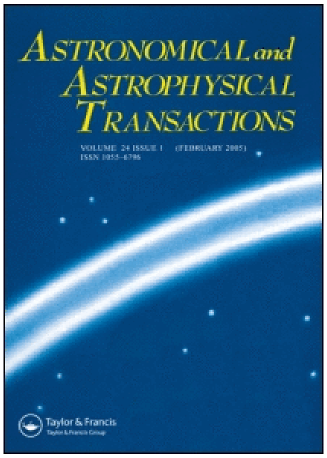

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RADIO RECOMBINATION LINES OF CARBON C165α AND C166α TOWARDS CAS A

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The carbon ratio recombination lines C165α and C166α have been detected in emission towards Cas A. They are the shortest-wavelength radio recombination lines detected in this direction. We determine the line to continuum ratio to be: $T_L/T_c = (2.5 \pm 0.3) \cdot 10^{-4}$. All Cas A data obtained from observations of carbon radio recombination lines, agrees with a model of a CII region, originating on the surface of the molecular cloud ionized by the interstellar UV radiation field.

KEY WORDS Recombination lines, Cas A, molecular clouds.

1. INTRODUCTION

A large number of carbon radio recombination lines (RRLs) have been detected towards Cas A at frequencies between 14.7 and 332 MHz (Konovalenko, 1984; 1990; Ershov *et al.* 1984; 1987; Payne *et al.*, 1989; 1990). At the low frequency side of the range (14.7–115 MHz), the lines are observed in absorption, and at higher frequencies (220–332 MHz), in emission. These results, apart from the latest ones at frequencies of $\nu = 14.7$ MHz (Konovalenko, 1990) and of $\nu = 332$ MHz (Payne *et al.*, 1990), are collected in the review paper by Sorochenko and Smirnov (1990), Paper I.

From the data, one concludes that the carbon lines originate in the Perseus Arm in a rather dense and cool medium with the electron density $n_e \gtrsim 0.1\ \mathrm{cm^{-3}}$, hydrogen density $n_H \gtrsim 300\ \mathrm{cm^{-3}}$ and electron temperature $T_e \lesssim 100$ K. The CII regions are supposed to originate on the surface of molecular clouds where H_2 can be dissociated and carbon can be ionized by the interstellar UV radiation field (Ershov *et al.*, 1987). Such molecular clouds with HI envelopes were detected toward Cas A by observations of formaldehyde and the 21 cm line with high angular resolution (Goss *et al.*, 1984).

However, the physical conditions in the region where the RRLs originate are still poorly known. The results available to date do not allow us to make a choice between two alternative models: "warm" and "cool". According to the "warm" model, the emission (absorption) of carbon RRLs occurs in a rarified and warm medium with $T_e = 50$–100 K, $n_e = 0.1$–$0.15\ \mathrm{cm^{-3}}$, $n_H = 300$–$450\ \mathrm{cm^{-3}}$. In the "cool" model, carbon RRLs originate in a cooler and denser layer of the molecular cloud with $T_e = 16$–20 K, $n_e = 0.3$–$0.4\ \mathrm{cm^{-3}}$ and $n_H \gtrsim 10^3\ \mathrm{cm^{-3}}$.

In the first case, when comparing the measured and calculated intensities of RRLs, low temperature dielectronic recombination was taken into account. This process, first introduced by Watson *et al.* (1980), assumes that the recombination at high levels in carbon atoms is accompanied by simultaneous excitation of the fine-structure level $^2P_{1/2} \rightarrow {}^2P_{3/2}$ in C^+ which considerably affects the population of the highly excited levels. The analysis of the "cool" model assumes that the dielectronic recombination effect is small because of the low temperature, and hence the population of the high n levels of carbon can be considered as hydrogenic.

One test which may help in deciding between these alternatives is to observe carbon RRLs at higher frequencies where the differences of the RRL intensities predicted for "cool" and "warm" model increase. With this aim we carried out observations towards Cas A of the carbon lines C165α and C166α.

