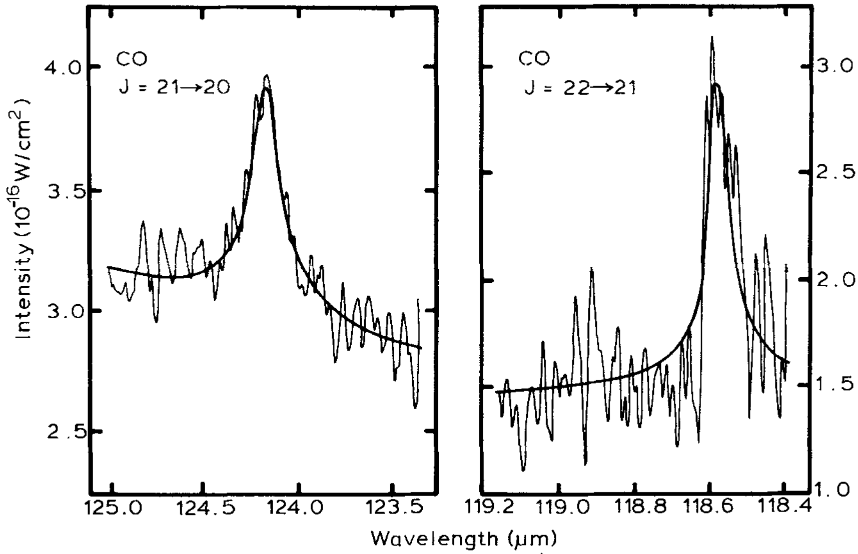

FIG. 25. Pure rotational emission lines of CO observed by Watson *et al.* (1980) using the Kuiper Airborne Laboratory. The emission originates from hot gas in and around the Kleinmann-Low infrared nebula. These lines lie just above those shown in Fig. 4.

Some specific interstellar sources

The Orion molecular clouds

Fig. 26 is a map of part of the sky in Orion taken from work by Kutner *et al.* (1977) which shows the extent of the stars, dust clouds and emission nebulae. The most familiar object is of course the Orion nebula (which has various aliases: Orion A, M42, NGC1976). Fig. 2 gives a good picture of what part of this region looks like. The well known Horsehead dark nebula shows up well as it is highlighted by the bright background HII region. The emission from Orion A is caused by the photoionizing radiation from a cluster of hot stars of which the four brightest form the Trapezium. Behind Orion A lies a molecular cloud, OMC1, within which resides a particularly dense, hot region roughly 1 ly further away than the Trapezium and just off the Trapezium line of sight. It is in this region that a cluster of infrared sources including the Kleinman-Low (KL) nebula and the Becklin-Neugebauer (BN) object are located. This region is at present being studied using every molecular probe available. The extent of the CO cloud is indicated in Fig. 26.

One of the first aims of the radio studies was to map objects such as the Orion cloud and compare their molecular compositions. These are of course two-dimensional maps of the radio intensity and care should be taken over their interpretation. Such a map is given in Fig. 27 (Turner and Thaddeus, 1977). It indicates that various molecules may not coexist and indeed it is not immediately obvious why N_2H^+ and HCO^+ do not have maxima in the same regions. Orion has been one of the two main hunting grounds for interstellar molecules and in general the molecules there have somewhat higher excitation temperatures than those in other colder regions. OMC1, which contains KL, has angular dimensions $\alpha \times \delta \sim 8' \times 4'$ and at the distance of Orion (1500 ly), 1′ of arc ~ 0.5 ly so the cloud is ~4 × 2 ly in plan. A second molecular cloud OMC2 lies about 10′ (~5 ly) north

