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# High-Resolution Interstellar Spectroscopy and Star Formation [and Discussion]

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# High-resolution interstellar spectroscopy and star formation

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During the past several years, high spatial and spectral resolution molecular spectroscopy has greatly contributed to our knowledge of the physics, dynamics and chemistry of interstellar molecular clouds and thus has led to a better understanding of the conditions that lead to star formation. According to their physical properties, molecular clouds can be grouped into four different types: (i) the dark clouds, (ii) the molecular clouds associated with $H^+$ regions, (iii) the 'protostellar' (or maser) environment, and (iv) the molecular envelopes of late-type stars. The first three types of cloud contain generally active regions of star formation. As typical examples the properties are discussed of individual clouds such as TMC 1 and L 183 for the cold clouds, S 140 and S 106 for the warm dark clouds with embedded infrared source, and Orion A for a region with associated $H^+$ region. In S 140, $NH_3$ is clumped on a scale of not more than 20″, whereas recent observations towards Orion A with the Very Large Array show that $NH_3$ clumps on a scale smaller than 5″.

## Introduction

Since the detection of the first polyatomic molecule ammonia, $NH_3$, in interstellar space in 1968 (Cheung *et al.* 1968), nearly 60 additional molecules have been identified. The excitement that molecular astronomy continues to arouse lies in the fact that it has given astronomers a powerful new tool for probing the physical conditions in molecular clouds, from their tenuous outer surroundings to their dense interiors. These clouds are opaque to visible and ultraviolet radiation, and reveal themselves optically as conspicuous dark regions that are not penetrated by starlight. However, molecular radio spectroscopy allows the properties of dark clouds to be derived with a fair amount of certainty. Molecular transitions are found in abundance throughout the entire centimetre, millimetre and far infrared regions of the electromagnetic spectrum. Owing to intrinsic properties associated with each molecular transition, different molecular lines trace regions with different physical conditions within interstellar clouds.

There is a reasonably large number of molecules that are widespread and abundant enough in the Galaxy and external galaxies to produce easily detectable spectra even in their rarer isotopic species. Thus, the molecular data have contributed substantially to our understanding of the physics, chemistry and dynamics of the interstellar medium, providing new information on a variety of long standing astronomical problems.

Four fruitful areas of astrophysics where interstellar molecules have strongly contributed over the past years can be mentioned.

1. Before the detection of interstellar molecules, galactic structure was essentially derived from stellar statistics and the 21 cm line of atomic hydrogen. Since then, the large-scale galactic distribution of neutral matter has been traced out by CO surveys, confirming that molecular clouds are preferentially located within the spiral arms.

2. The composition and chemistry of interstellar clouds remain an intriguing, highly active field of research. Apart from helium, interstellar molecules are essentially composed of the six

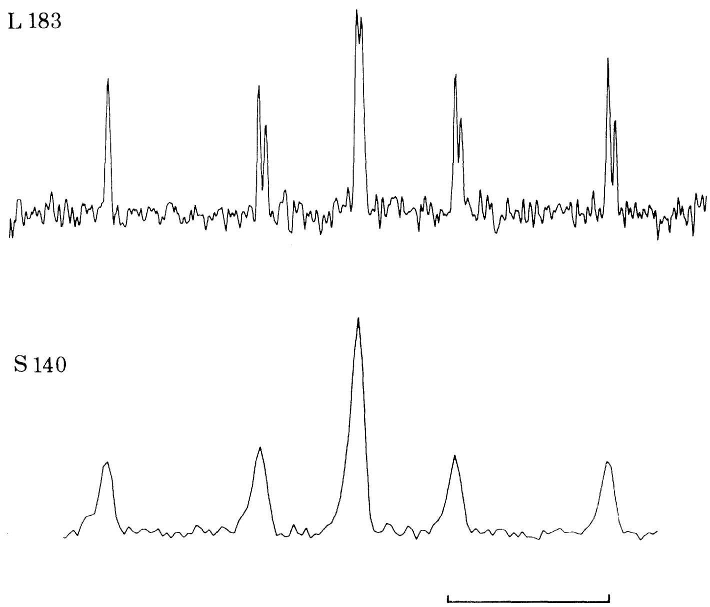


FIGURE 1. $NH_3(1,1)$ spectrum in L 183 and S 140. In S 140 ($d \approx 1$ kpc; 1 pc $\approx 3.09 \times 10^{18}$ cm) the magnetic hyperfine splitting is not resolved.

TABLE 1. CLASSIFICATION OF MOLECULAR LINE SOURCES

(From Winnewisser *et al.* (1979).)

| type | typical line widths km s$^{-1}$ | linear size pc | density cm$^{-3}$ | temperature K | mass/$M_\odot$ |
|---|---|---|---|---|---|
| dark dust clouds | 1 | 1–10 | $10^3$–$10^5$ | 10–20 | $10^2$–$10^4$ |
| molecular clouds associated with H II regions (giant) | 3–30 | 1–50 | $10^4$–$10^6$ | 20–80 | $10^5$–$10^6$ |
| 'Protostellar' environment | 0.1–2 | $10^{-5}$–$10^{-3}$ | $> 10^5$ | 100–1000 | 10 |
| envelopes of late type stars | 25 | 0.001–5 | $10^4$–$10^6$ | 100–1000 | $10^{-2}$ |

most abundant elements: hydrogen, carbon, nitrogen, oxygen, silicon and sulphur. In addition, a fair number of the rarer stable isotopes of these atoms have been detected in a large variety of molecules. Since these elements represent different processes of element synthesis (H, D and He are largely of cosmological origin, whereas the other elements have been produced by stellar nucleosynthesis) they are indicators of the past chemical evolution of the Galaxy. Detailed molecular observations have revealed that significant differences exist in the abundances between the isotopes in the Solar System and the corresponding values in the interstellar medium. These are interpreted as a measure of past stellar processing. Recent accounts of isotope work have been given by Wannier (1980) and Penzias (1980).

3. The subject of mass loss from stars is an area of considerable interest, since it is associated with the evolution of stars from their earliest formation processes to the unstable phases of their

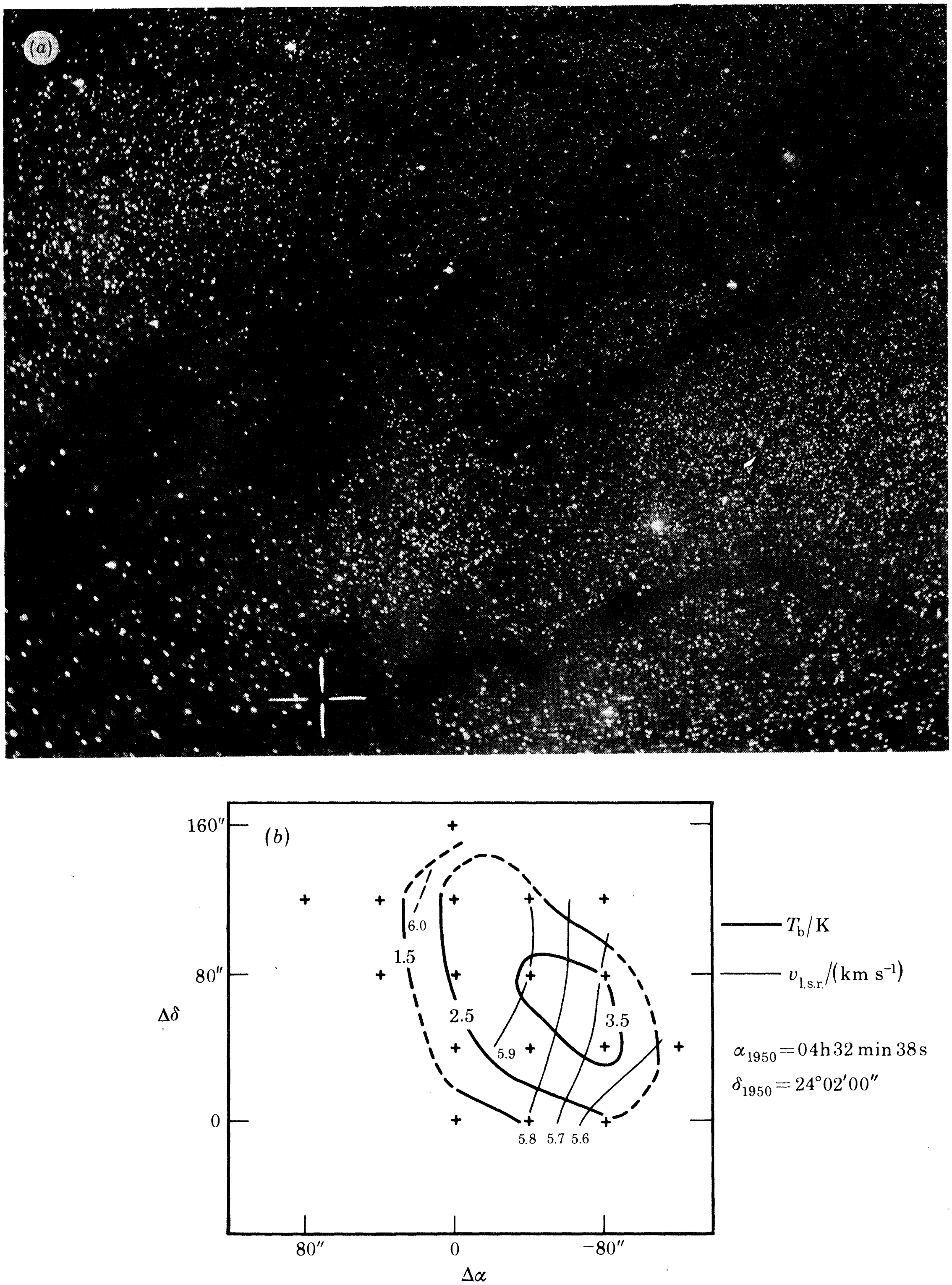


FIGURE 2. (*a*) Reproduction of a section of the Taurus region taken from the photographic *Atlas of selected regions in the Milky Way* by Barnard (1927). The distance to the Taurus region is *ca.* 140 pc. (*b*) The $NH_3$(1,1) map of TMC 3 (L 1533). The constant velocity contours in TMC 3 indicate rotational motion on a scale of 6 km s$^{-1}$ pc$^{-1}$.





