at the center of the cloud should usually be larger than at the edge for a line which is formed throughout the cloud, because the full range of velocities is seen at the center.

We shall now discuss how well observations fit into the picture.

3.2.1 Comparison of width of lines of different molecules

If one compares the width of an (unsaturated) line of a molecule which needs a high density to be excited, and thus is likely to be located at the center of the cloud, with the width of a line of a molecule formed in lower density regions, one has a chance to get information on the run of V(r) with r in a collapse model. This was done by Heiles (1973) who noticed that the lines formed by molecules of high excitation (NH_3 non metastable lines, CH_3OH, CS) are narrower than those lines requiring lower excitation (NH_3 metastable, H_2CO 2mm in Orion and Sgr B2). Sgr B2 has a complicated structure however (Scoville et al, 1975), which is not likely to be described by a simple collapse model. On the other hand, recent observations of various molecules in the center of the Orion cloud show that the lines all have a similar width ≃ 4 km/s (apart from lines showing the broad "plateau", which presumably come from a stellar envelope : Zuckerman and Palmer, 1975 ; however Zuckerman et al, 1976, have observed extended wings in CO that they attribute to a pre-, rather than post-main sequence object in the K-L complex). Exceptions are the maser lines (OH, H_2O, CH_3OH, SiO), the ^{12}CO line, the ^{13}CO line which is saturated in this cloud, and of course those lines which have hyperfine structure like HCN. The situation is not very different for other clouds like W 51, DR 21, W 3, etc... (note however the special behaviour of the NH_3 lines) : useful data are collected by Rydbeck et al (1975). Thus no firm conclusion can be derived on the run of V(r) with r.

Dickman (1975) and others find that the width of the 6-cm H_2CO absorption line in dark clouds is usually smaller by a factor 0.7 than the width of the ^{13}CO line. This might partly be due to optical thickness in ^{13}CO, but more probably the excitation conditions of both lines are very different (see above for the Orion cloud). A similar effect exists between the OH and H_2CO line widths (Crutcher, 1973). In view of our poor knowledge of the excitation of the anomalous H_2CO absorption (Lucas et al, 1976) any firm conclusion looks premature.

3.2.2 Evidence for collapse causing CO-line self-absorption

Snell and Loren (1976) have noticed that the ^{12}CO and ^{13}CO line profiles in several molecular clouds show a surprisingly good fit with what they predict in their collapse model (see table 1). In this model $V(r) \propto r^{-1/2}$ and T_K increases towards the center so that there are in general two regions at different distances from the center with similar velocities, the cooler external one absorbing the radiation of the hotter internal one.

Thus the thick ^{12}CO line is self absorbed, with the absorption displaced towards positive velocities (with respect to the average cloud velocity given by the ^{13}CO line) if the cloud is collapsing ; an expansion would correspond to a dip at negative velocities. The typical shape corresponding to collapse is not uncommon and has been observed in the following objects :

W3 (Dickel et al, unpublished : see Snell and Loren, 1976)

ρ Oph at molecular peak (Encrenaz et al, 1975)

Mon R2 (Kutner and Tucker, 1975 ; Loren, 1976 b) where $V(r) \sim r^{-1/2}$

NGC 1333 (Loren, 1976a)

Cep OB3 (A. Sargent, in preparation)

These cases are to my knowledge, the best clear-cut cases for cloud collapse. Note that the asymetrical, slightly self inverted profiles obtained by Lucas (1975) in its collapse turbulent model are of somewhat similar nature, but the dip is not strong enough to fit with the observations. More generally , no very strong self absorptions seem possible without gradients in kinetic temperature.

It must be noticed that sometimes ^{12}CO self-absorption is due to other causes than collapse : e.g., the dust lane in front of NGC 1579 = S 222 obviously is at the origin of self absorption (Knapp et al, 1976). In Sgr B2, the self absorption seen in all optically thick lines is almost certainly due to a colder envelope at the same average velocity as the core (Scoville et al, 1975).

3.2.3 Other evidence for collapse.

- possible redshift of the CH^+ optical absorption line in front of ζ Oph with respect to the CH and Ca II lines, which might indicate a collapse of the corresponding diffuse cloud (Chaffee, 1975). The effect is rather marginal, however, and its interpretation not straightforward.