2. OBSERVATIONS AND REDUCTION

The observations were carried out in May 1989. We used a two-channel receiver installed at the primary focus of the Effelsberg 100-m telescope receiving left and right circular polarisations. The receiver's pass band made it possible to receive two neighbouring lines C165α (1451.439 MHz) and C166α (1425.444 MHz). The 1024 channel autocorrelation spectrometer was split into 4×256 sub-receiver so that the independent information was available at four receiving channels: the two lines were simultaneously detected and each line in two polarizations. The spectral resolution was 3 kHz (0.64 km/s).

The method of observations consisted of consecutive three-minute integrations in total power mode on the Cas A position and on a reference position. In the latter case, a noise generator with power equal to that of the signal from Cas A was added to the receiver's input.

To reduce the data, the standard procedure for line observations, used in Effelsberg, was applied. Spectra from each of the four channels were averaged and baselines subtracted. The order of the fitted polynomial did not exceed two. Then, the resulting spectra were averaged. The total integration time for a single channel turned out to be 107 hours.

The measurements did not require absolute calibration since the aim is to measure the line-to-continuum ratio towards Cas A. Since the antenna temperature from Cas A ($T_c = 2800$ K) exceeded the receiver noise temperature ($T_s = 45$ K) by a large factor we normalized our spectrum by dividing it by the system temperature.

The spectral line parameters obtained by fitting a gaussian are given in Table 1.

Table 1 Results of the measurements in the lines C165α and C166α towards Cas A

Line to continuum ratio	$T_L/T_C = (2.5 \pm 0.3) \cdot 10^{-4}$
Line width (half intensity)	$\Delta V = (3.7 \pm 0.5)$ km/s
Radial velocity	$V_{LSR} = (-48.5 \pm 0.2)$ km/s
Integrated line intensity	$\int T_L/T_c \, dv = (4.7 \pm 0.8)$ Hz

3. DISCUSSION

Figure 1 shows an averaged spectrum obtained by averaging observations of the C165α and C166α lines. As expected at a wavelength of 21cm, the carbon RRLs towards Cas A were detected in emission. The spectrum contains only one line component observable above the noise with $V_{\rm LSR} = -48.5$ km/s. The second component with lower negative velocity $V_{\rm LSR} = -39$ km/s seen at lower frequencies $\nu \leqslant 325$ MHz (Payne *et al.*, 1989), is not detected with an upper limit $T_L/T_c = 9 \cdot 10^{-5}$ (3σ).

Figure 2 shows the comparison of the measured intensity of C165α–C166α lines, and the results for the lower frequency carbon lines collected in Paper I with the calculated values for different models.

We now describe how the theoretical curves were derived and compare them with observations.

3.1. *Calculated Curves. Dielectronic Recombination*

The curves in figure 2 were calculated using the expression (Shaver, 1975; Paper I):

$$\int T_L/T_c\, d\nu = -\int \tau_{C_n}\, d\nu = -\frac{2.05 \cdot 10^6\, \mathrm{EM}\, b_n}{T_e^{5/2}}\beta_n \qquad (1)$$

where $\mathrm{EM} = \int n_e n_{C^+}\, dl$ is the emission measure of the CII region, n_e and n_{C^+} are the electron and carbon ion concentration respectively, b_n and β_n are the factors accounting for departure from equilibrium population.

