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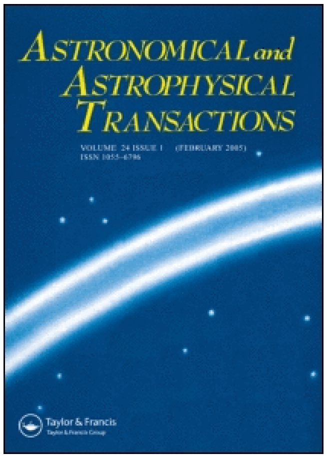

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Radio recombination lines of carbon as a tool for investigation of molecular clouds

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RADIO RECOMBINATION LINES OF CARBON AS A TOOL FOR INVESTIGATION OF MOLECULAR CLOUDS

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Radio Recombination Lines (RRLs) of carbon have been observed now in a wide range of wavelengths from mm to dam. They allow to investigate CII regions formed at the surface of molecular clouds exposed to external ionizing UV radiation. It is important to combine observations at high frequencies where the RRLs of carbon are observed in emission with those at low frequencies where they are observed in absorbtion. When analyzing carbon RRLs, it is useful to add observational data on the C^+ 158μm $^2P_{3/2} - {}^2P_{1/2}$ fine-structure line. This line is emitted by the same carbon ions which form the RRLs under recombination on high levels. Results for concrete sources are discussed.

KEY WORDS **Recombination lines, molecular clouds, CII regions, photodissociated regions**

1 INTRODUCTION

Radio recombination lines (RRLs) of carbon were detected by Palmer *et al.* (1967) soon after the discovery of hydrogen and helium RRLs. It is possible to distinguish two periods in their investigations. In the first one, at the end of the 60s and in the 70s, RRLs of carbon were observed at cm and dm wavelengths in directions to several HII regions. The observations showed that, unlike the hydrogen and helium RRLs, those of carbon originate in the cold medium, in molecular clouds at the boundaries with HII regions or around BO stars. At these places, CII regions arise and carbon RRLs provide a possibility to determine their physical conditions. The results of investigations during this period are reviewed by Brown *et al.* (1978).

The second stage of carbon RRL investigations began in the 80s when their observations were expanded into meter (Ershow *et al.*, 1984) and decameter (Konovalenko and Sodin, 1980) wavelengths. These observations involve serious difficulties.

The data obtained at low frequency showed the theory used for the interpretation of high-frequency carbon lines (that considered an exited carbon atom as hydrogenic) to be invalid. This theory cannot provide a satisfactory agreement between calculated and measured value of carbon RRL intensities in the whole range of observations.

The necessity to take into account the low-temperature dielectronic recombination (DR) in the calculation of the carbon RRL intensity became evident. According to the theory of this effect, recombination of carbon in cold interstellar matter (T_e = 100 K) may be accompanied by simultaneous transition between the fine structure levels $C^+\ ^2P_{3/2} - {}^2P_{1/2}$ ($\Delta E = 92$ K, $\lambda = 158\mu$m), which strongiy affects the intensity of the carbon RRL (Watson *et al.*, 1980). Taking in account the DR allowed to avoid difficulties in the interpretation of the carbon RRL observations and partially explain why the carbon lines are observed in absorbtion at $n > 400$ and in emission at $n < 300$.

The second problem was connected with the nature of the regions where the low-frequency carbon lines are formed. Towards Cas A, where these lines were detected, there are neither HII regions nor OB stars observed in the number required. For this reason, the models used to explain high-frequency carbon RRL observations, are inadequate.

Two interpretations of the observational results were proposed. The first one supposes that the low-frequency carbon RRLs are formed in diffuse interstellar matter and HI clouds, similar by to the 21 cm hydrogen line (Blake *et al.*, 1980; Konovalenko, 1984). Another one concludes that carbon lines originate at the surface of molecular clouds illuminated by an UV radiation field with $912 < \lambda$ A (Ershov *et al.*, 1984). Here the elements with a lower ionization potential than hydrogen are ionized and RRLs are emited (absorbed) in the process of their recombination and cascade transitions. Among them the carbon is the most abundant and the carbon RRLs formed at the surface of molecular clouds must be the most intense.

Let us consider this question in detail using the sources for which the most confident data about the physical condition in CII regions have been obtained.

2 THE EXPERIMENTAL DATA ON THE REGIONS OF CARBON RRL FORMATION

Cas A

The most extensive information on carbon RRLs has been obtained towards Cas A where the lines were observed in a wide wavelength range from 21 cm to 15 m. An example of the spectra of carbon RRLs is given in Figure 1. From the data, one can determine the physical conditions in CII regions where RRLs are formed. Figure 2 shows the observed dependence of the line width of carbon as a function of quantum number n. We have used the results of observations collected by Sorochenko and Smirnov (1990) and the latest data on the C165α and C166α (Sorochenko and Walmsley, 1991), C220α (Sorochenko *et al.*, 1991), C270α (Anantharamaiah *et al.*, 1994) and C537α–C540α lines (Kitaev *et al.*, 1994). The comparison of the widths