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latest stages of evolution. It is the major process for recycling matter in the Galaxy. During the final stages of formation, young stars or protostellar objects can eject, by various mechanisms, large amounts of mass (*ca.* $10^{-4}$ $M_{\odot}$ per year) back into the interstellar cloud out of which they formed. The infrared star cluster in the centre of the Orion nebula, a prototype star-formation region, represents a well studied (but not necessarily well understood) example of young objects that are losing mass. Some recent results will be discussed later. On the other hand, old, evolved stars are often surrounded by a thick circumstellar envelope of gas and dust into which they eject freshly processed matter. The dense shell of the carbon star IRC +10216 is one of the best studied examples. Mira variables are also often surrounded by dense envelopes.

4. There is now strong evidence from a large body of observational data that star formation is occurring in molecular clouds and probably only there. This information comes mainly from high-resolution molecular radio spectra and infrared spectroscopy.

To understand the conditions that lead to star formation and how the actual formation process takes place, a detailed knowledge is needed of the physical parameters and kinematics of molecular clouds and their environment.

The increasing clarity of our picture of the processes of star formation in molecular clouds is in considerable part due to the success of two experimental advances: improvements in the sensitivity of detecting systems permit the study of weaker spectral lines, while at the same time high-resolution interstellar spectroscopy has revealed fine details within individual clouds. In interstellar spectroscopy, 'high resolution' pertains to both high spectral and spatial resolution. It is the latter area where significant progress has been made, pushing the angular resolution to the point where, in nearby clouds, objects of almost stellar size (i.e. protostars) can be resolved.

As radio telescopes are diffraction-limited instruments, their angular resolution is determined (for wavelength $\lambda$/mm and telescope diameter $D$/m) by the relation for the half-power beam-width $\theta$/min

$$\theta \approx 4.2\lambda/D.$$

The spatial resolution of the Effelsberg 100 m radio telescope at 23 GHz is close to 40″. The effective diameter can be increased beyond the size of single-dish reflectors by simultaneously using two or more telescopes at large distances from each other (a radio interferometer). Baselines from several hundred meters to several thousand kilometres (distances between continents) have been used, pushing the angular resolution to 0.0001″ in some cases.

As the angular resolution improves, smaller areas within the clouds are being sampled. This often results in smaller linewidths, since contributions to the observed linewidth from small-scale turbulence and systematic motions within the beam are decreased. For quiescent clouds the observed linewidths are close to the thermal width, which for cold dark clouds is near 10 K. Figure 1 shows the $NH_3(1,1)$ emission from two dark clouds, as an example of high spectral resolution. Since the linewidth contains a wealth of physical information, which is spectroscopical and astronomical in nature, they can be used together with other physical parameters, such as cloud size, to classify the molecular clouds. Although there exists nothing like a standard molecular cloud, one can group the clouds roughly in four classes (Winnewisser *et al.* 1979) as summarized in table 1.

The most conspicuous feature of the dark dust clouds is the extremely narrow linewidth of every molecular transition found. In the second class, molecular clouds associated with $H^+$ regions, the linewidths are much larger. These sources contain OH and $H_2O$ masers. Their

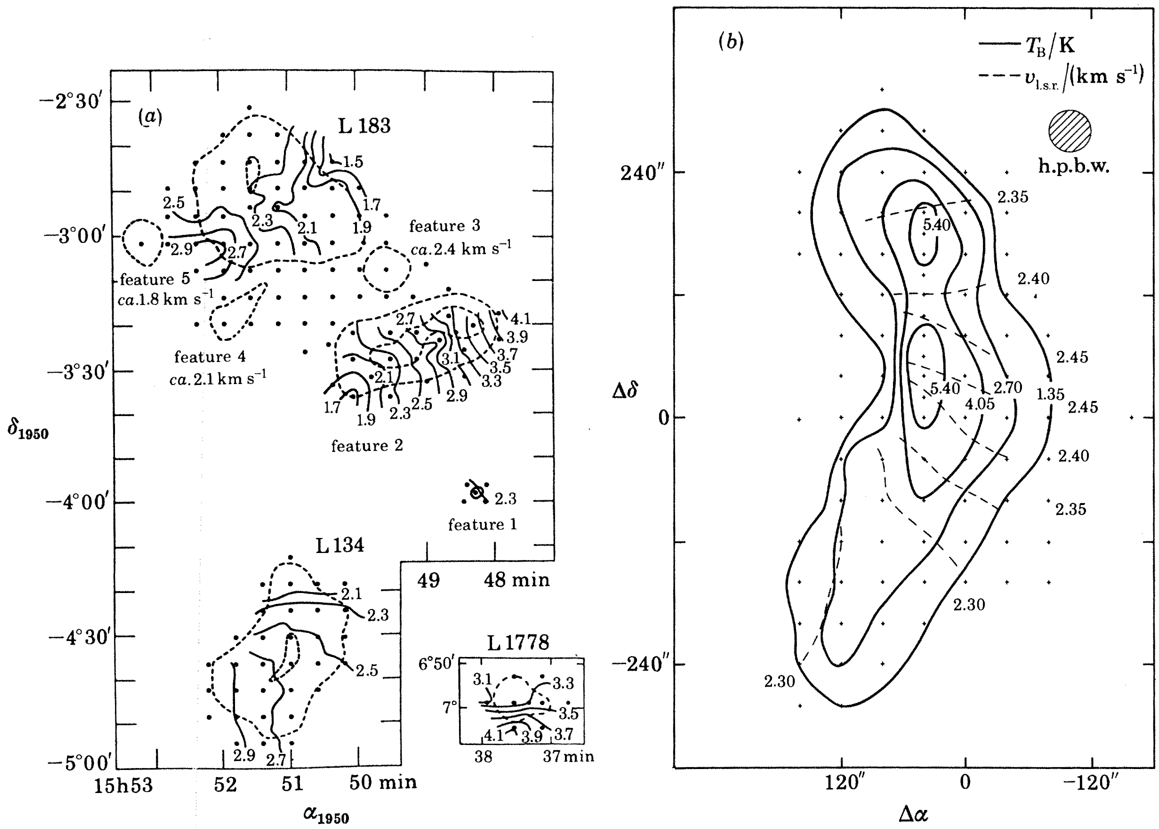


FIGURE 3. (*a*) Map of the L 183–L 134 cloud complex in the 6 cm $H_2CO$ absorption line is indicated by the dashed lines (inner and outer contours). The equal velocity contours (kilometres per second) are shown as solid lines. (From Clark & Johnson (1981).) (*b*) The central core of L 183 in $NH_3$. Dashed contours show the approximate velocity distribution. (From Ungerechts *et al.* (1980).)

close spatial coincidence with infrared sources and compact H$^+$ regions suggests the presence of young stars or current star formation. The maser or protostellar environment forms the third class and usually constitutes small regions embedded in a large molecular cloud. Finally, the fourth class consists of the circumstellar envelopes that often surround and completely obscure late-type stars. These are of considerable astrophysical interest because they are returning processed matter back into the interstellar medium.

Below I report on some recent interstellar molecular line work done by our group. I shall summarize the characteristics indicative of star formation for the first two classes of molecular clouds, i.e. the dark clouds and the molecular clouds associated with H$^+$ regions. Their temperature morphology is the primary criterion for the discussion, which will be limited to results obtained from $NH_3$ observations.

## DARK CLOUDS AND MOLECULAR CLOUDS ASSOCIATED WITH H$^+$ REGIONS

### (*a*) *Taurus complex and* L 183: *cold clouds*

Dark nebulae or dark dust clouds have been recognized for a long time. In his 'Account of some Observations tending to investigate the Construction of the Heavens', Herschel (1784, p. 448) notes in his description of the nebulae 'that the spaces preceding them were generally quite deprived of their stars, so as often to afford many fields without a single star in it'. He found himself as he figuratively expressed it 'on nebulous ground'. These are the regions in the sky where no stars are observable or where the number and brightness of background stars is drastically reduced relative to the surrounding areas. A particularly beautiful example of conspicuous dust clouds is given in figure 2*a*, which is a reproduction of Barnard's plate 5 of the Nebulous Region in Taurus (Barnard 1927). In his description of this region Barnard comments that 'very few regions of the sky are so remarkable as this one...', and he continues '... and bears strongest proof of the existence of obscuring matter in space'.

