A 10.5-GHz recombination line map of the W3 complex

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Summary. Observations of the W3 region have been made at 10.5 GHz with a resolution of 2.8 arcmin. They consist of a continuum map of the whole area, and 85α recombination line observations of H, He and C over the most intense regions of W3 and W3N. A narrow H85α line attributed to H I is found in the core of W3, and an upper limit is set for the X85α line attributed to heavy elements. Contour maps of radial velocity, hydrogen line width and electron temperature are presented, and the relationship to other observations of the area is discussed.

1 Introduction

W3 is one component of a large H I complex embedded in the Cassiopeia—Perseus spiral arm. It is in a region of large obscuration due to dust, which has an estimated extinction as large as 14 mag. The most recent radio continuum map at 5 GHz, with angular resolution of 2 arcsec (Harris & Wynn-Williams 1976) shows numerous H I components, the most intense appearing to have a shell structure. The whole region contains infrared sources, OH and H2O sources, and other molecular line emissions, and is undoubtedly one in which active star formation is taking place. However, though an interferometer with a resolution of 2 arcsec can resolve the small-scale features, this is at the expense of resolving the larger scale emission regions, in particular the general background variations of angular scale greater than 1 arcmin.

This paper describes an investigation of W3 and W3N using the 2.8-arcmin resolution of the 150-ft telescope at the Algonquin Radio Observatory. Observations were made at 10.5 GHz in the continuum, and also of the 85α recombination lines from H, He and C, such that their distribution was obtained over the more intense regions. The results, though influenced by the presence of components which are known to be unresolved, can be used to obtain information on the large-scale motion of the region so as to enable a comparison with the large-scale motion of the interstellar medium.

Carbon recombination line emission has previously been detected away from the continuum peak of W3 by Wilson, Thomasson & Gardner (1975) at 2.7 GHz with an angular resolution of 4.8 arcmin. However, they observed too few points in the nebula to obtain the
detailed distribution of carbon emission in W3, and had insufficient sensitivity to measure the recombination emission from helium.

The only previous large-scale recombination line map of the W3 complex has been that by Rubin & Mezger (1970) of H109α, with an angular resolution of 6 arcmin. They produced maps of hydrogen line velocities, widths and LTE electron temperatures, but did not report detection of helium or carbon emission. In addition, they state that their observations are contaminated by the overlapping emission of H109α and two higher order hydrogen recombination lines.

Our observations cover a somewhat smaller area of the W3 complex, but with more than twice the angular resolution of Rubin & Mezger and considerably higher sensitivity. Any contamination of our data by higher order recombination lines amounts to well under 1 per cent.

2 Observations

Observations were made using the 46-m telescope of the Algonquin Radio Observatory. At the wavelength of 2.8 cm the beamwidth was 2.8 arcmin and the aperture efficiency was 42 per cent. The receiver was a cooled parametric amplifier with centre frequency of 10.5 GHz and bandwidth of 100 MHz, and the spectrometer consisted of a bank of 100 filters each of width 100 kHz. The overall system noise temperature varied between 120 and 150 K. Observations were made in the period 1972 October to 1975 June.

In order to define the area to be investigated, a continuum map at 10.5 GHz was first obtained by taking a series of right ascension scans across the region, each scan being separated in declination by 0.2 beamwidth. The data were recorded on magnetic tape and processed by an IBM360/67 computer, using a mapping program developed by Higgs (1972). The resulting map with contours in units of 0.1 K is shown in Fig. 1. 1950.0 coordinates are used and the flux scale is related to the standard source, NGC 7027. Positional accuracy of the contours is ±10 arcsec.