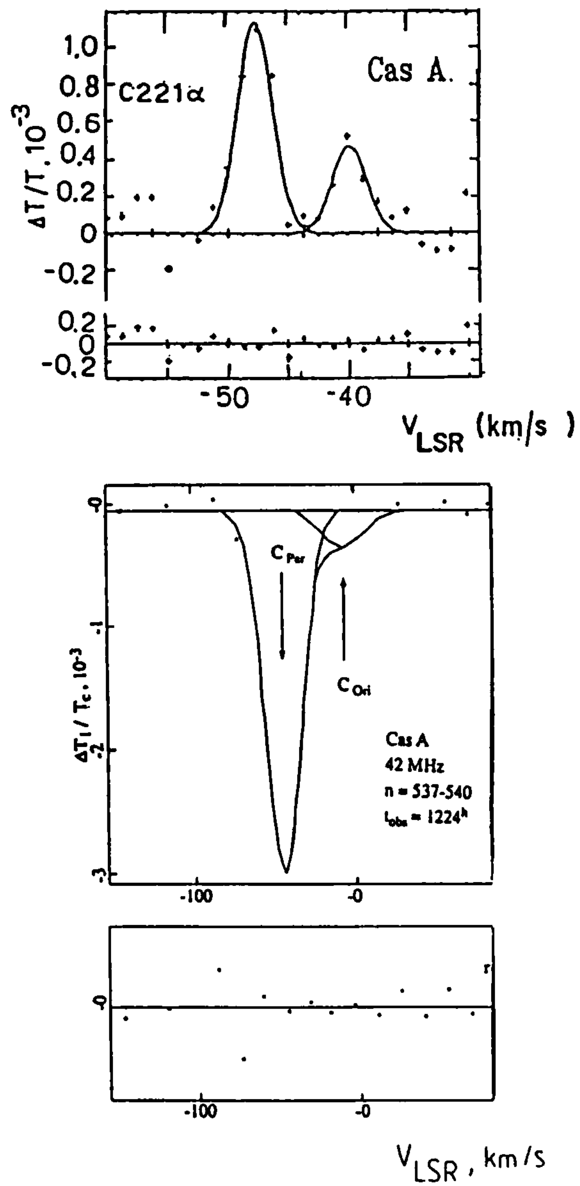

Figure 1 Carbon RRL spectra towards Cas A, obtained at the Pushchino Radio Astronomical Station. (Top): The C221α line ($\lambda \simeq$ 50 cm) observed at the 22-m radiotelescope (Sorochenko *et al.*, 1991). Two Perseus arm velocity components at $V_{\rm LSR} \simeq -40$ km/s and $V_{\rm LSH} \simeq -48$ km/s are visible in the spectrum of the emission line. (Bottom): An average spectrum of four nearby transitions C537α–C540α ($\lambda \simeq$ 7.2 m), observed at the cross-radiotelescope. The total observation time applied to one transition is 1224 hours (Kitaev *et al.*, 1994). The line is in absoption; because of broadening both Perseus arm components, observed in the C221α line, are blended. One can see also the week absorption at the Orion arm velocity. Residials after subtracting baselines and the Gauss-profile fitting are also shown under each spectrum.

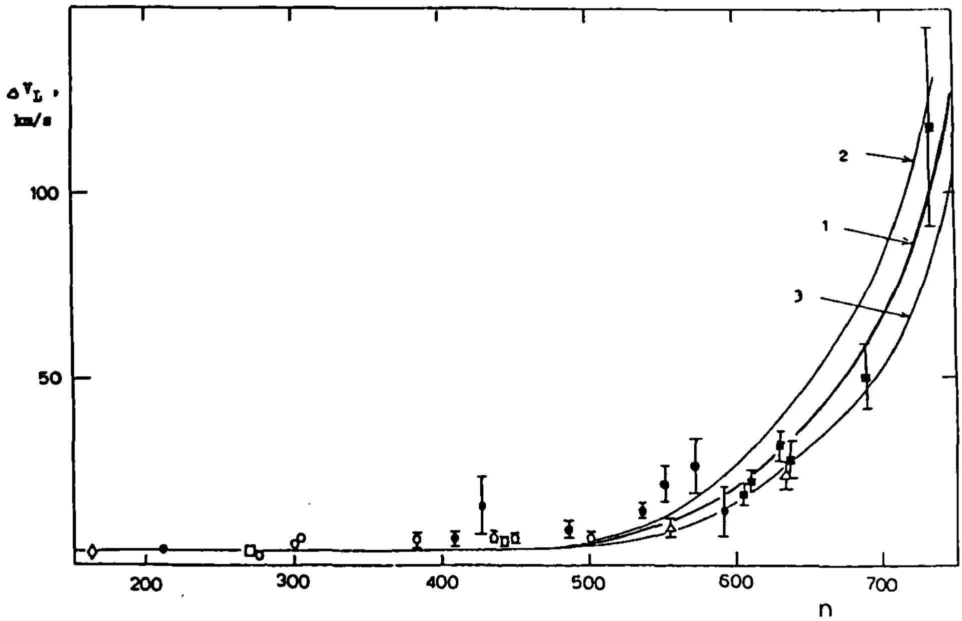

Figure 2 Width of the carbon RRL towards Cas A as a function of the principal quantum number. Filled squares indicated data from Kharkov observations (Konovalenko, 1984), filled circles, Pushchino observations (Ersov *et al.*, 1984, 1987; Lekht *et al.*, 1989; Sorochenko *et al.*, 1991; Kitaev *et al.*, 1994). Triangles (Anantharamaiah *et al.*, 1985) and open circles (Payne *et al.*, 1989) represent Green Bank observations, open squares show observations at the VLA (Anantharamaiah *et al.*, 1994) and diamonds indicate Effelsberg observations (Sorochenko and Walmsley, 1991). The C640α line results are corrected in accordance with recent data of Konovalenko (1995). *1*, the calculated curve $\Delta V_L(n)$ for $N_e(T_e/20)^{0.62} = 0.27$; *2*, *3*, the same dependence, but with $N_e(T_e/20)^{0.62}$ increased and decreased 1.5 times, respectively.

was made for a more intense component with $V_{\rm LSR} = -48$ km/s. The width of low-frequency unsplitted profiles is diminished by 8 km/s which is the distance between the components. Using the last results, the Doppler width of the feature was adopted as 3.9 km/s compared to 6.7 km/c adopted earlier.

