Carbon radio recombination lines in the Orion Bar

F. Wyrowski¹, P. Schilke¹,², P. Hofner³, and C.M. Walmsley⁴

ABSTRACT

We have carried out VLA D-array observations of the C91α carbon recombination line as well as Effelsberg 100-m observations of the C65α line in a 5′ square region centered between the Bar and the Trapezium stars in the Orion Nebula with spatial resolutions of 10″ and 40″, respectively. The results show the ionized carbon in the PDR associated with the Orion Bar to be in a thin, clumpy layer sandwiched between the ionization front and the molecular gas. From the observed line widths we get an upper limit on the temperature in the C⁺ layer of 1500 K and from the line intensity a hydrogen density between 5 × 10⁴ and 2.5 × 10⁵ cm⁻³ for a homogeneous medium. The observed carbon level population is not consistent with predictions of hydrogenic recombination theory but could be explained by dielectronic recombination. The layer of ionized carbon seen in C91α is found to be essentially coincident with emission in the v=1-0 S(1) line of vibrationally excited molecular hydrogen. This is surprising in the light of current PDR models and some possible explanations of the discrepancy are discussed.

Subject headings: ISM: clouds — ISM: individual (Orion Bar) — ISM: structure — radio lines: ISM — techniques: interferometric

¹I. Physikalisches Institut, Univ. zu Köln, Zülpicherstr. 77, D-50937 Köln, Germany
²Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
³Cornell University, NAIC, Arecibo Observatory, P.O. Box 995, Arecibo, P.R. 00613, USA
⁴Osservatorio Astrofisico di Arcetri, Largo E.Fermi 5, I-50125 Firenze, Italy
1. Introduction

The neutral gas surrounding H II regions is an excellent laboratory for the purpose of understanding the interactions between the UV radiation of young newly formed stars and the surrounding molecular clouds. Such photon dominated regions (PDR’s) have been the subject of both theoretical (e.g. Tielens & Hollenbach 1985, Sternberg & Dalgarno 1995) and observational attention (e.g. Herrmann et al. 1996). The most easily observable example of a PDR is perhaps that provided by the Orion Nebula and the surrounding hot neutral gas. Of particular interest is the elongated bar–like feature to the south–east of the Orion Trapezium stars known as the Orion Bar (see Tielens et al. 1993, Hogerheijde et al. 1995, van der Werf et al. 1996 for recent discussions). The Bar is elongated in a direction on the plane of the sky almost perpendicular to the line of sight to the O6 star Θ 1 C Ori in the trapezium, which is responsible for ionizing the H II region and heating the neutral gas. This fact makes it possible for us to observe stratification within the Bar along the line of sight to Θ 1 C Ori. Thus, the Bar seen in free–free emission from the ionized gas is clearly offset with respect to the Bar seen in rovibrational lines of H2 and fine structure lines of C II and O I from the neutral gas. These in turn are offset relative to the Bar as seen in various molecular species (see Tielens et al. 1993, Herrmann et al. 1996 for examples). It has been concluded that the observed stratification is consistent with a mean hydrogen density of $5 \times 10^4$ cm$^{-3}$. On the other hand, high angular resolution maps of the Bar in various molecular transitions (Tauber et al. 1994) have shown that the neutral gas is structured and quite inhomogeneous with clump densities as high as $10^6$ cm$^{-3}$.

The carbon radio recombination lines offer an alternative approach to studying PDR’s. Their emission is invariably optically thin and proportional to the square of the electron density (or equivalently of the carbon abundance in the neutral regions where carbon is singly ionized). Natta et al. (1994) demonstrate moreover that one can use the ratio of the radio line intensity to that of the far infrared [C II] 158 µm line to infer the density in the layer where carbon is singly ionized. They observed C91α with the Effelsberg 100-m telescope at several positions in Orion and derived densities of $10^6$ cm$^{-3}$. These observations however were made with a relatively poor angular resolution (80″) which rendered difficult the comparison with other PDR tracers in Orion. We have therefore undertaken new carbon radio line observations with the objective of allowing a comparison both with far infrared and molecular line data. In the first place, we have mapped the C65α line using the Effelsberg 100-m telescope at an angular resolution of 40″. This allows a reasonable comparison with the far infrared fine structure line maps of Stacey et al. (1993). Secondly, we have used the VLA to map C91α towards the Bar with 10″ resolution. This can usefully be compared with the H$_2^*$ maps of van der Werf et al. (1996) as well as with recent studies of $^{13}$CO(3–2) made with the CSO telescope (Lis et al. 1997). In this paper, we present
the results of the carbon radio line mapping and show that the stratification seen in other species is also clearly present in the VLA C91α maps.