The Taurus region is one of many dark dust cloud complexes containing a sizeable number of small ($l \approx 0.1$ pc; 1 pc $= 3 \times 10^{18}$ cm), dense ($n(H_2) \approx 10^4\ cm^{-3}$), cool ($T_{kin} \approx 10$ K), low-mass ($M < 5M_{\odot}$) fragments. Among the well studied cloudlets (TMC 1, TMC 2, TMC 3, L 1544, B 213) (see Churchwell *et al.* 1978; Myers *et al.* 1979; Avery 1979; Little *et al.* 1979) in the Taurus region, TMC 1 assumes a prominent role, for it encompasses a large projected area and has an unusually high abundance of cyanopolyynes (i.e. linear carbon chain molecules terminated by nitrogen on one end and hydrogen on the other). The cloud is elongated in a southeast–northwest direction forming a ridge of molecular emission. This ridge is present both in the cyanopolyyne and ammonia emission, but the maximum of the $NH_3$ emission is displaced from the cyanopolyyne maxima. High spectral resolution $HC_3N$ profiles (Toelle *et al.* 1981) in TMC 1 indicate that a slow rotation about the major axis is taking place, with an upper limit of 0.7 km s$^{-1}$ pc$^{-1}$ on any overall gradient. Thus, centrifugal force is currently of little dynamical importance. It is, however, quite likely that centrifugal force was important in the evolution of TMC 1. There has been considerable recent discussion of magnetic braking (Field 1978; Mouschovias & Paleologou 1979; Mestel & Paris 1979) as an effective means in removing angular momentum from condensed objects such as TMC 1 and hence permitting star formation if the magnetic field is sufficiently large. Another source in the Taurus region, TMC 3, clearly shows a systematic velocity gradient of 6 km s$^{-1}$ pc$^{-1}$, which can be interpreted as a rotation since the velocity contours of $NH_3$ are nearly parallel to each other as shown in figure 2*b* (Ungerechts 1980). Although the density estimates for TMC 3 are uncertain it is believed that gravitational and rotational energy are closely balanced. For most of these small condensations temperature and density are such that the cloud's mass $M$ is close to the critical mass $M_J$ calculated from the Jeans criterion for gravitational collapse. If the mass $M$ of a cloud is larger than the Jeans mass $M_J$,

$$M > M_J \approx 3.7\,(T_{kin}/10)^{\frac{3}{2}}\,(n(H_2)/10^4)^{-\frac{1}{2}}\,M_{\odot},$$

then the cloud is gravitationally unstable (ignoring effects such as magnetic fields and rotation). For a typical kinetic temperature of $T_{kin} = 10$ K and densities of $n(H_2) \approx 10^4\ cm^{-3}$ the critical mass is *ca.* 4 $M_{\odot}$. Thus, most of these clouds are not far from the critical conditions; however, the extremely narrow linewidth suggests that these clouds are currently in a quiescent phase of temporary gravitational equilibrium. (Thus slow accretion of matter or external influences such as shock waves may trigger eventual collapse.) Among other dark clouds where rotation has been detected, the system of interstellar clouds near L 183, L 134 is interesting for the observer and the theoretician alike. These sources are some of the closest molecular line sources ($d \approx 100$ pc), and are therefore extremely well suited for molecular line mapping.

Recent spectral line mapping of the extended regions of L 134 and L 183 by using the 2 and 6 cm $H_2CO$ transitions (Clark & Johnson 1981) and of the core region of L 183 by $NH_3(1,1)$

TABLE 2. CHARACTERISTICS OF DARK CLOUDS

(From Ungerechts (1980).)

| | distance/pc | size/pc | $T_r(NH_3)$/K | $T_{ex}(CO)$/K | $\Delta V_{int}$/km s$^{-1}$ | d$v$/d$r$/km s$^{-1}$pc$^{-1}$ | lg $N(NH_3)$/cm$^{-2}$ | lg $n(H_2)$/cm$^{-3}$ |
|---|---|---|---|---|---|---|---|---|
| cold dark clouds | | | | | | | | |
| TMC 1 | 140 | $0.06 \times 0.60$ | 10 | 10 | 0.30 | $< 0.7$ | 15.0 | 4.5 |
| TMC 3 | 140 | $0.06 \times 0.12$ | 9 | — | 0.30 | 6 | 15.0 | 4.5 |
| L 183 | 100 | $0.06 \times 0.17$ | 9 | 9 | 0.22 | $< 2$ | 15.5 | 4.5 |
| warm dark clouds | | | | | | | | |
| S 140 | 1000 | $1.2 \times 1.2$ | 13–23 | 15–35 | 1.0–2.0 | — | 15.0 | 4–5 |

and (2,2) (Ungerechts *et al.* 1980) indicate that the velocity gradient apparently reverses between the extended cloud of L 183 and its core region (figure 3). The observed data could be explained by one of two types of motion: radial motion or rotation, together with a time-dependent magnetic braking mechanism, is able to explain the observed reversal of angular momentum in L 183. Radial motions seem to be more problematic since this would imply that, if the material in the outer region is falling inwards, a small-scale outflow in the core region would have to take place, probably driven by a stellar wind. However, there is no indication of an embedded heat source (protostar), nor is the cloud gravitationally unstable. The Jeans length is 0.1 pc, which is approximately the thickness of the structure observed in $NH_3(1,1)$ by Ungerechts *et al.* (1980) and is consistent with the observed intrinsic linewidths of 0.2 km s$^{-1}$. Small-scale systematic motions (0.1 km s$^{-1}$) are less than one would expect if expansion at the speed of sound (0.28 km s$^{-1}$) were taking place. In summary, L 183, just like the Taurus cloudlets, seems to represent a quiescent stage in which the cloud is in gravitational equilibrium. There are probably many other clouds with similar characteristics.

### (*b*) *S* 140: *a warm cloud*

In contrast to the cold dark clouds, whose temperature ranges between 8 and 15 K, the warm dark clouds have temperatures greater than 15 K and are heated by embedded objects or stars located nearby. Table 2 summarizes the most important characteristics of some selected cold and warm dark clouds. All of the warm dark clouds show strong indication of current star formation. Some or all the following observational phenomena are associated with them.

1. There are usually embedded infrared sources that provide the heat supply to the cloud. The infrared spectra of these sources often show strong silicate absorption at 9.7 μm.
2. Associated with the infrared sources is strong maser emission of OH and $H_2O$ which often shows 'shell-type' features, characteristic of an expanding envelope.
3. $H_2$ vibrational emission lines at 2.2 μm ($v = 1 \rightarrow 0$) are present.
4. High excitation molecular emission exists. The hyperfine ratios of molecular transitions are not in l.t.e. The $NH_3(1,1)$ is particularly susceptible to this effect.
5. Ultracompact $H^+$ regions are often associated.
6. High-velocity molecular emission (CO) is often associated with sources of active star formation.

Many of these phenomena are explained by a model that assumes, as the basic process, an outflow of matter from one or several sources embedded in the molecular cloud.

One of the warm dark clouds exhibiting many of these phenomena and which has been studied in great detail is S 140–L 1204. This source has received much attention during the past years,

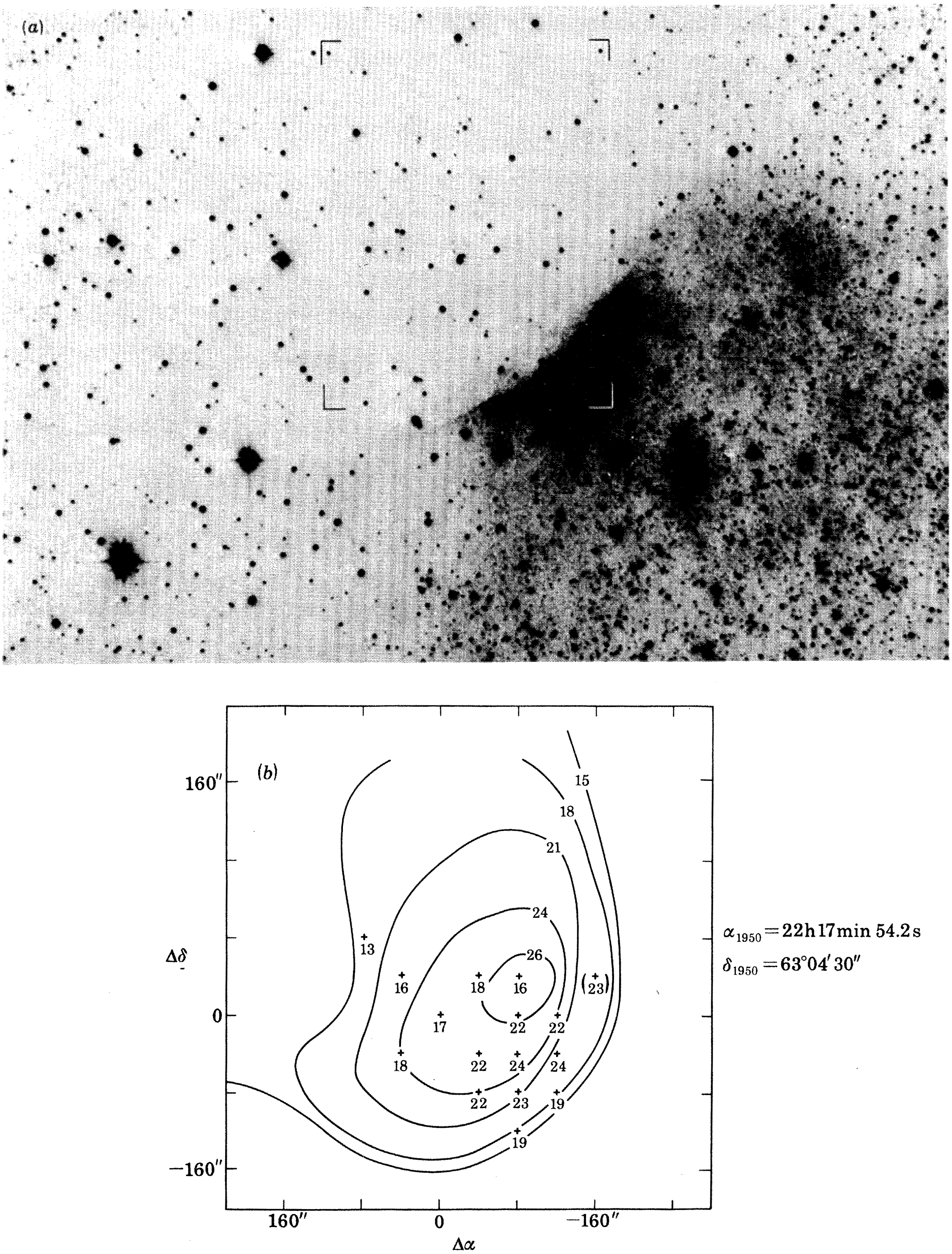


FIGURE 4. The S 140–L 1204 region. (*a*) Section from the Palomar Sky Survey. The frame indicates the approximate position of the CO map. Only that portion of the CO map from Blair *et al.* (1978) is reproduced that is of interest to the $NH_3$ rotational temperature determination. (*b*) The crosses in the CO map of S 140 indicate the positions where $NH_3$ has been measured and the rotational temperature determined. Numbers indicate the value of $T_r(NH_3)$. (*c, d*) Sample spectra for the $NH_3(1,1)$ and (2,2) transitions (*c*) (drawn to scale) and the $H_2O$ maser emission spectrum (*d*).

