MOLECULES IN DENSE CLOUDS AND PROTOSTARS

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Abstract. This paper deals with the interpretation of molecular line emission from class I OH/H_2O emission centers associated with compact H II regions and with the OH 18 cm emission from dark clouds in T-Tauri star associations. Observational evidence is presented, that class I OH/H_2O emission centers represent a particular stage in the evolution of a massive star (or a group of massive stars) whereas protostars of lower mass apparently do not go through such a stage.

It appears that in associations the low-mass stars are formed first and the massive O-stars are formed last. T-Tauri star associations may represent an early evolutionary stage of a star association where low-mass stars are formed. Evidence is presented that the physical conditions in some parts of the Taurus complex of dust clouds and T-Tauri stars are appropriate for the formation of single stars of about a solar mass.

1. Review of Earlier Work

Quite inadvertently the OH 18 cm line was found in strong emission close to galactic H II regions. At about the same time the first systematic surveys were made of radio recombination lines which are emitted by H II regions. The close correlation in the radial velocities of OH and recombination lines showed, that the positional coincidence was not fortuitious but that H II regions and OH emission centers were, in fact, closely associated in space (Mezger and Höglund, 1967).

It soon became clear that the OH emission centers had extremely small angular dimensions and that, therefore, incredibly high brightness temperatures were required to account for the observed line flux density. These characteristics made OH emission centers ideal objects for interferometry, and soon the CalTech and MIT groups (Cudaback *et al.*, 1966; Rogers *et al.*, 1966; Raimond and Eliasson, 1969) provided OH positions which were by orders of magnitude better than those of the associated H II regions. To match this positional accuracy Schraml and Mezger (1969) made a survey of most of the northern H II regions with high surface brightness, using the NRAO 140 ft telescope at the wavelength 1.95 cm. An angular resolution of 2′ and a positional accuracy of about 30″ was achieved. At about the same time Ryle and Downes (1967) applied, for the first time, the aperture synthesis technique to the observation of a galactic H II region, DR 21, in the Cygnus X region. Both groups independently discovered the existence of a new class of compact H II regions with high electron densities and small linear dimensions (Mezger *et al.*, 1967). The combination of our radio observations with optical observations led us to the conclusion, that these compact H II regions were the very early evolutionary stages of stellar subgroups first discovered by Blaauw (1964) in nearby OB-associations. This in turn led us to the hypothesis that the process of formation of massive stars was responsible for the OH emission (Mezger *et al.*, 1967). It was previously thought that pumping of the OH maser by UV radiation supplied by the H II regions and their exciting stars was the link between H II regions and OH sources. Models of non-

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thermal OH and OH/H_2O emission respectively by protostars were described in two previous papers (Mezger and Robinson, 1968; Litvak, 1969).

2. Star Formation

This paper deals with class I OH/H_2O emission centers associated with compact H II regions and with the quasi-thermal emission of the central OH 18 cm lines from dust clouds, especially from dust clouds which are associated with T-Tauri stars. The common link of both phenomena is the process of star formation. Therefore a brief outline of our present ideas how stars form out of the interstellar matter will be presented.

For the formation of stars, a certain volume of the interstellar space must become gravitationally unstable and contract. Gravitational contraction may be initiated by a density wave, which compresses the interstellar matter. Presumably this is the mechanism for the formation of Population I stars in genuine spiral arms. Gravitational contraction may also be initiated by a decrease of temperature and internal turbulence of the interstellar matter, for example as the result of increased cooling by an increased production of molecules and dust. This latter mechanism appears to pertain to the formation of stars in regions outside regular spiral arms.

Most of our present knowledge of star formation in clusters and associations is based on optical observations, which do not pertain to regular spiral arms. I therefore do not know, if the following picture also applies to the process of star formation by a density wave in regular spiral arms.