2. Observations

2.1. C65α observations of Orion with the Effelsberg 100-m telescope

The observations were carried out using the Effelsberg 100-m telescope on 4 sessions in September 1993, March 1994, January and December 1996. Pointing was tested on 3C120 and 3C161 at hourly intervals and has an accuracy of 5''. The facility K-band maser was used with system temperatures of 150 to 200 K. We observed a 5' square region centered between the Bar and the Trapezium in a total power mode with reference positions 75' to the east. The spectrometer was a autocorrelator which was split into two sections of 512 channels and centered on C65α (23415.9609 MHz) and H65α (23404.2793 MHz). Each section had a bandwidth of 12.5 MHz yielding a spectral resolution of 0.3 km s\(^{-1}\). The telescope half-power beamwidth at 23.416 GHz is 40''.

2.2. C91α observations of the Orion Bar with the VLA

We observed the Orion Bar in July 1996 using the VLA in its D configuration. The basic observing parameters were as given in Table 1. The phase center of our map was chosen to be slightly offset from the Bar in order to map also the total continuum radiation of the Orion A H II region. We observed a bandpass calibrator at intervals of 3 hours and made phase calibrations every 25 minutes. The data were processed using AIPS and resulted in synthesized beams of 11.7''×9.0'' with natural weighting and a final RMS noise of 2 mJy per beam (0.3 K) in a channel map. Our main difficulty is separating the blend of He91α and C91α which is done by subtraction of a linear spectral baseline from every data point in the uv plane using small windows in the immediate neighborhood of the carbon line. This works well for the Bar but could lead to overestimation of the line emission where the helium line dominates the spectra. A 3.5 cm continuum image was produced by summing over the line free channels. Comparing C91α VLA observations smoothed to the corresponding 100-m beam (80'') with C91α 100-m observations carried out in August 1996 of the Bar, we found that we underestimate the C91α intensity due to the missing short spacing information by less than 30%.
3. Observational Results

3.1. Morphology of carbon radio line emission

In Fig. 1, our C91\(\alpha\) (VLA) and C65\(\alpha\) (100-m) recombination line maps are shown compared with each other. Despite the difference in angular resolutions, one notes that the same basic features are seen on both maps. One sees the Bar to the south-east, a compact (1 arc minute in size) region 30\" to the south–west of Θ1C Ori in the central portion of the map, and another feature close to the BN-KL region on the northern edge of the map.

It is interesting to compare our C65\(\alpha\) (100-m) integrated intensity map with the \([C\ II]\) 158 \(\mu\)m contours from Stacey et al. (1993). In this case, both lines are probing ionized carbon and with similar angular resolution. It is striking to note again the similarity of the general characteristics of these maps in spite of different excitation characteristics (see Natta et al. 1994). Thus, we conclude that the FIR and radio lines come from essentially the same regions in space although the recombination line shows a higher contrast and there are likely to be differences on scales of a few arc seconds.

That the regions seen in the carbon radio lines represent PDR’s in the vicinity of ionization fronts is demonstrated by Fig. 2. It shows our VLA C91\(\alpha\) map compared with our 3.5 cm continuum map representing the distribution of free–free emission from the ionized gas. The Bar as seen in C91\(\alpha\) is parallel to but offset by about 20\" (0.05 pc) from the Bar of ionized gas. This is in the direction away from Θ1C Ori and is thus consistent with ionization and heating from that source. The distribution of \(^{13}\)CO(3–2) observed by Lis et al. (1997) using the CSO with a 20\" HPBW is offset a further 20\" to the SE relative to C91\(\alpha\) and thus, the carbon radio line emission is neatly sandwiched between the ionized and molecular media.

