Contrib. Astron. Obs. Skalnaté Pleso **53/1**, 17 – 27, (2023)
https://doi.org/10.31577/caosp.2023.53.1.17

The low-frequency carbon radio recombination lines in medium toward S140 nebula

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Received: February 24, 2023; Accepted: March 14, 2023

Abstract. Low-frequency carbon radio recombination lines (RRLs) serve as an effective probe of cold, partially ionized gas diagnostic. In this paper we report about studies of these lines towards the S140 nebula at UTR-2 near 26 MHz. As a spectrometer, the 4096-channel digital correlometer was used. Low-frequency carbon RRLs were detected for the S140 line of sight and its environs, the line of sight being shifted in 3° by declination to one and other side. For all three directions the similar relative line intensities were obtained. Measured line widths do not coincide with high-frequency RRLs line widths. This can tell us that a low-frequency line forming region is not associated with the S140 nebula itself. By an iterative analysis it was obtained that values of electron temperature $T_e = 50 \div 100$ K and electron density $N_e = 0.01\,\mathrm{cm}^{-3}$ most closely match our experimental data. Due to the fact that the sizes of the line forming region (or regions) exceed the solid angle of the S140 nebula, and due to the mismatch between the widths of low-frequency and high-frequency RRLs, and also based on our analysis of physical conditions of the line forming region it was proposed that low-frequency lines were formed in the local medium associated with HI clouds lying on the line of sight. Further observations and interpretation will help to describe the physical parameters of the medium in different Galactic directions.

Key words: cold interstellar medium – radio spectroscopy – radio recombination lines

1. Introduction

Currently, by methods of experimental radio astronomy a large number of spectral lines from various atoms and molecules have been detected and investigated. Spectroscopy of cosmic matter is one of the most important sources of information about physical parameters and chemical composition of the Universe.

A crucial issue in the problem of cosmic matter investigation is related to interstellar medium (ISM) studies. ISM serves as a star birthplace as well as a repository of their evolution products storage. Due to the continuous energy and matter exchange between stars and the surrounding environment, various ISM phases are possible. For example, the phases of cold neutral gas, warm neutral and ionized gas may exist (McKee & Ostriker, 1977). Its main physical parameters are very different. In cases when their temperature and density are relatively low the atoms can be excited up to high quantum states (such atoms are also often called as Rydberg atoms). They are formed mainly through the processes of ions' and electrons' recombination. Simultaneously with a free electron capture, captured or other electrons in a high quantum level jump into a less excited state. This "jump" produces the photon emission and spectral lines formed by such transitions are called "radio recombination lines" (RRLs) (Gordon & Sorochenko, 2002). The high-frequency RRLs (usually above 1 GHz) mainly trace the warm, dense gas in emission from HII-regions, while the low-frequency lines (usually below 500 MHz) trace a relatively cold and rarefied gas in absorption from diffuse, presumably neutral clouds.

Due to the fact that many astrophysical processes occur differently at low and high frequencies, and some processes do not manifest themselves at high frequencies, low-frequency RRLs provide a unique and powerful method of the ISM diagnostic. For the first time low-frequency RRLs were detected from the carbon in the late 1970s (Konovalenko & Sodin, 1981, and references therein). Detection of carbon lines and not hydrogen ones was due to a lower ionization potential of the carbon compared with the hydrogen (E_C = 11.2 eV, E_H = 13.6 eV). This makes it possible to almost completely ionize the carbon in cold rarefied regions located away from powerful ionization sources where the hydrogen will be almost all neutral. Decameter lines made it possible to study the ISM physical conditions in line forming regions (e.g. electron temperature, electron density, emission measure etc.) and to refine the kinematic parameters and dimensions of these regions (Konovalenko & Stepkin, 2005).