Optical observations and their theoretical interpretation (Iben and Talbot, 1966; Williams and Cremin, 1969) have shown, that in nearby associations stars of about one solar mass are formed first and the most massive O-stars are formed last. O-stars, and their associated stellar subgroups, appear to form out of clouds of some thousand solar masses (Blaauw, 1964). Once the O-stars reach the main sequence (MS) they ionize the remnant of the proto-cluster and star formation in this subgroup comes to a halt. This remnant appears to be tightly packed around the O-stars, in the form of a shell or cocoon, and the ionized gas is therefore first observed as a very compact H II region of high density, which subsequently rapidly expands.

The Trapezium cluster is the youngest of four stellar subgroups in the Orion association. It is associated with the compact H II region M 42. About $3\text{–}5 \times 10^5$ yr ago the Trapezium cluster apparently started to expand (Strand, 1958). At about the same time the Trapezium O-stars must have been formed out of a dense cloud located at the center of the Trapezium cluster. They reached the MS about 1.6×10^4 yr ago, as estimated from their dynamical age (Strand, 1970, private communication). At the same time the compact H II region M 42 must have formed, and its age of 1.4 to 2.3×10^4 yr, derived by Vandervoort (1964) agrees in fact perfectly with the dynamical age of the Trapezium stars. This picture leads to two predictions which are of importance in the context of this paper: there must be regions of star formation where predominantly low-mass stars are formed, embedded in which are dense clouds, out of which eventually an O-star or a close group of O-stars will form.

3. Class I OH/H_2O Sources

After this digression into the general problem of star formation let me come back to the proper topic of my paper, i.e. molecular lines emitted from dense clouds in regions of star formation.

Class I OH sources are those whose center lines at 1665 and 1667 MHz are greatly enhanced by some maser mechanism. They are always associated with H II regions, and the close correlation in radial velocities shows that this is not a projection effect. The apparent diameters of the individual OH emission centers are very small, corresponding to typical linear dimensions of some 10^{14} cm. The maser amplification may be as high as 10^{13}. Emission of the H_2O 1.35 cm line has been found close to the OH class I emission centers. The pioneering work of the MIT VLBI group has shown, that the apparent size of the H_2O emission centers is by an order of magnitude smaller than that of the associated OH emission centers (Burke *et al.*, 1970). Other characteristics of the H_2O emission are very similar to that of class I OH emission centers. Nearly all the strong OH emission centers are associated with H_2O emission which, however, is considerably stronger than the corresponding OH emission. Cases where no H_2O emission has been detected from class I OH sources may well be a result of the high system noise of the present H_2O radiometers. According to Turner and Rubin (1970, private communication) there is at present only one H II region, G 34.3+0.1, known, where no OH emission has been found from an H_2O emission center.

One of the most obvious characteristics of class I OH/H_2O emission centers is their association with compact H II regions, which appear to be the ionized cocoons of recently formed O-stars. I made a careful reinvestigation of the nature of this association of OH/H_2O emission centers and compact H II regions, based on recent 2 cm single dish observations (Churchwell *et al.*, 1969) and on aperture synthesis observations made by the NRAO and Cambridge groups, respectively. There are clear-cut cases like the two OH/H_2O emission centers associated with NGC 6334 or the two emission centers north of DR 21 in the Cygnus X region, where the emission centers may be embedded in an extended low-density H II region, but where the angular separation from the associated compact H II regions is 3′ or more. This is a confirmation of our earlier conclusion (Mezger *et al.*, 1967), that there is no physical connection between OH/H_2O emission centers and compact H II regions. How then shall we explain, that these emission centers are always found in the vicinity of compact H II regions? I suggest that compact H II regions and OH/H_2O emission centers represent different stages in the evolution of O-stars. Formation of O-stars, on the other hand, requires very special conditions of the interstellar matter, which prevail in an association only for a very limited time. And this, I feel, is the reason why compact H II regions and class I OH/H_2O emission centers are found to be associated.