A sample spectrum of the C91\(\alpha\) line towards the Bar is shown as an insert in Fig. 2 compared with the corresponding \(^{13}\)CO spectrum. One sees from this that the line profiles are very similar indicating a close link between the two. This kinematical agreement between molecular gas and carbon emission is found nearly everywhere showing the C II region to be very quiescent with only small velocity shifts. At most positions, the line emission is narrow with line widths between 2 and 2.5 km s\(^{-1}\). The VLA linewidths can be converted into upper limits on the kinetic temperature between 1000 and 1600 K in the region responsible for the C91\(\alpha\) emission in the Bar (assuming thermal broadening to be solely responsible for the observed line width). The carbon lines are broader towards the clump of C91\(\alpha\) emission to the SW of the Trapezium where we find an upper limit to the temperature of 3000 K.
3.2. Level populations in the C91α emitting region

By smoothing our VLA C91α data to 40″ resolution, we can make a direct estimate of the ratio of the intensities of the two recombination lines at several positions and Table 2 gives the results. We also give the [C II] 158 μm intensities at the same positions derived from the maps of Stacey et al. (1993).

Table 2 shows that we observe typical line intensity ratios $T_l \Delta v(C91\alpha)/ T_l \Delta v(C65\alpha)$ between 2.3 and 3.3 and ratios $T_l \Delta v(C91\alpha)/I([C II] 158 \mu m)$ of 800 K km s$^{-1}$ erg$^{-1}$ cm$^2$ s sr. One can compare the former with the ratios expected for hydrogenic departure coefficients ($b_n$’s) which, for example, are 5 for $T=800$ K and an electron density $n_e$ of 10 cm$^{-3}$ (see Natta et al. Fig. 7). Given our limits on the electron temperature and for reasonable electron densities, it is not possible to get agreement between observations and the line ratios predicted by hydrogenic recombination theory. We believe that the explanation of this is that dielectronic recombination of the type discussed by Walmsley & Watson (1982) causes the populations to be closer to being thermalised than hydrogenic theory predicts. If one goes to the extreme of thermalised level populations ($b_n = 1$), the predicted $T_l \Delta v(C91\alpha)/ T_l \Delta v(C65\alpha)$ is 2.7. A more reasonable assumption might be that atoms with a $^2P_{3/2}$ core have thermalised populations whereas atoms with $^2P_{1/2}$ cores are hydrogenic. Then, applying Eq. 8 from Walmsley & Watson(1982), we find $T_l \Delta v(C91\alpha)/ T_l \Delta v(C65\alpha)$ is 3.1 for $T=200$ K and $n = 10^5$ cm$^{-3}$. Given the errors, both of these are consistent with the observations and we conclude that the dielectronic process drives the level populations close to the values expected in LTE. In the following discussion, we have for simplicity set the $b_n$’s equal to unity.

3.3. Comparison with molecular hydrogen emission

Hot neutral gas in the neighborhood of ionization fronts is also traced by emission in the NIR 2μm lines of H$_2$ which are collisionally excited at temperatures upwards of 1500 K although one may observe fluorescence at low temperatures. It is thus of interest to compare our VLA map of C91α with the emission in the 1-0 S(1) line of H$_2$ which was imaged by van der Werf et al. (1996). The qualitative result of this is that the Bar as seen in H$_2$ corresponds generally with the carbon radio lines when one takes into account the difference in angular resolutions.

A closer view reveals that the carbon radio line emission appears to peak slightly closer to Θ1C Ori than does the emission from vibrationally excited molecular hydrogen. One obtains some insight into the situation from Fig. 3 which shows the results of an
homogeneous edge-on model derived using the PDR models of Tielens & Hollenbach (1985) with $n(H) = 10^5$ cm$^{-3}$ and $G_0 = 10^5$ extrapolated to a density of $7 \times 10^4$ cm$^{-3}$. We assume a perfectly edge-on model without a tilt. The intensity of the C91$\alpha$ line, which is proportional to $T^{-1.5}$, increases with depth into the PDR and reaches a peak just in front of the transition zone C$^+/C\text{I}/CO$. The observed cross cuts of C91$\alpha$ and H$_2$ v=1-0 S(1) shown in Fig. 3 are averaged over the Bar and the half-power point of the 3.5 cm continuum is used to define the ionization front. In contrast to the prediction of the homogeneous model, the observed C91$\alpha$ emission is broader and extends farther into the Bar. But while the predictions for C91$\alpha$ are in qualitative agreement with observation, the same is not true for molecular hydrogen which is expected by theory to lie between ionization front and C91$\alpha$.