The partially ionized gas plays an important role in processes of the evolution and energetic of cosmic matter as well as in star formation. In the case of the presence of a strong continuum source it's possible to observe the low-frequency carbon RRLs amplified by stimulated emission. These lines can be used for studying medium regions more distant from hot stars and less dense. Some of the above mentioned objects were already investigated at UTR-2 (Konovalenko & Sodin (1981), Konovalenko (1984a,b), Golynkin & Konovalenko (1991a,b), Konovalenko & Stepkin (2005), Stepkin et al. (2007), Stepkin et al. (2021)) and at other radio telescopes (Erickson et al. (1995), Kantharia et al. (1998), Kantharia & Anantharamaiah (2001), Roshi, D. Anish et al. (2002), Roshi & Kantharia (2011), Asgekar et al. (2013), Oonk et al. (2017), Salas et al. (2017), Roshi et al. (2022)) in previous years. If we take into account a high level of radio frequency interference (RFI) and weakness of received signals, the medium in the Perseus Arm lying on the line of sight toward the bright radio source Cassiopeia A is most suitable for spectroscopic observations at low radio frequencies. A great amount of unique information has been obtained by observations in this direction (see Konovalenko, 1984b; Kantharia et al., 1998; Stepkin et al., 2007; Asgekar et al., 2013; Oonk et al., 2017; Salas et al., 2017). This success led to believing that similar results may be obtained for other Galactic directions. Indeed, this was confirmed by a low-frequency carbon RRLs detection in several Galactic lines of sight (Konovalenko, 1984a; Golynkin & Konovalenko, 1991a,b; Erickson et al., 1995; Kantharia & Anantharamaiah, 2001; Roshi, D. Anish et al., 2002; Roshi & Kantharia, 2011; Roshi et al., 2022). For our studies we chose a very interesting line of sight – the direction toward the S140 nebula.

2. S140 nebula, observational methods and equipment

S140 is a bright rim located near the south-western borders of the cold molecular cloud L1204. S140 with L1204 together form a photodissociation region. Observations of these objects are very important at both high and low frequencies. This direction is also interesting because both the S140 region and the neighboring L1204 cloud represent two examples of different star formation stages. A large amount of data in many ranges of electromagnetic radiation was detected from L1204. This became possible due to intended existence of a strong infrared source (presumably an early type star) besides two known stars of B0V and B2V classes in this cloud. Also, it was proposed that almost all of gas ionizing photons in L1204 come from S140. The high-frequency RRLs observations (C142α and C166α lines) toward S140 were reported in Knapp et al. (1976). Smirnov et al. (1995) described similar observations (C165α − C166α lines) towards S140/L1204. The authors concluded that S140 is part of a larger HII region. Its electron temperature and electron density were preliminary determined as $T_e \sim 75 \div 200$ K and $N_e \sim 0.5 \div 9$ cm^{-3}, respectively.

In the paper by Golynkin & Konovalenko (1991b) the studies of decameter carbon RRLs toward the S140 nebula at UTR-2 near 25 MHz were described (C640α line). Observations were carried out with a 160-channel digital sign correlometer with the frequency resolution of about 1 kHz. Having integration time of hundreds of hours, the authors concluded that the lines were formed in the medium with $T_e > 20$ K and $N_e < 1$ cm^{-3}. It was proposed that traced by decameter carbon RRLs gas can be associated with large volumes of the low-density medium near the S140 nebula. Based on the low electron temperature proposed by authors, they did not consider the mechanism of low-temperature dielectronic-like recombination, which affects the populations of quantum levels of atoms at $T_e \sim 100$ K and, so, the observed line intensities (Watson et al., 1980).

Smirnov et al. (1992) made an attempt to detect the meter C540α RRL in the S140 direction near 42 MHz. No line was found in the obtained spectra, although it was expected that it would have a higher intensity than the decameter C640α line. However, Smirnov et al. (1992) obtained the upper limit of the intensity for RRLs detection in meter wavelengths ($\leq 3.6 \times 10^{-4}$). They also explained a rather large C640α line width obtained by Golynkin & Konovalenko (1991b). It was proposed that the main contribution to the line broadening is made by the high-speed turbulent motions in ISM rather than collisions between Rydberg atoms and electrons. Such a large line width is not consistent with high-frequency carbon RRLs line widths (approximately $2 \div 5$ km s^{-1}). Smirnov et al. (1992) suggested that the observed decameter carbon RRLs line forming region (CII-region) in the S140 direction is not associated with the S140 nebula itself. Observational data of C640α and HI lines were also compared by Smirnov et al. (1992). There was good correspondence between them (see Fig. 3 in Smirnov et al., 1992). Both line profiles' maxima correspond to radial velocities of about 0 km s^{-1}. It was also suggested that decameter carbon RRLs in the S140 direction are formed in multiple diffuse HI clouds located on the line of sight. Such clouds have typical values of $N_H = 6 \div 20$ cm^{-3}, $N_e \sim 0.02$ cm^{-3} and $T_e = 60 \div 80$ K. The carbon in these clouds is completely ionized by UV radiation with $912\ \mathring{A} < \lambda < 1100\ \mathring{A}$.