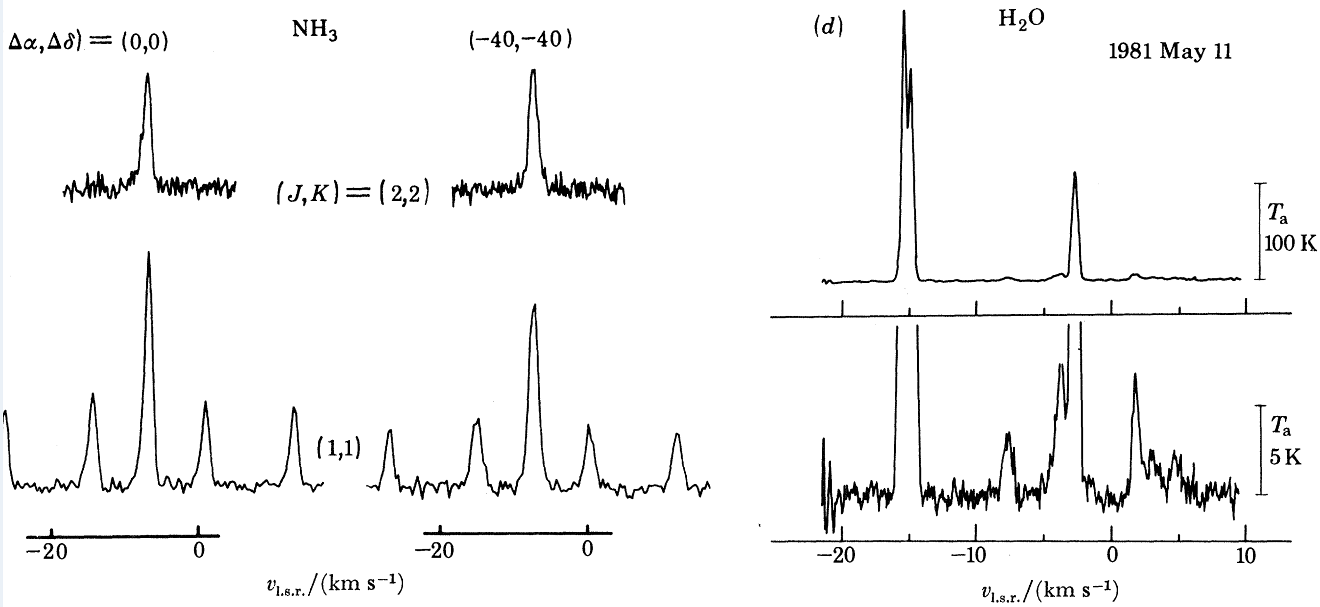


FIGURE 4*c*, *d*. For description see opposite.

partly because it is thought to be an active region of star formation and partly because it resembles the Orion molecular cloud but with a much simpler structure and on a smaller scale. It has been extensively mapped by several molecular transitions, notably CO (Blair *et al.* 1978). Figure 4 gives an optical reproduction of the S 140 area taken from the Palomar Sky Survey together with a small portion of the CO temperature contours (Blair *et al.* 1978). Almost coinciding with the CO temperature maximum is a group of three infrared sources IRS 1,2,3 (Beichman *et al.* 1979; Dinerstein *et al.* 1979). Strong far infrared emission has also been detected (Harvey *et al.* 1978; Tokunaga *et al.* 1978; de Muizon *et al.* 1980).

The $NH_3$ molecule is particularly well suited for studying the temperature distribution because the rotational temperature $T_r$ ran be determined easily by measuring the ratio of the intensities of the $NH_3$(1,1) and (2,2) transitions. Rotational temperatures have been determined for all the points indicated in figure 4 and the values for $T_r$ are given. The maximum $T_r$ coincides with the infrared (i.r.) position and decreases smoothly away from it. Sample spectra of $NH_3$(1,1) and $H_2O$ are given as well. The present observational data in S 140/L 1204 support a picture in which the i.r. sources (IRS 1,2,3 have a total luminosity of $L_{i.r.} \approx 4 \times 10^5 L_\odot$ (de Muizon *et al.* 1980)) heat the dense molecular cloud. $NH_3$ is clumped on a scale of $\leqslant 20''$, which corresponds to a linear size of 0.1 pc. Clumps of that size are resolved for nearby dust clouds like L 183. For $T_k = 20$ K (30 K) and $n(H_2) = 10^5\ cm^{-3}$, the Jeans length is 0.04 pc (0.05 pc), and thus the clumps are close to gravitational equilibrium. Fragmentation near the i.r. source is in an advanced state (Ungerechts *et al.* 1981).

### (*c*) *Orion molecular cloud and S* 106: *hot clouds*

One of the important conclusions of the S 140 $NH_3$ observations is that $NH_3$ may be clumped on a scale of 20″. Recently, Pauls *et al.* (1981) mapped the $NH_3$ (3,3) transition toward the KL infrared nebula in the Orion molecular cloud with the Very Large Array and find that $NH_3$ does indeed clump on a scale smaller than 5″.

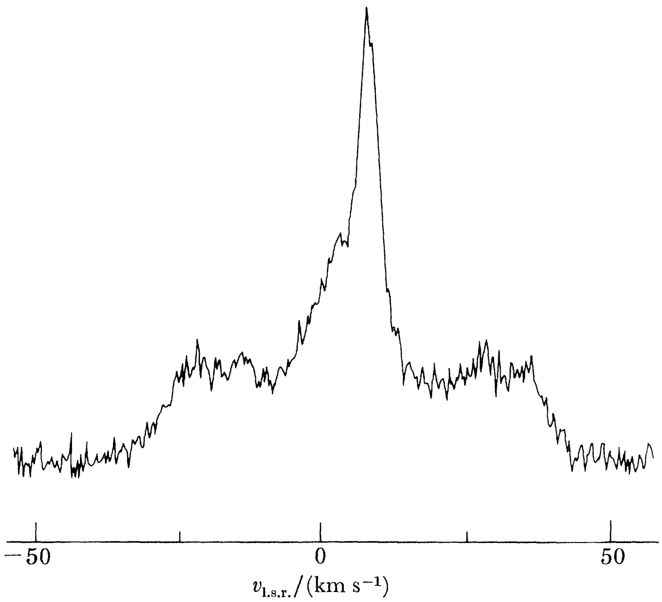


FIGURE 5. $NH_3(3,3)$ line profile at the Orion–KL nebula. Narrow and broad components are clearly visible, i.e. the spike, the hot core and the plateau emission (see text).

Although the structure of the Orion molecular cloud is much more complicated than that of S 140, it is the prototype source for detailed studies of the phenomena associated with star formation. The Orion molecular cloud and the infrared core have been studied using many different molecular transitions (see, for example, Winnewisser *et al.* (1979) for an overview).

Most molecular line profiles observed towards the Orion molecular cloud show three distinct features: (i) the 'spike', a strong but narrow line ($\Delta v \approx$ 3–4 km $s^{-1}$) centred at $v_{\mathrm{l.s.r.}} \approx 9$ km $s^{-1}$; (ii) the 'hot core', a weaker but still narrow line at 3 km $s^{-1}$ and (iii) a broad line ($\Delta v \approx$ 30 km $s^{-1}$) often referred to as the 'plateau' feature. The broad line is only seen near the infrared nebula, whereas the narrow, strong component is spatially extended over a large area. These three components are clearly seen in the $NH_3$ observations of Wilson *et al.* (1979), and figure 5 shows the $NH_3(3,3)$ profile reproduced from this work. The broad plateau feature with the superimposed narrow features at 9 and 3 km $s^{-1}$ are clearly seen. From the $NH_3$ maps of Wilson *et al.* (1979) it is evident that both the 'plateau' and the 'hot core' are confined to the KL nebula.

Very recently, high spatial resolution maps have become available for $NH_3(3,3)$ (Pauls *et al.* 1981), and for the infrared continuum emission at 20 μm (Downes *et al.* 1981). Both maps have a resolution of about 2″. While the latter map reveals many new infrared peaks showing good correlation with $H_2O$ maser positions, the V.L.A. map of $NH_3(3,3)$ indicates that the ammonia distribution has two distinct features. These are spatially close but not coincident with the projected i.r. positions of the map of Downes *et al.* (1981). In particular, they do not coincide with the compact infrared source IRc 2. The IRc 2 source has a very deep silicate feature at 9.7 μm and coincides with the SiO maser position. Genzel *et al.* (1981) find from their proper motion study of the $H_2O$ maser sources at 18 km $s^{-1}$ in the KL nebula that all masing gas cloudlets have a common origin from which large-scale outflow takes place. This point coincides with IRc 2, to within 5″, suggesting that all outflow phenomena are associated with IRc 2 rather than any of the other i.r. sources. IRc 2 loses mass at a rate of $10^{-4}$ to $10^{-3}$ $M_{\odot}$ per year,