The explanation of this is unclear but one possibility is that the heat input to the observed H$_2$ emission is due to a shock. One difficulty with this interpretation (see Hill and Hollenbach 1978, Tielens et al. 1993) is the general quiescence of the gas in the Bar discussed in Sect. 3.1. However, explaining our result seems to require either considerable heat input or fluorescence in a layer at a depth in the Bar corresponding to roughly 5 magnitudes of visual extinction.

### 3.4. Physical parameters in the C91$\alpha$ emitting region

We now summarize briefly the constraints on density and temperature in the layer of the Bar emitting C91$\alpha$. As noted in Sect. 3.1, we can place a limit of 1600 K on the kinetic temperature. In order to explain the observed C91$\alpha$ line intensity (5 K km s$^{-1}$ peak value), we find (taking $b_n = 1$, see last section) that the carbon line emission measure $E_l = \int n_e n(C^+) ds$ (in pc cm$^{-6}$) is equal to $2250 T_3^{1.5}$ where $T_3 = T/1000$. For an Orion carbon abundance $[\text{C}]/[\text{H}] = 3.4 \times 10^{-4}$ (Peimbert 1993) and assuming $n_e = n(C^+)$, we estimate the hydrogen density in the layer responsible for the observed C91$\alpha$ emission to be $n_H = 4 \cdot 10^5 T_3^{75} L_B^{-0.5}$ where $L_B$ (pc) is the depth of the Bar along the line of sight (of order 0.6 pc according to Hogerheijde et al. 1995). Thus for temperatures between 200 and 1600 K and $L_B = 0.6$, we find $n_H$ between $5 \times 10^4$ and $2.5 \times 10^5$ cm$^{-3}$ assuming a beam filling factor of 1. This is consistent with recent estimates of the density on basis of CN and CS observations with comparable resolution (Simon et al. 1997) and also consistent with our results of the previous section for a typical temperature in the C91$\alpha$ emission region of 300 K.
4. Conclusions

Our data show convincingly that carbon is ionized in a layer intermediate between molecular gas and ionization front. We put an upper limit on the temperature of the C II layer of 1600 K and find that the hydrogen density must be between $5 \times 10^4$ and $2.5 \times 10^5$ cm$^{-3}$. We also have found evidence that the dielectronic recombination process discussed by Walmsley & Watson (1982) plays an important role in populating high $n$ levels under the conditions of the Orion Bar PDR. Finally, we show that current models have difficulty in explaining the morphology of the vibrationally excited molecular hydrogen emission relative to ionized carbon in the Orion Bar.

We acknowledge use of the VLA of the National Radio Astronomical Observatory which is operated by Associated Universities Inc. under cooperative agreement with the National Science Foundation. Dr G. Stacey kindly made available to us his [C II] 158 $\mu$m map of Orion. We thank the referee (D. Hollenbach) for his comments on the manuscript. C.M.W acknowledges the support from ASI grants 94-RS-152 and ARS-96-66 and CNR grant 96/00317 for star formation research at Arcetri.

REFERENCES

Herrmann, F., Madden, S. C., Nikola, T., Poglitsch, A., Timmermann, R., Geis, N., Townes, C. H., & Stacey, G. J. 1996, ApJ (in press)

Hill, J. K., & Hollenbach, D. J. 1978, ApJ, 225, 390

Hogerheijde, M. R., Jansen, D., & Van Dishoeck, E. F. 1995, A&A, 294, 792

Lis, D. C., Keene, J., & Schilke, P. 1997, in prep.