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- Broadening of CO lines towards the cloud center : this is seen in many cases, e.g. Mon R2 (Kutner and Tucker, 1975) and R CrA, near Lk Hα 198 (Loren et al, 1974), in S 239 (Knapp et al, 1976). In the last case, a good fit is obtained between the observed line widths at various positions and a collapse model with $V(r) \propto r^{-1/2}$, implying a central condensation of $50\ M_{\odot} < M < 180\ M_{\odot}$, half the total mass of the cloud.

- Presence of a massive central core and velocities consistent with free-fall : L 134 seems a good case (Tucker et al, 1976 ; Sume et al, 1975), the core having $M > 25M_{\odot}$, half the total mass of the cloud.

- Good fit between calculated and observed line profiles : e.g. Gerola and Sofia, (1975), and de Jong et al, (1975), both for the Orion cloud ; the latter authors show that the imperfect fit in the $J = 2 \rightarrow 1$ lines obtained by the former is probably due to incorrect collision rates.

3.2.4 Cases where no evidence for collapse is present.

The existence of such cases is certainly not unexpected ! A possible example is that of the extended cloud L 1630 in Orion (Milman, 1975) where only simple, symmetrical profiles are seen with nearly everywhere the same width and velocity. Some clouds have obviously a complex structure in which it would be hard to disantangle radial motions from others : these are the cases of Sgr B2, characterized by an enormous velocity dispersion (Scoville et al, 1975), of ρ Oph outside the molecular peak, which seems to be composed of two separate clouds (Encrenaz et al, 1975)[1], of S 228 (Lucas and Encrenaz, 1975), etc....

A very remarkable example of complex structure is that of NGC 1333 (Loren, 1976 a) which is interpreted as two clouds experiencing an oblique collision. The colliding region is a hot core which seems to trigger collapse of the surrounding parts (see section 3.2.2 above). Young stars formed at earlier times are all seen on one side of the core region. This fascinating case shows that star formation can result not only from gravitational collapse of a single isolated cloud, but from cloud collision as

(1) However Myers et al (1976)find that the ρ Oph molecular cloud might be surrounded by an atomic envelope visible in the 21-cm line and contracting at 0.3 times the free-fall speed.

well. The ρ Ophiuchi cloud (Encrenaz et al, 1975) might have some similarities with NGC 1333.

3.3 Evidence for rotation

These evidences are quite rare, surprisingly enough. Bona fide cases are :

- The Sgr A clouds, as observed in the OH and H_2CO absorption lines (see in particular Fomalont and Weliachew, 1973 ; Sandqvist, 1974 ; Whiteoak et al, 1974 ; Bieging, 1976). According to the last author, there are two distinct clouds with linear sizes 15-20 pc exhibiting strong velocity gradients with position. If rotating, their equilibrium masses are 10^6 and $5\ 10^6\ M_\odot$, respectively. However, the velocity gradients might correspond to ejection of material by the galactic nucleus.

- The Orion molecular cloud (Linke and Wannier, 1974; Liszt et al, 1974 ; Evans et al, 1975) ; here the rotation has not much dynamical effect at the present stage.

- Mon R2 (Kutner and Tucker, 1975 ; Loren, 1976b) ; in this case rotation has only little dynamical effect .

- NGC 7129 (Loren 1976 b) : a case similar to Mon R2.

- Dust cloud in Taurus (Crutcher, 1974). This is suggested to be a stable disk of radius 4 pc, thickness 1 pc and mass $\simeq 10^3\ M_\odot$.

- Two dust globules (Martin and Barrett, 1976).

3.4 Magnetic fields

There is very little information on this point ; most attempts to measure magnetic fields by using the Zeeman effect have only given upper limits. Heiles (1971) has summarized early information concerning dark clouds. The 21-cm Zeeman measurements are somewhat irrelevant for these mostly molecular clouds. The (thermal) OH observations have given $B < 130\ \mu G$ in the ρ Ophiuchi cloud at a location where density is probably $\simeq 1000\ cm^{-3}$ (Turner and Verschuur, 1970) ; Crutcher et al(1975) have lowered this limit to $B < 50\ \mu G$, and obtained similar limits for other clouds. This field strength is smaller than expected if the field would have been frozen during isotropic cloud collapse (see section 2.3). Possible Zeeman effect in the OH maser sources in Orion has been taken as an evidence for a field of 3-5 milligauss (Chaisson and Beichman, 1975).