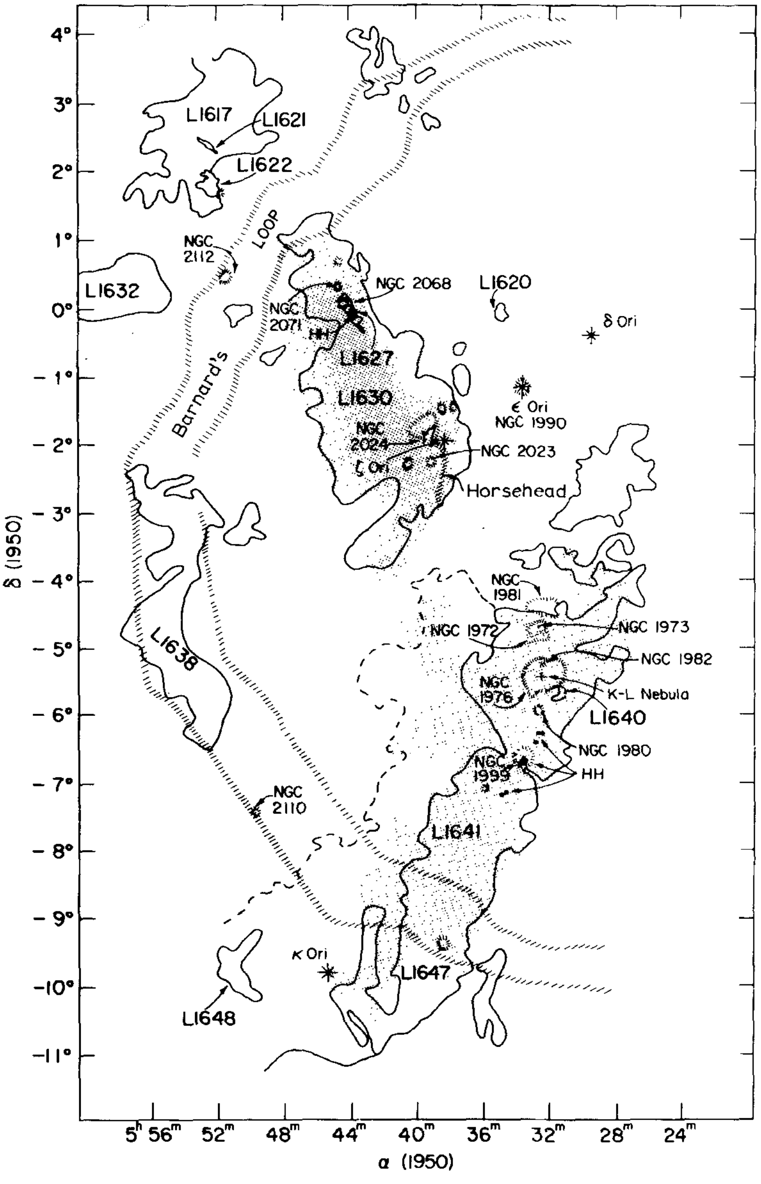

FIG. 26. Map of Orion given by Kutner *et al.* (1977). The three stars in the belt of Orion ζ, ε and δ Orionis are identified The Orion nebula is NGC 1976. The Horsehead shown in Fig. 2 is also identified just south of ζ Ori. The hatched boundaries indicate boundaries of optical emission or reflection nebulosity. The approximate boundaries of dust clouds, designated by Lynds (L) numbers are given by solid lines; dashed line is a lower extinction edge of L1641. The dotted shading has been added to show the approximate extent of the CO emission from the Columbia (4 ft) observations. The emission peaks strongly at K–L and also near to ζ Orionis. The lower cloud which subtends ~7 degrees is roughly 180 ly long (Orion is ~1500 ly away).

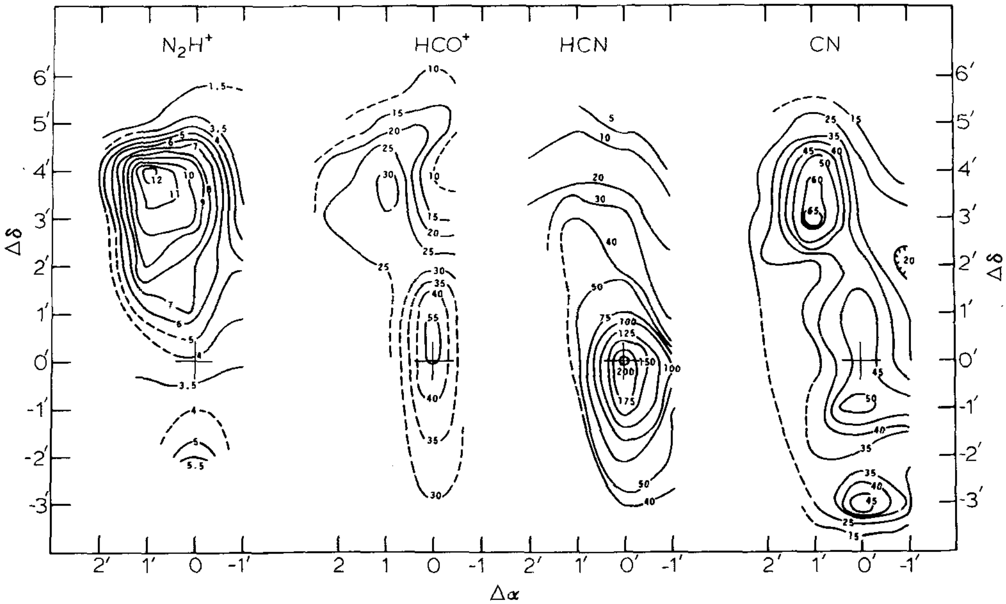

FIG. 27. Radio contour maps of integrated intensity for N_2H^+, HCO^+, HCN and CN published by Turner and Thaddeus (1977). The maps are all centred on K–L and show that the cloud is inhomogeneous in molecule distribution. In particular we see that HCO^+ has a maximum at a position where N_2H^+ has a minimum.

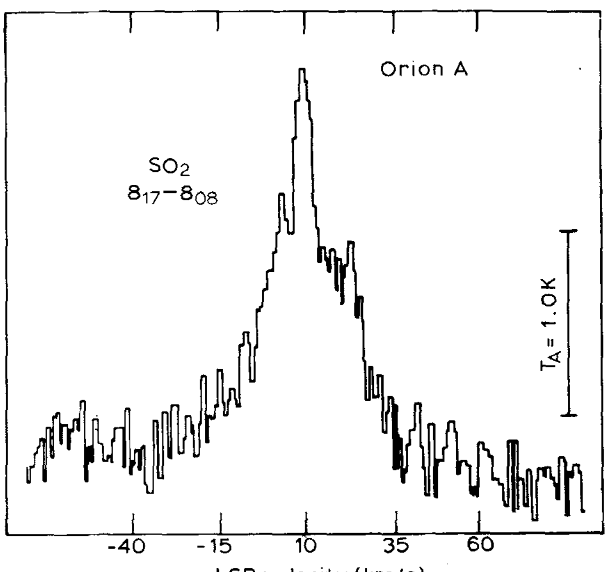

FIG. 28. The spectrum of SO_2 from Orion showing the two component characteristic: a wide plateau originating from KL and a narrow spike from the rest of the cloud.

