HIGH RESOLUTION OBSERVATIONS OF THE ORION NEBULA AT 408 MHz

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Summary

The Orion Nebula has been observed at 408 MHz with the 1 mile Cross radio telescope at the Molonglo Radio Observatory. NGC 1976 and NGC 1982 were observed separately and the former was well resolved.. Comparison with high frequency results shows that the central region is optically thick; the electron temperature was measured directly at 7 600°K ± 800 degK. Both nebulae are strongly concentrated towards their exciting stars.

I. Introduction

Recent observations of the Kardashev lines have indicated that electron temperatures in emission nebulae are considerably lower than the 10 000°K conventionally assumed. One might query this result because quite small departures from a thermal population of the highly excited hydrogen levels would have very marked effects on emission of the lines at radio wavelengths, where absorption and stimulated emission are nearly equal (Goldberg 1966). Similarly the much higher temperatures derived from measurements of the forbidden line spectrum undoubtedly suffer from selection effects favouring regions of high ionization. It is therefore very important to explore other methods of observation that are not subject to these criticisms.

The recently completed 1 mile cross-type radio telescope at the Molonglo Radio Observatory allows direct measurement of electron temperatures for those nebulae possessing regions of large optical depth more than a few minutes of arc in size. At the present operating frequency of 408 MHz, emission measures in excess of 10^5 are necessary for reasonably accurate measurements. The Orion Nebula has been investigated initially as it is in a region of low and uncomplicated background temperatures unlike those near the galactic centre; it is also very suitable for observation with the 3′ beam of the radio telescope. A recently completed map at $\lambda\,2\cdot85$ cm ($10\cdot5$ GHz) (Macleod and Doherty 1967) with similar resolution allows a direct comparison of spectra in different regions. In particular, both instruments separate NGC 1982 from the Orion Nebula proper (NGC 1976).

It is found that the resolved central region of NGC 1976 has an optical thickness considerably more than 5 at 408 MHz and so radiates effectively as a black body. The antenna beam temperature is therefore closely equal to the electron temperatures (T_e) averaged over the nearer parts of the nebula. After making the necessary small corrections for optical thickness and finite resolution, T_e is found to be 7 600°K,

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with a standard error estimated to be about 800 degK. This result is approximately 1 200 degK higher than values deduced from measurements of the Kardashev lines (Dieter 1967; Mezger and Höglund 1967). While the difference is not inconsistent with the combined errors, the most natural conclusion is that there is a real discrepancy.

In addition to the temperature measurements, the observations have clearly shown a low level emission more or less coinciding with the tenuous outer regions of the nebula. It is evident that the optical appearance is largely dictated by the emission regions rather than by the disposition of obscuring clouds.

An estimate of electron temperature in the neighbouring NGC 1982 has also been made and a value of the order of 8 000°K obtained. This nebula is not completely resolved by the telescope so that the result is very uncertain.

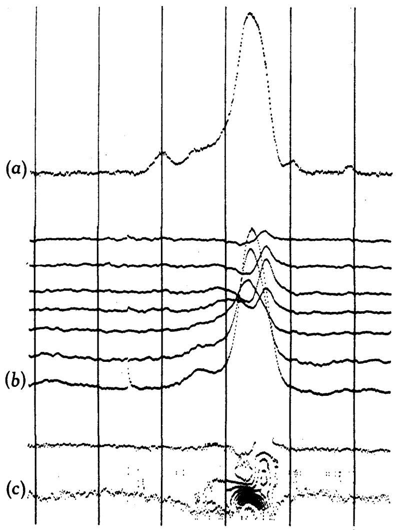

Fig. 1.—A reproduction of one of the Faximile records used in the analysis showing (*a*) the total power fan beam of the east–west antenna, (*b*) the seven independent pencil beams of the Cross, and (*c*) a rough contour map produced in real time. The vertical lines are the 1 min time marks.