Recombination line spectra were then taken at a grid of points which covered those regions of comparatively intense continuum radiation where a signal/noise ratio of greater than 10 could be obtained in less than 200 min of integration. The grid points, which are shown in Fig. 1, were separated by 1.5 arcmin, approximately half a beamwidth. The regions selected encompassed W3 and W3N, but W3(OH) was omitted due to its small diameter and the fact that the recombination line in its direction had already been observed (Hughes & Viner 1976). With the exception of one grid point at the north-west corner of W3, the signal/noise ratio attained for the H85α line was >13:1.

At each of the grid points a number of spectra were obtained, each spectrum being the result of 10 min of integration 'on-source' from which was subtracted a comparison 'off-source' spectrum obtained from 10 min of integration east of the point covering the same range of hour angle. The spectra at each point were then averaged, each individual spectrum being weighted according to the rms noise on the baseline. During the process some records were rejected due to inordinately large baseline variations. At intervals of about 1.5 hr, continuum scans were made across the region so as to monitor the small changes in antenna temperature produced by changes in zenith angle and weather conditions, and also to maintain pointing accuracy to within ±15 arcsec. A standard noise signal was injected at intervals to maintain a calibration for the continuum intensity. Because slightly different centre frequencies were used for the line observations, individual spectra did not cover identical frequency ranges, with the result that the averaged spectra covered a range of 8.3 MHz rather than 10 MHz. Averaged spectra were stored in the form of punched paper tapes for
Figure 1. The W3 complex as observed at 10.5 GHz with a resolution of 2.8 arcmin. The contour units are 0.1 K. The main components are indicated as W3, W3N and W3(OH) as shown. The crosses indicate the 34 grid points at which 85α recombination line observations were made.

Further processing. The total on-source integration time for all positions observed was 75 hr.

Further processing consisted of using a non-linear least-squares program to fit, simultaneously, up to three Gaussian line-profiles and a sinusoidal baseline ripple, the latter being the result of standing waves set up by reflections between the primary focus and the main surface of the telescope. The spectral lines consisted of the main H line, the He line and a third line attributed to C. Processing of the H line was accomplished for each of the grid points. In addition, spectra from groups of four and also groups of nine grid points were combined prior to the final processing in order to improve the signal/noise ratio for the He and C lines.

3 Results

3.1 Hydrogen Line

The results obtained from the H85α spectra at the 34 grid points observed in W3 and W3N are given in Table 1. All errors quoted are one standard deviation. The positions given are the


<table>
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<th>Position</th>
<th>$T_C$ (K)</th>
<th>$T_L$ (mK)</th>
<th>$\Delta v^a$ (kHz)</th>
<th>$V_{LSR}$ (km/s)</th>
<th>$T_e$ (K)</th>
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<th>Position</th>
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<th>$V_{LSR}$ (km/s)</th>
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<th>$T_L$ (mK)</th>
<th>$\Delta v^a$ (kHz)</th>
<th>$V_{LSR}$ (km/s)</th>
<th>$T_e$ (K)</th>
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<td>76.1 ± 3.6</td>
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<td>8120 ± 500</td>
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<td>8620 ± 600</td>
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</table>

* Corrected for instrumental broadening.

offsets in right ascension and declination from the continuum peak in units of 1.5 arcmin (or 12.7 for RA). The position of W3 (0,0) from Fig. 1 is $\alpha_{1950.0} = 02^h 21^m 53.8^s$, $\delta_{1950.0} = 61^\circ 52' 29''$, and the position of W3N (0,0) is $\alpha_{1950.0} = 02^h 23^m 02.6^s$, $\delta_{1950.0} = 62^\circ 02' 13''$. The continuum antenna temperatures quoted in column 2 were taken from the map in Fig. 1.
Figure 2. (a) Contour map of H85α radial velocities in km/s overlaid on the continuum map of W3. The crosses indicate where observations were made. The positions of condensations observed by Sullivan & Downes (1973) and Harris & Wynn-Williams (1976) are shown as filled circles. (b) Same as (a), but for W3N.
3.1.1 Velocity

Fig. 2 shows the variation in velocity across both W3 and W3N. For W3N there is only a small variation of about 2 km/s, but for W3 the picture is more complex. Around the core of W3 the contours have a saddle-shape distribution, with a line of relatively constant velocity running from the north-east to the south-west, and more negative velocities toward the north-west and south-east.