It is important to realize, that obviously only the massive stars go through the stage of strong OH/H_2O masering. In further support of this statement note, that

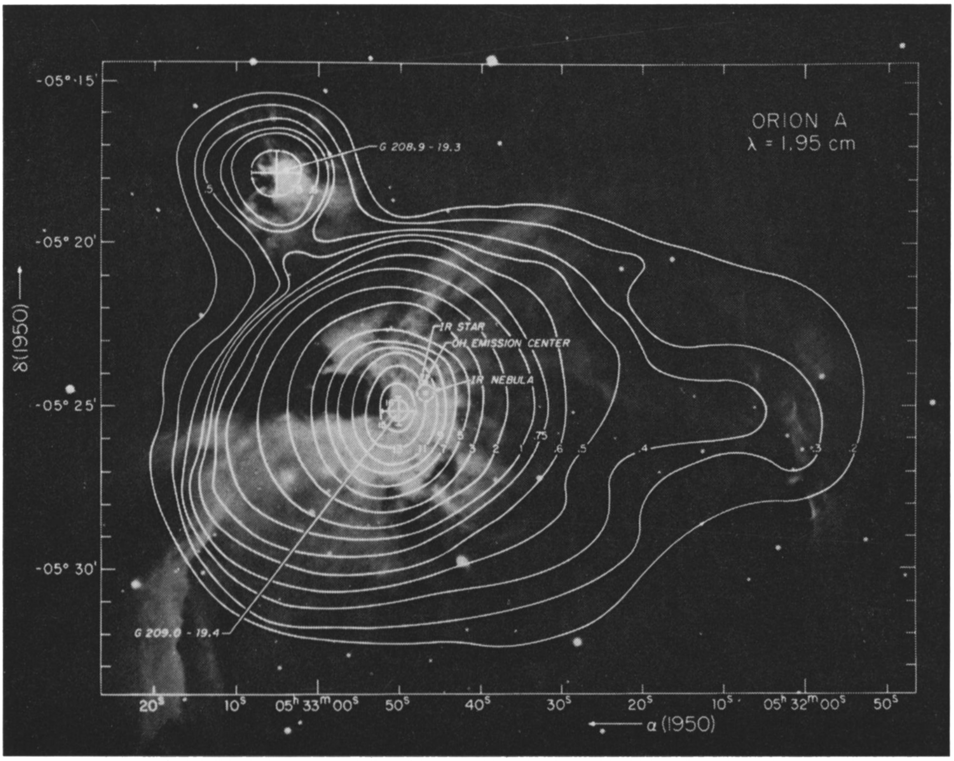

Fig. 1. Overlay of radio contours of the Orion Nebula on an Hα photograph. Observed at 15.4 GHz with an angular resolution of 2′ (Schraml and Mezger, 1969).

although formation of low-mass stars in T-Tauri associations goes on for a long time, no strong OH/H_2O emission has been detected in these regions (Ball, 1970, private communication; Turner, 1969). There are other cases like M 42, IC 1795/W 3 and W 49, where single dish continuum observations do not exclude the possibility of a coincidence of OH/H_2O emission center and compact H II region. Only aperture synthesis observations can bring a decision. I will leave W 49 out of this discussion; with a distance of about 14 kpc this giant H II region is too far away. The case of M 42, the compact H II region associated with the Trapezium cluster (Figure 1), I have discussed in two papers last year (Mezger, 1970a, b). Although the OH/H_2O emission center lies within the boundaries of the compact H II region, the aperture synthesis map by Webster and Altenhoff (1970) shows no conspicuous feature in the free–free emission at the general position of the emission centers. This can be explained in two ways: either the molecules are formed and emit in the H II region proper; or the positional coincidence is a mere projection effect. For reasons which I will state later I believe in this latter explanation. I suggest that this association of OH/H_2O emission centers with an IR nebula and an IR star north–west of the Trapezium is the fifth and youngest subgroup of the Orion association, where the

O-stars are in the process of formation but have not yet reached the MS. In another 10^4 yr, the present compact H II region M 42 will have evolved into a low-density H II region, but another compact H II region may be seen at the location of the OH/H_2O emission centers.

