OBSERVATIONS OF THE ROSETTE NEBULA USING THE DECAMETER WAVE RADIO TELESCOPE AT GAURIBIDANUR

A. A. DESHPANDE, R. K. SHEVGAONKAR, and CH. V. SASTRY

Raman Research Institute, Bangalore

and

Indian Institute of Astrophysics, Bangalore, India

(Received 31 August, 1983)

Abstract. A map of Rosette Nebula in continuum absorption is made at 34.5 MHz using the Decameter Wave Radio Telescoe at Gauribidanur, India, with a resolution of 26′ × 40′, is presented. These observations are combined with the 2700 MHz measurements of Graham *et al.* (1982) to derive the electron temperature distribution across the nebula. It is found that the temperatures in the southeastern parts of the nebula are around 5000 K and increase up to 8000 K towards the northwestern regions. It is suggested that the lower electron temperatures in the southeastern regions are due to the presence of more dust there compared to other regions in the nebula.

1. Introduction

The structure of the Rosette Nebula is wel studied optically and at radio-frequencies above 400 MHz. However, estimates of its mean electron temperature range from 2000 K (Parrish, 1972) to more than 8000 K (Holden, 1968). Recently, Graham *et al.* (1982) derived a temperature of 4100 K by combining their high sensitivity observations at 2700 MHz with measurements at low radio frequencies. At radio frequencies where an H II region is optically thick it may appear as a continuum absorption feature against the non-thermal galactic and extragalactic background emission. Such absorption measurements on the Rosette Nebula have been made by Krymkin (1978) and a mean electron temperature of 3690 K over the nebula was derived. No attempt has hitherto been made to derive the detailed electron temperature distribution over the nebula, although temperatures at several discrete points have been derived using recombination line measurements. It is possible to derive the electron temperature distribution over an H II region if high resolution radio maps are available, both at a frequency where the nebula is optically thin and at a lower frequency where it is optically thick. In this paper we present our observations of the Rosette Nebula in continuum absorption at 34.5 MHz. These observations, together with observations at 2700 MHz by Graham *et al.* (1982), have been used to derive the electron temperature distribution over the nebula.

2. Equipment and Observations

The observations reported here were made with the low frequency radio telescope at Gauribidanur (longitude 77°27′07″ E, latitude 13°36′12″ N) at 34.5 MHz. The tele-

Astrophysics and Space Science **102** (1984) 21–27. 0004–640X/84/1021–0021$01.05.

TABLE I

A comparison of the coordinates of sources detected at Gauribidanur, 4C Survey and Holden

Source	Gauribidanur		4C		Holden	
	R.A.	Decl.	R.A.	Decl.	R.A.	Decl.
4C 04.22	$06^h19^m12^s$	04°33′	$06^h19^m13^s.8$	04°39′.1	$06^h19^m28^s$	04°38′.2
4C 04.24	06 23 18	04 33	06 23 13.2	04 39.4	06 23 30	04 32.7
4C 04.25	06 33 50	04 24	06 33 25.6	04 35.8		
4C 05.29	06 42 50	05 30	06 42 36.7	05 33.0	06 42 30	05 34.1

scope consists of two broad-band arrays arranged in the form of a 'T'. The outputs of the two arrays are correlated to produce the telescopic beam pattern. The half-power beamwidths are 26′ and 40′ sec (δ − 14°.1) in right ascension and declinations, respectively. The effective area is approximately $250\lambda^2$. A brief description of the electronic multibeam control system of this telescope is given by Sastry and Shevgaonkar (1983).

The Rosette Nebula was observed as part of a general survey of the Monoceros region. We have mapped the region in the declination range 3°.5 to 7°.5 and from 06^h00^m to 06^h50^m in R.A. This was previously mapped by Holden (1968) at 178 MHz with a resolution of 24′ × 26′. The positions of four unresolved sources detected by us and also listed in the 4C catalog are given in Table I. We measured the positions of these