As can be seen from the Figure 2 the line width grows with n. This is caused mainly by collisions of exited atoms with electrons and by induced transitions caused by the Galactic background radiation. The rate of both processes quickly increases with n. The width of the RRLs increases accordingly: $\delta\nu_{em} \sim n^{5.65}$ for the broadening by emission and $\delta\nu_{\rm col} \sim N^{5.1}$ for the broadening by collisions with electrons, where $\delta\nu$ is the width of the line in frequency units (Sorochenko and Smirnov, 1990).

The best agreement of the measured and calculated values of the line width occurs if

$$N_e[T_e/20]^{0.62} = (0.27 \pm 0.05)\,{\rm cm}^{-3}{\rm K}^{0.62}; \tag{1}$$

this dependence is shown by thick curve in Figure 2.

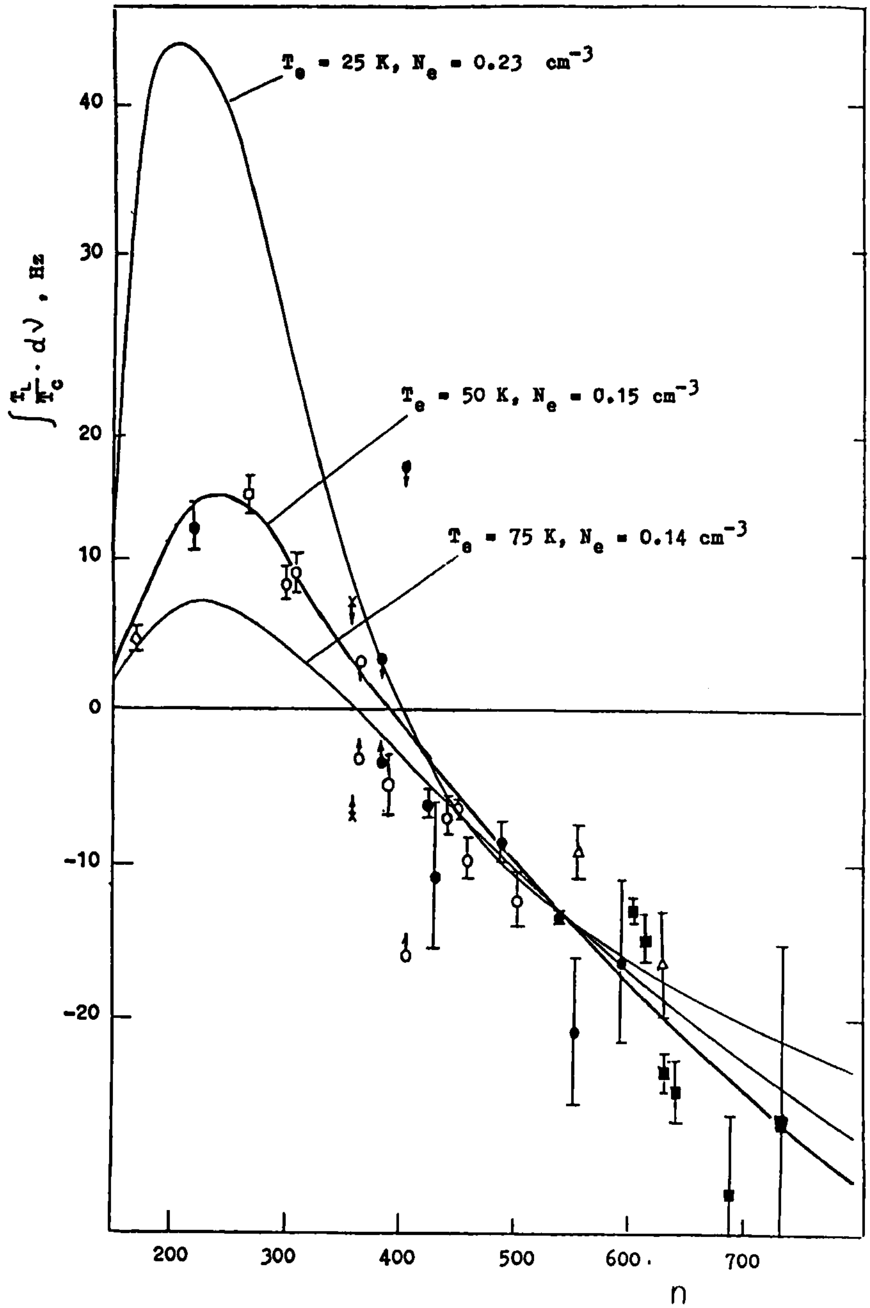

Figure 3 A comparison of the observed ratios of integrated carbon RRLs to continuum toward Cas A with calculated curves. The same experimental data and notation as in Figure 2 are used. The intensities of profiles which have two components at $V_{\rm LSR} \simeq -40$ km/c and at $V_{\rm LSR} = - \cong$ 48 km/c were determined as a sum of both details.

The second measured parameter is the intensity of carbon RRLs at different wavelengths; this allows us to reveal the uncertainty in Eq. (1) and to find the temperature and density of CII region. Figure 3 shows the comparison of the measured and calculated intensities of carbon RRLs.