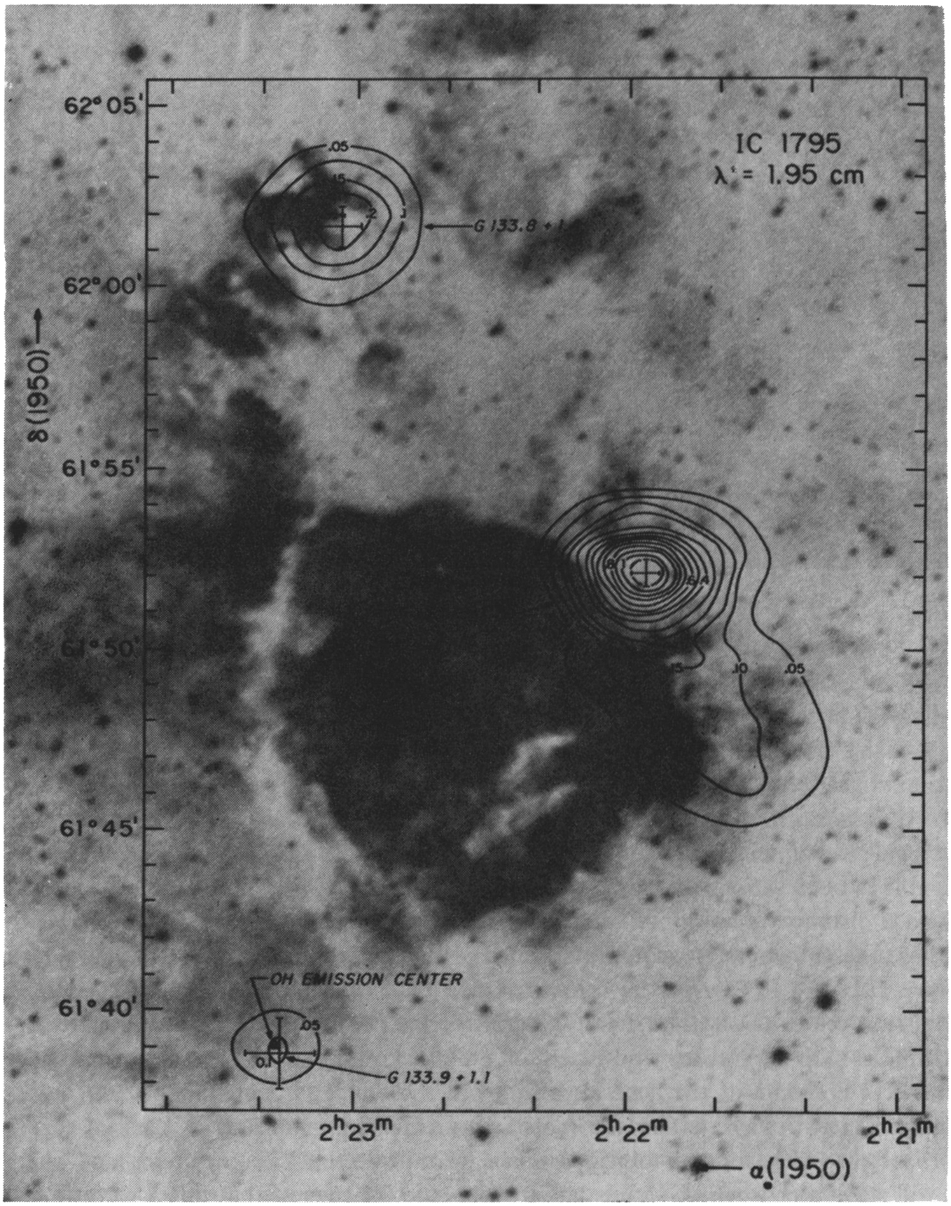

Fig. 2. Overlay of radio contours of the thermal source W 3 on an Hα photograph of IC 1795. Observed at 15.4 GHz with an angular resolution of 2′ (Schraml and Mezger, 1969).