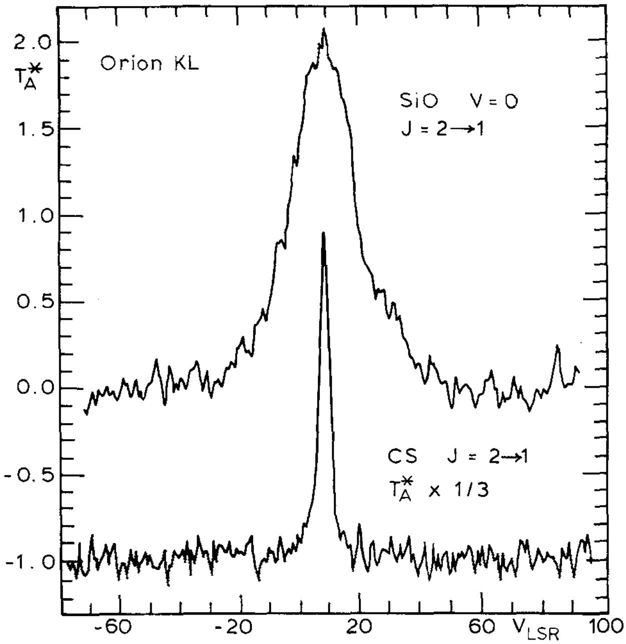

FIG. 29. The spectra of SiO and CS ($J = 2 \rightarrow 1$) emission from the KL nebula in Orion. The SiO line width is large which indicates it emanates from the high velocity core. The CS line is narrow indicating it resides mainly in the quiscent surrounding molecular cloud. Since these two molecules have similar excitation requirements the differences implies that SiO may have condensed out in grains by the time it gets into the cold surrounding cloud. From Scoville (1980).

of OMC1. OMC1 has a mass of $\sim 10^3\ M_\odot$ and OMC1 and OMC2 together have a combined mass of $\sim 10^4\ M_\odot$. The whole Orion GMC complex has a mass of $\sim 10^6\ M_\odot$. The average kinetic temperature in OMC1 is ~70 K.

Radio linewidths towards KL often have a composite shape as shown in Fig. 28 for SO_2. The wide plateau 30 km s^{-1} wide emission seems to come from an expanding warm cloud emanating from KL, whereas the sharp spike corresponds to emission from the OMC1 cloud itself. The comparison of SiO with CS from this same region Fig. 29 indicates that SiO appears only to have a plateau line shape and CS essentially only a spike. This may indicate that SiO is produced in some form of circumstellar type envelope and has condensed out into grains by the time it has reached the surrounding cooler and quiescent molecular cloud region.

The value of NH_3 due to the frequency proximity of various transitions with differing excitation requirements is indicated by the spectra in Fig. 15 obtained by Morris, Palmer and Zuckerman (1980). They show that these lines originate from a hot dense 220 K core with $n_{H_2} \sim 10^7\ cm^{-3}$ in KL. They interpret the data as emanating from a very young star i.e. a protostellar cloud on the verge of collapse.

Recent high spatial resolution molecular line aperture synthesis of this region has confirmed that the plateau is an expanding envelope centred on KL (Welch *et al.*, 1981). This type of study is certainly a most important direction for future molecular line work to follow.

The higher spatial resolution inherently available in the infrared due to the lower diffraction limit is being exploited in the study of the KL/BN region of OMC1. Beckwith *et al.* (1978) obtained the interesting map shown in Fig. 30 at 5″ resolution from their H_2 quadrupole emission studies. This should be compared with a 13″ resolution map (Beckwith *et al.*, 1978) and indicates how *qualitatively* different a picture can often be obtained with increased resolution. This is an instructive lesson in the care with which low resolution data should be treated. Beckwith *et al.* (1978) indicate that the emission emanates from a thin sheet, $\sim 10^{13}$ cm (or 10^{-5} ly) thick of H_2 gas heated to ~2000 K with a column density $\sim 10^{19}$ cm^{-2}. The source of excitation is not clear but a shockwave from a supernova explosion is possible. The CO ($v = 4 \rightarrow 2$) vibrational emission near BN observed by Scoville *et al.* (1979) implies a compact collisionally excited region with $n_H >$ 10^{10} cm^{-3} and $T_{ex} \sim 3000$–5000 K. Airborne infrared experiments by Watson *et al.* (1980)