The theoretical curves were calculated for three value of temperature, 25, 50, and 75 K, and the density derived for each temperature from Eq. (1). The b_n and β_n factors accounting for departures from the equilibrium population calculated by Ponomarev and Sorochenko (1992) were used. All the curves are refered to the observation of the C537α–C540α lines (Figure 1), where, owing to large integration time of 1224 hours, the smallest measurement error in intensity measurements was reached (Kitaev *et al.*, 1994).

As can be seen in Figure 3, the best agreement between the calculated and measured values occurs if T_e = 50 K and N_e = 0.15 cm^{-3}. These values are averages for the whole CII region.

The Galactic Center

Towards the Galactic Center, the carbon RRLs were observed in a narrower range of wavelengths than in the case of Cas A. Neverthless, the lines were detected both in emission, at dm wavelengths, ν = 325–409 MHz (Pedlar *et al.*, 1978; Anantharamaiah and Bhattacharya, 1986) and in absorbtion at meter wavelengths, at the frequencies 42 MHz (C537α–C540α, Smirnov *et al.*, 1996), 75 MHz (C438α–C444α, Anantharamaiah *et al.*, 1988) and 76 MHz (C443α and C447α, Erickson *et al.*, 1995). The comparison of the measured and calculated parameters of carbon lines at different frequencies in the same manner as it was done for Cas A alows to derive the physical conditions of CII regions seen towards Galactic Center. The electron temperature and density turned out to be T_e = 25 K and N_e = 0.4 cm^{-3} (Smirnov *et al.*, 1996).

The S 140/L 1204 complex

This complex is a small bright rim-emission nebula S140 bordering the south-western part of the dark molecular cloud L 1204. It was investigated in the carbon lines C165α and C166α, which were observed at three positions on the molecular cloud: both on the border with the emission nebula and deeper into the molecular cloud. An example of the spectrum in one direction is shown in Figure 4. In addition to carbon, RRLs of hydrogen and sulphur were also detected in the direction of L 1204.

It was concluded from the data obtained that there is a CII region of about 5 pc in projected size in the molecular cloud on its border with the HII region (the visible nebula S 140 is a part of this region). The estimation of the physical characteristics of this CII region gives: T_e = 75K and N_e = 0.5 cm^{-3} (Smirnov *et al.*, 1995). To obtain these data about physical conditions in direction of L 1204, the results of fine structure C^+, 158μm line observations were used. More details about combining observations of RRLs and the 158μm fine structure line will be discussed below.

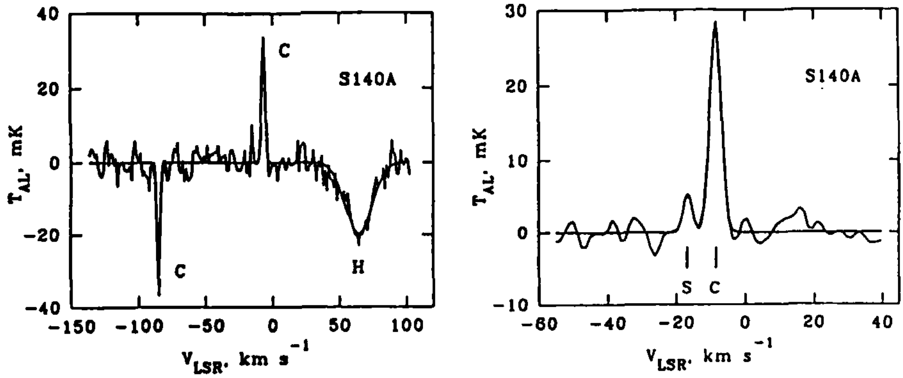

Figure 4 Recombination line spectrum toward S 140/L 1204 which is average of the nearby transitions 165α and 166α. Frequency-switched spectra *a prior* to folding containing narrow profiles (positive and negative) of the carbon lines (C) and a broad profile (negative) of the hydrogen lines (H) are shown in the left panel. The folded and smoothed spectra containing the carbon and sulfur lines are shown in the right panel. The positions of these lines are marked by vertical lines (Smirnov *et al.*,1995).

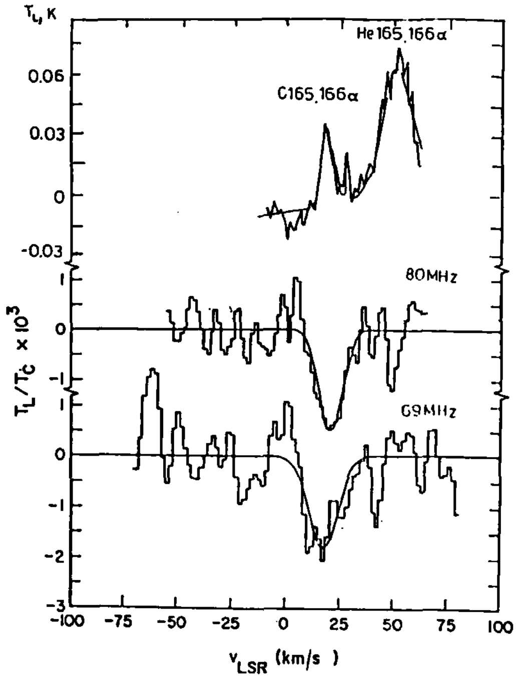

Figure 5 Recombination line spectra towards M 16. (Top): An averaged spectrum of the transitions 165α and 166α. The carbon line which has two components is located on the slope of the helium recombination line (Sorochenko and Smirnov, 1995). (Middle and bottom): The spectra of carbon lines near 80 MHz (the average of C431α, C435α, C437α and 438α lines) and near 69 MHz (the average of C456α and C457α), respectivelly (Anantharamaiah *et al.*, 1988). All the spectra have the same velocity scale related to carbon.