$$\beta_n = \left(1 - \frac{20.8 T_e}{\nu}\frac{d \ln b_n}{dn}\right),$$

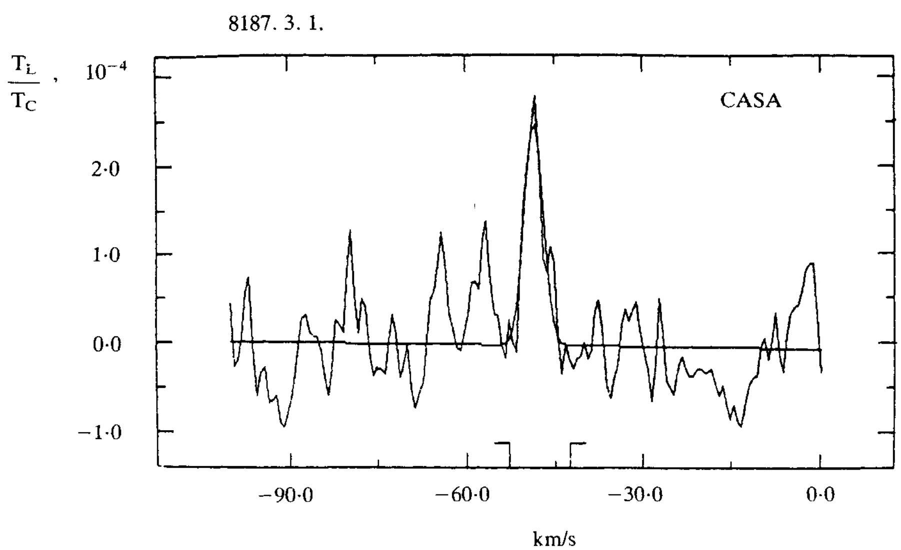

Figure 1 An average spectrum of the C165α and C166α lines. The fitted gaussian profile is indicated by the smooth curve.