Over the years the new models of the CII-region based on multi-frequency carbon RRLs data for Cassiopeia A direction were proposed (Kantharia et al., 1998). The best agreement is obtained for $T_e = 75$ K, $N_e = 0.02$ cm^{-3} and the association of CI-regions with neutral atomic HI clouds seems to be most plausible. Also, over the years the spectral equipment of the UTR-2 radio telescope has been improved; in particular, the number of spectral channels of the digital sign correlometer has been increased to 4096, which greatly increases the measurement sensitivity and width of bandpass.

In this paper we will try to discuss the results of high-precision low-frequency carbon RRLs observations performed at the UTR-2 radio telescope toward the S140 nebula at a frequency of 26 MHz. The Ukrainian UTR-2 is the world largest decameter radio telescope. It has an effective area of about 140 000 m^2 and the maximal angular resolution of about $\alpha \times \beta = 30' \times 30'$ at 25 MHz (Konovalenko et al., 2016). Observations reported in this paper were carried out in November 2003 at the North − South array of UTR-2, which has dimensions 1800 m × 54 m and consists of 1440 dipoles. The beam of this array is oriented along the east-west line and has a size of $\alpha \times \beta = 12° \times 40'$ at 25 MHz.

As it was mentioned, the 4096-channel digital sign correlometer serves as a radio telescope back-end (Konovalenko & Stepkin, 2005). The bandpass width during the observations was 1.2 MHz and the frequency resolution was chosen as 1.1 kHz. Spectra, obtained by the Fourier transform of an autocorrelation function of the signal, were recorded on a PC with 4-minute intervals. The obtained data were processed for RFI removal by a special routine. Due to the fact that at the decameter range adjacent high excited quantum levels have a small energy difference, we can consider the neighboring levels as equivalent and fold the lines resulting by transitions from these levels. Regarding this, we fold all lines which fall into the digital correlometer bandpass (stacking 11 lines leads to the increase of sensitivity more than 3 times).

3. Results

In Fig. 1 the averaged spectrum of carbon RRLs of C627α – C637α obtained toward the S140 nebula is presented. Integration time was 108 hours. The line radial velocity is close to 0 km s^{-1}, which implies the location of the CII-region within the local spiral arm.

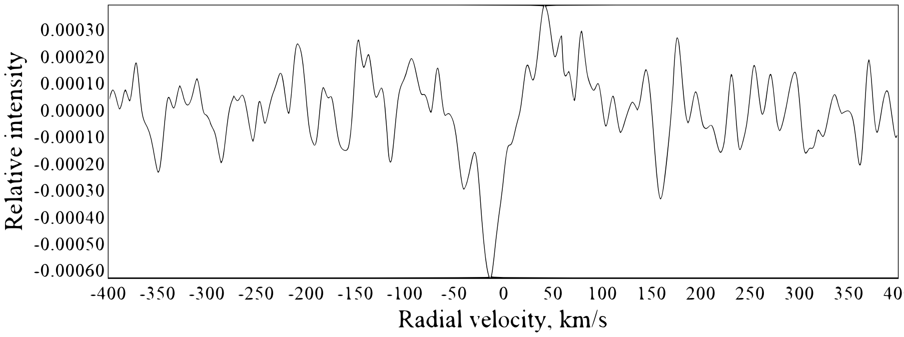

Figure 1. The spectrum of low-frequency carbon RRLs series of C627α – C637α, measured in the S140 nebula direction.