The M 16 Region

Figure 5 shows RRLs spectra in the directions of M 16, obtained at 21 cm, an average of the nearly transitions 165α and 166α of carbon and a blended helium line (Sorochenko and Smirnov, 1995). Figure 5 (bottom) shows the spectra of carbon RRLs in the same velocity scale, obtained in the direction of M 16 at the meter wavelengths: an average of four lines in the frequency range of 80 MHz and two lines at the frequency 69 MHz (Ananthmaraiah *et al.*, 1988). In accordance with the theory, decimeter lines are observed in emission and meter ones, in absorbtion. An analysis of carbon RRL data carried out in the same manner as for Cas A and Galactic Center gives the following (so far preliminary) values of physical parameters towards M 16: $T_e = 200$ K and $N_e = 0.65$ cm^{-3} (Sorochenko and Smirnov, 1995).

3 DISCUSSION

The above data show that carbon RRLs originate in rather dense regions. Taking into account that electrons in these regions are formed mainly as a result of carbon ionization and assuming the solar abundance of carbon to be $N_C/N_H = 3 \times 10^{-4}$, the density of hydrogen in CII regions should be $N_H \simeq 10^3$ cm^{-3} even without taking into account the possibility of carbon capture. Such a density is typical of molecular clouds, but not of diffuse interstellar matter and HI clouds. Essentially the same results were derived not only for the complexes S 140/L 1204 and M 16, where the CII regions are formed on the border with HII regions, but also towards Cas A, where HII regions are absent, and in the direction to the Galaxy Center where the CII region traced by RRLs is also apparently not connected with an HII region.

An additional argument that carbon RRLs are connected with molecular clouds follows from a comparison of the recombination line and molecular line spectra. Figure 6 (left) shows such a comparison for the C221α line (Sorochenko *et al.*, 1992) and the 1_{10}–1_{11} formaldehyde line (Goss *et al.*, 1984) observed in the direction of Cas A. Both lines are averaged over the solid angle of Cas A. The formaldehyde line is observed in absorption and the C221α line as an amplification of the Cas A continuum emission at the frequency of the corresponding transition (in this case spontaneous is low relative to the stimulated one). As one can see, both lines have the same form of spectra and LSR velocities. Figure 6 (right) shows the same comparison of for the spectra of the C165α–C166α lines (Sorochenko and Smirnov, 1995) and CO (Mufson *et al.*, 1981) detected in the direction of M 16. Here, as in the case of Cas A, one can see an evident agreement between the LSR velocities and the forms of both spectra.

The distinct correlation between the spectra of carbon RRLs and molecular lines showed in the two above mentioned cases may be scarcely occasional. Probably it reflects a common origin of these two lines and connection in the spatial lacations of CII regions and molecular clouds. One can support this conclusion with one more experimental fact illustrated in Figure 7. This figure shows a contour map of

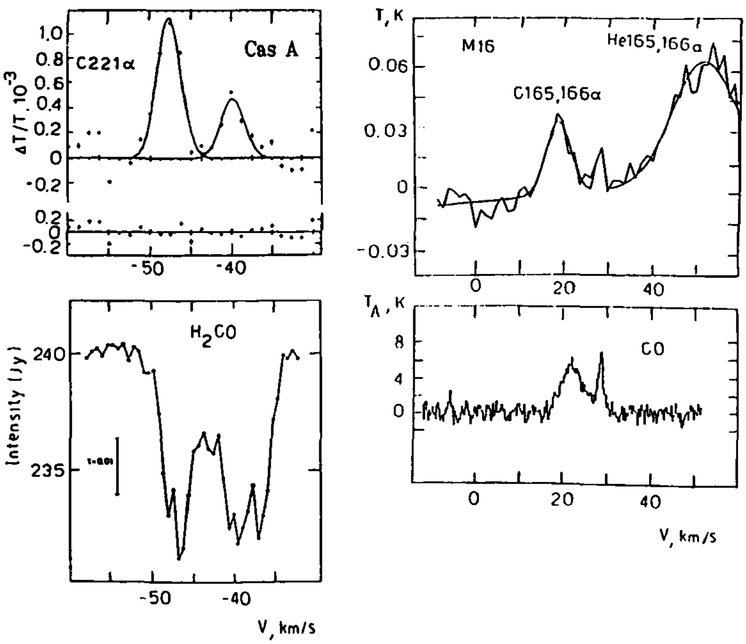

Figure 6 A comparison of the carbon RRLs and molecular line spectra. (Left): The spectra towards Cas A. The upper spectrum represents the C221α line, the lower spectrum is the 1_{10}–1_{11} formaldehyde line. (Right): The spectra in the direction of M 16. At the top is the same 165α and 166α spectrum as in Figure 5, and at the bottom the CO (1–0) line is shown. References are given in the text.