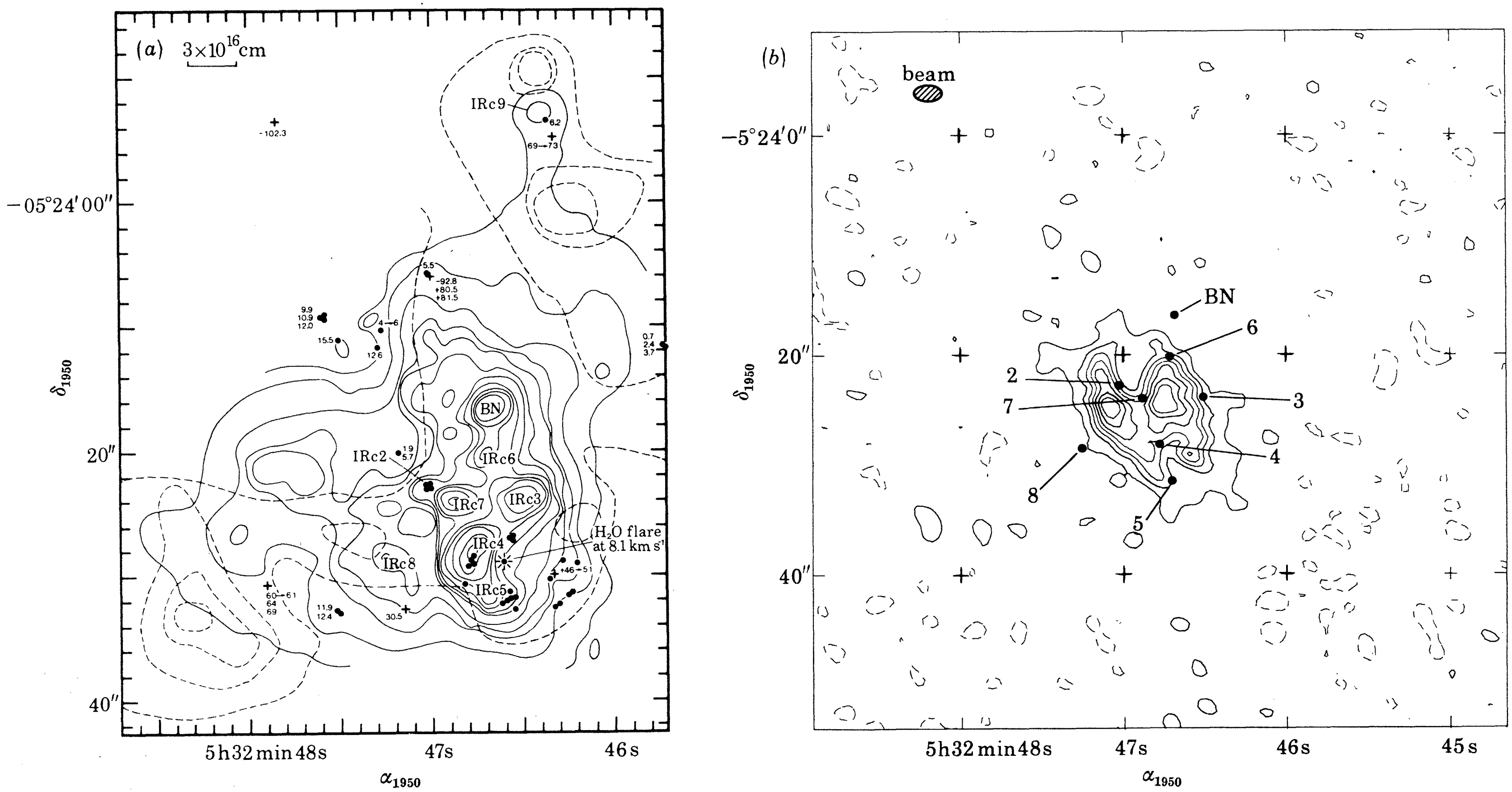


FIGURE 6. (*a*) Map of the Kleinmann–Low nebula at the wavelength of 20 μm, together with the $H_2O$ maser positions (dots and crosses) and the $v = 1 \rightarrow 0$ S(1) $H_2$ emission (broken contours). (From Downes *et al.* (1981).) (*b*) V.L.A. map of the $NH_3$ broad emission from the KL nebula. (From Pauls *et al.* (1981); the bandwidth was 6.5 MHz centred at 0 km $s^{-1}$.)

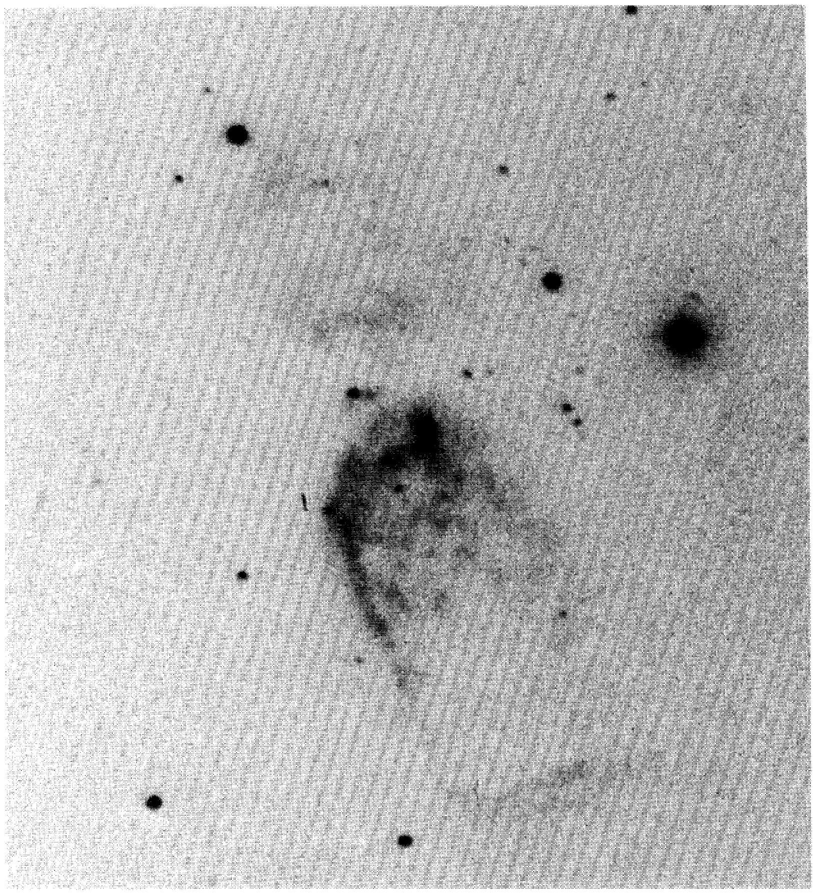

FIGURE 7. The infrared photograph (at 0.92 μm (I)) taken with the 2.2 m telescope on Calar Alto, Spain, probably reveals the central exciting star of the S 106 region (Elsässer, personal communication 1981).

and is presumed to be a young massive star in the last stages of formation. In figure 6, the 20 μm map of Downes *et al.* (1981) and the $NH_3(3,3)$ broad-band map of Pauls *et al.* (1981) are both reproduced. Recent aperture synthesis maps of SO, SiO, HCN and $HCO^+$ (Welch *et al.* 1981) show that SO peaks close to IRc 4 rather than IRc 2. Nevertheless the data are consistent with the idea of mass outflow whereby a common source provides the energy for the flow.

Observations of other molecular clouds with embedded $H_2O$ maser sources in the Galaxy suggest that mass loss is rather common in many regions of current star formation. The region S 106, which is considerably simpler than the Orion–KL complex, shows a strong $H_2O$ maser source and an ultracompact $H^+$ region sandwiched between two molecular clouds. Although earlier low spatial resolution measurements have been made (Little *et al.* 1980*b*), recent high spatial resolution measurements with the 100 m telescope reveal a wealth of fine detail. For the two $NH_3$ clouds, the hyperfine ratios of the (1,1) transition show spatially dependent non-l.t.e. effects. The $H_2O$ maser found earlier by Cesarsky *et al.* (1978) has disappeared. Instead a new strongly time-dependent maser source appeared between the two $NH_3$ clouds. The position of this $H_2O$ maser seems to agree with the infrared stellar object recently identified by Eiroa *et al.* (1979) as the single exciting source of this bipolar nebula. Figure 7 presents a recent infrared photograph (at 0.92 μm (I)) of the S 106 region taken with the 2.2 m telescope on Calar Alto, Spain (Elsässer, personal communication 1981). It clearly shows the pointlike object located