IC 1795/W3 appears to me the most relevant case and I will therefore discuss it at more length. IC 1795 is probably the youngest of three optically visible H II regions in the Perseus arm, the others being IC 1805 and 1848, respectively. Figure 2 shows an overlay of 2 cm radio contours on an Hα photograph of IC 1795. The main radio component G 133.7+1.2 of W 3 lies to the west of IC 1795. In my opinion this compact giant H II region is not part of the optically visible H II region IC 1795 but rather represents the fourth and youngest in this sequence of spiral arm H II regions.

OH/H_2O emission has first been detected from a point about 17′ southeast of the main component of W 3. Subsequently, by observations in the short centimetre wavelength continuum, one of the most compact and therefore, probably youngest H II regions, G 133.9+1.1, was found to coincide with the OH emission center (Mezger *et al.*, 1967; Aikman, 1968). More recently, both H_2O and weak OH emission was also found close to the main radio component G 133.7+1.2.

The southern compact component, G 133.9+1.1 was observed by Wynn-Williams, using the Cambridge aperture synthesis telescope at 5 GHz, where the source is still optically thick. He derived its position ($\alpha = 2^h\,23^m\,16.48^s$; $\delta = 61°38'56.8''$) with an accuracy of 0.5″. Adopting an electron temperature of 10^4 K and a flux density of 3 fu at 15 GHz, he estimates an apparent diameter of 1.7″, corresponding to a linear diameter of 6.5×10^{16} cm. Density and mass of this compact H II region are then found to be $N_e = 2 \times 10^5\ \mathrm{cm}^{-3}$ and $M_{\mathrm{HII}}/M_\odot = 0.04$, respectively (Wynn-Williams, private communication). The excitation parameter is about 38 pc cm^{-2}, corresponding to an exciting star of spectral type O7, if the compact H II region is ionization bounded.

Interferometer positions of the OH emission center have been obtained by Raimond and Eliasson (1969). The more accurate 1665 MHz position is $\alpha = 2^n\,23^m\,16.8^s \pm 0.2^s$ and $\delta = 61°38'\,54'' \pm 1''$. Moran *et al.* (1968) have resolved the 1665 MHz emission source into at least seven individual emission centers of a typical linear size of about 2×10^{14} cm, which are distributed in an area of size 1.2″ × 2.3″. The centers of OH and free-free emission are hence separated by about 3″, which is about 2.5 times the mean positional uncertainty. A positional coincidence of compact H II region and OH emission center cannot be ruled out completely; however, it appears highly unlikely.

Again, I suggest, that we are observing here two O-stars (or close groups of O-stars) in different evolutionary stages. The northern O-star has just reached the MS and is starting to ionize the remnants of the protostar. The southern O-star is in an earlier evolutionary stage. The solid angle from which OH emission is observed has about the same size as the solid angle subtended by the adjacent compact H II region. This makes me believe that the seven emission centers resolved by VLBI observations pertain to one single massive protostar. With an apparent diameter of 2.3″ and a total mass of, say, 50 $M_\odot$, the average density of this protostar would be 2×10^6 atoms cm^{-3}, and its diameter would be 9×10^{16} cm, corresponding to the early stages of free-fall contraction of a protostar (Hayashi and Nakano, 1965).

Maser action would be seen whenever the physical conditions along the line of sight are appropriate. It was objected that the differential velocity of a protostar in free-fall contraction would limit the pathlength of the maser severely. Dr Nakano

(1970, private communication) has kindly computed the velocity field of a contracting protostar of 10 $M_\odot$ and of radius 3.7×10^{16} cm. For polytropic indices $n=0$ and 1.5 the free-fall velocity changes from 0 km sec^{-1} at the center to less than 3 km sec^{-1} in the outer layers of the contracting protostar. For polytropic index $n=4$, the free-fall velocity attains a maximum of about 5.25 km sec^{-1} at 0.17 times the radius of the protostar and subsequently decreases monotonically to 2.7 km sec^{-1} in the outermost layers. Differential velocity along the line of sight therefore does not appear to be a severe limitation to maser action. On the other hand, especially if combined with a rotation of the protostar, one can conveniently explain the velocity range of 7.4 km sec^{-1} covered by the seven individual emission centers.