II. Observations

During the last two years the east–west arm of the Molonglo radio telescope has been operating as a fan-beam total power instrument; the present results are the first to be described using the completed Cross. A certain amount of adjustment and calibration work remains to be carried out and consequently the initial programmes are rather limited in their scope. Nevertheless, it is considered that the present imperfections are of little consequence in the work described here. The chief difficulties are the presence of unnecessarily large sidelobe responses, which distort the contours in places, and the lack of a simple and accurate temperature calibration procedure. The temperature scale had to be derived indirectly, as described below, with a consequent loss in accuracy.

The output of the telescope may be recorded digitally on magnetic tape but the computer programmes are not yet fully operational, so that for the present observations the Faximile analogue output was employed (Mills *et al.* 1963).

A sample record is reproduced in Figure 1. Seven independent beams (b) are recorded simultaneously (finally 11 such beams will be available), together with the output of the east–west arm (a). Beneath these individual scans a crude contour map (c) is reproduced, in real time, as an aid to interpretation. In order to cover the complete range of declinations at which emission was detectable, three other such records were necessary, the coverage being so arranged that the outer scans overlapped.

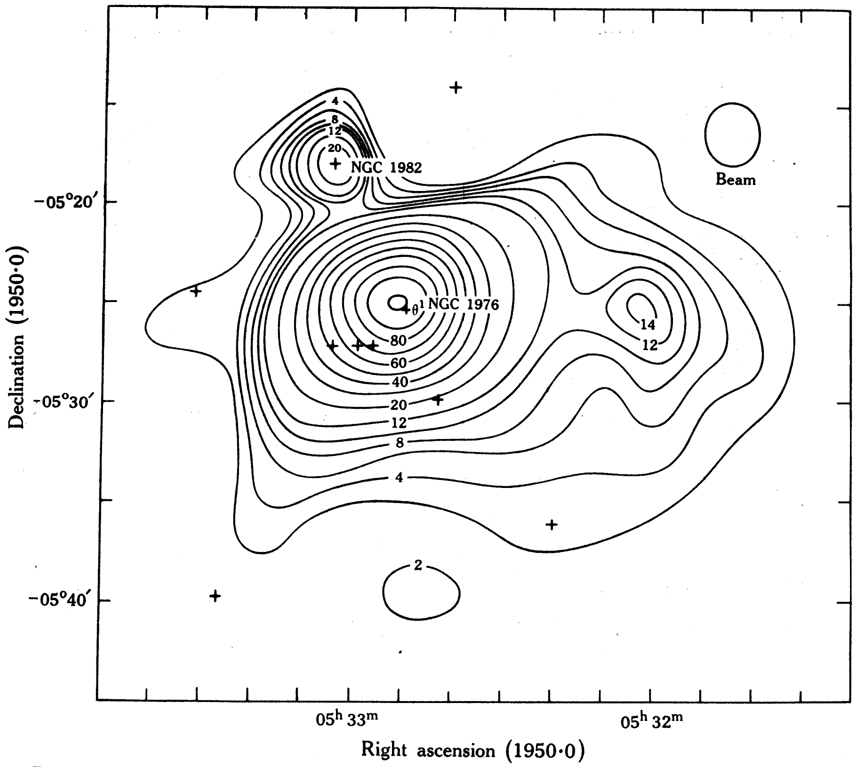

Fig. 2.—Derived beam temperature contour map of the Orion source complex. The contour unit is 66±7 degK and the peak beam temperature for NGC 1976 is 6 700°K and for NGC 1982, 1 590°K. The positions of some bright stars are indicated by crosses, while the exciting star θ^1 Orionis is separately marked. For contour levels less than 30 the contour interval represents an emission measure of 2 360.

The relative calibrations of each of the scans in a single record were determined by injecting a reference noise signal simultaneously into each of the independent beam systems. The calibration between different records was obtained by matching overlapping scans. A set of corrected scans was then prepared from which the contour map shown in Figure 2 was drawn. This map represents the relative antenna beam temperatures and therefore adequately describes the shape of the nebula, as smoothed by the beam, which measures 2′·8 east–west by 3′·2 north–south to half-response points. A small negative sidelobe appears immediately north of the main peak, probably causing some distortion of the contours on the western side of NGC 1982;

the distribution of low level emission south of the peak may be similarly distorted. A simplified set of contours is superimposed on a photograph of the nebula in Figure 3, where the general correspondence between the radio and optical appearance is well demonstrated.