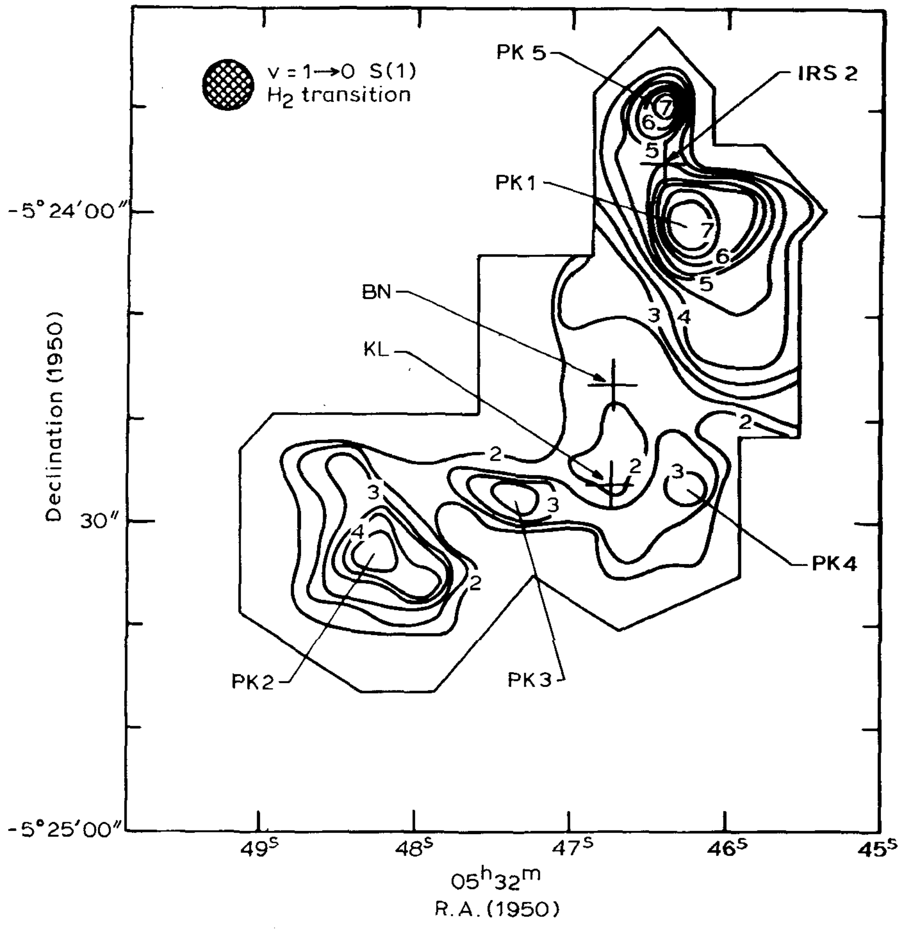

FIG. 30. Contour map of H_2 quadrupole vibrational emission at 5″ spatial resolution. At this resolution six peaks in the emission are detected and the picture changes quite considerably from a previous 13″ resolution map. From Beckwith *et al.* (1978). The emission arises from a thin (10^{-5} ly) sheet of hot (2000 K) H_2 gas perhaps heated by a shockwave from a supernova.

have succeeded in detecting strong $J = 21$–20 and J 22–21 emission from post shocked gas at $T = 500$–1000 K in the region of KL (Fig. 25).

At present, the information we have about the convoluted activity in the murky depths of OMC1 may only be the tip of the iceberg as indicated by the recent detection of many new infrared sources in KL by Downes *et al.* (1981). With a great deal more dedicated study it should be possible to decipher the information being leaked out by the molecular moles in the core and so obtain detailed information on the birth of a star or indeed a cluster of stars.

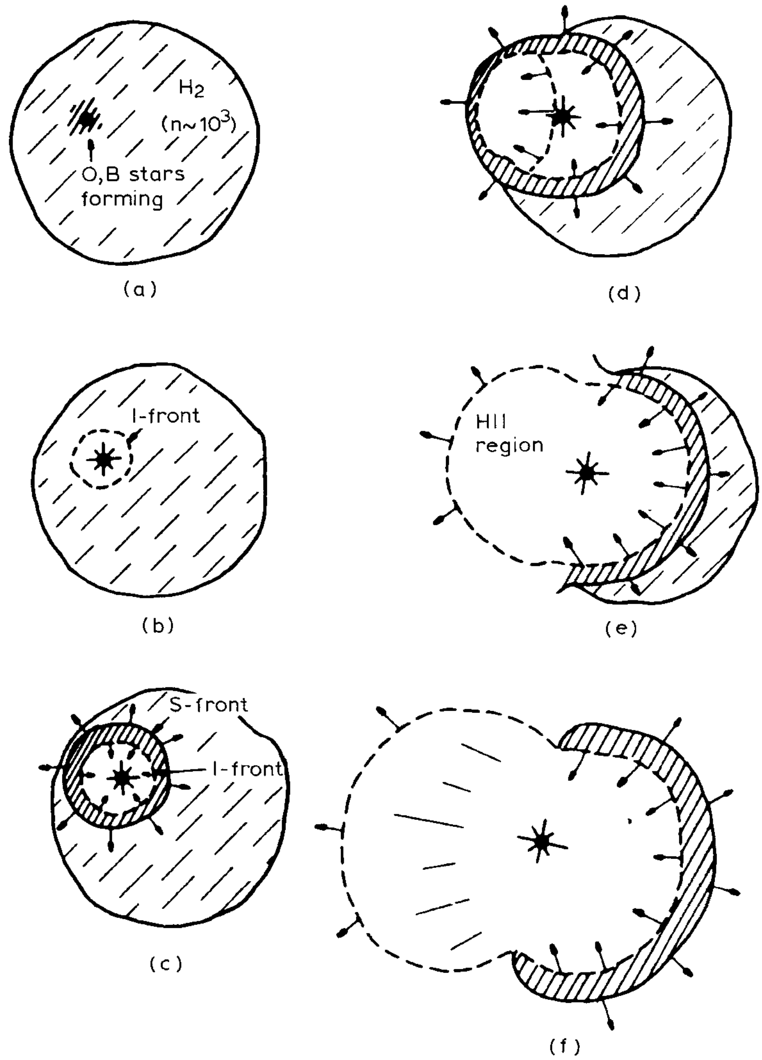

FIG. 31. A schematic diagram of the evolution of an HII region in a molecular cloud. Hot O and B stars form in the molecular cloud (a) and after some 3×10^6 years (f) the star becomes visible as the hot hydrogen blasts out of the molecular cloud. I indicates the ionization front and S the preceding shock front. This diagram is given by Bally and Scoville (1978) who suggest that the W80 complex of clouds and hot gas is in stage (f).

Thus we have a possible scenario for the Orion Nebula and a possible future one for the KLBN region similar to that presented in Fig. 31 by Bally and Scoville (1980) for the North American and Pelican Nebulae, W80. The Trapezium star cluster formed just inside the molecular cloud, and, once born, the hot O and B type stars ionized the surrounding molecular cloud. The resulting hot, high pressure HII region expands and sweeps up material behind a shock front. Eventually the HII bubble bursts through the surface to form the blister that we see optically as the Orion emission nebula and the stars become visible. The KLBN region may be the scene of a second performance which originates ~1 ly deeper in the molecular cloud. Perhaps at some time in the future (1000 years) the second bubble will burst and reveal the star or star cluster optically. Figure 31 shows how this may happen and how eventually the HII region might eat its way back through the rest of the cloud.

In Fig. 32 is given a schematic cross section of the Orion nebula and the molecular cloud behind it as suggested by Zuckerman (1973) and Zuckerman and Palmer (1974). This shows that the bright nebulae are essentially blisters which break out of the surface of molecular clouds (Chaisson, 1977).