It is dubious however that this value applies to a more extended and less dense region of the cloud (Zuckerman and Palmer, 1975). Polarization of the IR dust emission in the core of the Orion cloud can be taken as an indirect evidence for magnetic fields (see e.g. Dyck and Beichman, 1974).

3.5 Conclusion

Nature is obviously complex, and rarely offers the simple cases of collapsing clouds that one would like to compare to the theory. Indeed, it is rather surprising that several clear-cut cases for collapse (and not expansion) have been evidenced via a particular shape of self-absorption in the ^{12}CO line. It seems clear, however, that the "turbulent" cloud models - either microturbulent or clumpy, cannot apply to most of the molecular clouds. Large scale motions must exist in many cases, although not necessarily radial, and many clouds exhibit a complex line structure which cannot be interpreted as coming from a simple, well ordered object. Obviously many more observations are requested with increased angular resolution in the CO lines and in other molecular lines. We may then hope to obtain a better picture of the density, temperature and velocity structures of molecular clouds, as well as of their clumpiness which is highly probable (see e.g. the discussion by Lucas, 1975 of the CS lines and by Barrett et al, 1976 of the NH_3 lines) but not proven and would indicate how clouds fragment to form stars.

A final remark is that, if collapse is present, it often seems to occur at velocities quite smaller than the free-fall velocity. An example is given by the CO fragments observed next to M 17 by Elmegreen and Lada (1976) where the line widths, if interpreted as due to collapse, yield velocities 0.3 times the free-fall velocity. It might be that magnetic fields retard the collapse. However the masses of molecular clouds are so uncertain that these conclusions are only tentative.

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4. MASERS IN MOLECULAR CLOUDS : GENERALITIES ON PUMPING MECHANISMS AND PHYSICAL CONDITIONS.

Interstellar masers are usually believed to have something to do with protostars. It is thus of interest to review their properties and their possible connection to star formation. Amongst recent reviews of interstellar masers one can cite those of Litvak (1974), Zuckerman and Palmer (1974), Goldreich (1975), Burke (1975), Burdjuzha et al (1975), etc.. We do not discuss here the observations of masers, which will be assumed to be known of the reader.

4.1 Interstellar OH masers

Interstellar OH masers correspond to inversions in the 1665 and 1667 MHz main lines of the $^2\Pi_{3/2}$, J = 3/2 ground state (Type I masers), and occasionally in the 1720 MHz satellite line of this state. Interstellar masers have also been observed in the $^2\Pi_{3/2}$, J = 5/2 and J = 7/2 states as well as in the $^2\Pi_{1/2}$, J = 1/2 state. There exist all sorts of combinations between these possibilities. For example, I would like to mention a $^2\Pi_{1/2}$, J = 1/2 maser in W3 (A) without associated ground-state maser (Crovisier et al, 1975).

4.1.1 The pumping mechanisms for OH masers are still very poorly known. The case of the satellite-line stellar masers (which are of little interest for us here) is the only one for which a reasonable theory exists.

Near-IR pumping seems to invert mainly the satellite lines, but probably is only able to give a low-gain 1720 MHz maser close to IR sources (Elitzur, 1976).

Far-IR pumping is not impossible in dense cloud conditions and would invert also the satellite lines, not the main lines.

UV pumping is energetically rather inefficient but seems not unable to invert the main lines close to hot stars or the edge of compact HII regions : this model, which had not been widely accepted in the past, is in fact worth serious consideration again since all OH type I masers might be associated with a compact HII region.

Chemical pumping (Gwinn et al, 1973) is supposed to be linked to formation of OH via the reaction $H_2O + H + 0.69 \text{ eV} \rightarrow OH^* + H_2$, the excited