Conversion of the relative temperature scale in Figure 2 to an absolute scale has been carried out via the fan-beam observations. This has proved necessary because the sensitivity of the Cross system varies with declination in a way that has

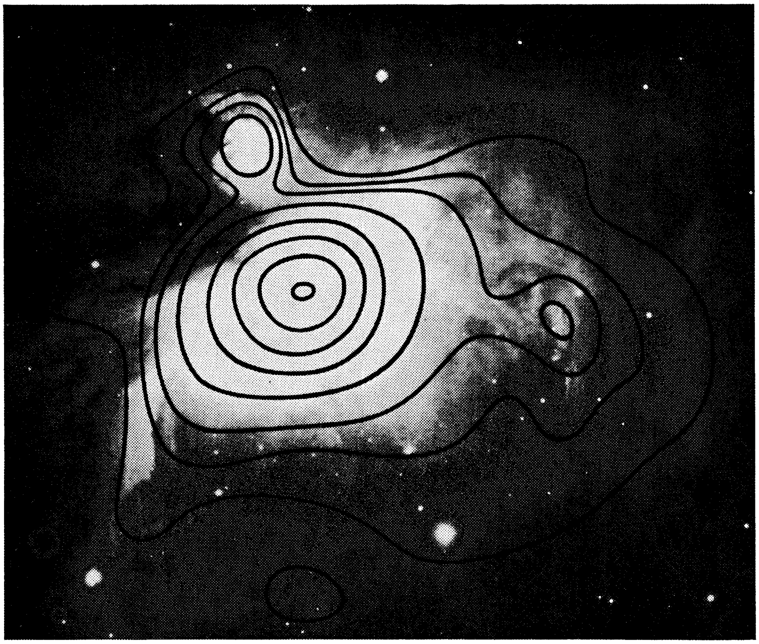

Fig. 3.—A simplified version of the contours of Figure 2 superimposed on a photograph of the nebula.

not yet been adequately determined, whereas the east–west antenna gain is practically independent of declination. Scans were made through the Orion region and two reference sources of small angular size (MSH 06−*04* and MSH 12+*08* (3C 273)) using high sensitivity and a normal paper chart recorder for improved accuracy. The integrated emission of the Orion complex was then obtained relative to the reference sources by intercomparison of the areas under the response curves, after correction for the relative gains of the receiver. These were established for each source by injection of a standard signal from a noise diode.

Unfortunately, an acceptable *absolute* standard of flux density does not exist at the lower frequencies. The common and useful CKL scale (Conway, Kellerman, and Long 1963) is basically a *relative* flux scale in which several low frequency absolute determinations have been adjusted to fit an assumption that Cassiopeia A has a simple power law spectrum. Most absolute determinations at metre wavelengths fall above this scale, particularly for the southern sources. More than a year ago a programme of absolute flux determinations was instituted at the Molonglo Radio Observatory and the values used for our reference sources have been supplied by D. Wyllie (personal communication), who has now established a preliminary scale at 408 MHz with a standard error of 6%. It falls approximately 15% above the CKL scale when averaged over the sources common to both.

The flux densities of the reference sources MSH 06−0*4* and 3C 273 are 44·5 and 65·1 f.u.* respectively on Wyllie's scale. The derived flux density of the whole Orion complex is 213 f.u., with an estimated standard error of 8%. In obtaining this value a small reduction of 5 f.u. was made to allow for the expectation value of weak sources within the area of the fan beam; it was derived from a study of neighbouring regions.

The pencil-beam temperature scale was obtained by fitting the integrated flux from Figure 2 to that derived above. The contour unit was thus found to be 66 ± 7 degK (standard error). The corresponding peak beam temperatures for NGC 1976 and NGC 1982 are 6 700 and 1 590°K respectively.

