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330-MHz radio continuum observations of the H II regions M42 and M43

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SUMMARY

We present a radio continuum image of the Orion Nebula (M42 and M43) made with a resolution of 57 arcsec at a frequency of 330 MHz. At this low frequency, the H II region M42 appears to be asymmetric on all scales exceeding an arcminute, whereas M43 appears to have circular symmetry. The intensity distribution in M42 is flat topped and has a sharp cut-off to the north-east, whereas diffuse emission with a low surface brightness extends to the south and west. Towards the continuum peak of M42 the optical depth is large ($\tau \gg 1$) and the imaging directly measures the electron temperature to be $T_e = 7865 \pm 360$ K, where the uncertainty is the rms error expected.

1 INTRODUCTION

The Orion A complex (W10), comprising the Great Orion Nebula (NGC 1976, M42) and the smaller nebulosity to the north (NGC 1982, M43), is the most studied H II region (Goudis 1982). Observations of the nebulae at radio frequencies, both in the continuum and in recombination lines, have led to derivations of the physical conditions in the ionized regions and models for the distribution of the electron temperatures and densities (Wilson & Jäger 1987). The studies have focused on the central regions of the Orion Nebula, and the physical conditions in the outer tenuous gas beyond about 4 arcmin (0.6 pc) are not well understood. The principal reason for this is the lack of high-resolution images at a frequency where the central regions are opaque and the emission received is mainly from the outer regions.

The total radio spectrum of the Orion Nebula (Shaver 1980) suggests that the continuum arises from thermal bremsstrahlung emission. At frequencies above 5 GHz where the entire nebula is believed to be optically thin, low-resolution ($\approx$2–4 arcmin) images made in the radio continuum (e.g. see Gordon & Meeks 1968; Macleod & Doherty 1968; Gordon 1969; Schraml & Mezger 1969; Goss & Shaver 1970) resolved the nebula into the H II regions M42 and M43. These observations gave the impression that the H II regions had homogeneous smooth spherical morphologies. M42 was seen to have diffuse structures extending towards the south and west. At arcminute resolutions (Wilson & Pauls 1984), the core of M42 was observed to have pronounced asymmetry. The radio continuum images of M42 made with subarcminute resolutions (Ohashi *et al.* 1989 and references therein) have shown emission centred on the Trapezium stars and the optically bright bar. The radio morphology in these core regions is very similar to the optical line emission structure. At a longer wavelength of 20 cm, Yusef-Zadeh (1990) has observed structures on scales from a few arcsec to about 25 arcmin, and the overall morphology has again been found to be similar to that of Hα images of the H II regions. At frequencies (<1 GHz) well below the low-frequency turnover in the total spectrum of the nebula, the only image available is the 3-arcmin resolution image by Mills & Shaver (1968) made at 408 MHz.

Theoretical models of H II regions have been inconclusive regarding the radial distribution of electron temperatures. Some models predict a general increase away from the centre (Hjellming 1966) while others predict a radial decrease at least for the inner regions (Rubin 1968). The integrated radio recombination line intensities along with the radio continuum emission intensities have been used observationally to infer the electron temperatures (T_e) in the ionized nebulae. Wilson & Jäger (1987) have derived a semi-empirical model for the electron density and temperature distributions in M42 based on their H110α and H139β line observations as well as on previous radio results. They infer $T_e \approx 8500$ K for the core region, with a decrease in T_e out to at least 4 arcmin, and claim that this result is in agreement with the recent determinations based on ratios of optical lines of [O III]. Thum *et al.* (1978), from their 91α hydrogen and helium recombination line observations, estimated the electron temperature in M43 to be 6700 K. Radio continuum observations at low frequencies, where the optical depths are large,

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provide a direct measurement of the electron temperature that is free from any assumptions regarding the departures of the excited level populations from local thermodynamic equilibrium (LTE). From their 408-MHz continuum observations made with a resolution of 3 arcmin, Mills & Shaver (1968) derived a $T_e = 7600 \pm 800$ K towards the continuum intensity peak of M42 with the uncertainty in their flux density scale dominating their error estimate. They also estimate a $T_e \sim 8000$ K towards M43 but consider this value to be relatively very uncertain because their measured size for M43 was only slightly larger than their antenna beam. We have made an image of M42 and M43 with a resolution of 57 arcsec in the radio continuum at a frequency of 330 MHz. In the following sections we present the observations and derive the electron temperatures towards the continuum peaks.

