Mon. Not. R. astr. Soc. (1992) **254**, 719–722

Radio jet in the H II region Orion B

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Accepted 1991 September 23. Received 1991 September 19; in original form 1991 June 17

SUMMARY

An arcmin-resolution image is presented of the nearby H II region Orion B (NGC 2024, W12) made in the radio continuum at a frequency of 330 MHz. The image displays a spectacular jet-like feature extending northwards and up to 10 arcmin from the core of the nebula. The radio jet is parallel to a molecular bipolar flow seen in the associated molecular cloud. Continuum radio emission is also detected to the south of the H II region and positionally coincident with the southern molecular jet. Despite the large optical depth, the imaging shows surface-brightness variations in the main body of the H II region. The brightness temperature towards the peak of the continuum emission directly measures the electron temperature of the ionized gas to be 8400 ± 1000 K.

1 INTRODUCTION

Orion B is a compact H II region lying eastwards of the bright star ζ Orionis and north-east of the extended nebula IC434 (Horsehead nebula). Since the source has a linear diameter of about 0.5 pc and is located at the relatively small distance of 0.5 kpc from the Sun, Orion B has been the target of several observational studies that have resulted in a detailed geometric model for the region (Barnes *et al.* 1989 and references therein).

The observational investigations have revealed distinctive properties that have made Orion B an atypical H II region. Recombination lines of carbon and an unknown heavier element are observed with a narrow width ($\Delta v \approx 4$ km s^{-1}). Hydrogen recombination lines with a narrow ($\Delta v \approx 4$ km s^{-1}) profile are seen in addition to the normal broad lines (with $\Delta v \approx 30$ km s^{-1}). These narrow lines (Pankonin *et al.* 1977) indicate the presence of a cold, partially ionized medium and have been attributed to the outer portion of the ionization front that forms the interface between the H II region and the H I/molecular cloud associated with the nebula (Zuckerman & Ball 1974). The recombination lines have also been used to infer a kinetic temperature of $T_K \approx 500$–1000 K for the cold ionized interface compared to the 8000-K estimate for the hot H II region. A bipolar molecular jet was discovered in the associated dense molecular cloud (Sanders & Willner 1985) and the flow is the most highly collimated known. Since the centre of the flow is located close to the ionization front, its influence on the H II region is of interest. Russell *et al.* (1980) have detected [C II] fine-structure emission lines from the nebula, indicating the presence of cool interstellar atomic gas with $T_K \approx 100$ K. These unique features in Orion B make it a strong candidate for a study of the interface between an ionization-bounded H II region and an H I/molecular cloud.

The extended low-surface-brightness radio emission in the region containing Orion B and IC434 was imaged at 2.7 GHz by Caswell & Goss (1974) using a half-power beamwidth (HPBW) of 8.2 arcmin. Gordon (1969) imaged the 7.8-GHz continuum as well as the 94α hydrogen recombination line from the nebula with an HPBW of 4.2 arcmin. Krügel *et al.* (1982) observed the distribution of 76α recombination lines from hydrogen, helium and carbon over the source and obtained a 15-GHz continuum image of Orion B with an HPBW of 1 arcmin. A 21-cm aperture-synthesis image with an HPBW of 0.9 arcmin was made by Löbert & Goss (1978). At the much higher resolution of 0.22-arcmin HPBW, Crutcher *et al.* (1986) observed the 4.8-GHz continuum and H_2CO absorption line with the VLA. Barnes *et al.* (1989) used the VLA at 1667 MHz to image the H II region in the radio continuum and OH absorption line with an HPBW of 4.3 arcsec, the highest to date. The 1424-MHz continuum and the H166α, C166α narrow recombination lines of Orion B were imaged with an HPBW of 45 arcsec by Anantharamaiah, Goss & Dewdney (1990). Below the low-frequency turnover in the total spectrum of the H II region, the only available image is that of Shaver (1969) who observed the 408-MHz continuum with an HPBW of 3.2 arcmin.

This paper presents an arcmin-resolution, 330-MHz radio-continuum image of the H II region Orion B. At this low frequency, the total spectrum of the nebula has turned over, indicating that the denser regions are optically thick. The aim of the observation was to study the temperature

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§The Australia Telescope National Facility is operated in association with the Division of Radiophysics by CSIRO.

structure of the H II region. Low-frequency radio observations constitute a probe of the cooler interface region between the H II gas and the associated molecular cloud. The observations revealed a spectacular jet extending beyond 1 pc from the core of the nebula. The following sections present the observations and speculate on the origin of this jet-like feature. The electron temperature in the nebula is derived from the observed brightness towards the peak of the continuum intensity. We also discuss the similarities and differences between the various other features seen in our image with those in previous continuum images obtained at higher frequencies.