3.1.2 Linewidths

Fig. 3 shows the variation in width of the H85α across W3 and W3N. Again, W3N shows a lack of complexity. The results for W3 can be compared with those by Rubin & Mezger, who find a ridge of nearly constant width running from north-east to south-west. As expected, the present results agree in general with those of Rubin & Mezger, but show more detail. It is interesting to note that the linewidths are narrower towards the north-west and south-east, namely in those regions where the radial velocity is significantly more negative.

3.1.3 Electron temperatures

The electron temperature was determined from the relationship (Terzian 1974)

\[ T_e = 5.79 \times 10^4 \nu^3 \left( P \ln \left( 4.95 \times 10^{-2} \nu^{-1} T_e^{4.5} \right) \right) \]  \hspace{1cm} (1)

where \( P = \Delta \nu_1 T_L / T_C \), \( \nu \) is in GHz and \( \Delta \nu_L \) in kHz. It was assumed that the region was in local thermodynamic equilibrium (LTE) and that \( N(\text{He}^+)/N(\text{H}^+) = 0.1 \). Equation (1) has been corrected for a 3 per cent numerical error in the constant term as quoted by Terzian (1974).

The results are shown in Fig. 4. On the average, the temperatures obtained appear to be about 2000 K higher than those found by Rubin & Mezger (1970) from their H109α data. Since our LTE temperatures are comparable to those obtained by Wilson et al. (1975) from H134α, we must conclude that the contamination of H109α by H196γ and H206η is larger than the 6 per cent suggested by Rubin & Mezger.

Our data show a gradual increase in temperature across W3 from 8000 K in the west to 11000 K at the eastern edge. W3N shows a similar gradient of about 2000 K from south-west to north-east. These gradients are not seen in the data of Rubin & Mezger, and are only marginally apparent in the data of Wilson et al.

3.2 Helium and Carbon Lines

Due to the much smaller relative amplitude of the helium and carbon lines, the signal-to-noise ratio at each of the grid points was quite small. An improvement was made by averaging together, as a group, the spectra from four adjacent positions. Each single spectrum was given an equal weight. The spectrum from each of the groups was then processed in a similar fashion to that for the individual grid points. The results obtained for the helium and carbon lines are compared with those from hydrogen and are shown in Fig. 5. The size of the blocks are scaled so that the corners of each block represent the position of each individual grid point. C85α was not detected in W3N.

In some cases the helium line appears to be blended with an additional line. One result of this shows up as an increase in the half-width of the helium line which in some cases has a value comparable to that of the hydrogen line. An exception is the outer four blocks to the south-west where the He lines are significantly narrower and the ratio of \( N(\text{He}^+)/N(\text{H}^+) \) appears to be lower than the values for the rest of the region. It is likely that the blended line is a carbon line from a foreground cloud at a velocity of -22 km/s. This will be discussed later.
Figure 3. (a) Contour map of H85ω line widths in kHz overlaid on the continuum map of W3. (b) Same as (a), but for W3N.
Figure 4. (a) Contour map of LTE electron temperatures in K overlaid on the continuum map of W3. (b) Same as (a), but for W2N.
Figure 5. (a) Schematic representation of H, He and C 8.3a line parameters obtained from averages of data over groups of four grid points in W3. The filled square shows the position of the continuum peak of W3 \((\alpha_{J2000} = 02^h 21^m 53^s.2, \delta_{J2000} = 61^\circ 52' 29'')\), and the corners of each square are located at each grid point observed. The separation of the grid points in each coordinate is 1.5 arcmin. Line strengths \(T_L\) are given in mK. Line widths \(\Delta V_L\) are corrected for instrumental broadening and are given in kHz. (b) Same as (a), but referred to the continuum peak of W3N \((\alpha_{J2000} = 02^h 23^m 02^s.6, \delta_{J2000} = 62^\circ 02' 13'\).
3.3 THE X85α LINE

Previous observations of W3 using the 92α line set (Chaisson 1974), have shown the presence of a further line, displaced from that due to carbon by $-11 \text{ km/s}$. It has been observed also in a number of H II regions and is attributed to an element of mass greater than carbon, or to a group of heavy elements. The line is often referred to as the X-line.