Then, in order for estimate the angular sizes of the medium region where detected low-frequency carbon RRLs were formed, in the same period there were made the additional observations toward the line of sight shifted from the S140 direction by 3 degrees in declination. In Fig. 2 and 3 we present the spectra measured in G105.15+2.8 and G108.48+7.83 directions shifted by three degrees to the side of negative and positive declinations from the S140 line of sight, respectively. Integration times were 46.2 and 72 hours, respectively. Carbon RRLs were detected in both spectra with similar relative line intensities, which have a good correspondence with the measured relative line intensity for the S140 line of sight. This may imply that lines in all three directions were formed in a medium with similar physical conditions. Obviously, they may be formed in the same cloud, or a complex of interstellar clouds. The values of line widths were obtained by fitting of a Gaussian into the line profiles. The line widths for all three directions have basically similar values (for the G105.15+2.8 direction pointed near the Galactic plane the width is slightly larger due to the presence of large gas volumes near the plane with different radial velocities). Obtained line widths in terms of radial velocities are consistent with the line widths measured in other Galactic plane line of sights at slightly higher frequencies, Erickson et al. (1995) and Kantharia & Anantharamaiah (2001). The line widths practically do not change with frequency, therefore the Doppler broadening mechanism plays a predominant role.

In Table 1 the obtained values of main line characteristics are listed.

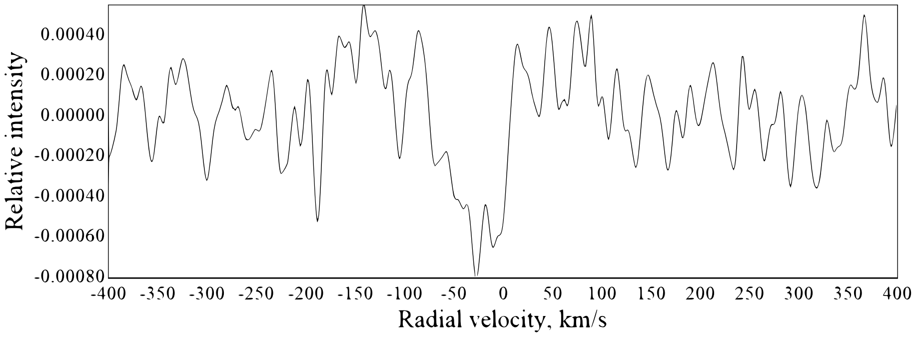

Figure 2. The spectrum of low-frequency carbon RRLs series of C627α – C637α, measured in the G105.15+2.8 direction.

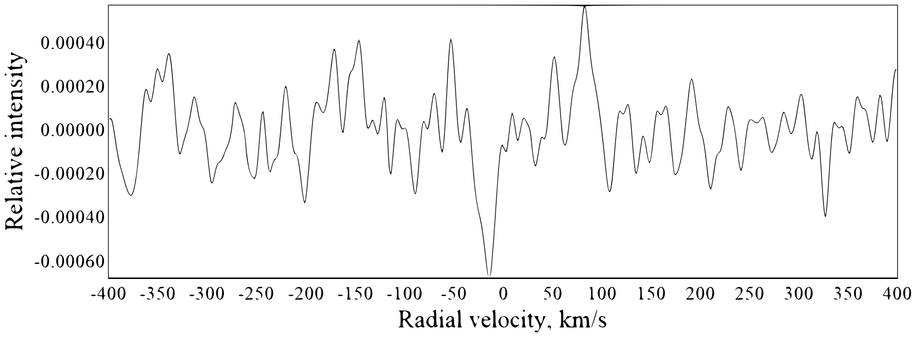

Figure 3. The spectrum, of low-frequency carbon RRLs series of C627α – C637α measured in the G108.48+7.83 direction.