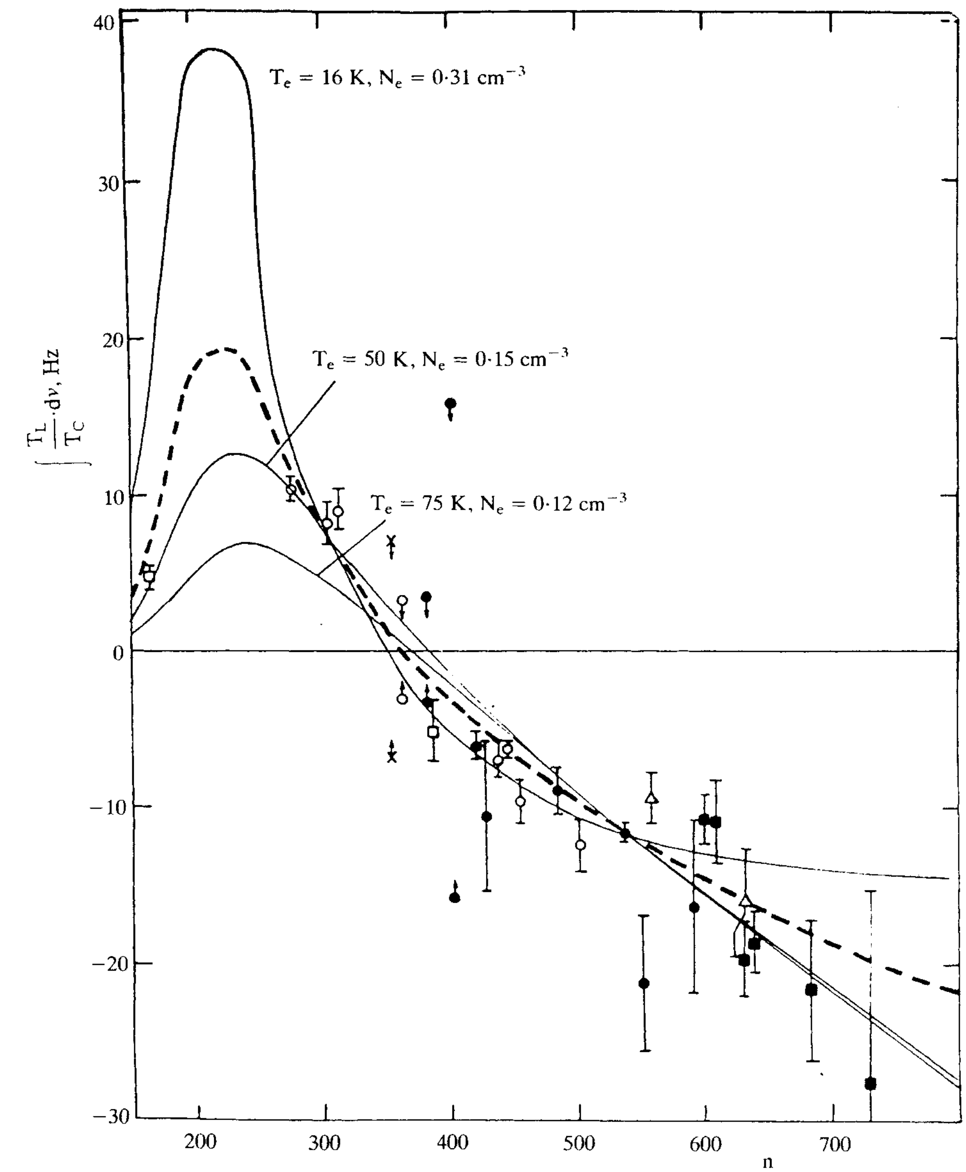

Figure 2 The comparison of the measured ratios of integrated line to continuum for the C165α–C166α lines and for lower frequency lines collected in Paper I, with calculated curves for different models. The dashed curve—model where the "warm" part of CII region (T_e = 60 K) provides 2/3 intensity of the lines and the "cool" one (T_e = 17 K)—the remaining 1/3. See text.

where ν is the line frequency in GHz. All the curves were normalized to match the observational results of the C537α–C539α lines, which were carried out with the lowest measurement error.

Previously, in the analysis of low frequency RRL observations, the calculation of b_n and β_n were made with two different procedures: for $T_e \geq 50$ K the dielectronic recombination was taken into account, and for lower temperatures the carbon atom was considered to be hydrogenic (Ershov *et al.*, 1984; 1987; Payne *et al.*, 1989). It appears that it would be more appropriate not to make this distinction, and in the calculations of level populations of carbon in the interstellar medium, always to consider the low temperature dielectronic recombination (DR).

The DR influence decreases with temperature but for $T_e < 50$ K is still important. For $T_e = 30$ K and $n_e = 0.2\ \mathrm{cm}^{-3}$ for instance, DR enhances the absorption in carbon lines for $n > 600$ 2.5–4 times; even for $T_e = 17$ K and $n_e = 0.3\ \mathrm{cm}^{-3}$, the absorption for $n > 600$ is increased because of DR by 10% relative to that expected for hydrogenic population (Ponomarev, 1991).

The DR effect in carbon depends on the relative population of levels $^2P_{3/2}$ and $^2P_{1/2}$ of C^+ ion being different from that expected in LTE (Walmsley and Watson, 1982). For known physical parameters of the medium—density and temperature—the population of a fine structure level can be estimated by the equation of statistical equilibrium:

$$\frac{n_k}{n_j} = \frac{n_e\gamma_{jk}(e) + n_H\gamma_{jk}(H)}{n_e\gamma_{kj}(e) + n_e\gamma_{kj}(H) + A_{kj}} \tag{2}$$

where n_k, n_j, n_e and n_H are the number densities of C^+ ions in the upper ($P_{3/2}$) and lower ($P_{1/2}$) levels, and the number densities of electrons and hydrogen atoms respectively; $\gamma_{jk}(e)$ and $\gamma_{jk}(H)$ are the collision excitation rate $P_{1/2} \rightarrow P_{3/2}$ for collisions with electrons and hydrogen atoms respectively; $\gamma_{kj}(e)$ and $\gamma_{kj}(H)$ are the deexcitation rates of $P_{3/2}$ level for analogos collisions; A_{kj} is the probability of spontaneous transition $P_{3/2} \rightarrow P_{1/2}$; $A_{kj} = 2.4 \cdot 10^{-6}\ \mathrm{s}^{-1}$.