To check for its possible presence, the spectra from nine points centred on W3 were averaged, and the resulting high-frequency part of the spectrum is shown in Fig. 6. Also shown are the residuals after subtracting the He and C lines. Taking as a criterion for detection that the line amplitude must be at least $3 \sigma$, our upper limit to the antenna temperature for the line is $9.7 \text{ mK}$. With this upper limit and assuming that the linewidth of $4.1 \text{ km/s}$ for 92α scales to a value of $144 \text{ kHz}$ for 85α, the upper limit to the ratios of the line strengths of the carbon and X line is 0.27 for $85\alpha$. This result is not inconsistent with the corresponding ratio of $0.35 \pm 0.16$ as obtained by Chaisson for 92α.

3.4 THE NARROW H85α (H I) LINE

A narrow line, blended with the broad H line, has been reported previously for H157α (Chaisson 1972b) and for H134α (Wilson et al. 1975), and has been attributed to a cool H I cloud in the line of sight to W3. The line was also found in the present observations by fitting two Gaussians simultaneously to the broad H85α line. The results are summarized in Table 2, and are compared with the other observations. At the peak continuum position the narrow line showed up with a signal-to-noise ratio of 7. No significant detections were found at any other grid points in the map.

Similar fits were attempted to the averages of four grid points surrounding the central peak in order to delineate the angular extent and position of the emitting region. In these spectra, the intensity of the narrow line was weaker than that at the central peak by about a
factor of 3, indicating that the angular size of the region is less than 1 arcmin. Similarly, a comparison of the intensities obtained from these four spectra show the peak emission to be displaced \(20 \pm 40\) arcsec toward the south-east of W3 (0, 0).

Further measurements of the narrow line in H66\(\alpha\), H85\(\alpha\) and H100\(\alpha\) are in progress in order to enable a model of the region to be developed.

4 Discussion

4.1 W3

W3 is a complex source, consisting of a number of H\(\text{II}\) condensations embedded in a more diffuse region of emission. Fig. 7 shows a map of the core of W3 obtained at 5 GHz with an angular resolution of 2 arcsec (Harris & Wynn-Williams 1976). The shell component ‘A’ appears to be optically thin and has a flux density of \(33 \pm 4\) Jy at 5 GHz. At the same frequency, H109\(\alpha\) observations (Wellington et al. 1976) show a range in radial velocity of –36 to –48 km/s across the source, with most of the emission at about –40 km/s. By comparison, W3B has a continuum flux density of \(10 \pm 2\) Jy and a radial velocity of about –35 km/s.

High-resolution recombination line data are not available for any of the other H\(\text{II}\) condensations in W3, but the above examples show the difficulty in a detailed interpretation of the velocity distribution as measured with a 2.8-arcmin beam. The positions of the 11 components resolved in W3 by Harris & Wynn-Williams (1976) and by Sullivan & Downes (1973) are plotted in Fig. 2. Our H85\(\alpha\) maps must be interpreted in terms of average physical conditions along the line of sight in the area of the antenna beam, which may or may not include one or more of the condensations.

Clearly, the radial velocity of the H\(\text{II}\) in W3 as a whole is about –41 km/s, while that of W3N is about –48 km/s. The mass motion of material along the line of sight towards the W3 complex can also be discerned from observations of neutral hydrogen, carbon monoxide and formaldehyde, which are widely distributed throughout the Galaxy.