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OH being mainly in the upper levels of each Λ doublet. It thus can provide inversion in the main lines in the $^2\Pi_{3/2}$ J = 3/2, 5/2 and 7/2 states but does not work for the $^2\Pi_{1/2}$, J = 1/2 level. It also requires that H atoms fall on OH molecules with a relative velocity of a least 14 km s^{-1}, a not unlikely situation at the edge of a compact HII region, or at the shocked boundary of the core of a collapsing protostar. Although attractive this model is at best qualitative because of our poor knowledge of the relevant properties of the OH molecule. In this connection, I would like to mention that ter Meulen et al (1976) have observed that OH produced in the laboratory by H + NO_2 → OH + NO exhibits inversions in low-lying Λ doublets which are similar to what is observed in interstellar masers. Main-line emission in $^2\Pi_{3/2}$, J = 3/2, 5/2 and 7/2 have been seen as well as in $^2\Pi_{1/2}$, J = 1/2. The higher $^2\Pi_{1/2}$ Λ doublets show little or no inversion ; satellite-line emission is also detected in $^2\Pi_{3/2}$, J = 3/2, J = 3/2 and $^2\Pi_{1/2}$, J = 1/2. Ter Meulen et al, attribute these inversions to chemical pumping in the formation reaction. Although this chemical reaction is almost certainly not the one which forms interstellar OH, these observations are a strong indication that chemical pumping is a most likely mechanism for type I interstellar OH masers.

Collisional pumping is usually considered as relatively unefficient, but could however excite interstellar 1720 MHz masers (Elitzur, 1976).

4.1.2 Physical conditions

The total density should be high enough to give appreciable gain, but not too high in order to avoid collisional quenching. Reasonable figures are $10^6 < n_{tot} < 10^8$ cm^{-3} for type I masers ; 1720 MHz masers pumped collisionally require a lower density, $10^3 < n_{tot} < 10^{5-6}$ cm^{-3}.

The temperature is not determined and can be low. It must be < 200 K for a collisionally pumped 1720 MHz maser (if not the 1612 MHz line would appear instead).

The true sizes of the type I OH maser components are presumably 10-100 times the VLBI-measured diameters and are in the range 10^{15} - 10^{17}cm per component (100 - 10^4 a.u.).

The corresponding masses are << 50 $M_\odot$, more probably in the range 10^{-2} - 1 $M_\odot$.

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The total diameters of the groups of OH masers are in the range $10^{16} - 3 \times 10^{17}$ cm ($10^3 - 2 \times 10^4$ a.u.).

The line width is usually $\lesssim 1$ km/s, implying temperatures < a few 100 K if the lines are not to narrowed by unsaturated maser action.

The velocity scatter in groups of OH masers is usually < 10 km s^{-1}.

The magnetic field is known with some certainty only in the cases of 1720 MHz masers, for which Lo et al (1975 a) find by an analysis of the Zeeman patterns B = 3 to 9 milligauss. Note that the law of conservation of magnetic flux with isotropic collapse $B = 3\ (n/10)^{2/3}$ μG predicts B = 1.4 milligauss for $n = 10^5$ cm^{-3}, a reasonable figure for 1720 MHz masers (see above).

4.1.3 Cooling properties

The luminosity of OH masers is small, at most 10^{-4} $L_\odot$ and usually less than 10^{-5} $L_\odot$ per component (assuming that they radiate isotropically). They are thus certainly not efficient coolants for dense interstellar clouds and can be ignored in the thermal balance.

4.2 Interstellar H_2O masers.

These masers emit the $6_{16} - 5_{23}$ line of H_2O, at 450 cm^{-1} above the ground state. They are more powerful than OH masers and have been thoroughly studied ; however their pumping mechanism (s) and properties are not better known than those of the OH masers.

4.2.1 Possible pumping mechanism

Near-infrared pumping by 6.3 μ photons through the v = 1 state followed by collisional deexcitation, has been proposed by Goldreich and Kwan (1974 b).

Collisional pumping (de Jong, 1973) inside v = 0 is possible for particular selection rules for the collisions which are similar to radiation selection rules, and collisional cross sections proportional to the square of the dipole moment of the transition ; it can operate only for weak masers because deexcitation is via strong IR lines which are easily optically thick and must however escape from the maser or be absorbed by internal dust.