For thermal equilibrium,

$$(n_k/n_j)_{\mathrm{TE}} = \frac{g_k}{g_j} e^{-h\nu_{kj}/kT} \tag{3}$$

where $g_k = 1$ and $g_j = 2$ are the statistical weights of upper and lower levels correspondingly, $\nu_{kj} = 1.9 \cdot 10^{12}$ Hz is the transition frequency between fine structure levels, k and h are Boltzman and Planck constants.

Let us introduce the value R, equal to the ratio of the equilibrium level population of $P_{3/2}$ and $P_{1/2}$ and their actual population for the given conditions:

$$R = \frac{(n_k/n_j)_{\mathrm{TE}}}{(n_k/n_j)} = \frac{n_e\gamma_{kj}(e) + n_H\gamma_{kj}(H) + A_{kj}}{n_e\gamma_{kj}(e) + n_H\gamma_{kj}(H)} \tag{4}$$

In the frequency range of $T_e = 10$–100 K, the deexcitation rate of the C^+ ion for collisions with hydrogen atoms has a small dependence on temperature, and equals $\gamma_{kj}(H) = 8 \cdot 10^{-10}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$ (Spitzer, 1978). Assuming the solar abundance of carbon, and assuming C^+ to be the only abundant positive ion, we have $n_e/n_H = 3 \cdot 10^{-4}$. Substituting in (4) we have:

$$R = 1 + \frac{2.4 \cdot 10^{-6}}{n_e[\gamma_{kj}(e) + 2.4 \cdot 10^{-6}]} \tag{5}$$

The deexcitation rate of the $P_{3/2}$ level by collisions with electrons at $T_e = 50$ K is $\gamma_{kj}(e) = 10^{-6}\,\mathrm{cm^3\,s^{-1}}$, with a temperature dependence close $T^{1/2}$ (Ponomarev, 1991). Therefore, in determining the fine structure level populations, collisions with H atoms are roughly twice as important as collisions with electrons. If one neglects the contribution of electron collisions, one has:

$$R = 1 + \frac{1}{n_e}$$

The b_n and β_n calculations were carried out using the program of Brocklehurst and Salem (1977), supplemented by consideration of DR (Walmsley and Watson, 1982). The dependence of fine structure levels upon concrete physical conditions is determined using (5). Since from the measured widths of carbon RRLs towards Cas A, it follows that electron temperature and density are linked with each other by (Paper I):

$$n_e\left(\frac{T_e}{20}\right)^{0.62} = (0.27 \mp 0.05)\,\mathrm{cm^{-3}\,K^{0.62}}, \tag{6}$$

in calculations for assumed T_e values, the n_e values were not arbitrary but were derived from (6). The results derived from the calculation with these assumptions are shown as solid curves in Fig. 2. Curves are plotted for a "cool" model with $T_e = 16$ K, $n_e = 0.31\,\mathrm{cm^{-3}}$ and for a "warm" model with $T_e = 50$ K, $n_e = 0.15\,\mathrm{cm^{-3}}$ and $T_e = 75$ K, $n_e = 0.12\,\mathrm{cm^{-3}}$.

3.2. *CII Region Model*

As one sees on Fig. 2, the observations of C165α and C166α radiolines turned out to be critical for the "cool" model, with $T_e = 16$ K, which gave good correspondence with observations at lower frequencies. For $n = 166$ the calculated values of the RRL intensities are several times higher than the values obtained from observations. However, the "warm" model does not give good agreement, either. For $T_e = 50$–75 K, the calculated turnover from absorption to emission occurs a $n = 370$–385, whereas the observational data reveal $n = 350$–360. The measured values of RRL intensities in the range $n = 380$–500 are noticeably higher than those calculated.