^{13}CO at different intervals of $V_{\rm LSR}$ towards Cas A with an angular resolution of 20″, obtained by Wilson *et al.* (1994). One can see a correlation between the distribution of CO and features of the C221α line spectrum (see Figure 6). In the southern part of Cas A, a molecular cloud with a velocity in the interval $V_{\rm LSR} = (-48 \div -46)$ km/s can be distinguished; it is exactly the velocity of the intense component of the C221α line. Two other molecular clouds, those most intense in the ^{13}C line, are located in the central and western parts of Cas A. They have a velocity in the interval $V_{\rm LSR} = (-40 \div -38)$ km/s, which well agrees with the velosity of the second maximum of the C221α line. In the intermediate range at $V_{\rm LSR} = (-46 \div -42)$ km/s and out of the spectrum of the C221α line, at $V_{\rm LSR} < -48$ km/s and $V_{\rm LSR} > -38$ km/s, the intensity of the emission of the molecular clouds in the ^{13}CO line drops down.

It is nesessary to say, however, that the above conclusion about the connection of CII regions with molecular clouds is not generally accepted now. An alternative point of view is that carbon RRLs towards Cas A are formed in diffuse medium.

In their observations at the VLA, Anantharamaiah *et al.* (1994) obtained a C270α line optical depth image of Cas A with a resolution of 2.7 x 2.4. After a comparison of these results with the distribution of the 21 cm line optical depth (Kalberla *et al.*, 1995) and the distribution of the CO line emission over Cas A,

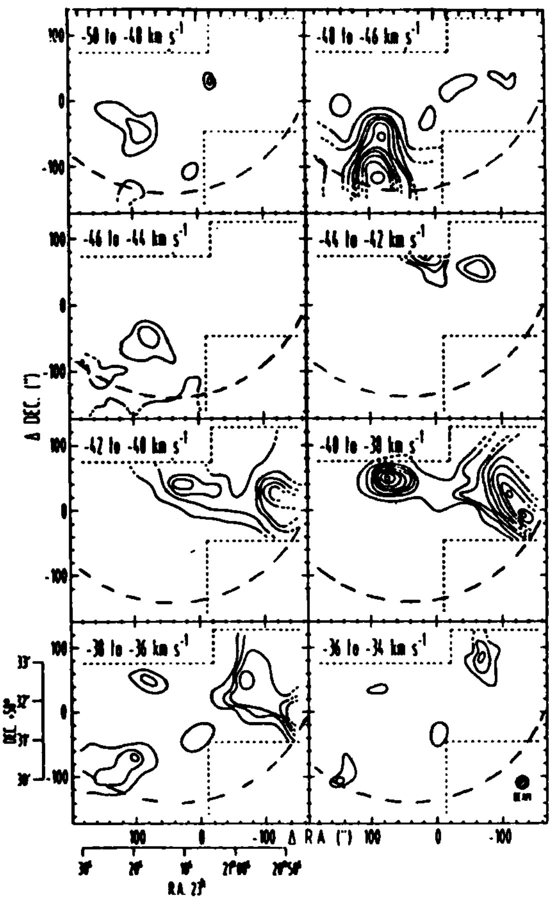

Figure 7 A contour map of ^{13}CO for eight V_{LSR} intervals. These are summed over 2 km/s intervals in velocity identified in the upper right (Wilson *et al.*, 1994). Thick dashed lines show the boundary of Cas A.

the authors concluded that the C270α region is associated with HI rather than with molecular clouds. But we consider this conclusion to be not sufficiently justified.

The 21 cm optical depth is very high in the direction of Cas A, escpesially in the interval $V_{LSR} = (-51 \div -46)$ km/s, where $\tau > 5$ (Bieging *et al.*, 1991). Because of this, a comparison between the distribution of the 21 cm line and the distribution of the main component of the C270α line at $V_{LSR} = -48$ km/s (the spectrum of the C270α line, averaged over Cas A, is very similar to the spectrum of the C221α line, see Figure 1) is very difficult and seems to be practicallly impossible. The optical depth of the 21 cm line at the velocity of another component of the C270α line at $V_{LSR} = (-40 \div -38$ km/s) is lower, but the signal-to-noise ratio (4.5σ), as measured at the VLA, is too low for a definite conclusion to be drawn.