2 OBSERVATIONS AND DATA REDUCTION

Orion B was observed 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. A total integration time of 2.5 hr was obtained in a CD hybrid configuration in 1988 April and 1.7 hr in a D-array configuration in 1988 July; the observing time was distributed over a wide range of hour angles in both the configurations. The observations were calibrated in amplitude and phase with the nearby unresolved source 3C138 whose flux density was bootstrapped to 3C48. The flux density of this primary calibrator (3C48) was taken to be 44.72 and 44.26 Jy at the frequencies 327.5 and 333.0 MHz respectively, based on the BJPW scale (Baars *et al.* 1977). Observations of 3C48 with the VLA (Perley & Crane 1986) have shown that the formula in Baars *et al.* gives the flux density at 330 MHz with an accuracy of 2 per cent. Therefore the uncertainty in the final flux-density scale due to calibration errors is not expected to exceed ± 2 per cent.

The standard DEC-10 calibration programs and AIPS image-reconstruction routines of the NRAO were used in the data reduction. Many data obtained at the shortest baselines (particularly in the D-array configuration) showed obvious effects of interference and shadowing, and were rejected. The data obtained in the two array configurations were independently self-calibrated using the routines of Schwab (1980, 1981). In the first two self-calibration iterations, only the phases were corrected. Further iterations also performed amplitude corrections and the residuals were clipped in amplitude to eliminate correlator-based errors. The data from the two arrays were independently scaled by comparing the binned amplitudes before and after the amplitude self-calibration iterations. The errors in the final flux-density scale are estimated to be within ± 10 per cent. All the data were concatenated, time-averaged over 3-min intervals, and imaged using the Cotton–Schwab algorithm (Schwab 1984). A 1.5-Jy source, located within the primary beam and 1°.7 from Orion B, was imaged in a separate field centred on this source so that its sidelobes were accurately removed in the deconvolution. A super-uniform weighting scheme was adopted to obtain images at the highest resolution.

3 THE 330-MHz CONTINUUM IMAGE

The Fourier synthesis observations have provided visibility measurements in the range 30 to 3250 wavelengths. Since none of the single-dish images of Orion B has shown evidence for structure on scales exceeding ≈ 15 arcmin, we expect to have reproduced all the large-scale features and also to have recovered the total flux density at 330 MHz.

A contour representation of our Orion B image is shown in Fig. 1. The half-power beam area is indicated by the ellipse in the lower left-hand corner. The clean components have been restored with a Gaussian beam of HPBW 90 × 60 arcsec² at a position angle of 64°. The rms noise in the image is 11 mJy beam^{-1} and the peak intensity is 3.25 Jy beam^{-1}. The lowest contour is at 2.3 times the standard deviation of the noise in the image. The visibilities, when extrapolated to zero spacing, indicate a total flux density of ≈ 40 Jy in the primary beam field-of-view. The primary beam has an HPBW of 149 arcmin and the total cleaned flux density in a (171 arcmin)² area is 40.2 Jy. By integrating over the region of the source, we estimate the total flux density of Orion B to be 34.3 ± 3 Jy at 330 MHz. This is consistent with the total spectrum of the source (Goudis 1975) that was derived from measurements with single-dish total-power telescopes.

4 COMPARISON WITH PREVIOUS RADIO-CONTINUUM IMAGES

The new result obtained following these observations is the spectacular jet emerging from the main body of the H II region and extending north up to 10 arcmin from the core of the nebula (Fig. 1). There are indications for the existence of