It is possible to obtain an agreement between observation and theory by hypothesising a combination of these two models. The CII region, where the radiolines originate, can comprise both warm and cool parts. This assumption is consistent with the model of such a region, representing a complex of "HI envelope–molecular cloud" (Paper I). The outer "warm" layer of CII, coincides with the HI envelope and has a temperature of $T_e = 50$–75 K. The inner layer is already in a cooler molecular cloud. According to CO (Troland *et al.*, 1985) and NH_3 (Batrla *et al.*, 1984) observations, the temperature of molecular clouds towards Cas A in Perseus Arm is of order 15–20 K.

Good agreement with the observational data is achieved for a model in which the "warm" part of the CII region has the temperature $T_e = 60$ K, and provides 2/3 of the integrated intensity of the lines, and the "cool" one with $T_e = 17$ K—the other 1/3. For this model, the emission measure of the warm part averaged over the Cas A disc ($D = 3.8$ pc) must be $\langle EM_{warm} \rangle = 8.5 \cdot 10^{-3}$ cm^{-6} pc and $\langle EM_{cool} \rangle = 2.6 \cdot 10^{-3}$ cm^{-6} pc. The intensity dependence of C$n\alpha$ upon the quantum number for this model is shown in Fig. 2 as the dashed line. We see that there is a satisfactory agreement with the observations throughout the whole frequency range. The RRL intensity obtained from the present measurements of C165α and C166α is approximately 1/3 lower than the calculated ones. This discrepancy is explained by the fact that the noise level was exceeded by only the velocity component with $V = -48.5$ km/s. The second component with $V = -39$ km/s, which, according to measurements at longer wavelengths, has less than half of the first component's intensity, turned out to be beneath the noise level and therefore was not included in our estimate of the integrated intensity.

Figure 3 gives a schematic image of the model "HI envelope—molecular cloud" complex with the CII region in the surface layer. The outer HI envelope diameter is $D_{out} = 0.9$ pc, the inner one $-D_{in} = 0.5$ pc, the thickness of the envelope is $\Delta R = 0.2$ pc. These numerical values are consistent with the data of Goss *et al.* (1984), who found, towards Cas A molecular clouds surrounded by HI envelopes with an average thickness equal to $\Delta R = 0.19$ pc, and outer diameters in the range $D_{out} = 0.5$–0.87 pc.

According to the model, carbon in the envelope is in the atomic state, and practically entirely ionized. The physical conditions in the envelope are $T_e = 60$ K, $n_e = 0.14$ cm^{-3}, $n_H = 420$ cm^{-3}. These are average values. It is natural to assume

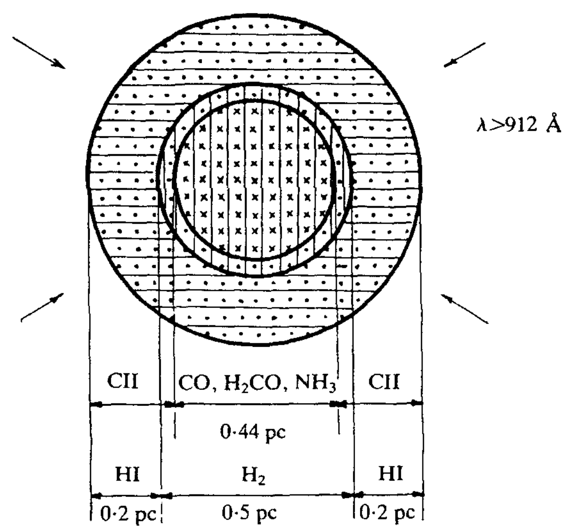

Figure 3 A schematic image of the "HI envelope–molecular cloud" complex with a CII region in the surface layer. The dissociation of molecular hydrogen and carbon ionization is caused by the interstellar emission field with λ912 – 1100 Å.