Does OH and H_2O masering occur in the same volume of space? Interferometer positions for the H_2O emission centers are still lacking. But there is other observational evidence that OH and H_2O masering does not occur in exactly the same regions of the protostar. The OH and H_2O emission spectra usually cover the same velocity range, but there is no one-to-one correspondence in the individual emission spikes, whose widths – if interpreted as thermal Doppler broadening – correspond to kinetic temperatures of about 20 K for the OH and several 100 K for the H_2O. If these lines were produced by an unsaturated maser they would be narrowed and the kinetic temperature could go up by a factor of, say, twenty. But even then at least the OH temperatures would be considerably lower than that of a typical H II region. This is another argument that OH/H_2O emission comes from dense neutral condensations.

We can estimate upper and lower limits for the density range of these condensations. The fact that Doppler broadening appears to dominate over collisional broadening yields upper limits of 3×10^{14} and 2×10^{15} atom cm^{-3} for the density of OH and H_2O emission centers, respectively. A lower limit of the density can be derived from the condition that the molecules must be shielded against photo-ionization and dissociation. Effective shielding of the Lyman continuum radiation in the vicinity of an O-star requires densities of $N_H \gtrsim 10^4$ cm^{-3}. Effective shielding against UV radiation longward of the Lyman continuum limit requires densities of $N_H \gtrsim 10^6$ cm^{-3}.

I have deliberately not touched upon the subject of the total mass involved in the OH/H_2O masers. Such an estimate involves the esoteric process of pumping of the molecules which will be dealt with in a subsequent panel discussion. And it involves an estimate of both the number of oxygen atoms tied up in OH and H_2O molecules and the geometry of the maser. But a straight forward estimate, based on the number of emitting molecules, leads usually to masses of the masering volumes ranging from sub-stellar to stellar masses. I don't think that other estimates, based on improved pumping models, will come up with radically different answers.

In summary I conclude, that the physical conditions derived for class I OH/H_2O emission centers are compatible with the hypothesis that this emission comes from proto-stars. The association of OH/H_2O emission centers with compact H II regions on the one hand, absence of strong class I OH/H_2O emission from T-Tauri star associations on the other hand indicates, that only the very massive protostars evolve through the stage of class I OH/H_2O emission centers.

4. Dark Clouds and T-Tauri Associations

One of the most striking features of all molecular lines is their correlation in both position and radial velocity with galactic H II regions. Galactic H II regions, on the other hand, are found in those regions of our Galaxy where the neutral hydrogen (H I) attains its maximum surface density and presumably also its highest space density (Kerr *et al.*, 1968; Mezger *et al.*, 1969). In other words, stars appear to be formed in regions of high density of the neutral interstellar gas. In the context of this review paper we are interested in two problems: (1) What do O-star associations look like at the time when the low-mass stars only are present and the O-stars still wait for their formation. (2) Is the formation of dust and molecules a consequence of the formation of low-mass stars as suggested by Herbig (1970); or is star formation rather initiated by an increased production of dust and molecules and a subsequent increased cooling of the gas in dense clouds. The obvious place where low mass stars are formed in large quantities and over a large volume of space are T-Tauri associations. T-Tauri stars are only found in or near regions of significant dust concentration and it is now recognized that the T-Tauri stars are formed out of the dust clouds in which they are found. The large volume covered by some of the T-Tauri associations speaks against a process of gravitational collapse of a large cloud and subsequent dispersal of the stars so formed. It is clear in some observed cases (Herbig, 1970) that single T-Tauri stars have been formed from small discrete dust clouds; therefore, we have to face the question of how single stars of about 1 $M_\odot$ can form. The answer is that, for a minimum temperature of the interstellar gas of 3 K, and a gas density of 10^4 atom cm^{-3}, the Jeans's mass is about 1.6 $M_\odot$.