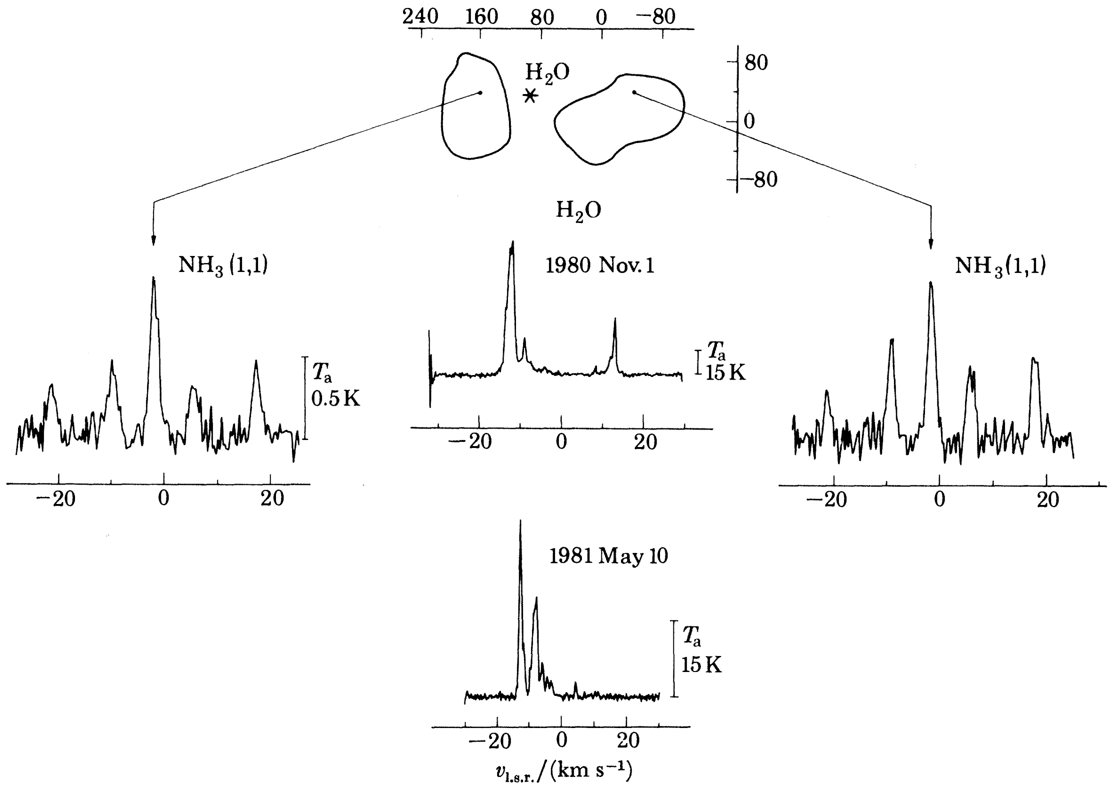


FIGURE 8. $NH_3$ and $H_2O$ spectra from S 106 and relative position of the molecular clouds and $H_2O$ maser source. The contours indicate $T_a$ = 0.5 K, and the offsets are relative to $\alpha_{1950}$ = 20 h 25 min 25 s; $\alpha_{1950}$ = 37°12′ 30″. The $H_2O$ maser profile has changed considerably between 1980 Nov. 1 and 1981 May 10. The shell-type feature has disappeared in the 1981 May 10 spectrum. It may also be noticed that the maser discovered by Cesarsky *et al.* (1978) is not seen.

between the two nebulous shells, the southern rim of which is particularly conspicuous. The positions of the molecular clouds are to the east and west and are shown relative to the new $H_2O$ maser position in figure 8, together with some recent spectra of $NH_3$ and $H_2O$. It remains to be seen whether the $NH_3$(1,1) transition will also show time-dependent variation of its hyperfine ratios.

I wish to express my sincere gratitude to many of my colleagues for making some of their most recent work available to me for this summary. In particular, I wish to thank D. Downes, T. Pauls, H. Ungerechts and T. L. Wilson. I wish to thank H. Elsässer for making available the infrared photograph of S 106.

## REFERENCES (Winnewisser)


Avery, L. W. 1979 In *Interstellar molecules* (I.A.U. Symposium no. 87) (ed. B. M. Andrew), pp. 47–58.

Barnard, E. E. 1927 *Atlas of selected regions of the Milky Way* (ed. E. B. Frost & M. R. Calvert). Carnegie Institution of Washington.

Beichman, C. A., Becklin, E. E. & Wynn-Williams, C. G. 1979 *Astrophys. J. Lett.* **232**, L47.

Blair, G. N., Evans, N. J. III, Vanden Bout, P. A. & Peters, W. L. 1978 *Astrophys. J.* **219**, 896.

Cesarsky, C. J., Cesarsky, D. A., Churchwell, E. & Lequeux, J. 1978 *Astron. Astrophys.* **68**, 33–39.

Cheung, A. C., Rank, D. M., Townes, C. H., Thornton, D. D. & Welch, W. J. 1968 *Phys. Rev. Lett.* **21**, 1701–1703.

Churchwell, E., Winnewisser, G. & Walmsley, C. M. 1978 *Astron. Astrophys.* **67**, 139.
Clark, F. O. & Johnson, D. R. 1981 *Astrophys. J.* **247**, 104–111.
de Muizon, M., Rouan, D., Lena, P., Nicollier, C. & Wijnbergen, J. 1980 *Astron. Atrophys.* **83**, 140.
Dinerstein, H. L., Lester, D. F. & Rank, D. M. 1979 *Astrophys. J. Lett.* **227**, L 39.
Downes, D., Genzel, R., Becklin, E. E. & Wynn-Williams, C. G. 1981 *Astrophys. J.* **244**, 869–883.
Eiroa, C., Elsässer, H. & Lahulla, J. F. 1979 *Astron. Astrophys.* **74**, 89–92.
Field, G. B. 1978 In *Protostars and planets* (ed. T. Gehrels), p. 243. University of Arizona Press.
Genzel, R. & Downes, D. 1979 *Astron. Astrophys.* **72**, 234.
Genzel, R., Reid, M. J., Moran, J. M. & Downes, D. 1981 *Astrophys. J.* **244**, 884–902.
Harvey, P. M., Campbell, M. F. & Hoffmann, W. F. 1978 *Astrophys. J.* **219**, 891.
Herschel, W. 1784 *Phil. Trans. R. Soc. Lond.* **74**, 437–451.
Little, L. T., MacDonald, G. H., Riley, P. W. & Matheson, D. N. 1979 *Mon. Not. R. astr. Soc.* **189**, 539.
Little, L. T., Brown, A. T., MacDonald, G. H., Riley, P. W. & Matheson, D. N. 1980*a* *Mon. Not. R. astr. Soc.* **193**, 115.
Little, L. T., MacDonald, G. H., Riley, P. W. & Matheson, D. N. 1980*b* In *Interstellar molecules* (I.A.U. Symposium no. 87) (ed. B. H. Andrew), pp. 89–90.
Mestel, L. & Paris, R. B. 1979 *Mon. Not. R. astr. Soc.* **187**, 337.
Mouschovias, T. C. & Paleologou, E. V. 1979 *Astrophys. J.* **230**, 204.
Myers, P. C., Ho, P. T. P. & Benson, P. J. 1979 *Astrophys. J. Lett.* **233**, L 141.
Pauls, T., Martin, R. M., Bieging, J. H. & Wilson, R. L. 1981 (In preparation.)
Penzias, A. A. 1980 *Science, N.Y.* **208**, 663–669.
Toelle, F., Ungerechts, M., Walmsley, C. M., Winnewisser, G. & Churchwell, E. 1981 *Astron. Astrophys.* **95**, 143–152.
Tokunaga, A. T., Erickson, E. F., Caroff, L. J. & Dana, R. A. 1978 *Astrophys. J. Lett.* **224**, L 19.
Ungerechts, H. 1980 Doctoral dissertation, University of Bonn.
Ungerechts, H., Walmsley, C. M. & Winnewisser, G. 1980 *Astron. Astrophys.* **88**, 259–266.
Ungerechts, H., Walmsley, C. M. & Winnewisser, G. 1981 (In preparation.)
Wannier, P. G. 1980 *A. Rev. Astr. Astrophys.* **18**, 399–438.
Wilson, T. L., Downes, D. & Bieging 1979 *Astron. Astrophys.* **71**, 275–282.
Welch, W. J., Wright, M. C. H., Plambeck, R. L., Bieging, J. H. & Baud, B. 1981 *Astrophys. J. Lett.* **245**, L 87–90.
Winnewisser, G., Churchwell, E. & Walmsley, C. M. 1979 In *Modern aspects of microwave spectroscopy* (ed. G. W. Chantry), pp. 311–503. Academic Press.

## *Discussion*

D. Field (*School of Chemistry, University of Bristol, U.K.*). Professor Winnewisser has produced a very interesting classification of interstellar clouds according to linewidths. Professor Wing earlier this morning [discussion contribution not submitted for publication] mentioned the laboratory phenomenon of kinematic compression of the Doppler width in laser ion beam spectroscopy. I should like to put these two ideas together and mention a phenomenon that is significant in recent work upon which I have been engaged on output powers of interstellar masers. I should very much like to hear comments from Professor Winnewisser about this. The idea is as follows: in the astrophysical medium, molecules are accelerated through a gravitational potential. This is analogous to the acceleration of ions through an electrical potential. Molecules so accelerated will therefore show kinematic compression of the Doppler width; for example, in W3(OH), according to recent observations (Reid *et al.* 1980), OH maser regions are accelerated through gravity to a speed of 5.7 km $s^{-1}$. This will narrow the Doppler width, and increase the gain coefficient for OH masers by a factor 23.5, assuming roughly constant temperature. The opposite phenomenon, of kinematic expansion, will occur if a molecular cloud is slowed down in a gravitational potential. This may, turbulence and bulk motions apart, be useful in explaining broad line shapes that are often found among astrophysical observations.

### *Reference*

Reid, M. J., Haschick, A. D., Burke, B. F., Moran, J. M., Johnston, K. J. & Swenson, G. W. 1980 *Astrophys. J.* **239**, 89.

G. Winnewisser. In answer to Dr Field's valid comments on the linewidths, I should like to emphasize that the linewidths of interstellar transitions contain a wealth of information about astrophysical processes and emission mechanisms. The classification that I have discussed, that of interstellar clouds according to linewidths, should be considered as being coarse.

Concerning the emission mechanisms of interstellar masers, line narrowing during unsaturated amplification and rebroadening to the full Doppler width during saturated amplification are predicted from theory. Contributions of the sort that Dr Field mentions are also likely. However – as I see it – the problem lies in the ability to separate uniquely the various contributions that add to the linewidth and thus to recognize their relative importance. With good line profiles now becoming available from detailed observations, I am certain that solving this problem will become an interesting task for the future.