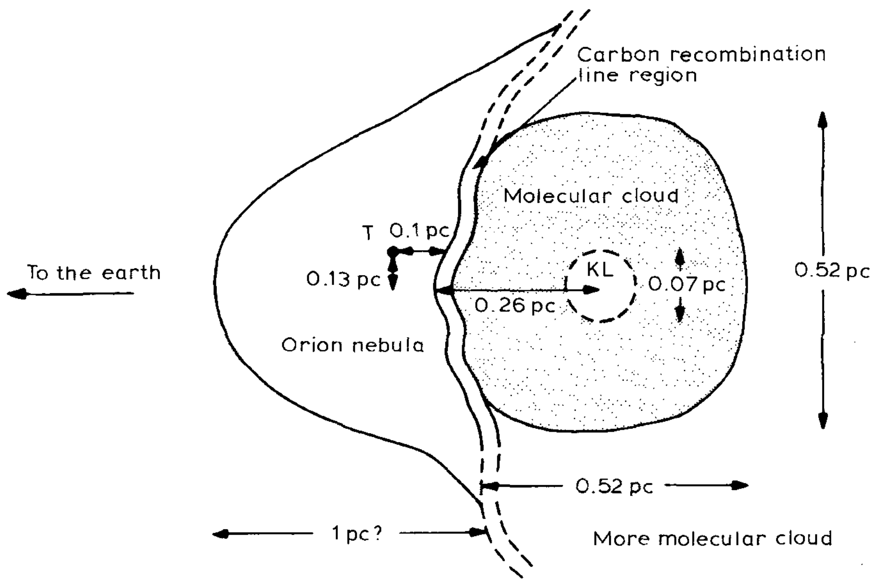

FIG. 32. A schematic cross sectional representation of a possible structure of the Orion nebula and the background molecular cloud as given by Zuckerman (1974).

SgrB2

The molecular soup with the most ingredients is the GMC, SgrB2, which lies some 30 000 ly away, very close to the centre of the Galaxy. Until recently every molecule detected had been observed in SgrB2. It is unfortunate that it is so far away because the distance limits our ability to probe the spatial fine structure. At this distance 1′ arc ≡ 10 ly as compared with ~0.5 ly for orion some 20 times nearer. SgrB2 is obscured by ~25 magnitudes* (a factor of 10^{10}) of scattering by interstellar dust. It has a dense core (~1′ ≡ 10 ly) surrounded by a less dense halo (~5′ ≡ 50 ly).

* 1 mag ≡ $100^{1/5}$—Astronomers (uncharacteristically) seem to use a magnitude factor smaller than other scientists i.e. 2.51 as opposed to 10.

Any deductions about the physical conditions in such a cloud must be treated with caution. A good example of the way in which misleading conclusions, on such matters as column density, can be drawn is shown in Fig. 16 where the complications in the line shapes of NH_3 transitions observed by Walmsley, Winnewisser and Churchwell (1979) are evident. At low resolution they appear to be essentially emission lines (Morris *et al.*, 1973) whereas at higher resolution the line is resolved into a more complex absorption/emission feature which implies a multicomponent cloud lies along the line of sight. The inhomogeneity of a cloud like SgrB2 can only be guessed at and it is known to contain several compact objects. The characteristics of SgrB2 and Orion have been reviewed by Winnewisser, Churchwell and Walmsley (1979).

IRC+10216

The variable infrared source IRC+10216 is a carbon star surrounded by an expanding dusty shell (Morris, 1975). The first molecule detected in the extended envelope was CO (Solomon *et al.*, 1971) and since then some 20 more have been observed. The line shapes depend on the optical thickness and whether the source is resolved or not. In Figs. 33 and 34 some examples are shown. In the radio studies one observes emission from the whole shell whereas in the infrared the absorption spectra use the star's infrared continuum emission as the background source and only the foreground part of the shell is detected (Ridgway and Hall, 1980). The results indicate that this and other objects such as CIT6 (Knapp, Kuiper and Zuckerman, 1979) are important molecule factories and there may be many more. The high spatial resolution infrared absorption results give information on the inner molecular component which is of the order of 1 AU in diameter. Ridgway and Hall (1980) have interpreted their infrared data shown in Fig. 34 as indicating a *double* expanding shell, an inner warm (300–700 K) shell expanding at 11 km/s and a cooler (150–250 K) outer shell expanding at 16 km/s.

Circumstellar absorptions due to CO, HCN, C_2H_2 and CH_4 have all been detected using a ground based infrared interferometer (Ridgway *et al.*, 1976; Ridgway, Carbon and Hall, 1978; Hall and Ridgway, 1978). Using an infrared heterodyne spectrometer on the

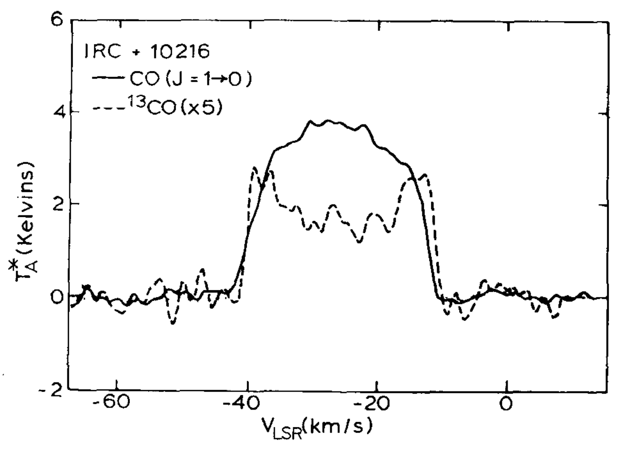

FIG. 33. Two examples of line shapes from IRC+10216. The $^{12}C^{16}O$ emission is optically thick and that of $^{13}C^{12}O$ is optically thin. The latter indicates quite nicely that two emission components, from sections at the front and back of the expanding molecular shell are being detected. *Half* the doppler velocity separations indicates the velocity of the outflowing gas. From Wannier and Linke (1978).