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An interesting question that can be raised is whether H_2O masers occuring in groups are individual objects, each with its own pump (local theory), or whether each one represents a special path more favorable for amplification in the middle of a more or less homogeneous region with large velocity gradients, and with only one or a few pump sources (global theory). In the local theory, the H_2O masers are likely to be spherical with true sizes quite larger than their apparent VLBI sizes, and radiate isotropically ; in the global theory, they might rather be long cylinders radiating directively and their true diameter is nearer to their apparent VLBI diameter Kwan and Thuan (1974) have given various arguments against the global theory. However several recent observations clearly favor global models with common, radiative sources of maser pumps. In W 49, Gammon (1976) and Heckman and Sullivan (1976) have observed quasi-simultaneous variations of H_2O lines produced in spatially distinct locations. The most likely pump in this case is the near-IR radiation of dust heated by a single variable young massive star (this recalls the model proposed by Burdjuzha et al, 1975). Lada et al (1976) have observed the appearance of two new H_2O components in M 17 within a time span of 7 months : if they were protostars, this would yield an incredibly high rate of star formation, thus a global model is indicated. On the other hand, the large overall extent of the system of H_2O masers in M 17, in Orion and in W 49 (Moran et al, 1973 ; Baudry et al, 1974), as well as in Sgr B2 (Waak and Mayer, 1974 ; Morris, 1974) might require more than one energy source. The accurate absolute positions of H_2O masers obtained by Forster et al, (1976) in W 3 (OH) show that they are definitely not coïncident with, but distant by 8" from the compact HII region, the associated OH masers and infrared source. Because of this large distance, the available pumping radiation from the latter objects is far too small. Thus is it not yet possible to chose between the global and the local theories, in view of these opposite evidences. Correlated variability has also been reported for CH_3OH masers (Barrett et al, 1975) and sometimes OH masers (Sullivan and Kerstholt, 1976) : a global theory may also be appropriate.

4.2.2 Physical conditions

The total density can be estimated by the same reasoning as for the OH masers as $10^7 < n_{tot} < 10^{10}$ cm^{-3}.

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The temperature has to be high in collisional pumping models, since the maser levels are 450 cm^{-1} above the ground level : thus $T_K > 400$ K in these models probably. Models with radiative pumping do not require such high temperatures.

The true sizes of the individual masers in the local theory are probably 10-100 times the VLBI diameters and lie in the range 10^{14}-10^{16}cm (10-1000 a.u.). They are closer to the VLBI diameters in global models. Thus the masses are certainly << 5 $M_\odot$.

The total diameters of the maser groups are in the range 10^{16}- $3x10^{17}$cm but reach 10^{19} cm in the case of Sgr B2.

The individual line widths are usually < 1 km s^{-1} thus a T_K = 500 K already require some line narrowing (which can be important if the masers are unsaturated).

The velocity scatter in groups is usually < 20 km s^{-1} for the strongest masers, but weaker components are spread over much larger velocity ranges, which reach 500 km s^{-1} in the case of W 49 (Goss et al, 1975 ; Morris, 1976).

The magnetic fields has not been measured. Linearly polarized H_2O masers may contain milligauss fields.

4.2.3 Cooling properties

The luminosity of the H_2O masers in the maser line is larger than that of the OH masers. It reaches 1 $L_\odot$ in W 49, but is usually of the order of 10^{-3} $L_\odot$ if radiating isotropically. The thermal energy of 1 $M_\odot$ at 500 K is ≃ 400 ($L_\odot$ x yr).

Thus cooling by direct H_2O emission may or may not be important depending of the mass involved, which infortunately is not known (for average conditions, n = $10^{8.5}$ cm^{-3}, diameter 10^{15} cm, the mass is 3 $10^{-4}M_\odot$ and cooling by a 10^{-3} $L_\odot$ maser is efficient ; however given the small mass involved this has little effects on star formation).

If pumping is radiative (Goldreich and Kwan's model) the pump power required is very large and the maser must be close to a strong 6.3 μ source. If the pumping is collisional at relatively low temperature inside v = 0, the cooling of the gas is not only via the maser transition (s)

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but also via the far-IR deexcitation photons ; a quantitative estimate is very difficult, but the cooling efficiency could be several hundred times that by the radio photons themselves and become significant. If the pumping were collisional at a higher temperature via v = 1, each 22 GHz photon would be accompanied by many 6.3 μ photons and the gas would be cooled in less than a year : thus this model is viable only if there is a quantity of hot dust (heated by some powerful radiation source) to heat the gas collisionally : the physical conditions would be those favorable to radiative pumping !

In summary, it is extremely difficult to reach a conclusion about the cooling efficiency of H_2O masers, which depends mainly on IR photons rather than on radio photons, as far as the pumping mechanism is not elucidated. Their possible role in the energetics of star collapse is thus very difficult to assess, although it might be important.