4. Discussion

The line widths obtained in this work (Table 1) are several times smaller than those in Golynkin & Konovalenko (1991b). This may be due to the higher measurement sensitivity secured through the increased number of digital correlometer channels, a wider bandpass and, therefore, a larger number of simultaneously observed transitions as well as the more correct usage of the profile fitting procedure. At the same time, the line widths obtained in this work ($10 \div 28$ km s^{-1}) significantly exceed the widths of the high-frequency lines ($2 \div 5$ km s^{-1}) (Knapp et al., 1976; Smirnov et al., 1995). Smirnov et al. (1992) also described that widths of high-frequency and low-frequency carbon RRLs in the S140 direction do not coincide. This may indicate that the formation of two line types occurs in different, spatially unrelated ISM regions. This implies that low-frequency line forming regions are apparently not directly related with the

Table 1. Obtained low-frequency carbon RRLs characteristics.

Direction	$\Delta T_L/T_C$ $\times\ 10^{-4}$	V_{LSR} [km s^{-1}]	$\Delta\nu$ [kHz]	ΔV [km s^{-1}]	I_L [s^{-1}]
S140	6.2	-16	1.63	18.82	-1.54
G105.15+2.8	8.1	-29	2.47	28.55	-2.92
G108.48+7.83	6.8	-16	0.9	10.38	-1.04

S140 nebula and high-frequency line forming regions.

In Golynkin & Konovalenko (1991b) the lines at the UTR-2 North – South array were observed with a relative intensity of about 8 × 10^{-4} against the continuum. Relative intensity values obtained in this work are consistent with those of Golynkin & Konovalenko (1991b) and with theoretical calculations by the formula

$$\frac{\Delta T_L}{T_C} = -\tau_L = -\tau_L^* b_n \beta_n, \tag{1}$$

where $\Delta T_L/T_C$ is the relative line intensity, τ_L is the optical depth, τ_L^* is the equilibrium optical depth (optical depth at LTE conditions), b_n is the departure coefficient and β_n is the stimulation emission coefficient,

$$\beta_n = 1 - \left(\frac{kT_e}{h\nu}\right)\left(\frac{d\ln b_n}{dn}\right), \tag{2}$$

where h is Planck's constant ($h = 6.6261 \times 10^{-27}$ erg·s).

Integrated line intensities I_L were experimentally determined (Table 1), the values of which were used for T_e and N_e estimates by the formula

$$I_L = \int\limits_{\nu} \frac{\Delta T_L}{T_C} d\nu \approx -2 \times 10^6 \frac{N_e^2 s}{T_e^{5/2}} b_n \beta_n, \tag{3}$$

where s is the path length in pc. The value of s was taken equal to 5 pc as an average typical value for the size of HI clouds in Galaxy. From six T_e and N_e combinations (T_e = 50 K, N_e = 0.01 cm^{-3}; T_e = 50 K, N_e = 0.1 cm^{-3}; T_e = 50 K, N_e = 1 cm^{-3}; T_e = 100 K, N_e = 0.01 cm^{-3}; T_e = 100 K, N_e = 0.1 cm^{-3}; T_e = 100 K, N_e = 1 cm^{-3}) and corresponding $b_n\beta_n$ values (which are taken from Walmsley & Watson (1982)), our results for the S140 direction are most consistent with values of T_e = 50 and 100 K, N_e = 0.01 cm^{-3} which are consistent with a model by Kantharia et al. (1998). $b_n\beta_n \approx 20$ for T_e = 50 K and $b_n\beta_n \approx 90$ for T_e = 100 K for corresponding $n \sim 630$.

Relative intensities of low-frequency carbon RRLs from directions deviating from the S140 line of sight practically do not differ from those measured towards S140 itself. It should be noted that the relative line intensity is a unit of the line strength used in this work. The real line intensity will differ from the observed relative intensity by

$$\left(\frac{\Delta T_L}{T_C}\right)_{real} = \left(\frac{\Delta T_L}{T_C}\right)_{observed} \frac{\Omega_S}{\Omega_A} \frac{T_B}{T_B + T_F} \frac{T_A}{T_A + T_N}, \tag{4}$$

where Ω_S and Ω_A are solid angles of the source and radio telescope beam, respectively, T_B and T_F are Galactic background brightness temperatures behind and in front of the source and T_A and T_N are the antenna background temperature at the receiver input and the receiver noise temperature, respectively (Golynkin & Konovalenko, 1991b). Since until now the exact values of T_B and T_F have been unknown, it is not possible to determine the real line intensities.