III. Discussion

It is evident from Figure 3 that qualitative features of the emission nebulae are reproduced well in the radio isophotes. The maximum in the radio emission also occurs very close to the exciting stars: θ^1 Orionis is approximately 30″ from the peak in NGC 1976; BD−5°1325 is approximately 15″ from the peak in NGC 1982. The radio peaks are believed to be positioned with a standard error of about 5″ arc.

It is clear that, while the central region of the Orion nebula appears to be quite symmetrical, there is a marked asymmetry in the brightness distribution of the extended component; the assumption that has been made in the past that the Orion nebula is spherical, centred on the Trapezium, with a radius of 22′ arc (Osterbrock and Flather 1959; Menon 1961; Vandervoort 1964) is therefore incorrect.

Both nebulae show very strong central concentrations, which are much more evident when the 10·5 GHz observations of Macleod and Doherty (1967) are taken into account. The nebulae are everywhere optically thin at this frequency so that the surface temperature is equal to τT_e. We may scale the results to 408 MHz on multiplication by the ratio of optical depths.

Taking

$$\tau = \frac{3\cdot 02\times 10^{16} EM}{\nu^2 T_e^{3/2}}\left(19\cdot 8+\ln(T_e^{3/2}/\nu)\right),$$

where the emission measure $EM = \int N_e^2\,\mathrm{d}s$ and the electron temperature $T_e = 7\,600°\mathrm{K}$, as derived below, we find

$$\tau_{400}/\tau_{10\,500} = 875\,.$$

* 1 flux unit $= 10^{-26}$ W m^{-2} Hz^{-1}.

In Figure 4 we have plotted temperatures along a section taken through the centre of both peaks. The observed beam temperature at 408 MHz (curve 1) is plotted, along with the corresponding beam temperature at 10·5 GHz multiplied by the ratio of optical depths (2). A small zero adjustment (200 degK) has been made to the high frequency result to bring the outer skirts into coincidence with the 408 MHz beam temperatures. The effect on the 408 MHz temperatures of the large optical depth in the centre of NGC 1976 is very evident.

The electron temperature must be slightly higher than the observed peak temperature at 408 MHz both because of resolution effects and the finite value of τ (>5). The correction, however, is not great and need not be known accurately.

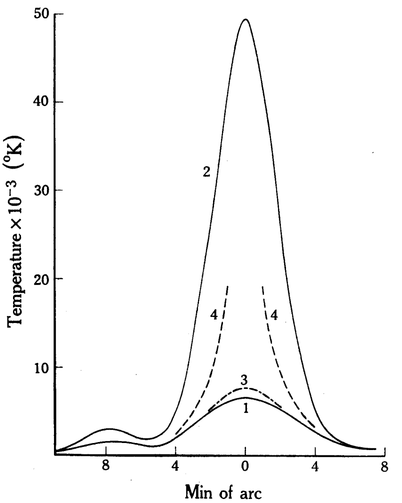

Fig. 4.—Temperatures plotted along a section through the peaks of NGC 1982 and NGC 1976:

1, present 408 MHz observations

2, 10·5 GHz observations of Macleod and Doherty multiplied by $\tau_{408}/\tau_{10\,500}$

3, 408 MHz distribution partially corrected for resolution of antenna beam

4, τT_e derived directly from 408 MHz observations

We have used the chord construction described by Bracewell (1955) to correct partially for the finite resolution, as shown by curve 3 in Figure 4. The nearly flat top of the restored distribution suggests that the degree of restoration is adequate and that the further correction due to finite optical depth is negligible. We adopt an electron temperature of 7 600°K$\pm$800 degK, which adequately fits the observations.

With this value of electron temperature, which will be assumed constant throughout the nebula, it is possible to obtain τ directly from the brightness temperature at 408 MHz, which is equal to $T_e(1-e^{-\tau})$. Curves 4 of Figure 4 show the quantity τT_e derived from our restored beam temperatures. As the uncertainty increases rapidly near the centre, the plot is continued only to a radius of 1′ arc. It should be emphasized that both this result and that obtained at 10·5 GHz are affected by the finite resolution of the antenna beams and the actual distribution is likely to be considerably more peaked at the centre than either result. An estimate of the actual shape can best be derived from the high frequency results, but as this requires detailed knowledge of the antenna response it has not been attempted here. A very rough estimate of the central optical depth suggests that it is at least double that indicated, i.e. about 10 or more at 408 MHz, corresponding to an emission measure of the order of 3×10^6.