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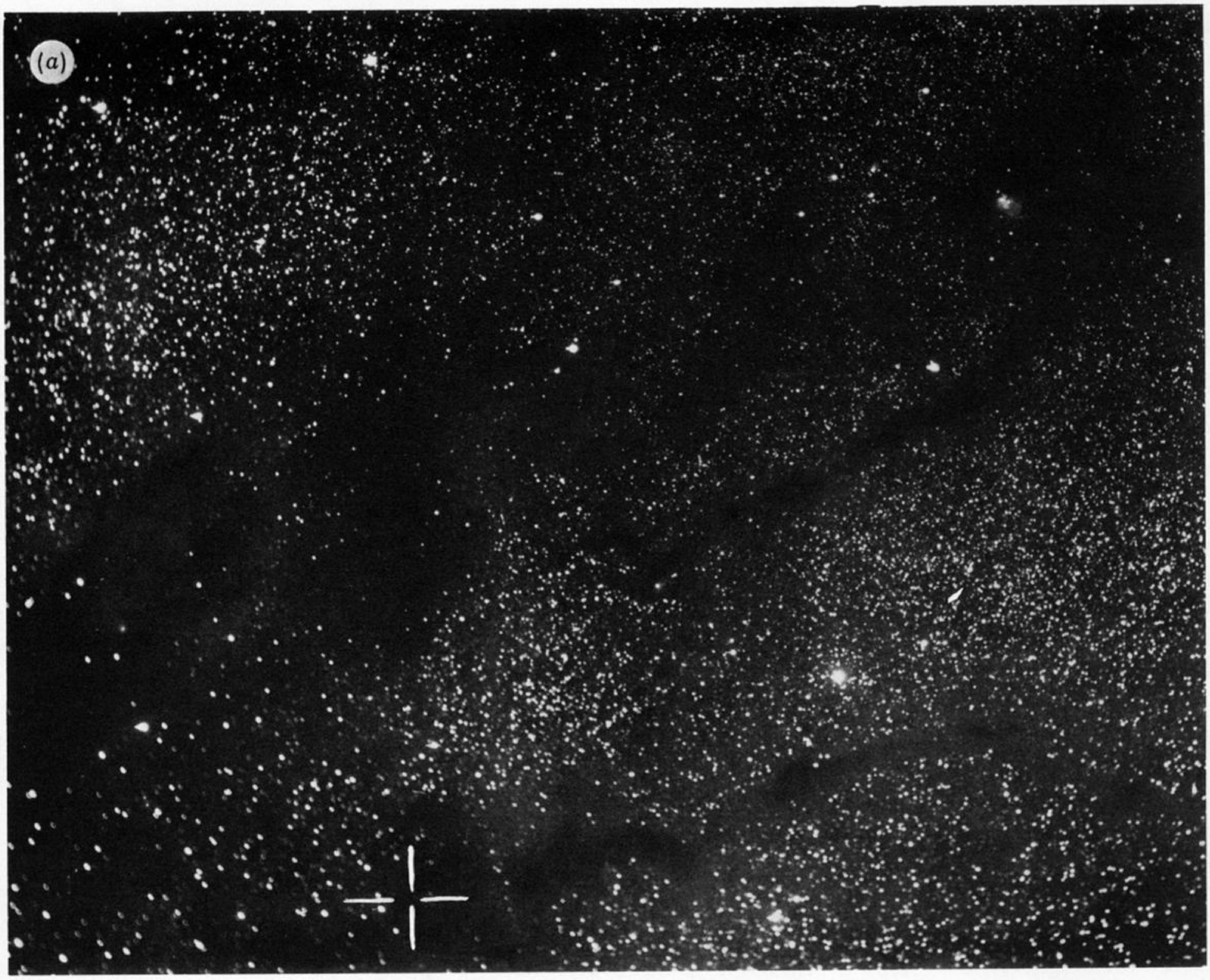




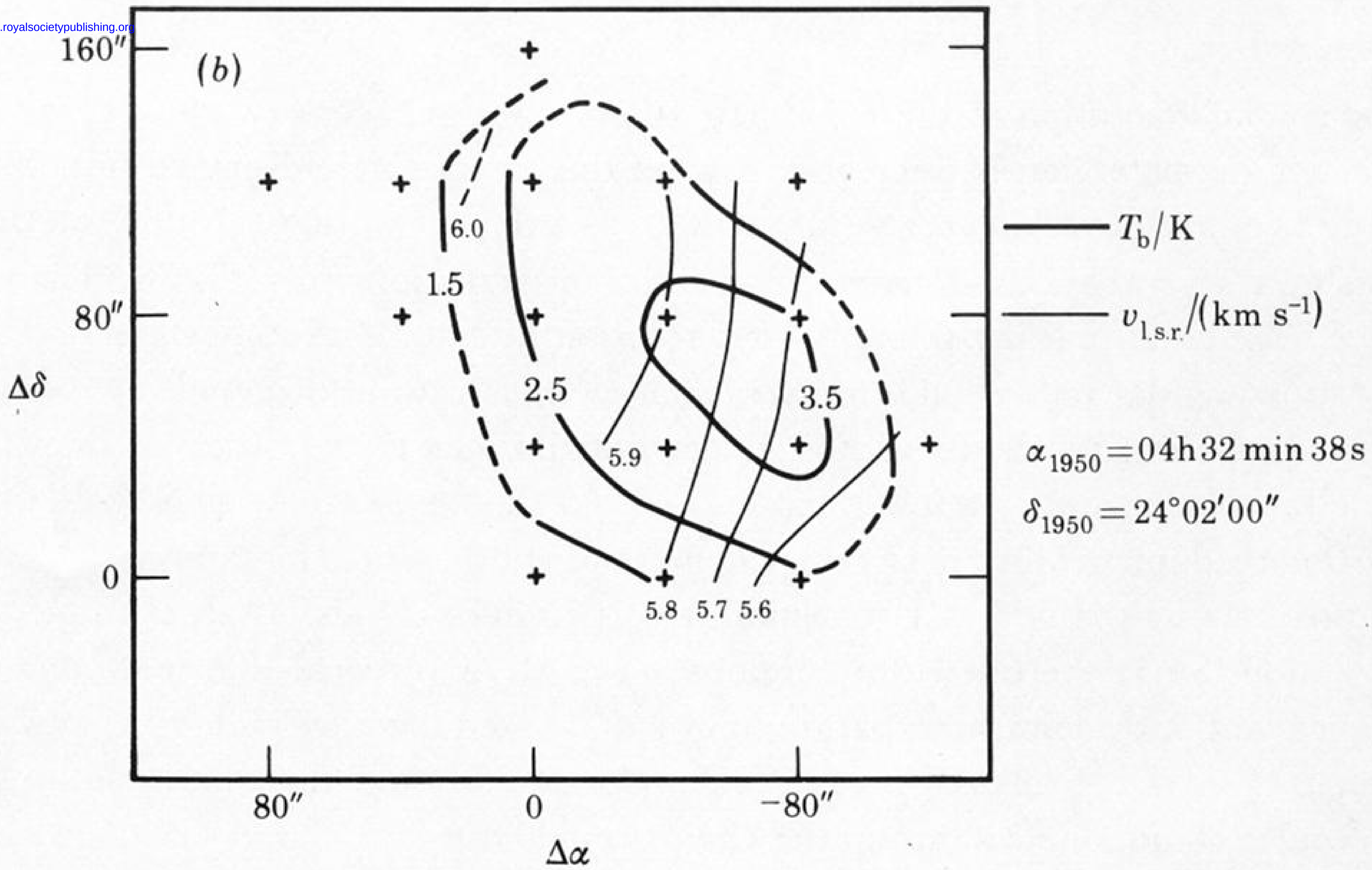


FIGURE 2. (*a*) Reproduction of a section of the Taurus region taken from the photographic *Atlas of selected regions in the Milky Way* by Barnard (1927). The distance to the Taurus region is *ca.* 140 pc. (*b*) The $NH_3$(1,1) map of TMC 3 (L 1533). The constant velocity contours in TMC 3 indicate rotational motion on a scale of 6 km $s^{-1}$ $pc^{-1}$.