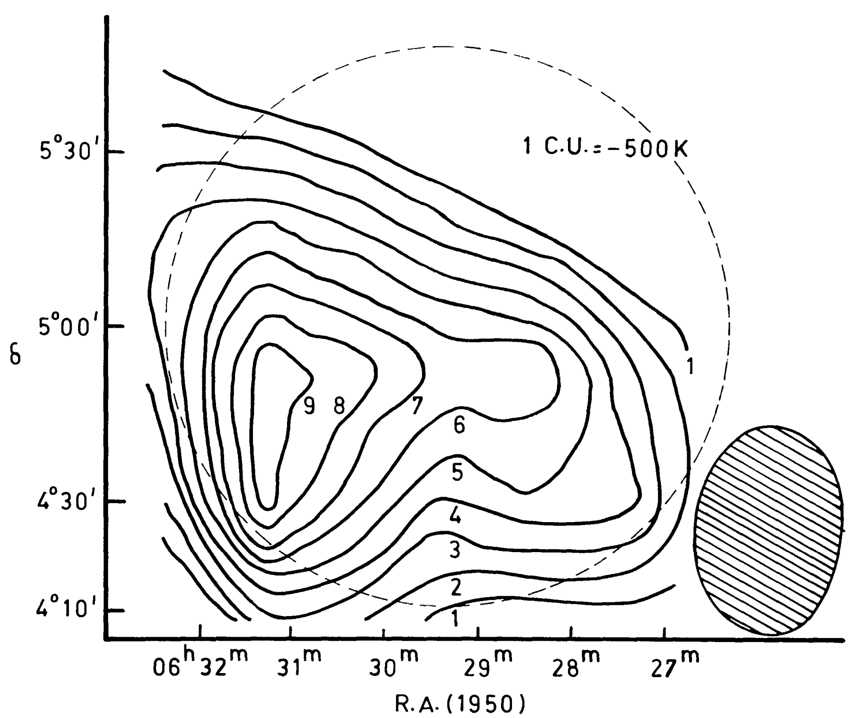

Fig. 1. Map of Rosette Nebula in continuum absorption at 34.5 MHz obtained with the Decameter Wave Radio Telescope at Gauribidanur. The dashed circle indicates the extent of the optical and high frequency radio emission from the nebula.

sources in Holden's (1968) map and these are also given in Table I. It can be seen that our positions agree to within $\pm 6'$ in declination and ± 15 s in R.A. with the 4C positions for all sources excepting 4C 04.25 where the difference is 12′ in declination and 25 s in R.A. It should be pointed out that the source 4C 04.25 is very close to Rosette and appears as a slight extension of the Rosette Nebula emission in Holden's (1968) map. It is possible that our position measurements were also affected by the proximity of the Rosette and our beam size. The brightness temperature scale of the radio telescope was determined using several point sources at various declinations. The estimated error in the brightness temperatures is ± 970 K. The map of Rosette Nebula was cleaned to reduce sidelobe effects and the CLEAN components were convolved with a gaussian beam of $26' \times 40'$ to obtain the final map, shown in Figure 1.

3. Discussion

Figure 1 shows the nebula to be partially resolved by the present observations. The maximum absorption lies in the southeastern part of the nebula. There is a secondary absorption maximum slightly towards the west of the map center. A comparison of our continuum absorption map with those made in emission at frequencies above 408 MHz reveals that the peak of absorption approximately coincides with the emission source G 206.6 − 1.7. Another emission source G 206.2 − 2.3 lies in the region of the secondary peak of absorption. Around the sources G 206.0 − 1.7 and G 206.0−2.1 the continuum emission at high frequencies is quite strong but there is no apparent absorption in our map. A superposition of our radio continuum absorption isophotes on an optical photograph of Rosette Nebula taken in Hα light reveals that the continuum absorption maximum lies in the region where the optical emission is patchy. The secondary absorption peak is close to the central hole in the nebula. There is very little radio continuum absorption in the northwestern regions where the optical emission is intense and continous.