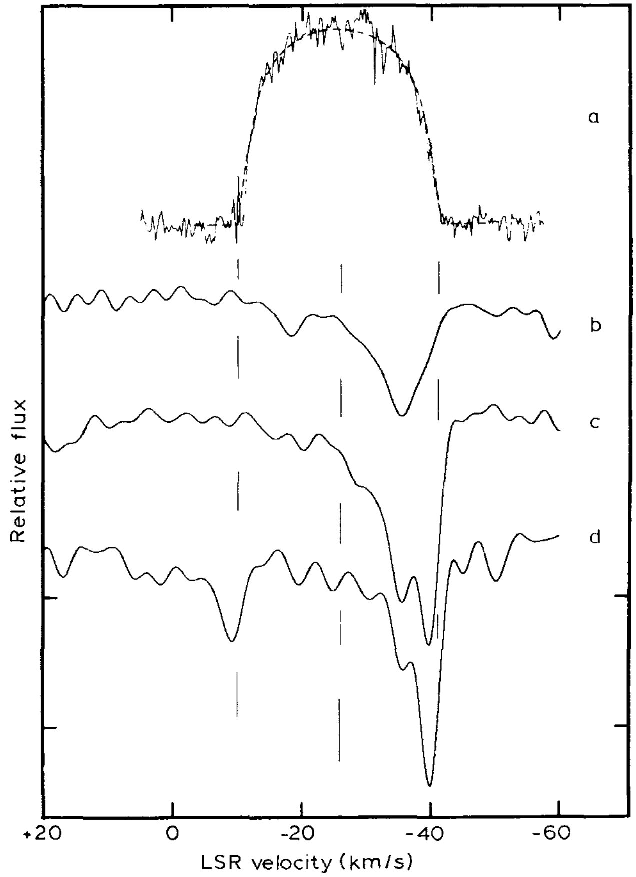

FIG. 34. CO line profiles in IRC+10216 (a) $J = 1 \rightarrow 0$ emission from Kuiper *et al.* (1976). (b) $v = 2$–0 absorption high excitation profile. (c) $v = 2$–0 absorption medium excitation profile. (d) $v = 2$–0 absorption low excitation profile. The clear doubling is interpreted as indicating a warm (300–700 K) inner shell expanding at 11 km/sec and a cooler (150–250 K) outer shell expanding at 16 km/sec. In all but (d) absorption is only observed from foreground gas. From Ridgway and Hall (1980).

Kitt Peak solar telescope Betz, McLaren and Spears (1979) have detected NH_3 and Betz (1981) has detected C_2H_4.

Radio studies yield information about the more tenuous outer shell which has a diameter of ~1 ly apparently consisting of molecules being continually ejected in puffs from the inner regions. This is a clear example of molecules being injected into the general ISM.

The detections of the radicals C_4H and C_3N were made in this object (Guélin and Thaddeus, 1977; Guélin, Green and Thaddeus, 1978) and until recently not detected elsewhere. The detection of the long chain polyyne, HC_7N, in IRC+10216 (Winnewisser and Walmsley, 1978) may not be a coincidence. In addition it may be significant that no ions have been detected in IRC+10216. McCabe, Smith and Clegg (1979) have carried out a chemical equilibrium study to match the molecular abundances assuming a freezing-in mechanism and have suggested that a compressed gaseous shell may be formed between the successive dust shells lost by the central star at each cycle.

It would be very interesting to discover more of these stars but so far IRC+10216 is by far the most well studied, mainly because it is the one of the brightest infrared objects. The interesting point is that apart from ions the same types of molecules appear to be observed being emitted from this star as are observed in some of the dense clouds.

Taurus molecular clouds

A particularly interesting region of dark clouds in Taurus is depicted in the beautiful photograph taken by Barnard (1927) (Fig. 35). This shows long black patches streaking across the sky obscuring the stars behind. Dotted around are also a few HII emission nebulae. Winnewisser, Churchwell and Walmsley (1979) have reviewed the radio studies in these types of dark clouds. Down near the left hand (SE) corner of this photograph lie the Taurus molecular clouds (TMC). TMC1, a molecular cloud buried in Heiles' cloud 2, in particular was found to be a very cold cloud (~10 K) with a high abundance of HC_3N (Morris *et al.*, 1976). In Fig. 36a a scale map of formaldehyde taken from that of Sume, Downes and Wilson (1975) is shown and Fig. 36b shows the appropriate region of Fig. 35