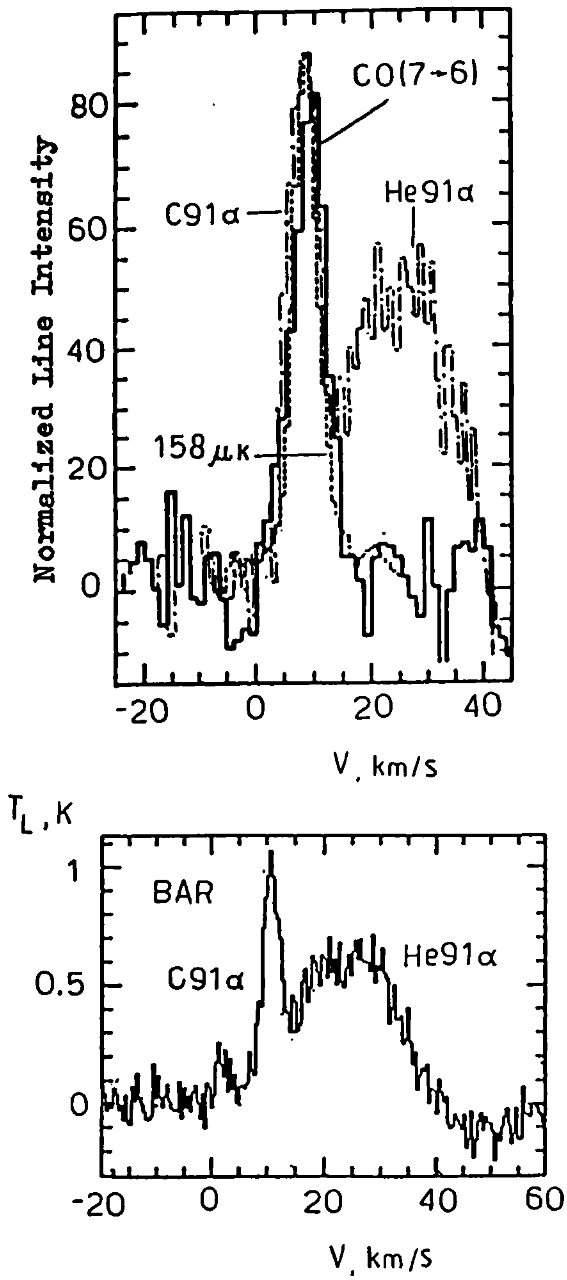

Figure 8 Superposition of the spectra of the C^+ 158μm, C91α and CO (7–6) lines towards Orion. The line intensities are normalized. The dashed line shows the spectrum of C^+ (Boreiko *et al.*, 1988) and the solid line is the spectrum of CO in the direction of θ^1Ori C (Stacey *et al.*, 1993). Dash-dotted line is the spectrum of C91α and He91α in the direction of the "Orion Bar", also shown separately at the bottom (Natta *et al.*, 1994).

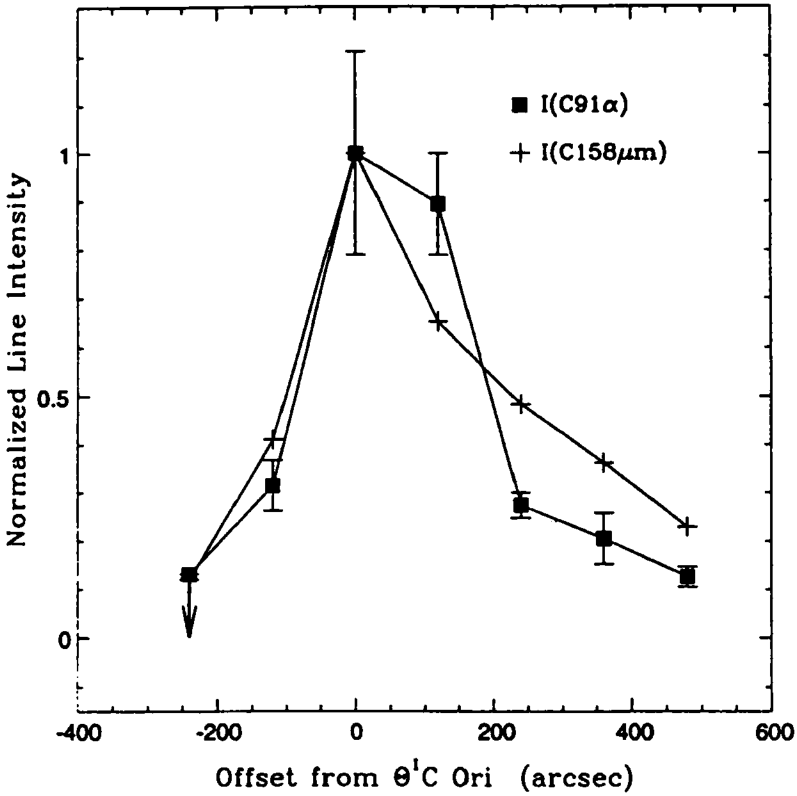

Figure 9 A comparison of the integral intensities of the C91α and C^+ 158μm lines. The results are displayed as a function of the angular offset E–W from θ^1C (Natta *et al.*, 1994).

At the same time, the distribution of the C270α line at $VLSR = -48$ km/s indicates a qualitative agreement with the distribution of the CO line: the VLA observations show that the emission from this component originates in the south part of Cas A and in the same direction a CO cloud with $V_{\rm LSR} = (-48 \div -46)$ km/s is located (see Figure 7).

Observations of the fine structure C^+, $^2P_{3/2} - {}^2P_{1/2}$, 158μm line give very important information about CII regions. The line originates from the same carbon ions which emit (absorb) carbon RRLs due to recombinations to high levels and the following cascade transitions. Therefore investigating the CII regions using the 158μm line we obtain, at the same time, data about the nature of the regions where RRLs are formed.

As one could expect, both the profiles and the spatial distributions of these lines are in a close correlation. Figure 8 shows the spectrum of the 158μm line towards θ^1Ori (Boreiko *et al.*, 1988) superimposed on the spectrum of the C91α line, observed in a nearby direction of the "Orion Bar" (Natta *et al.*, 1994). The carbon line is located on the slope of the helium He91α line, which is illustrated in

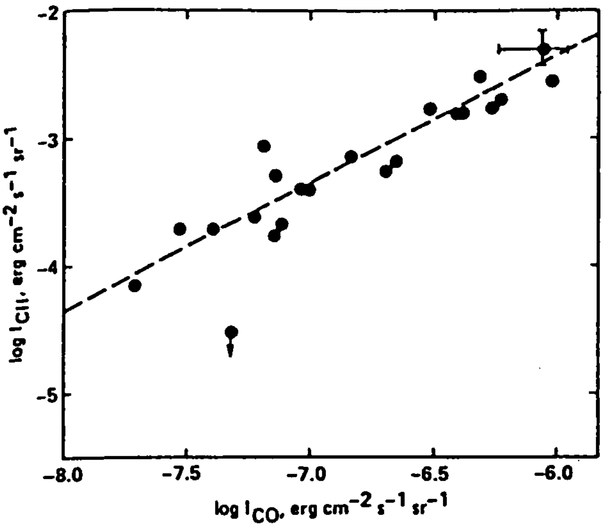

Figure 10 The observed CII 158μm intensity, $I_{\rm CII}$, vs the ^{12}CO (1–0) intensity, $I_{\rm CO}$, for the Galactic and extragalactic photodissociation regions (Wolfire *et al.*, 1989).

the lower part of the same figure. The spectrum of the CO (J = 7–6) line obtained towards θ^1Ori (Stacey *et al.*, 1989) is also shown superposed. As one can see, all the three lines 158μm, C91α and CO are very close both in line width and velocity. Such an agreement shows again that atomic carbon lines as RRLs and also the 158μm line originate in molecular cloud.