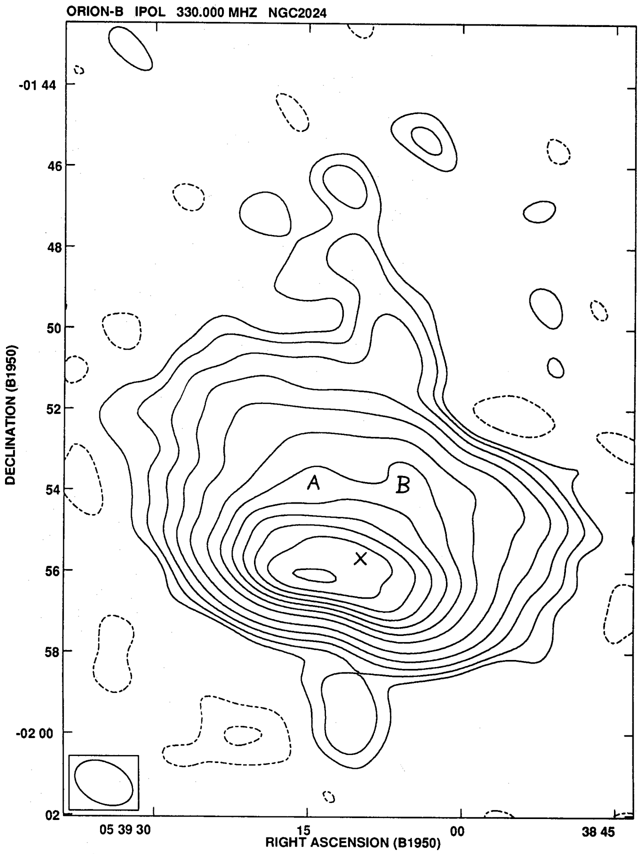

Figure 1. VLA image of Orion B at 330 MHz. The ellipse in the lower left-hand corner indicates the half-power beam size. Contours are at 25 × (−2, −1, 1, 2, 4, 8, 16, 32, 48, 64, 80, 96, 112, 128) mJy beam^{-1}. The lowest contour is at a level of 2.3 times the standard deviation of the noise in the image.

such a feature in the 7.8-GHz continuum image of Gordon (1969) and the 1.4-GHz image of Anantharamaiah *et al.* (1990). The low-resolution 2.7-GHz image of Caswell & Goss (1974) suggests that the jet could extend up to 30 arcmin from the core. Whereas the high-resolution Fourier synthesis images lack the low spatial frequencies necessary to reproduce this feature, the intermediate- (e.g. Krügel *et al.* 1982) and low-resolution (e.g. Shaver 1969) images lack the sensitivity required to detect the jet. The image in Fig. 1 is also indicative of a low-surface-brightness extension to the south of the emission peak which is parallel to the jet in the north. This feature does not seem to have been detected previously. The jets are observed with a peak brightness exceeding 2 per cent of the peak intensity. Images of unresolved sources in the field do not show errors above the image noise and indicate that any calibration uncertainties probably do not result in image errors at a level of 2 per cent of the peak intensity. However, because of the low declination of the source, the VLA synthesized beam has large sidelobes (≈ 10 per cent) in the north–south direction and hence instabilities in the deconvolution could result in significant artefacts to the north and south of the intensity peak. As a check, we have separately deconvolved the image with the Cornwell & Evans (1985) algorithm that uses the maximum entropy method. Jets to the north and south so obtained had similar extents and brightness distributions to those obtained using the Cotton–Schwab algorithm. The radio jet to the north is 5–9 standard deviations above the image noise whereas the southern jet is a 5–5 standard-deviation feature.

Barnes *et al.* (1989) resolved the core of the H II region into a sharp ionization front to the south and a pair of overlapping loops of emission. Our 330-MHz image shows a sharp intensity gradient to the south of the intensity peak corresponding to the ionization front. The peak itself appears to be a blend of the peak of the ionization front and the southernmost bright parts of the eastern and western loops observed by Barnes *et al.* Löbert & Goss (1978) observed a secondary peak about an arcmin to the northwest of their image maximum. Our 330-MHz image is consistent with the presence of this secondary peak (at the position marked X in Fig. 1) and indicates that the peak might be part of an east–west elongated feature. The extensions marked A and B in Fig. 1 are perhaps diffuse extensions of the 'crab-claws' observed by Crutcher *et al.* (1986) and the eastern and western loops seen by Barnes *et al.* at higher resolutions.

5 DISCUSSION

The main body of the H II region shows surface-brightness variations that are indicative of east–west elongated emission features. Radio-continuum images at low frequencies are representative of the temperature structure in the opaque regions of the nebula whereas high-frequency images are more representative of the variations in emission measure over the source. This suggests that the brightness variations observed at 330 MHz may be due to variations in the electron temperature rather than to density.

The 330-MHz image shows features towards the core regions of the nebula that are identified with features present in higher frequency images where the nebula is optically thin. This supports the suggestion of Barnes *et al.* (1989) that the far side of the H II region alone is ionization bounded, since this would imply that low temperatures and high opacity are present only on the far side.

In agreement with the higher resolution images at higher frequencies, our image has shown the ionization front to the south to be concave. This structure is perhaps indicative of the presence of multiple sources for the UV ionizing radiation that is eating into the dense molecular cloud to the south, or could be indicative of the structure of the dense gas that is being eroded.

5.1 Electron temperature

Radio-continuum imaging of H II regions at a low frequency at which the region is opaque directly yields a measurement of the electron temperature of the gas. Unlike the estimates derived from observations of recombination lines, the continuum measurement is independent of assumptions regarding the departures of the level populations from local thermodynamic equilibrium.