I first use molecular line emission to probe, if conditions in dark clouds and T-Tauri associations are compatible with the formation of single stars. In some dark clouds OH emission has been observed and these lines can be used to estimate the temperatures. Cudaback and Heiles (1969) derive temperatures between 6 and 9 K for four clouds where the OH lines are seen in absorption against background continuum radiation. Assuming LTE emission for the two central OH lines, Heiles (1969) derived temperatures from 4.4 to 10 K. Turner (1970, private communication) quotes even lower temperatures of 3.6 K for the Taurus cloud, and 5.4 K for the Ophiuchus cloud. Densities of dust clouds can only be inferred by adopting a value for the mass absorption coefficient. Heiles (1970, private communication) estimates densities between 10^2 and 10^3 atom cm^{-3}, which are probably underestimates since not all heavy elements are tied up in grains and the grains are probably not of optimum size. In fact, if the temperature of the interstellar gas is to be lower than about 11 K, it must be shielded against both subcosmic particles and the UV radiation longward of the Lyman continuum which can ionize carbon and metals (Hjellming, 1970, private communication). Werner (1970) finds, that such shielding is effectively achieved for clouds of densities $>10^4$ atom cm^{-3}. Thus, temperatures and densities within the dark clouds appear to be very close to those required for collapse of 1 $M_\odot$ stars. However, in the above estimate I applied the Jeans's criterion assuming no turbulence.

Line widths observed for OH are typically of the order of 1–2 km sec^{-1}. These usually resolve into two or more components, with widths of about 0.75 km sec^{-1}. This corresponds to thermal velocities in a cloud with a temperature of 200 K, and it is clear that most of the observed line widths must be due to internal mass motions. These motions may explain why low-mass stars form more easily than high mass stars, a fact not explained by the Jeans's criterion alone. It is possible that 1 $M_\odot$ stars form in small regions in the cloud where the relative motions are low, while the probability of finding a volume in such a cloud containing 10 $M_\odot$ and more in which relative motions are negligible may be very small.

The largest account of data relating to dark clouds and the associated stars is that for the Taurus complex, so I will refer mainly to that region; sparser evidence for other regions indicates that the same conditions apply. Figure 3 shows the area of the Taurus complex. Absorption of greater than 1 magnitude is extensive; the contours derived by McCuskey (1938) are shown. Within the general absorption are many small regions of extremely heavy absorption – probably greater than 5 magnitudes (Heiles (1968) estimates 8 magnitudes for the center of the largest cloud in Taurus). Those heavily obscured areas that have been observed for OH (Heiles, 1970; Heiles, 1968; Cudaback and Heiles, 1969) are indicated by hatching; most of these regions are too small to affect McCuskey's large scale contours (in many cases the clouds