2 OBSERVATIONS AND DATA REDUCTION

The observations were made with the Very Large Array (VLA; Napier, Thompson & Ekers 1983) using a pair of continuum bands, each of 3.125-MHz width, centred at the frequencies 327.5 and 333.0 MHz. An integration time of 3.5 hr was obtained with the array in the CD-hybrid configuration in 1988 April, and 4.3 hr in a D-array configuration in 1988 July; these integration times were distributed over an hour-angle range of ±5 hr. The data were calibrated in amplitude and phase with 3- to 4-min duration observations of the secondary calibrator 3C138, obtained every 25 min. The flux density scale was set by bootstrapping the amplitudes to a 10-min observation of 3C48. The flux density of this primary calibrator (3C48) was adopted to be 44.72 Jy at 327.5 MHz and 44.26 Jy at 333.0 MHz on the scale of Baars *et al.* (1977).

The standard DEC-10 calibration programs and AIPS image-reconstruction routines of the NRAO were used in the data reduction. The D-array visibilities were first self-calibrated using the routines of Schwab (1980, 1981). The images for the self-calibration iterations were made with the D-array data alone by using the AIPS MX routine that implements the Cotton–Schwab algorithm (Schwab 1984). On the basis of a comparison of the scalar-averaged amplitudes in bins of spatial frequency that were obtained before and after the amplitude self-calibration iterations, the final visibility amplitudes were scaled to preserve the flux density scale. As a second step in the data reduction, the CD hybrid-array visibilities were self-calibrated. The model images for these self-calibration iterations were constructed by concatenating the CD-array visibilities with the calibrated D-array visibilities obtained in the previous step. The images were made using the AIPS MX routine with a superuniform weighting scheme and a smooth-stabilized deconvolution algorithm (Cornwell 1983). This procedure enabled images of 72-arcsec resolution to be constructed without obvious instabilities. As in the case of the D-array data reduction, the self-calibrated C-array visibilities were appropriately scaled to preserve the flux density scale. Observations of the primary calibrator, 3C48, with the VLA (Perley & Crane 1986) have shown that the formula of Baars *et al.* (1977) gives the flux density at 330 MHz with an accuracy of 2 per cent. Our self-calibration procedure introduces an uncertainty of 3 per cent in the image intensities. Hence the final flux density scale is expected to be accurate to within ±4 per cent.

Owing to the smooth structure of the nebula, the conventional AIPS MX routine resulted in artefacts in the form of coherent 'clean stripes' when we attempted to deconvolve arcminute-resolution images of the field. Therefore, the final high-resolution images were made using the AIPS maximum entropy method (MEM) deconvolution routine VTESS that implements the algorithm of Cornwell & Evans (1985). The MEM-deconvolved image was convolved with a Gaussian beam and the residuals were added. This technique produced an image with a resolution of 57 arcsec which, when smoothed to a resolution of 72 arcsec, was in excellent agreement with images produced by the AIPS MX deconvolution.

3 THE 330-MHz CONTINUUM IMAGE

A contour representation of our 330-MHz radio continuum image of the H II regions M42 and M43 is shown in Fig. 1. The contours are of total intensity – Stokes parameter *I*. The image has a resolution corresponding to a Gaussian beam of half-power size 57×57 arcsec^2 and the rms noise in the image is 8 mJy beam^{-1}. The VLA antennae have a half-power beamwidth of 149 arcmin at 330 MHz and the image has been corrected for the attenuation due to this primary beam.

The spectrum of the nebula (Goudis 1982) suggests a total 330-MHz flux density of 170 Jy for M42 and M43 together. The visibility amplitudes, when extrapolated to zero wavelength, indicate a total flux density of 180 Jy in the primary beam field-of-view and the integrated flux densities of M42 and M43 in our image are 158.4 and 12.4 Jy respectively. Therefore, the flux density in our interferometric image is consistent with the expected value derived from single-dish total power measurements. In addition, since the observation has provided useful visibility measurements over the spatial wavelength range from 30–4000 wavelengths and consequently the image is expected to have reproduced all the large-scale features up to ≈30 arcmin in size, we believe that our image has no missing flux density.