The observed depth of absorption at a point (α, δ) in the direction of the H II region at a frequency ν is given by

$$T_{0\alpha}(\alpha, \delta, \nu) = \int\int [T_e(\alpha + \alpha', \delta + \delta') - T_f(\nu) - T_x(\nu)] \times$$

$$\times [1 - \exp(-\tau(\alpha + \alpha', \delta + \delta', \nu)] \frac{P_\nu(\alpha', \delta', \nu)}{\int\int P_\nu \, d\alpha \, d\delta} \, d\alpha' \, d\delta' ,$$

where

$T_e(\alpha, \delta)$ = electron kinetic temperature;

T_f = brightness temperature due to galactic nonthermal emission on the far side of the H II region;

T_x = extragalactic component of the brightness temperature;

$\tau(\alpha, \delta, \nu)$ = optical depth at frequency ν;

$P_\nu(\alpha, \delta)$ = polar diagram of the radio telescope at frequency ν.

At a frequency ν_{HF}, sufficiently high that the H II region appears optically thin, the following relation for the brightness temperature T_{bHF} applies:

$$T_{\mathrm{bHF}}(\alpha, \delta) = \tau_{\mathrm{HF}}(\alpha, \delta) T_e(\alpha, \delta) .$$

The optical depth at a low frequency τ_{LF} is related to the brightness temperature T_{bHF} at ν_{HF} in the following way:

$$\tau_{\mathrm{LF}}(\alpha, \delta) = \frac{T_{\mathrm{bHF}}(\alpha, \delta)}{T_e(\alpha, \delta)} \left(\frac{\nu_{\mathrm{HF}}}{\nu_{\mathrm{LF}}}\right)^2 \times \frac{\ln(49.55 T_e^{1.5} \nu_{\mathrm{LF}}^{-1}}{\ln(49.55 T_e^{1.5} \nu_{\mathrm{HF}}^{-1})} .$$

Therefore, it is possible to estimate the expected depth of absorption at every point (α, δ) if the values $T_{\mathrm{bHF}}(\alpha, \delta)$, T_f, T_x, and $T_e(\alpha, \delta)$ are known. We have taken the $T_{\mathrm{bHF}}(\alpha, \delta)$ values from the map of Graham *et al.* (1982) at 2700 MHz where the nebula is heavily resolved and optically thin. We have assumed that the values of T_f and T_x remain constant over the small region of the sky occupied by the Rosette Nebula. Graham *et al.* (1982) estimated a galactic background temperature of 5800 K in the direction of the Rosette Nebula at 38 MHz. According to Bridle (1967) the isotropic extragalactic background is 30 $\pm$ 7 K at 178 MHz. The corresponding total background temperature in the direction of Rosette Nebula at 34.5 MHz then turns out to be 10 000 K. In this estimation we have assumed spectral indices of 2.38 and 2.75 for the galactic and extragalactic components, respectively. The integrated flux density of our map is -96 ± 19 Jy. This agrees quite well with the expected flux at this frequency from the spectrum of the Rosette compiled by Graham *et al.* (1982). From this flux density we derive a mean electron temperature over the whole nebula of 5450 $\pm$ 910 K.

Assuming a temperature distribution T_e (α, δ) over the entire nebula, a map of fractional absorption at 34.5 MHz is produced from the 2700 MHz map. This map is convolved with our beam and subtracted from the observed map. The resultant difference map was used to modify the assumed electron temperature distribution. This process was repeated until the difference between the observed and derived fractional absorption maps is a minimum. The best fit map of derived fractional absorption so obtained is shown in Figure 2. The temperatures at every point in this map are within $\pm$ 500 K of the observed map shown in Figure 1. The corresponding best fit temperature distribution over the nebula is shown in Figure 3. It can be seen that the temperatures in the southeastern parts of the nebula are in the range 5000 to 6000 K whereas they increase upto $\geq$ 8000 K in the northwestern regions. The electron temperatures at various points in the Rosette Nebula have been derived previously using recombination line measurements (Pedlar and Mathews, 1973; Viner *et al.*, 1979; Gordon *et al.*, 1974). However, no detailed map of the electron temperature distribution in the nebula has been made using recombination lines. The measurements of Pedlar and Mathews (1973) were made with a beam of $31' \times 33'$ which is similar to ours. They have measured electron temperatures at five discrete points in the nebula. These points and with the measured temperature values are also indicated in Figure 3. It can be seen that the agreement between the two measurements is satisfactory. As noted above there is a definite