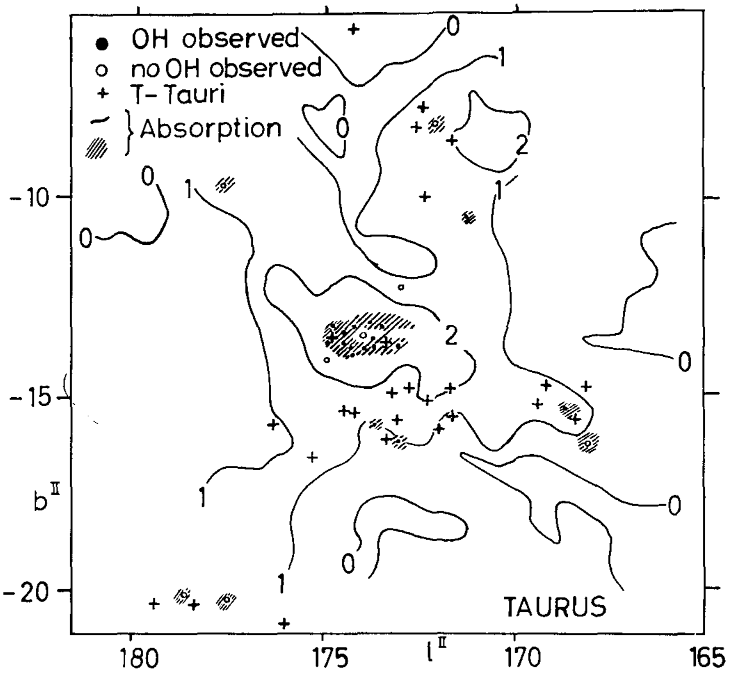

Fig. 3. The relative distribution of OH sources, T-Tauri stars and visual absorption in the region of Taurus.

measure only about 10 min arc, and are therefore even smaller than the hatched areas on the diagram). Positive results for the OH observations are indicated by filled circles, negative results are indicated by open circles. Positions of T-Tauri stars, as given by Herbig (1962) are indicated by crosses. They are found in large numbers throughout the Taurus complex – within regions where the absorption is 1.5 magnitude or greater.

Quasi-thermal OH emission is only found within the regions of *very* dense absorption. The central horse-shoe-shaped cloud has been the most carefully studied. Within the boundaries of the heaviest absorption on the red plates of the Palomar Atlas (the cloud appears quite sharply bounded) are found OH (Heiles, 1970), formaldehyde (Palmer *et al.*, 1969), and cold neutral hydrogen (Heiles, 1970; Sancisi and Wesselius, 1970; Rohlfs, 1970, private communication). Outside the boundaries of the absorbing cloud, none of these are observed.

The present observations do not allow a decision, whether this is a result of the higher surface density of OH molecules in these sharply bounded areas of high optical absorption (to which I refer to hereafter as 'dark clouds'), or shielding of molecules from UV radiation by heavy dust layers enabling survival for a longer time. We do know that conditions for the formation of low-mass stars are appropriate in these dark clouds. However, the T-Tauri stars are not confined only to the dark clouds. But we cannot decide whether T-Tauri stars can also form in regions of lower absorption, or have been formed originally in dark clouds with most of the dust and gas ending up in stars.

It is interesting to speculate, whether or not a massive dark cloud like the horse-shoe-shaped cloud in the Taurus cloud, for which Heiles (1970, private communication) estimates a total mass of about 100 $M_\odot$, will evolve eventually into a subgroup of an O-star association. If this hypothesis were correct, it should sometime in the future become a strong class I OH/H_2O emission center which some ten thousand years later would turn into a compact H II region such as G; 33.9+1.1 in W 3.

The evolution of a dark and cool cloud through a T-Tauri star association, class I OH/H_2O emission centers and compact H II regions into an O-star association should be considered as a working hypothesis with many gaps to be filled by future observations. I do not feel that our present observations allow us to conclude, where and why dust and molecules form. The importance, however, of molecular lines as probes of the physical conditions of the interstellar gas and especially of regions of star formation is already clear. I am sure that within the next few years more important information will be obtained that eventually will allow us to solve the problem how stars are formed out of the interstellar matter.

Acknowledgements

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DISCUSSION

Townes: The excitation temperature of OH may be rather different from the cloud's kinetic temperature. Other evidence gives kinetic temperatures considerably higher than the 5–10° of OH. Furthermore, there is a collisional mechanism which appears to cool OH below the kinetic temperature in much the same way that CH_2O is abnormally cooled in the dark clouds.

Sancisi: The anticorrelation of interstellar extinction and H I emission in the direction of the dense

Taurus clouds may be explained as due to a local decrease of the spin temperature of the neutral hydrogen connected with the dust. In fact it may indicate that a large amount of cold atomic hydrogen exists in the dust cloud. Molecular hydrogen may also be present but the 21 cm line results alone are no direct evidence for it, as claimed by Solomon.

A possible association between hydrogen and T-Tauri stars in the area of Taurus was pointed out at the Symposium on 'Pre-Main Sequence Stellar Evolution' held at Liege in 1969.