4 DISCUSSION

4.1 M43

Our 330-MHz image of M43 has a peak flux density of 1.24 ± 0.05 Jy beam^{-1} which corresponds to an average brightness temperature of 4300 ± 170 K over the beam. A deconvolution of the image indicates that M43 has been well resolved and the peak intensity has been reduced by only about 10 per cent as a consequence of the smoothing by the telescope synthesized beam. We correct for the effects of finite resolution by increasing the brightness temperature by 10 per cent (430 K) and estimate that this correction is uncertain by as much as ±150 K. We estimate the brightness temperature of the Galactic background in the region of the Orion Nebula to be 35 K at 0.33 GHz by an extrapolation of the 408-MHz measurements of Haslam *et al.* (1982). Because a Fourier synthesis image is insensitive to any uniform background and there is absorption of background emission within the source, we deduce that our imaging will underestimate the peak brightness at 330 MHz by about 20 K. These corrections lead us to infer a value of 4750 ± 230 K

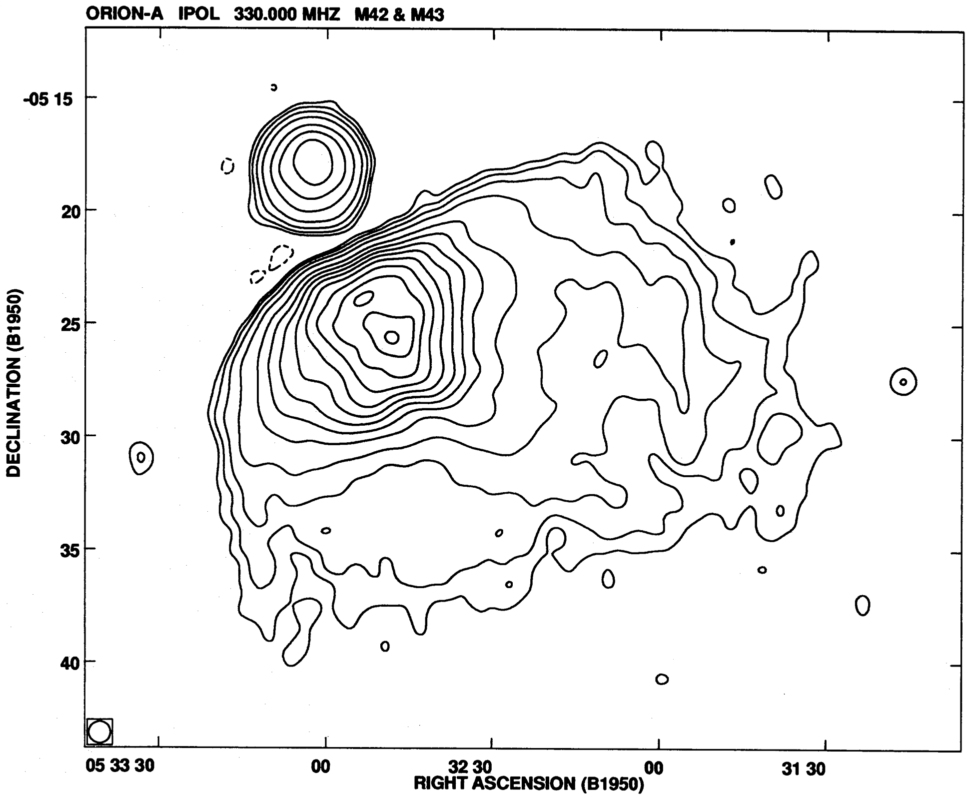

Figure 1. VLA image of M42 and M43 at 330 MHz. The contours are at 32 × (−1, 1, 2, 4, 8, 16, 24, 32, 40, 48, 56, 62, 65, 68) mJy beam^{-1}. The half-power area of the beam is 57 × 57 arcsec^2 and is indicated by the circle in the lower left corner. The image has been corrected for the primary beam response of the telescope.