Natta, A., Walmsley, C. M., & Tielens, A. G. G. M. 1994, ApJ, 428, 209

Peimbert, M. 1993, Rev. Mex. Astron. Astrofis., 27, 9

Simon, R., Stutzki, J., Sternberg, A., & Winnewisser, G. 1997, A&A, submitted

Stacey, G. J. et al. 1993, ApJ, 404, 219

Sternberg, A., & Dalgarno, A. 1995, ApJS, 99, 565

Tauber, J. A., Tielens, A. G. G. M., Meixner, M., & Goldsmith, P. F. 1994, ApJ, 422, 136
Tielens, A. G. G. M., & Hollenbach, D. 1985, ApJ, 291, 722

Tielens, A. G. G. M., Meixner, M. M., van der Werf, P. P., Bregman, J., Tauber, J. A., Stutzki, J., & Rank, D. 1993, Science, 262, 86

Walmsley, C. M., & Watson, W. D. 1982, ApJ, 260, 317

van der Werf, P. P., Stutzki, J., Sternberg, A., Krabbe, A. 1996, A&A, 313, 633
Fig. 1.— Comparison of C91α (VLA) integrated intensity (HPBW 10′′, greyscale) and C65α (100-m) integrated intensity (40′′ HPBW, bold contours, contours are 30, 50, 70, 90 % of peak intensity 0.9 K km s⁻¹). The dashed contours are [C II] 158 μm of Stacey et al. (1993, contours 50, 70, 90 % of peak intensity 3.9 · 10⁻³ erg cm⁻²s⁻¹sr⁻¹). The star symbols mark the positions of the Trapezium stars (Θ1 C Ori filled) and Θ2 A Ori. Position used in Table 2 are marked as white circles and the phase center is marked by a cross.
Fig. 2.— VLA 3.5 cm continuum (grey–scale, compared to C91\(\alpha\) (VLA) integrated intensity (thick full contours: 30, 50, 70, 90 % of peak intensity 5.5 K km s\(^{-1}\)) and \(^{13}\)CO(3–2) integrated intensity from Lis & Schilke (1997, thin contours, only the region around the Bar was mapped). The black and white contours are \(H_2\)(1-0 S(1)) image of van der Werf et al. (1996). The insert in the lower left shows a comparison of C91\(\alpha\) (smoothed to 20\(''\)) and \(^{13}\)CO (peak 29 K) spectra towards the indicated position in the Bar.
Fig. 3.— Averaged intensity distribution of 3.5 cm continuum, H$_2$ (1-0 S(1)), and C91$\alpha$ across the Bar. The thin lines show for comparison results of PDR model calculations scaled to $n$(H)=$7 \times 10^4$ cm$^{-3}$ and $G_0 = 10^5$. The double line shows the model temperature distribution (right hand scale).
Table 1: VLA Observing Parameters

| Parameter                      | Value                        |
|--------------------------------|------------------------------|
| Rest Frequency (C91α)          | 8.589104 GHz                 |
| Total Bandwidth                | 3.125 MHz                    |
| Number of Channels             | 256                          |
| Channel Separation             | 12 KHz (0.43 km s\(^{-1}\))  |
| Synthesized Beam FWHM          | 11.7 x 9.0 arcsec            |
| Primary Beam FWHM              | 5.2 arcmin                   |
| Phase Center of Map            | \(\alpha_{1950}=05:32:51.30, \delta_{1950}=-05:26:21.0\) |
| Time On Source                 | 7 hours                      |

Table 2: Integrated Intensities of C91α, C65α, and [C II] 158 \(\mu\)m at selected positions. The C91α data was smoothed to a 40\(^{\prime\prime}\) beam in order to match the different beam sizes.

| Object          | Offset arcsec | \(I(\text{C91}\alpha)\) K km s\(^{-1}\) | \(I(\text{C65}\alpha)\) K km s\(^{-1}\) | \(I(\text{[C II]} 158 \mu\text{m})\) \(10^{-4}\) erg cm\(^{-2}\) s\(^{-1}\)sr\(^{-1}\) |
|-----------------|---------------|----------------------------------|----------------------------------|----------------------------------|
| Bar SW          | (-45, -85)    | 1.7                              | 0.75                             | 22                               |
| Bar center      | (45, -40)     | 2.1                              | 0.79                             | 28                               |
| Orion South     | (-55, 25)     | 2.6                              | 0.83                             | 36                               |
| North of KL     | (-30, 145)    | 2.9                              | 0.89                             | 29                               |