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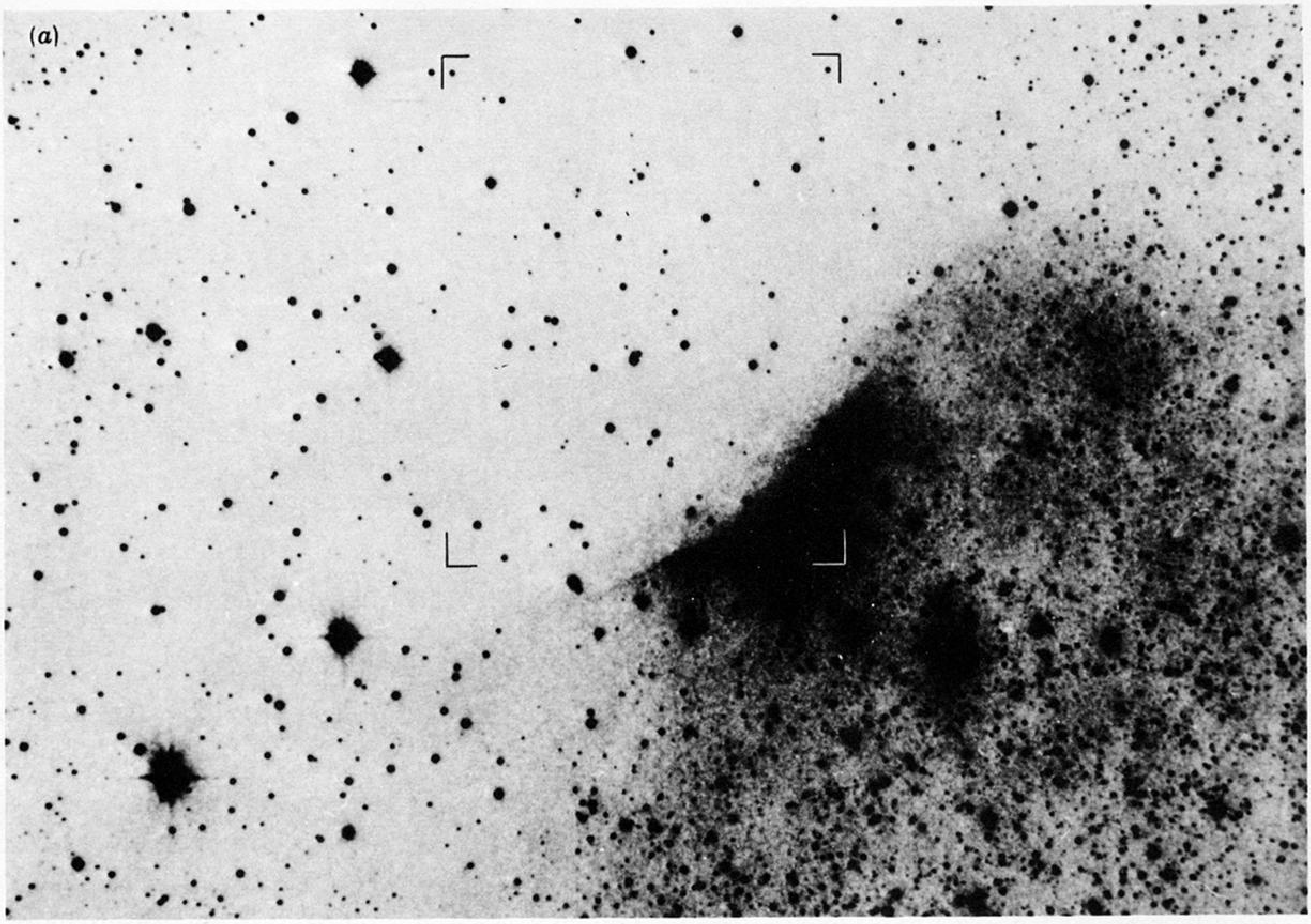
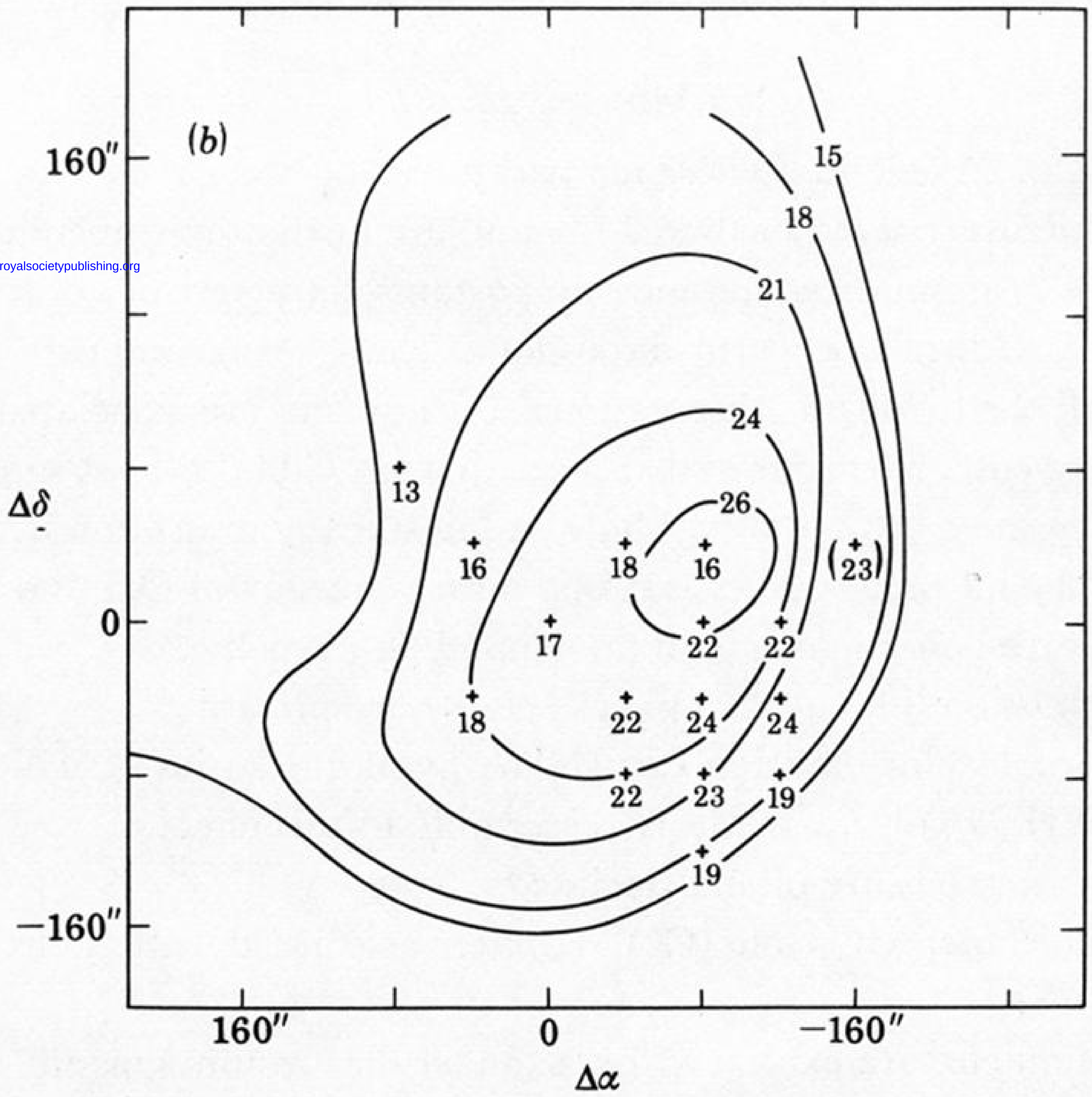


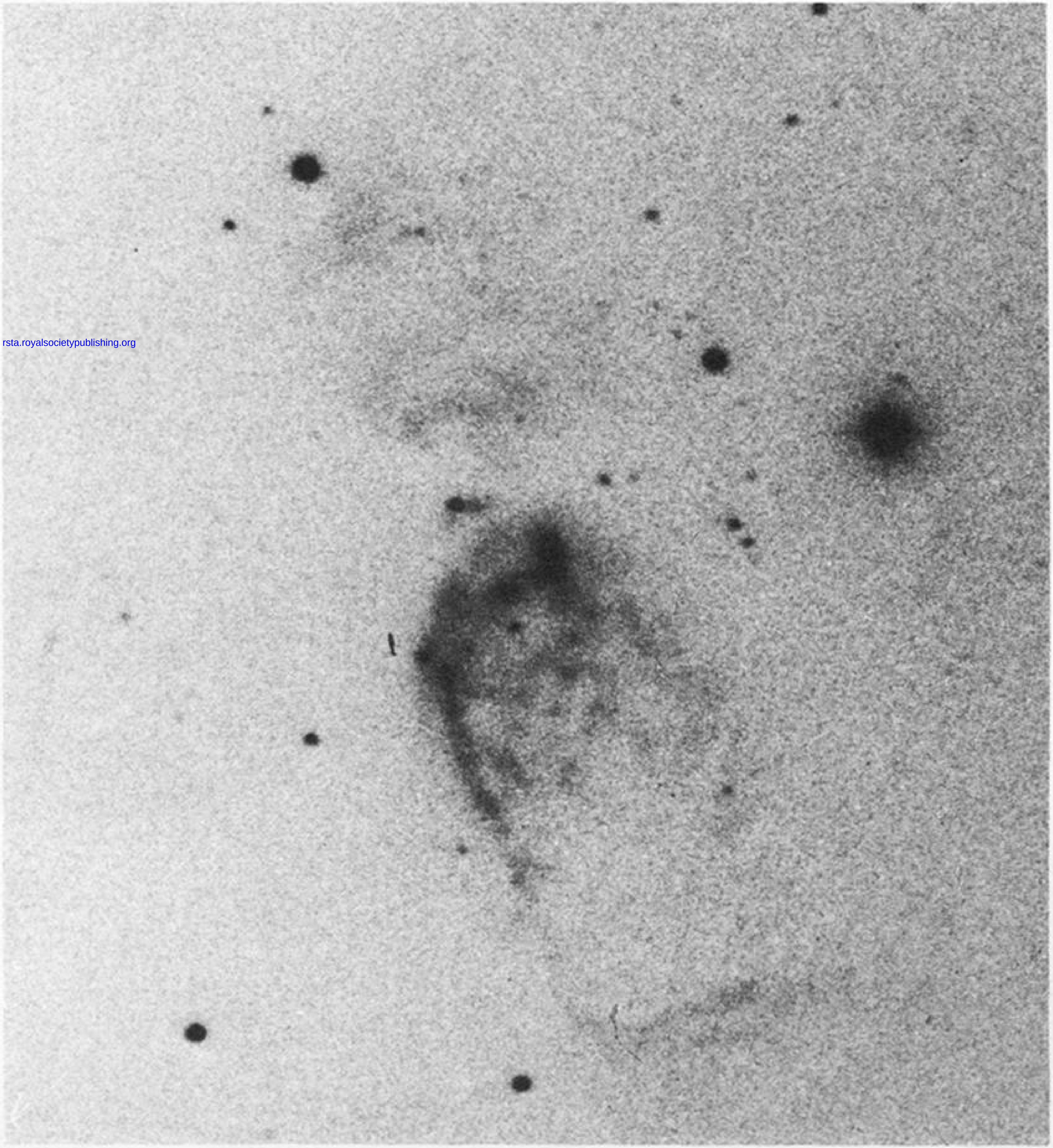




$\alpha_{1950} = 22\text{h}\,17\text{min}\,54.2\,\text{s}$

$\delta_{1950} = 63°04'30''$



FIGURE 4. The S 140–L 1204 region. (*a*) Section from the Palomar Sky Survey. The frame indicates the approximate position of the CO map. Only that portion of the CO map from Blair *et al.* (1978) is reproduced that is of interest to the $NH_3$ rotational temperature determination. (*b*) The crosses in the CO map of S 140 indicate the positions where $NH_3$ has been measured and the rotational temperature determined. Numbers indicate the value of $T_r(NH_3)$. (*c*, *d*) Sample spectra for the $NH_3$(1,1) and (2,2) transitions (*c*) (drawn to scale) and the $H_2O$ maser emission spectrum (*d*).





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IGURE 7. The infrared photograph (at 0.92 μm (I)) taken with the 2.2 m telescope on Calar Alto, Spain, probably reveals the central exciting star of the S 106 region (Elsässer, personal communication 1981).