Emission measures over the remainder of the nebula, where optical depths are small and the nebula well resolved, may be readily obtained. Thus, for surface brightness temperatures less than about 2 000°K (i.e. contour levels less than 30) the contour interval corresponds to an emission measure of 2 360.

NGC 1982 is much less amenable to analysis because of its small size. The measured distribution at 408 MHz is only slightly wider than the antenna beam, so that actual brightness temperatures are considerably higher than beam temperatures. The ratio of the solid angle of the observed distribution to that derived for the actual distribution is approximately 3·6, whence the brightness temperature at 408 MHz is, very roughly, 6 000°K. If it is assumed that the high frequency temperature is increased in the same ratio, we find that the central optical depth is 1·4 and the electron temperature is of the order of 8 000°K. However, this is a very uncertain estimate.

To conclude, we would emphasize that, because of the high optical depth, the present work is a direct measurement of electron temperature in NGC 1976 and is not dependent on any theory for the population of excited levels. The only significant uncertainties arise in correcting the result for finite resolution, and in the absolute temperature scale. The former uncertainty is quite small and may be ignored in comparison with the latter, which depends critically on the absolute flux scale derived by Wyllie and on evaluation of the relative response of the Orion complex using a fan beam. Wyllie's work has not yet been published and, in fact, further observations are planned to decrease the error. However, we believe that his derived flux densities for the reference sources are the best available absolute determinations at 408 MHz and that the quoted standard error of 6% is realistic. Nevertheless, it cannot be overlooked that the CKL scale lies 15% below Wyllie's when averaged over the southern sources common to both and would yield an electron temperature of 6 600°K. It is not unreasonable to suppose that, within the errors, our assumed flux densities of the reference sources are more likely to be high than low, but we find that there are too many unknowns to assign a weight to the CKL scale and use it to improve our estimate of the temperature.

In evaluating the relative flux density of the Orion complex we have made an allowance of 5 f.u. for the integrated effect of weak sources within the response of the fan beam. No sources are listed in the region in any catalogue, so that this uncertainty should be adequately covered by our estimate of the error. One possible source of excess emission is the NGC 1973, 5, 7 complex, half a degree to the north.

Both the above uncertainties should be reduced by future work, allowing more reliable estimates. At present we conclude that the electron temperature is very significantly less than 10 000°K, but probably slightly more than the 6 400°K obtained from Kardashev line measurements. The derived temperature refers to the nearer region of the nebula in front of the central concentration around θ^1 Orionis, whereas the Kardashev lines are derived from the emission over the whole nebula; because of the nonlinear dependence on T_e, the line results tend to be weighted towards regions of lower temperature.

A further interesting result is the demonstration that obscuring clouds have little effect on the overall appearance of the nebula. The sharp cutoff in the northfollowing sector is real and implies that the ionized gas does not extend in this direction. Likewise, the nebula NGC 1982 is a separate entity, with a strong central concentration around the exciting star BD$-5°1325$. Taken in conjunction with a similar concentration around θ^1 Orionis in NGC 1976, the implication is that both nebulae are very new formations resulting from the gravitational contraction and fragmentation of a gas cloud. This view is supported by the evidence for new star formation in NGC 1976 (e.g. Becklin and Neugebauer 1967).

IV. Acknowledgments

This work was supported by grants from the U.S. National Science Foundation and the Australian Grants Committee. We are indebted to Dr. L. H. Doherty for making available his measurements at $\lambda 2 \cdot 85$ cm and to Mr. D. Wyllie for providing the absolute flux densities of the reference sources. The photograph for Figure 3 was supplied by Dr. R. R. Shobbrook.

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