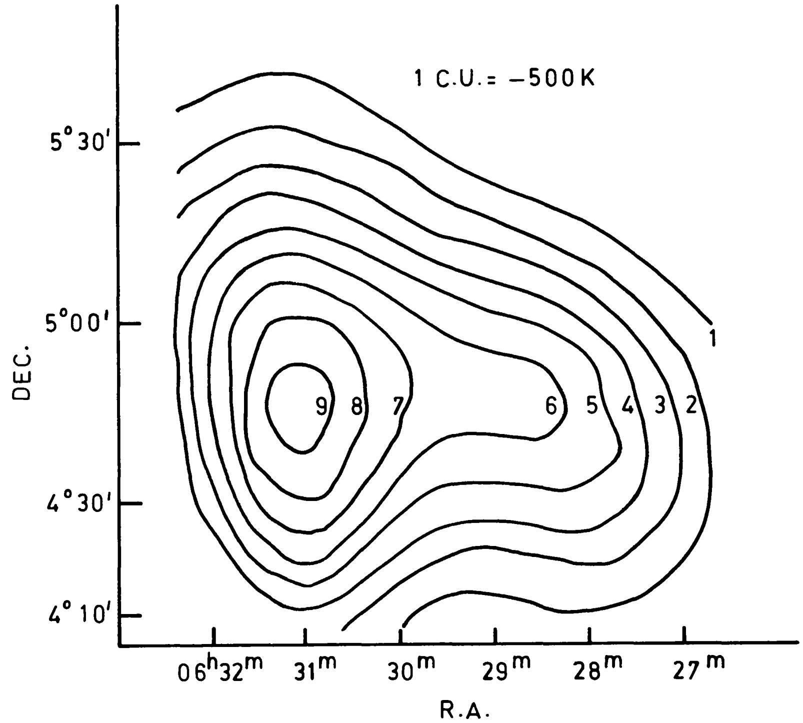

Fig. 2. Best fit map of derived fractional absorption at 34.5 MHz.

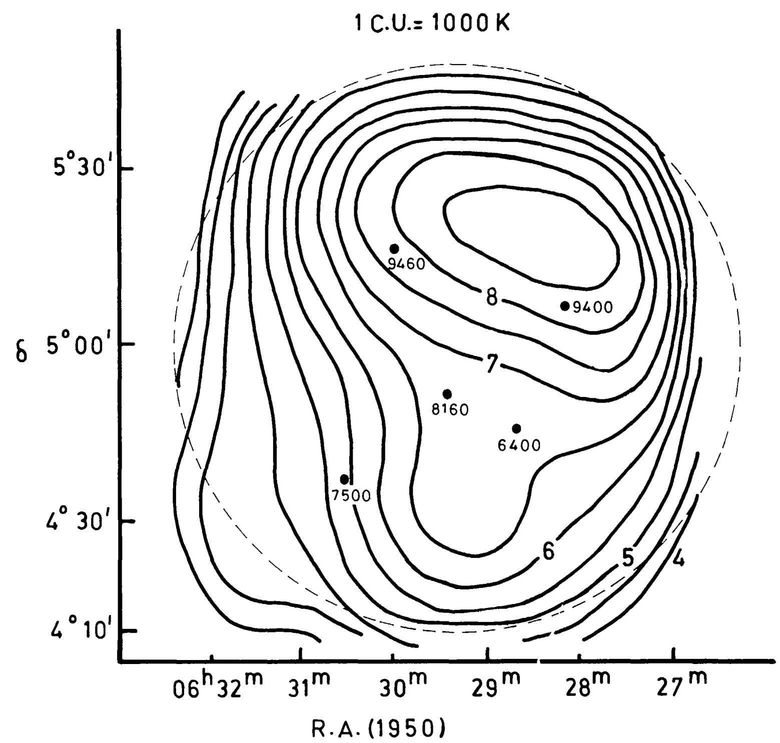

Fig. 3. Temperature distribution over Rosette Nebula. The points at which temperatures are measured by Pedlar and Mathews (1973) are indicated by dots. Their measured values of temperatures are given adjacent to the dots. The dashed circle indicates the extent of the optical and high frequency radio emission from the nebula.

variation in the amount of fractional absorption across the nebula. There is strong continuum emission at decimeter and centimeter wavelengths in the northwestern region – i.e., around the source G 206.0 – 1.7 and G 206.0 – 2.1 but no absorption at low frequencies. If the nebula were isothermal and optically thick the depth of absorption would have been the same at all places. Therefore it would appear that the increase in the electron temperature in the northwestern regions is well established.