Figure 9 shows the cut of θ^1Ori in the 91α and 158μm lines (Natta *et al.*, 1994). One can see a close spatial correlation of the intensities of the both lines.

Observations of the 158μm line now exhibit a rapid progress. This line has been detected from several tens of Galactic and extragalactic sources. A good correlation has been observed between the 158μm and CO line emissions (Figure 10) which indicates their common origin (Wollfire *et al.*, 1989). At the same time, the correlation between the 158μm line and the 21 cm line is absent (Crawford *et al.*, 1985).

The above arguments apparently leave not much doubt that CII regions in Cas A and in other sources analyzed are in a close correlation with molecular clouds rather than with diffuse atomic hydrogen. The connection of these regions with HI may lie in the fact that a molecular cloud must be surrounded by a layer of atomic hydrogen, which is necessary to protect H_2 molecules from destruction by external UV radiation (Federman *et al.*, 1974). In this photodissociation region, where hydrogen is atomic, the ionization of carbon and formation of CII regions take place. The carbon RRLs originate in these regions and one can observe them in a wide range of wavelengths. With a recent detection of a carbon line at λ = 8 mm (Sorochenko and Tsivilev, 1996), it ranges from millimeter to decameter.

Table 1. CII region parameters

Molecular clouds names	*Exciting stars*	*Electron temperature T_e, K*	*Electron density N_e, cm^{-3}*	*Hydrogen density N_H, cm^{-3}*	*Ref.*
Cas A	–	50	0.15	500	1
Towards Galactic Center	–	25	0.4	1300	2
S140/L1204*	BOY	75	0.5	1600	3
W3*	06, 5	100–200	0.2	700	4
M16*	05; 07	100–200	0.6	2000	5
Orion*	06	300–1000	> 30	> 10^5	6,7

Note. *Besides the RRL data, results of the C^+ 158μm line measurements were used to derive physical parameters.
References: 1) Sorochenko and Walmsley, 1991; 2) Smirnov *et al.*, 1996; 3) Smirnov *et al.*, 1995; 4) Howe *et al.*, 1991; 5) Sorochenko and Smirnov, 1995; 6) Natta *et al.*, 1994; 7) Stacey *et al.*, 1993.

Principally the carbon RRLs should originate also in diffuse interstelar matter at hydrogen density of $N_H \sim 10$ cm^{-3}. But due to low electron density, $N_e \sim (10^{-2}$–$10^{-3})$ cm^{-3}, the intensity of RRLs in such a region must be very weak, essentially lower than observed in the above sources. This conclusion was confirmed by a recent detection of the 158μm line from diffuse matter (Bock *et al.*, 1993): the intensity of this line was 1–2 orders of magnitude lower than that observed from CII regions. For RRLs this difference must be still higher since the ratio of the intensities of RRLs and the 158μm line decrease with N_e (Natta *et al.*, 1994).

In Table 1 the data on physical conditions in CII regions are compiled, which were derived from recent observation of RRLs and 158μm line. Besides the sourses considered in Part 2, the data on CII regions in W3 (Howe *et al.*, 1991) and in Orion (Natta *et al.*, 1994) are also included in the Table 1. As one can see, the electron temperature of CII regions is in the range from $T_e = (25$–$50)$ K (for molecular clouds which are not connected with HII regions) to hundreds K in Orion. Obviously, this depends on the source of ionization. Towards Cas A, the ionization of carbon is caused by diffuse UV radiation; there are no O and B stars and HII regions adjacent to molecular clouds. The same situation takes place, probably, for carbon RRL source in the direction to the Galactic Center, and the temperature of both CII regions is low. In S 140, where the source of ionization is well known to be the BO Y star HD 211880, we have $T_e = 75$ K. In the latter three CII regions, the ionization of carbon is caused by O-stars and, accordingly, $T_e \geq 100$ K. The electron density also increases from Cas A to the Galactic Center and futher to M 16 and Orion. Accordingly, the hydrogen density also increases from $N_H \sim 10^3$ cm^{-3} to $N_H > 10^5$ cm^{-3}.

The discussion above shows the great possibilities and perspectives in investigation of molecular clouds using carbon recombination lines. A combination of three types of observations is of principal importance:

(1) observations of carbon RRLs at a high frequency, where these lines are observed in emission,

(2) observations at a low frequency where carbon recombination lines are observed in absorption and one can derive (by Stark broadening) an electron density of CII region,

(3) using the data on the fine structure of the C^+ 158μm line which gives once more dependence between the line intensity and physical conditions.

Employing carbon RRLs, observed in a wide range of wavelengths from millimeter to decameter, one can investigate CII regions, formed both in molecular clouds at borders with HII regions and around isolated molecular clouds. Such observations can give important information about molecular clouds and their evolution.

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