that the temperature decreases and the density grows from the periphery to the centre. The dissociation of molecular hydrogen and carbon ionization is caused by the interstellar emission field with $\lambda > 912$ Å. The emission measure of the CII region, originates in HI envelope with adopted outer and inner diameters

$$\mathrm{EM} = \frac{2}{3} \cdot \left(D_{\mathrm{out}} - \frac{D_{\mathrm{in}}^3}{D_{\mathrm{out}}^2} \right) n_e^2 = 10^{-2}\,\mathrm{cm}^{-6}\,\mathrm{pc}.$$

For $\langle \mathrm{EM}_{\mathrm{warm}} \rangle = 8.5 \cdot 10^{-3}\,\mathrm{cm}^{-6}\,\mathrm{pc}$, 15 such envelopes are needed. Goss *et al.* (1984) found in the solid angle, Cas A, not less than 16 molecular clouds with HI envelopes. The HI column density necessary for forming the envelope's amounts, in the model to $N_{\mathrm{HI}} = 4 \cdot 10^{20}\,\mathrm{cm}^{-2}$, averaged over the Cas A disc. This is 10% of the neutral hydrogen atoms in the Perseus Arm, found by measurements of the 21 cm line towards Cas A (Troland *et al.*, 1985).

The boundary of the transition of HI to H_2 is not identical with the CII boundary. The outer UV radiation penetrates into the molecular cloud and creates, on its surface, a "cool" CII region. According to the current model, here $T_e = 17$ K, $n_e = 0.3\,\mathrm{cm}^{-3}$, $n_H = 10^3\,\mathrm{cm}^{-3}$. For $\langle \mathrm{EM}_{\mathrm{cool}} \rangle = 2.6 \cdot 10^{-3}\,\mathrm{cm}^{-6}\,\mathrm{pc}$ with 15 molecular clouds, the CII layer thickness must be equal to 0.03 pc.

This model is naturally somewhat arbitrary and its parameters can change within definite limits. The data, however, does allow one to conclude that the carbon RRLs towards Cas A in Perseus Arm, originate in dense and compact formations, which are obviously linked with molecular clouds, rather than in extended diffuse clouds.

One additional argument for such a conclusion is the recent observation of carbon RRLs towards Cas A by the VLA with a resolution of 2′. Although the angular resolution did not suffice to give a definitive result, the observations reveal a rough correlation between the position of the C270α line emitting region, and the position of the most massive molecular clouds (Payne *et al.*, 1990).

The possibility that the CII regions form in "HI envelope–molecular clouds" complexes is confirmed by a series of other investigations. The theoretical calculations show that the molecular cloud must be surrounded by a layer of atomic hydrogen, which is necessary for the protection of H_2 molecules from destruction by the external interstellar UV radiation. Carbon in the HI envelope is in atomic form, and ionized. The thickness of the transition layer HI/H equals:

$$L_{\mathrm{tr}} = \frac{9.5 \cdot 10^{-5} \varepsilon^{-1.4}}{\langle n_H \rangle}, \ \mathrm{pc},$$

where $\varepsilon = 6 \cdot 10^{-5}$–$2 \cdot 10^{-4}$ is the dimensionless parameter, defined by the ratio of the rates for formation and destruction of hydrogen molecules and depends on the hydrogen column density in the transition layer (Federman *et al.*, 1974).

HI envelopes have been detected in a number of dark nebulae and molecular clouds. In L134, the thickness of the HI envelope equals $\Delta R = 0.2$–0.6 pc, and the atomic hydrogen density is $n_H = 40$–$200\,\mathrm{cm}^{-3}$ (van den Werf, *et al.*, 1988). In the molecular clouds L1599, S255, Per OB2 and Mon OB1, the thickness of the detected envelopes was between 0.4 pc and several parsecs with sizes perhaps being overestimated, due to an insufficient angular resolution (Wannier *et al.*, 1983).