for the brightness temperature towards the continuum peak of M43. The dominant causes of the errors in this estimate are the uncertainty in the absolute flux density scale and the error in the determination of the deconvolved continuum peak from the finite-resolution image. At 10.7 GHz, we have estimated the brightness temperature towards the radio continuum peak of M43 to be 4.5 ± 0.25 K by a deconvolution of the image presented in Thum *et al.* (1978). Modelling the source as an isothermal H II region, we derive the optical depth at 330 MHz towards the continuum peak to be 0.7 ± 0.3 and the electron temperature to be 9000 ± 1700 K. This value is consistent with the T_e estimates derived by Mills & Shaver (1968) from their 408-MHz continuum observations, but significantly larger than the estimates of Thum *et al.* (1978), which were based on recombination line observations at a much higher frequency. Perhaps this indicates that the electron temperatures in this spherically symmetric H II region may increase away from the core regions.

4.2 M42

The 330-MHz image of M42 has a flat brightness distribution over the central regions of the nebula with the intensity lying within 10 per cent of the peak value over a 4-arcmin region. A comparison with the 23-GHz image made by Wilson & Pauls (1984) indicates that the central ≈ 40 arcmin^2 area has an optical depth exceeding unity. The intensity decreases away from the peak although the opaque central region is well resolved by the 57-arcsec beam, and this is consistent with the conclusions of Wilson & Jäger (1987) that the electron temperatures fall away from the centre.

At the resolution of 57 arcsec, our 330-MHz image of M42 has a continuum peak flux density of 2.19 ± 0.09 Jy beam^{-1}, and this implies an average brightness temperature of 7600 ± 300 K over the beam. We examined the decrease in the peak intensity on smoothing the image to progressively lower resolutions and determined the deconvolved peak intensity by an extrapolation of this behaviour to infinite resolution. This led us to increase the measured brightness towards the peak by 3 per cent (230 K) to correct for the finite resolution in our image. The associated uncertainty in this correction is about ± 200 K. Since the opacity at 330 MHz towards the continuum peak of M42 is large, we add a value of 35 K to the peak brightness to account for the insensitivity of our Fourier synthesis image to the Galactic continuum background. These corrections finally yield an estimate of 7865 ± 360 K for the peak brightness towards M42. A comparison with the 23-GHz image of Wilson & Pauls (1984) indicates that the optical depth towards the peak exceeds 25. This implies that, if we assume the H II region to be isothermal, the above estimate for the peak brightness is also the electron temperature. The estimate is in good agreement with that of Mills & Shaver (1968). The multiple-slab model by Wilson & Jäger (1987) predicts a peak brightness of 7465 K at 330 MHz and is in marginal agreement with our measurement.

There is some evidence indicating that the 330-MHz image is double peaked – the northern peak being the brightest part of the sharp front and the southern peak located at the Trapezium group of stars. A molecular bipolar flow has been detected, centred in the molecular cloud behind the H II region with a blueshifted jet that terminates at the southern continuum peak (Schmid-Burgk *et al.* 1990). It is intriguing that this structure is similar to that observed in another blister H II region, NGC 2024 (Subrahmanyan, in preparation), where, again, a background molecular bipolar flow has been discovered. Its blueshifted jet impinges on the H II region/molecular cloud interface at a point close to a secondary continuum peak that is distinct from a sharp ionization front.

5 CONCLUSIONS

We have made arcminute-resolution images of the H II regions M42 and M43 at a frequency of 330 MHz. M42 appears to be a complex nebula with a sharp cut-off in the extent of the ionized gas to the north-east and diffuse extensions to the south and west. Towards the central opaque regions of the nebula, our continuum observations directly measure the electron temperature to be 7865 ± 360 K, which is consistent with the model of Wilson & Jäger (1987). M43 appears to be a 'standard' spherically symmetric H II region. We estimate that $T_e = 9000 \pm 1700$ K for this region from our continuum observations, indicating that this nebula could have an electron temperature increasing radially away from the core.

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