4.3 An interstellar SiO maser ?

The SiO molecule produces maser emission in vibrationally excited states. The observed maser transitions are v = 1, J=1 → 0,2 → 1,3 → 2,v=2 J = 1 → 0. All the known masers are associated with red giant or supergiant star envelopes ; however one is seen in the direction of the Orion molecular cloud : it differs from the other SiO masers by its strong variability (times scales of ≃ 1 hour) (Spencer and Schwartz, 1975) and circular polarization, indicating the presence of a magnetic field (Johnson and Clark, 1975). Pumping for SiO masers is presumably by near-IR radiation, with an important role of the differences in optical thicknesses in the various IR transitions involved (Kwan and Scoville, 1974 ; Pelling, 1975) : thus they are presumably close to a strong near-IR source. Collisions quench the maser action only for $n_{tot} > 10^{10} cm^{-3}$ thus the density can be very large in the maser region. Habing et al, (1975) have adapted Kwan and Scoville's model (initially built up for cold-star masers) to a collapsing object and are able to obtain good agreement with the observations for the following conditions : $n_{tot} \simeq 10^8\ cm^{-3}$, infall velocity ≃ 10 km s^{-1}, $T_k \simeq 500$ K, $T_{rad} \simeq 2000$ K with a dilution factor $W \simeq 10^{-2} - 10^{-3}$. This seems representative of a cocoon around a bright IR object like one of the KL objects. Unfortunately position measurements for the SiO maser are not good enough to check this association or a possible association with OH and H_2O masers in the Orion cloud.

In view of our very limited knowledge of the possible methyl alcohol and other molecular interstellar masers, they will not be discussed here.

5. MASERS IN MOLECULAR CLOUDS : RELATIONSHIP WITH PROTOSTARS

We have seen that interstellar masers require large densities and, in the case of H_2O and SiO masers, high temperatures and/or IR radiation fields. Apart from the envelopes of red giant stars, these conditions seem to be met only in protostellar environments. It is interesting at this stage to summarize briefly what is known of the association of OH - H_2O masers together and with various astrophysical objects.

5.1 Association of OH-H_2O interstellar masers with astrophysical objects.

a) OH and H_2O masers, when co-existing in the same region (a frequent case) are not coincident in the best documented cases ; see Baudry et al, (1974) for Orion and W 49 N, Mader et al, (1975) for W 49 and W 3 (OH) and Forster et al, (1976) for W 3 (OH) ; in the two last cases, the separation between the groups of OH and H_2O masers is 4.8×10^4 a.u. and 1.8×10^4 a.u., respectively.

b) There are many cases where H_2O masers are seen but not OH masers : see e.g. Yngvesson et al, (1975) for W 12 and W 37, and Lo et al, (1975 b) for S 235, S 152, etc... The reverse situation seems less frequent (is there an observational selection ?).

c) OH (and H_2O to a lesser extent) masers are very often associated with compact HII regions, which are believed to be late stages of stellar formation, and not with extended HII regions (Habing et al, 1974 ; Lo et al, 1976 a). Such an association is clear for more than 50% of the OH masers. However the details of the association are often complex and difficult to understand (see e.g. Mader et al, 1975 and Hughes and Viner, 1976, for the case of W3 (OH)).

However there are masers which are associated with molecular clouds and apparently not with a thermal continuum small-diameter source (compact HII region). Examples are Orion, W 33 A, W 75 S, OH 0739-14, with OH/H_2O

masers (Habing et al, 1974) ; Mon R2 where there is a "flickering" H_2O maser and an OH maser (Knapp and Brown, 1976, Morris and Knapp, 1976, Knapp and Morris, 1976) ; S 140 with a H_2O maser (White and Little, 1975, Morris and Knapp, 1976, Knapp and Morris, 1976) ; OMC2 with a H_2O maser (Morris and Knapp, 1976). The case of Sgr B2 (Waak and Mayer, 1974, Morris, 1976) is not as clear because of our poor knowledge of the continuum radiation of this region.