The hydrogen column densities of the transition region from these data are equal to $N_{HI} = 10^{20}\,cm^{-2}$, which is in good agreement with the theoretical estimates. Such a thickness for the atomic hydrogen layer is not sufficient to absorb the UV radiation capable of ionizing atomic carbon. According to the calculations, considering the effect of UV radiation with $\lambda > 912$ Å, a layer must be formed where hydrogen is molecular, and carbon (and the elements with the ionization potential less than carbon: Si, S, and others) is atomic and ionized (Viala and Walmsley, 1977; Brown *et al.*, 1978). In this layer, carbon is not bound in molecules, this is confirmed by 21 cm and CO line observations.

A strip from the centre to the periphery of some molecular clouds shows that the 21 cm line emission, arises not at the CO emission boundary, but at some distance behind it (Wannier *et al.*, 1983). From these measurements, one may assume that the inner diameter of the HI envelope is larger than the dimensions of the CO molecular cloud. Hence, it can be supposed that the space between the HI envelope and the CO cloud, in accordance with theory, is the layer H_2/C^+.

Therefore, the proposed model of carbon RRLs originating in the "HI envelope–molecular cloud" complexes, is in reasonable agreement with both observations, and our knowledge of the physical processes on the surface of the molecular cloud. It may be useful in the choice of programs of further investigation of the interstellar medium with the help of carbon RRLs at low frequencies.

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References

Batrla, W., Walmsley, C. M. and Wilson, T. L. (1984). *Astr. Ap.*, **136,** 127.
Brown, R. L., Lockman, F. J. and Knapp, G. R. (1978). *Ann. Rev. Astroph.*, **16,** 445.
Brocklehurst, M. and Salem, M. (1977). *Computer Phys. Comm.*, **13,** 39.
Goss, W. M., Kalberla, P. M. W. and Dickel, H. R. (1984). *Astr. Ap.*, **139,** 317.
Ershov, A. A., Ilyasov, Yu. P., Lekht, E. E., Smirnov, G. T. and Sorochenko, R. L. (1984). *Sov. Astr. Lett.*, **10,** 348.
Ershov, A. A., Lekht, E. E., Smirnov, G. T. and Sorochenko, R. L. (1987). *Sov. Astr. Lett.*, **13,** 8.
Federman, S. R., Glassgold, A. E. and Kwan, J. (1979). *Ap. J.*, **277,** 446.
Konovalenko, A. A. (1984). *Sov. Astr. Lett.*, **10,** 353.
Konovalenko, A. A. (1990). *Radio Recombination Lines*: 25 *Years of Investigation,* Ed. Gordon, M. A., and Sorochenko, R. L., Kluwer Acad. Publ.
Payne, H. E., Anantharamaiah, K. R. and Erickson, W. C. (1989). *Ap. J.*, **341,** 890.
Payne, H. E., Anantharamaiah, K. R. and Erickson, W. C. (1990). *Radio Recombination Lines*: 25 *Years of Investigation*, Ed. Gordon, M. A., and Sorochenko, R. L., Kluwer Acad. Publ.
Ponomarev, V. A. (1991). To be published.
Shaver, P. A. (1975). *Pramana,* **5,** 1.
Sorochenko, R. L. and Smirnov, G. T. (1990). *Radio Recombination Lines*: *25 Years of Investigation,* Ed. Gordon, M. A., and Sorochenko, R. L., Kluwer Acad. Publ.

Spitzer, L. (1978). *Physical Processes in the Interstellar Medium,* New York, J. Wiley, p. 93–95.
Troland, T. H., Crutcher, R. M. and Heiles, C. E. (1985). *Ap. J.*, **298,** 808.
Van der Werf, P. P., Goss, W. M. and Vanden Bout, P. A. (1988). *Astr. Ap.*, **201,** 311.
Viala, Y. P. and Walmsley, C. M. (1976). *Astr. Ap.*, **50,** 1.
Walmsley, C. M. and Watson, W. D. (1982). *Ap. J.*, **260,** 317.
Watson, W. D., Western, L. R. and Christensen, R. B. (1980). *Ap. J.*, **240,** 956.
Wannier, P. G., Licten, S. M. and Morris, M. (1983). *Ap. J.*, **268,** 727.