It should, however, be pointed out that any nonuniformity in the background temperature distribution will alter the electron temperature distribution derived by us. We also assume that the effect of the emission from the nonthermal Monoceros Nebulosity on the electron temperature distribution is very small since we did not detect any emission from this supernova remnant in the declination range between 5° to 6°. According to Holden (1968) the non-thermal emission due to the Monoceros peaks sharply at $\delta = 07\overset{\circ}{.}5$.

The patchiness in the southeastern parts of the Rosette Nebula seen on optical photographs is a possible indication of the presence of more dust there compared with other regions in the nebula. Further evidence for the presence of dust comes from maps of molecular clouds associated with Mon OB2 made by Blitz (1980). Blitz found that the peak CO emission is concentrated towards southeastern parts of the Rosette Nebula. Very little CO emission was detected in the northwestern regions. It is well known that molecular clouds are associated with dust (Rowan-Robinson, 1980). The effect of dust on the ionization and thermal structure of H II regions, has been discussed by Balick (1975), Sarazin (1975), and others. The absorption of the ionizing radiation by dust changes the spectrum of that radiation and thereby the heating rate. If the absorption increases with frequency the gas temperature is reduced by this effect. According to Balick (1975) electron temperatures can decrease by up to 15% because of the radiation softening effects of dust. It is, however, pointed out by Shaver *et al.* (1982) that dust can also contribute to the heating of the nebula. It is not clear from these theoretical calculations which effect will dominate but the present measurements seem to indicate that the electron temperatures will be lowered by the presence of dust. Infrared line and continuum observations will be very useful in detecting the presence of more dust in the southeastern parts of the nebula.

Acknowledgements

The low frequency Radio Astronomy Project at Gauribidanur owes its existence to the keen interest and kind support of the late Prof. M. K. V. Bappu and Prof. V. Radhakrishnan. We would like to thank V. Radhakrishnan and C. J. Salter for many useful discussions and for critically reading the manuscript. Our thanks are also due to P. A. Shaver and D. C. V. Mallik for their comments. D. A. Graham is thanked for supplying the 2700 MHz data obtained at Effelsberg.

References

Balick, B.: 1975, *Astrophys. J.* **201**, 705.
Blitz, L.: 1980, *Giant Molecular Clouds in the Galaxy*, Pergamon Press, New York, p. 211.
Bridle, A. H.: 1967, *Monthly Notices Roy. Astron. Soc.* **136**, 219.
Gordon, K. J., Gordon, C. P., and Lockman, F. J.: 1974, *Astrophys. J.* **192**, 337.
Graham, D. A., Haslam, C. G. T., and Wilson, W. E.: 1982, *Astron. Astrophys.* **109**, 145.
Holden, D. J.: 1968, *Monthly Notices Roy. Astron. Soc.* **141**, 57.
Krymkin, V. V.: 1978, *Astrophys. Space Sci.* **54**, 187.
Parrish, A.: 1972, *Astrophys. J.* **174**, 33.
Pedlar, A. and Mathews, H. E.: 1973, *Monthly Notices Roy. Astron. Soc.* **165**, 381.
Rowan-Robinson, M.: 1980, *Giant Molecular Clouds in the Galaxy*, Pergamon Press, New York, p. 83.
Sarazin, C. L.: 1977, *Astrophys. J.* **211**, 772.
Sastry, Ch. V. and Shevgaonkar, R. K.: 1983, *J. Astron. Astrophys.* **4**, 47.
Shaver, P. A., McGee, R. X., Lynette M. Newton, Danks, A. C., and Pottasch, S. R.: 1983, *Monthly Notices Roy. Astron. Soc.* **204**, 53.
Viner, M. R., Vallee, J. P., and Hughes, V. A.: 1979, *Astron. J.* **207**, 53.