The line radial velocities observed in this work and velocities from Golynkin & Konovalenko (1991b) practically coincide. This suggests that the lines were apparently formed in gas lying in the Perseus and Orion arms.

Based on the presence of lines in spectra in Fig. 2 and 3 with similar widths, relative intensities and radial velocities, we can assume that angular dimensions of the CII-region, where low-frequency carbon RRLs in the S140 direction were formed, are greater than 6° by declination. If we convert this value into linear dimensions units (assuming the distance to S140 of about 1 kpc) by the formula

$$a = \frac{360^\circ}{2\pi} \left(\frac{d}{D}\right), \tag{5}$$

where a is the angular size in degrees, d is the linear size in pc and D is the distance from the observer to the source in pc, we find that linear dimensions of the medium region (or multiple regions) where the detected low-frequency carbon RRLs were formed, is no less than 100 pc. Only giant molecular clouds can correspond to such linear dimensions, but the formation of low-frequency RRLs in these objects is extremely unlikely (Kantharia et al., 1998). A reasonable explanation could be that the detected lines were formed in medium regions lying on the line of sight to S140, but which are located much closer to us. Based on the aforementioned facts and dimensional estimates, the CII-region (CII-regions) cannot be associated with the S140/L1204 complex but with medium regions lying on the line of sight.

The question of particular importance is the nature of CII-region when low-frequency carbon RRL was formed. Golynkin & Konovalenko (1991b) noticed that this CII-region could be associated with the S140 nebula itself. It was also noted that, in principle, there could be a variant of these lines' formation in a local medium lying on the line of sight under the influence of a low-temperature dielectronic-like recombination mechanism (Watson et al., 1980). In this work carbon RRLs detected from all the three directions with almost the same intensities, line widths and radial velocities, and we may suppose that these lines originated in the same gas volume. Based on the analysis carried out by Smirnov et al. (1992) and the analysis of physical conditions carried out in this work, it can be assumed that observed RRLs can be formed in diffuse HI clouds on the line of sight towards S140. HI clouds are widespread in the Galactic Plane, have typical physical conditions' values coinciding with those obtained above ($T_e = 50 \div 100$ K, $N_e = 0.01$ cm^{-3}) and have typical linear dimensions up to 10 pc (usually $4 \div 6$ pc).

5. Conclusions

In this work we present the low-frequency carbon RRLs studies toward the S140 nebula carried out at the UTR-2 radio telescope near 26 MHz. Observations were made using a 4096-channel digital correlometer within the 1.2 MHz bandpass with the frequency resolution of 1.1 kHz.

Low-frequency carbon RRLs were detected in absorption in both the S140 nebula direction and its environs (line of sights shifted from S140 in 3° by declination). In all the three cases the relative line intensities have similar values. The measured line widths are comparable with those for other Galactic plane directions and apparently have a Doppler broadening mechanism. Results obtained for the width of low-frequency RRLs do not agree with the width measurements of high-frequency lines, which virtually eliminates the possibility of low-frequency RRLs formation in a region associated with S140 itself. An analysis of CII-region physical conditions showed that the best fit to our observational data have the values $T_e = 50 \div 100$ K, $N_e = 0.01$ cm^{-3}, which is consistent with the currently most correct multi-frequency model of a CII-region. Taking these facts into account and also the fact that line characteristics for the three line of sights have very close values, we can suppose that detected toward S140 carbon RRLs were formed in a spatially extended medium region with angular sizes no less that 6°. The most reasonable explanation of all of this is the association of a low-frequency lines' forming region with diffuse HI clouds lying in the local medium on the line of sight toward S140. Further RRLs studies in both S140 and other Galactic directions in a wide frequency range will allow us to create a more reliable and comprehensive model of the CII-region where low-frequency carbon RRLs are formed.

Acknowledgements. This work was based on the authors' report at the Young Science Conference on Astronomy and Space Physics which was held in April 2018 in the Taras Shevchenko National University of Kyiv. The authors are grateful to Dr. Olena Shubina for useful advice and discussions that led to a deeper analysis of the obtained results and preparation of this work.

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