In the direction of W3, the most prominent H\(\text{I}\) emission feature occurs at –45 km/s, while absorption features occur at –2, –19 and –42.5 km/s (Chaisson 1972a) with optical depths of 0.5, 2.0 and > 3.8 respectively (Crovisier et al. 1975). This indicates the presence of extremely dense H\(\text{I}\) in the immediate vicinity of W3.

The radial velocities of 115 GHz CO emission in the direction of W3, W3N and W3(OH) are –41, –41 and –47 km/s respectively (Wilson et al. 1974). However, the more extensive survey of 4.8-GHz H\textsubscript{2}CO absorption in W3 and surrounding regions (Minn & Greenberg 1973) shows an interesting variation of velocities. In a region of about 10-arcmin diameter centred on W3, H\textsubscript{2}CO has a velocity of about –41 km/s, while outside this region velocities of –48 to –52 km/s are observed.

The above velocities of interstellar gas in the direction of W3 must eventually be reconciled with a model for the source and its interaction with streaming motions in the nearby galactic spiral arm.
Figure 7. A contour map of the central portion of W3A obtained at 5.0 GHz with a resolution of 2 arcsec (Harris & Wynn-Williams 1976). The cross indicates the position, with error bars, of the 10.5-GHz continuum peak.
4.1.1 H85α line

The presence of the ‘A’ component with a velocity of about −40 km/s and the ‘B’ component at −35 km/s contribute to the increase in the value of the velocity contours from −44 km/s to the west of the main peak to > −40 km/s to the east. There does appear to be a tendency for velocities to have a more negative value at the outer regions of the source except for the region to the south-east. This trend appears more evident in the more extended but lower resolution H109α observations by Rubin & Mezger (1970), and appears to fit the pattern of the H2CO observations of Minn & Greenberg (1973). Small variations could be the result of a contribution from the background diffuse emission as seen in the map of Fig. 1.

The apparent increase in temperature across W3 may also be the result of the presence of the various compact components, but this is considered unlikely since a similar gradient is apparent in W3N and in NGC 2024 (MacLeod, Doherty & Higgs 1975). An alternative explanation might be that some external mechanism, possibly related to the position of the HII region with respect to the inner edge of the nearby spiral arm, produces the gradients in apparent temperature. This mechanism would presumably operate through non-LTE effects, since the gradients are less pronounced at H134α.

4.1.2 He85α and C85α lines

The results for the He and C line observations are given in Fig. 5. Over most of the region there is general agreement between H and He velocities except from the south-west part of the region where differences of up to about 2 km/s may exist. The line width for He is comparable to that for H, as a result of the blending of two lines. This blending was first observed in W3 by Gordon & Churchwell (1970) and by Chaisson (1971). Because of the small signal-to-noise ratio, it was not practicable to fit more than one Gaussian profile to the line, but the second line appears to be a C line at a velocity of −22 km/s. The line would then be due to C in a foreground cloud and associated with the observed H1 and H2CO which are seen in absorption at this velocity. The ratio He/H appears to have a typical value of about 0.08, with the exception of the extreme south-west where the ratio appears to be somewhat lower. But in these regions the line width implies a somewhat lower temperature and the He may well be associated with the diffuse continuum emission.

The C line has a velocity similar to that of H and He over most of the region, except for one position to the south-east. The narrow width of the C line implies that it originates in a low-temperature cloud outside the HII region, probably in the foreground. This is not unexpected, since any C within the HII region will be doubly ionized by photons of the same energy as those which ionize the He. It is particularly interesting that over most of W3, the H, He and C recombination lines show similar velocities, which are also similar to those of H2CO and H1 in absorption. It must be concluded that the HII regions are embedded in the dense H1, such that they are ionization limited.

The angular size of the C emission region favours the spontaneous emission model of Hoang-Binh & Walmsley (1974) over the stimulated emission model of Dupree (1974) if all of the emission comes from a single cloud.