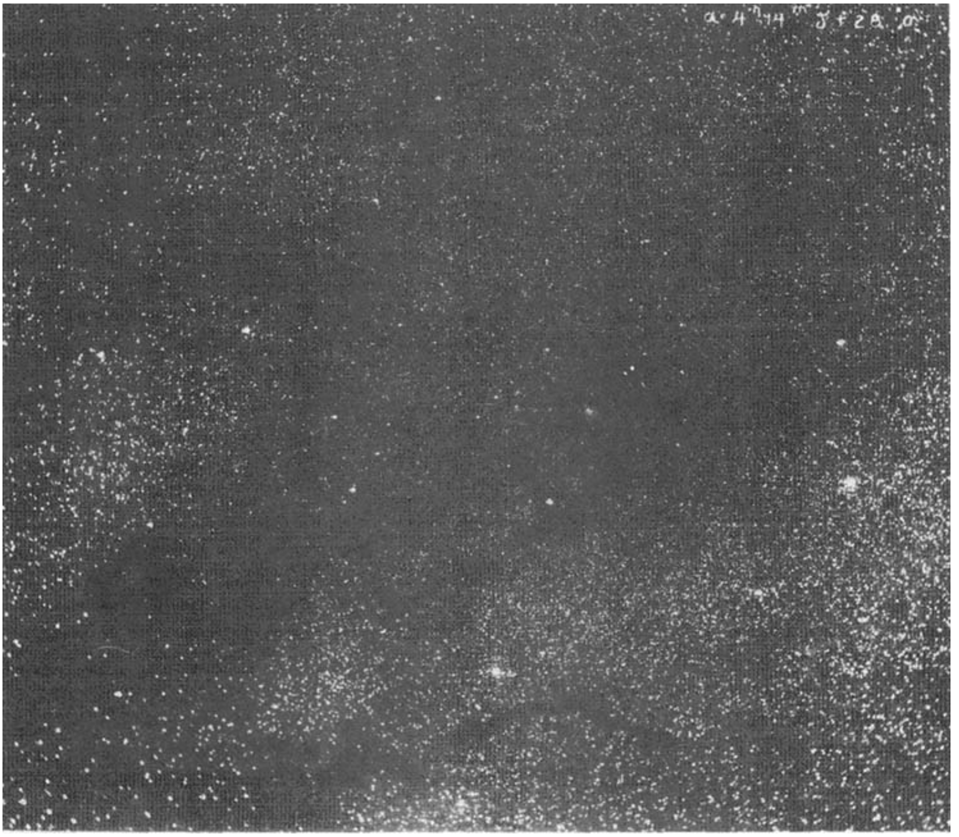

FIG. 35. The dark clouds in Taurus from Barnards (1927) Survey. The region of TMC1 is near the bottom LH (SE) corner and is shown to larger scale in Fig. 36.

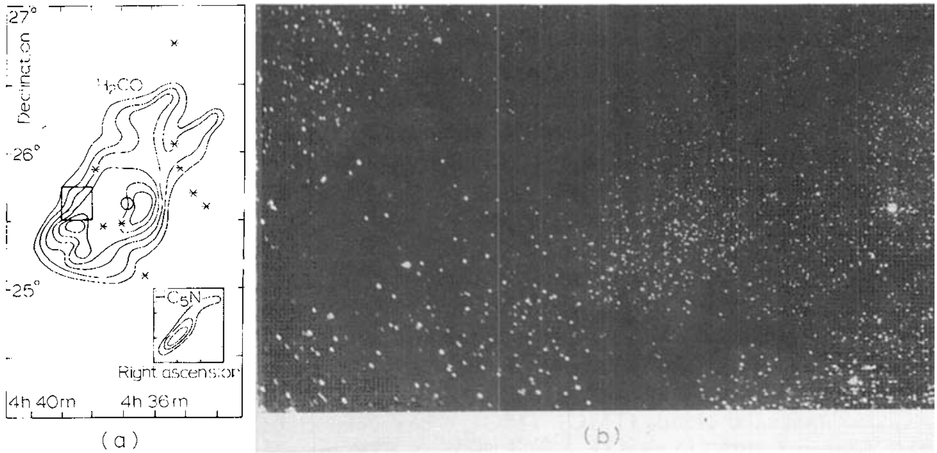

FIG. 36. (a) Shows a scale contour map of H_2CO from Sume, Downes and Wilson (1975). There is a minimum between the two H_2CO maxima which has been omitted. The inset shows the HC_5N map of Little *et al.* (1977) which has been enlarged and displaced from the square which lies on the side of the H_2CO cloud. This indicates the extent of the HC_5N cloud in TMC1. The left hand edge of the map coincides with the left hand edge of the photograph (b). There are two prominent stars near the map's centre.

expanded to scale. On the side of the formaldehyde hill, as indicated in Fig. 36, lies TMC1 and in the inset is given the HC_5N map of Little *et al.* (1978). This shows that the HC_5N cloud in TMC1 is an elongated ridge running from SE to NW with dimensions $\sim 10' \times 2' \cong 0.4 \times 0.08$ pc ($\cong 1.2 \times 0.24$ ly). The total mass of TMC1 appears to be $\sim 1\ M_\odot$ (Myers, Ho and Benson, 1979). TMC1 has also been mapped in NH_3 and the NH_3 cloud appears to be rather similar in size, shape and orientation but displaced so that the maximum coincides with the NW tip of the HC_5N cloud (Avery, 1980). The C_2H map (Wooten, *see* Avery, 1980) has twin peaks coinciding with the NH_3 and HC_5N peaks. From HC_3N measurements TMC1 appears to consist of $1' \times 3'$ core ($T = 20$ K) with $n_{H_2} \sim 6 \times 10^4$ cm^{-3} and $2.5' \times 10'$ halo ($T \sim 10$ K) with $n_{H_2} \sim 10^4$ cm^{-3}. The ratio n_{HC_3N}/n_{H_2} is 3×10^{-9} in the core and 4×10^{-8} in the halo (Avery, 1980). The detection of HC_7N (Fig. 22; Kroto *et al.*, 1978) and also that of HC_9N (Broten *et al.*, 1978) were both made at the HC_5N summit shown in Fig. 36a.

It is not at all clear whether the high cyanopolyyne abundance indicates that there may be something special about TMC1 and its neighbour TMC2 which is similar. Certainly one should note that they are some of the nearest molecular clouds (~ 100 pc $\cong 300$ ly) and so are some of the more readily studied. It is certainly important to keep in mind that the cyanopolyynes have large dipole moments and simple partition functions and that no other large molecules match them for (radio) visibility. However chains of at least nine and almost certainly more C atoms are clearly there and even taking into account line dilution one would expect a molecule, such as $CH_3(C{\equiv}C)_2C{\equiv}N$, to be more abundant and the spectra (Fig. 6) easier to detect than that of HC_9N, which does not appear to be the case.