Towards the continuum peak, our 330-MHz image has an average brightness temperature of 6700 K over the beam. It is deduced that the finite resolution of the image has resulted in the peak brightness being underestimated by about 20 per cent. The brightness temperature of the Galactic background radiation at 330 MHz in the line of sight towards Orion B is estimated to be 35 K from an extrapolation of the 408-MHz observations by Haslam *et al.* (1982). Since our imaging instrument is an interferometer, a constant brightness corresponding to this background would be absent in the image. However, towards the continuum peak, the background would have a very diminished contribution due to the high opacity of the gas, and therefore the peak brightness estimated from the interferometric image would underestimate the true brightness by a value close to 35 K. Correcting for these effects, the brightness towards the continuum peak is 8400 ± 1000 K. In an isothermal approximation, the 15-GHz flux densities of Krügel *et al.* (1982) were used along with the 330-MHz measurements, and a value of 4.5 ± 0.5 for the optical depth τ towards the continuum intensity peak was derived. The large optical depth implies that the measured brightness temperature is a good estimate (less than 2 per cent errors) of the electron temperature of the gas, and I conclude that the ionized gas towards the continuum peak has an electron temperature of 8400 ± 1000 K. The dominant contributors to the uncertainty in this estimate are the possible errors arising from the use of amplitude self-calibration in the imaging, and the uncertainty associated with the correction for the effects of finite resolution.

The comparison with the 15-GHz image by Krügel *et al.* (1982) suggests that the central ≈ 10 (arcmin)^2 area of the nebula is opaque ($\tau > 1$) at 330 MHz. Therefore, our image of this region, as well as the electron temperature estimate, is representative of peripheral regions removed from the core where the optical depth along the line of sight becomes unity. Krügel *et al.* (1982) estimate $T_e = 7000$–8000 K from their H76α line-to-continuum ratios assuming LTE. Their measurement probes the central regions of maximum emissivity. The T_e measurements together suggest that the electron temperatures are fairly constant over the inner 0.2 pc of the nebula.

5.2 The radio jet

A comparison of our 330-MHz image with the low-resolution 7.8-GHz image made by Gordon (1969) indicates that the northern radio jet has a spectrum consistent with thermal bremsstrahlung emission from an optically thin region. Sanders & Willner (1985) discovered a molecular jet in Orion B that is centred in the dense molecular cloud about 0.5 arcmin south of the ionization front. The jet axis is directed north–south and is parallel to the northern and southern radio jets seen in our 330-MHz image. My hypothesis is that this molecular bipolar flow, which is the most collimated high-velocity flow yet observed, is responsible for the radio jets. The radio jet towards the south is positionally coincident with the molecular jet. Besides, the southern radio jet has a deconvolved width of $\leqslant 0.1$ pc, in agreement with the estimated size of the molecular jet. Hence the radio emission in this southern jet probably originates in shock-heated gas entrained in the molecular jet. Whereas the southern redshifted molecular jet moves unhindered, the northern blueshifted molecular jet is shorter and sharply bent to the west at a distance of about 1.5 arcmin north of the ionization front. It is possible that, although the centre of the bipolar flow is located in the dense molecular cloud behind the H II region, the northern blueshifted jet impinges on the ionized gas/molecular cloud interface on the far side of the H II region. The transfer of momentum to the ionized gas probably results in the bend and termination of the molecular jet as well as in an acceleration of the ionized gas to form the northern radio jet. Knots have been observed in the molecular jets suggesting that the outflows result from periodic outbursts from the central source. Indeed, the northern radio jet also shows condensations. At a wavelength of 18 cm, the jets are expected to be observable with a surface brightness of about 3.5 K and a kinematic study of the radio jets through radio recombination-line observations would enable computation of the energetics of the phenomenon.

6 CONCLUSIONS

A 330-MHz radio-continuum image has been made of the H II region Orion B with an arcmin resolution. The image has revealed a radio jet extending up to 1 pc from the core of the nebula. The radio jet is parallel to a molecular bipolar flow located in the associated molecular cloud. A southern radio jet has also been observed that is positionally coincident with the southern molecular jet. The imaging represents the first detection of thermal bremsstrahlung emission over the entire area of a molecular outflow. The continuum imaging, at a frequency where the core regions of the nebula are opaque, directly measures the electron temperature in the H II region to be 8400 ± 1000 K and this is consistent with the estimates by Krügel *et al.* (1982) which were based on recombination-line observations.

ACKNOWLEDGMENTS

I thank Govind Swarup and Gopal-Krishna for their encouragement. The radio images were made with the NRAO VLA which is operated by Associated Universities, Inc. under cooperative agreement with the National Science Foundation. The data were reduced at the NIPFA at the Radio Astronomy Centre, Ooty. This facility is financed by the DST, Government of India.

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