4.1.3 The narrow H85α line

The apparent change in velocity and line width of the narrow line with transition number shown in Table 2 is barely significant and may be attributed to the dependence of optical depth on frequency. The width of the H85α line implies an upper limit of 1600 K for the temperature of the emitting region, but the actual temperature may be much lower since
some turbulent broadening is expected. A comparison of the line strengths in the three transitions seems to favour spontaneous emission rather than stimulated emission as the mechanism of choice. Discussion of these factors, and a model for the region, will be left to a further paper.

It is apparent from their sizes, positions and velocities that the C- and H II-emitting regions do not originate in the same volume of space, although both presumably arise in or near W3.

4.2 W3N

The source W3N appears to be a comparatively simple H II region with no known fine structure. At 1.4 GHz using the resolution of $25 \times 28$ arcsec, Sullivan & Downes (1973) found that it has a size of $110 \times 90$ arcsec. It is not known as a source of molecular lines and, because of its low continuum flux density, the only known recombination-line observations have been those of Rubin & Mezger (1970). The present results show no complexity of structure and the parameters derived present no difficulty of interpretation. There appears to be only a small velocity gradient across the source and the velocity of about $-48$ km/s is in agreement with the H109α results by Rubin & Mezger. The hydrogen line widths are also comparable to those obtained at H109α. The electron temperature of 9000 K is 1500 K higher than the H109α value, but this could be due either to the effects of non-LTE, to the better angular resolution of the present results, or to an underestimation of the electron temperature by Rubin & Mezger because of a blending of higher order lines with the H109α line.

The helium line observations give $N(\text{He}^+)/N(\text{H}^+) = 0.08 \pm 0.02$, in agreement with typical values for H II regions. The helium velocities are in agreement with hydrogen velocities to within a $2\sigma$ level.

Conclusions

This paper has presented the results of high-sensitivity recombination line mapping of the W3 complex with a resolution of 2.8 arcmin. Though interferometer observations of recombination lines with the higher resolution of 8 arcsec are important for determining the detailed structure and dynamics of the H II condensations, and for showing how infrared and the small-diameter OH and H2O sources relate to these, the lower resolution observations are of equal importance. Not only can they show the presence of other emission, for example, the narrow H II line, but also they show how the velocities of various components in the region fit in with those covering a wider area. For instance, H2CO appears to have a more general distribution with velocity of about $-48$ km/s, but in the direction of W3 the velocity is about $-41$ km/s, in general agreement with our measured values for H, He and C, and with that for the dense H I cloud seen in absorption profiles. It does not appear that the individual H II components, in particular to the south of the region, can be entirely responsible for the less negative recombination line velocities, but rather that there is a common velocity in the direction of W3 for the more generally distributed components of the interstellar medium. A point of interest is the apparently large abundance of C in this direction which must be outside the compact H II regions, otherwise it would appear as C III. In the direction of W3N, recombination lines give velocities of $-48$ km/s, but dense H I is still present at about $-41$ km/s.

In the direction of W3(OH), the velocity of $-48$ km/s for the widely distributed H2CO is similar to that for the other molecules, though the compact H II region has a velocity of $-54$ km/s. However, the diffuse H II around W3(OH) has a velocity of $-41$ km/s, in agreement with that for the dense H I of W3 and W3N. This common velocity, the fact that the
diffuse H II is probably the weakly ionized component of a dense H I cloud, as suggested in the model for W3(OH) by Hughes & Viner (1976), and that there is a diffuse H II emission over most of the W3 complex, suggests that the dense H I cloud covers most of the region and its density is about $10^5$–$10^6$ cm$^{-3}$.

How these observations fit in with the general picture of galactic structure, and in particular how the velocities relate to the streaming which is expected due to the presence of the spiral arms, is not at present clear, and must await the production of a consistent model.

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References