Recently C_3N, first detected in IRC+10216 has been found in TMC1 (Friberg *et al.*, 1980). This is an interesting observation and suggests that there may be some close relationship between these two apparently rather different types of object. The possibility that the molecules detected in clouds such as TMC1 could have been produced in a circumstellar shell has been considered but presents problems (Dalgarno and Black, 1976).

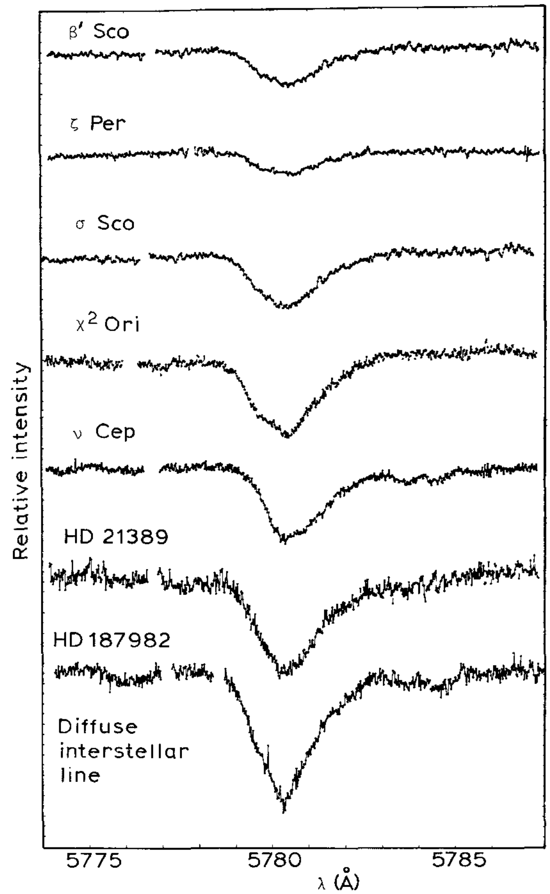

FIG. 37. A set of observations of the diffuse interstellar line at 5780 Å observed against several background stars by Snell and Vanden Bout (1981).

The question is, however, whether the problems with this molecule production mechanism are any more serious than are those that beset grain surface catalysis and gas phase ion–molecule schemes? It is not at all clear that they are.

Giant molecular clouds (GMC)

The tiny 4 ft Columbia University telescope has mapped vast regions of the galaxy in CO (Cohen *et al.*, 1979). Because it is small, it is possible to sample the large areas much more quickly than is feasible with a large telescope, though of course the high spatial resolution information is lost. How important this loss is to the conclusions drawn from low resolution data remains to be seen. Solomon and Sanders (1979) have carried out complementary higher resolution surveys with a larger telescope (Fig. 17). These and other studies have culminated in the result that the inner region of the galaxy is littered with GMC's like those in Orion (Fig. 26). Some 5000 or so appear to be concentrated in a roughly doughnut shaped ring 8–4 kpc in radius about the galactic centre. Their average mass is $\sim 10^6$ $M_\odot$ and their dimensions 100–200 ly. These clouds appear to be the largest and most massive, single, gravitationally-bound objects in the Galaxy. It is not clear how old these objects are, however they do appear to be at least 10^7 years old (Cohen *et al.*, 1979) and perhaps even older (Solomon and Sanders, 1979; Solomon, Scoville and Sanders, 1980). The Columbia studies indicate that the GMCs congregate mainly in the spiral arms but in the other study this is not so obvious. The surveys indicate that CO is taking over from the H 21 cm line as the major probe of galactic structure. The future task of mapping the Galaxy in CO and determining the relationships between large and small scale studies is the most important in galactic astronomy.

Comets

Similar types of molecule to those observed in the ISM have been detected in comets. The identification by Douglas (1951) of C_3 seems to fit rather neatly with the recent detection of carbon chain molecules. Ions and radicals have been identified and most interestingly so too has the ion H_2O^+ by Wehinger *et al.* (1974). This detection may be an indicator that icy water particles are a major component of the comet's structure. A short recent review of the chemistry of comets has been given by Oppenheimer (1980).

These objects demand further attention because they may well be test tube samples of the ISM brought directly to our doorsteps for analysis. We tend to think of comets as individual objects but it is possible that large clouds of comet-type objects exist which emit radio waves and it could be difficult to show that the cloud has such an inhomogeneous microstructure. Certainly the rôle of comet-size objects in the formation of stars and planets is not understood and it is possible that such objects form at some important phase of cloud collapse.

So far the molecules CH, CH^+, CN, C_2, C_3, CO, CO^+, CO_2^+, CS, OH, OH^+, H_2O^+, NH, NH_2, HCN, CH_3CN and N_2^+ have been detected in comets.

INTERSTELLAR CHEMISTRY

Ever since the detection of CH, CH^+ and CN the problem of how such molecules could be formed and survive in the ISM has been a field for study. The detections of OH and the further molecules detected since 1968 (*see* Table 1) have injected the study of interstellar chemistry with a new lease of life. It is not at all clear at this moment that we really understand the problem. New discoveries always seem to chip away at the confidence previously placed in a particular scheme. A general review has been presented by Watson (1976).

There are three main theories each with adherents who cling (like all true believers) with grim attachment to their own particular credo. The three main processes are:

1. Reactions on grain surfaces.
2. 2-Body gas phase ion molecule reactions.
3. Circumstellar shell formation followed by ejection into the ISM.

Of course all three may be important in general and one may be more or less important in one part of the ISM than another. The balance is certainly not at all clear.

In general two colliding atoms (i.e. two H atoms) cannot stick together unless the excess kinetic energy is taken away by a third body. This may be a simultaneously colliding third body, an emitted photon or an electron. The first process is governed by the 3-body collision lifetime

$$\tau_{3b} = \sim 3 \times 10^{23}/n^2 \text{ years} \qquad (28)$$