Habing et al (1974) think however that all type I OH masers might be associated with a compact HII region, sometimes not detected because of lack of sensitivity or excessive optical thickness in the continuum : further interferometric observations at high frequencies with high sensitivity are requested to check this point. A one-to-one association H_2O masers and compact HII regions is much more questionable (Lo et al, 1975 b ; Lo et al, 1976 a ; Forster et al, 1976)

d) A number of H_2O masers, but few OH masers, are associated with apparently late stages of star formation (Herbig-Haro objects, T Tauri, Be stars with reflection nebulae, etc...) In such cases they do not coincide with the star but lie at some distance. Examples are : T Tauri with H_2O maser (Schwartz and Buhl, 1975 ; Knapp and Morris, 1976) and OH maser (Johansson et al, 1974) : the OH maser is a unique case ; Herbig-Haro objects with H_2O masers (Lo et al, 1975 b ; Lo et al, 1976 b), but no OH maser (Nguyen Quang Rieu, private communication);Be stars and reflection nebulae with H_2O masers (Schwartz and Buhl, 1975) ; M1-92, a possible object of that kind, has an associated 1667-1612 maser (Lépine and Nguyen Quang Rieu, 1974).

e) OH/H_2O masers are often, but not always, associated with IR sources (Wynn-Williams and Becklin, 1974). There is a tendency for the IR sources associated with masers to be "hot", small and to show strong silicate absorption at 10 μ (see e.g. some IR-maser sources with properties similar to Orion, described by Pipher and Soifer, 1976). It seems rather surprising at first glance that H_2O masers exist without reported IR emission, since whatever the pumping model they are hot objects (and in a some models they are illuminated by a powerful near-IR object). However the observational situation might be similar to the situation with the association OH masers-HII regions ; it might be that in such cases the position of the H_2O maser has not been looked at for IR emission, or that the radio position was not accurate enough or the IR sensibility insufficient. Further searches using accurate radio positions and high sensitivity are obviously needed.

5.2 Evolutionary models for OH/H_2O masers and protostars

Many authors seem to agree on a common evolutionary scheme (although not perhaps in the details). Relevant references are Israël et al (1973) ; Morris et al (1974) ; Lo et al (1975 b) ; Burke (1975) ; Habing (1975). The sequence of events would be the following :

Cloud collapse would, after fragmentation, form H_2O masers when suitable conditions are achieved (these conditions depend of course on the pumping mechanism but a possibility seem to exist anyhow in conventional collapse models, e.g. Larson, 1972). Each maser would be a separate condensation, and the usual velocity scatter in group of masers $\Delta V \simeq 30$ km/s in dimensions $10^3 - 10^5$ a.u. would correspond to a bound system of $10^3 - 10^5$ $M_\odot$. It is not clear whether each maser actually corresponds to a separate protostar ; however they are so numerous that this is difficult to believe.

The recent discovery of simultaneous variations of maser components spatially distinct, which require a strong common radiative pump, suggests however that at least several important groups of H_2O masers surround a (variable) star already formed. H_2O masers would not correspond to individual protostars and would appear in a later stage of early stellar evolution than in the "classical" model.

OH masers would correspond to a stage where the star is already formed. Perhaps the OH molecules, if not pre-existing, would be formed by photodissociation of H_2O by the UV radiation of the star, and themselves would be photodissociated later. In the mean time a OH maser develops, associated with a compact HII region ionized by the star and is perhaps visible before the HII region can be detected by conventional techniques. Thus in this model OH masers would not be protostars themselves.

Although this might be frustrating for the reader, these schemes cannot really be much criticized or improved, given our ignorance of the pumping mechanisms and the lack of key observations. A breakthrough should come from more observations of variations and of accurate positions of maser sources, and high-sensitivity, high resolution observations of associated IR-radio continuum-molecular sources, in relatively simple cases where not too many generations of stars coexist. I should like to mention that some observations do not clearly fit into the previous schemes. i) What are H_2O masers and the few OH masers associated with Herbig-Haro objects or other late stages of star formation, and why do they show usually more negative velocities than the associated objects (Lo et al, 1975 b, 1976 b) ? Is that due to mass outflow ? ii) What is the cause of the enormous velocity spread in groups of H_2O masers (W 49, etc...) ? Theories to explain these observations by non-Doppler effects e.g. Raman scattering by molecules (Radhakrishnan et al, 1975) seem to fail. Other theories involve a blast- wave from a supernova having exploded recently, the stellar wind from a luminous protostar , etc.. (see e.g. Baudry et al, 1974 ; Morris, 1976 ; Heckman and Sullivan, 1976) ; in any case these are obviously not gently collapsing protostars !

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