

# Radio recombination lines of highly excited carbon near DR 21 and S 140

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(Submitted July 23, 1990)

Pis'ma Astron. Zh. 17, 16–22 (January 1991)

Carbon recombination lines in absorption in the decameter range have been detected in the directions of the nebulae DR 21 and S 140. This indicates the presence of comparatively large masses of cold, partly ionized interstellar matter with an electron density less than  $1 \text{ cm}^{-3}$ . We have identified discrepancies between models of the regions producing the highest- and lowest-frequency carbon lines.

**Introduction.** The partially ionized medium in the transition layer between an H II region and the surrounding neutral cold gas illustrates the interconnectivity, energetics, and evolution of a complex consisting of an emission nebula and a neutral cloud. High-frequency recombination lines of carbon, corresponding to such thin layers, are observed close to, for example, a score of H II regions, and they yield valuable astrophysical information, which is discussed in the review of Pankonin (1980).

These objects are of much interest when studied in the decameter range because the presence of intense sources of ionization increases the probability of detecting decameter recombination lines. Moreover, as the assessments have shown, it may be possible to use these lines to study regions of partially ionized matter which are further away from the hot stars and which are less dense. This class of objects is being studied with the UTR-2 decameter radio telescope as part of a systematic survey of various components of the interplanetary medium in radio recombination lines. So far the most complete information we have is for the nebulae DR 21 and S 140.

DR 21 is part of a large gas and dust complex in Cygnus X. It has been studied carefully in many frequency ranges, both in the continuum and in spectral lines, including recombination lines. In particular, Pankonin et al. (1977) detected in it the high-frequency emission lines of carbon C158 $\alpha$  and C166 $\alpha$ .

Knapp et al. (1976) have reported the detection of C142 $\alpha$  and C166 $\alpha$  near S 140. However, this result, as pointed out by Falgarone (1980), has not been verified by other investigations at higher angular resolution. Nevertheless, studies of this object in the recombination lines of the decameter range are of interest, since the proximity of an emission nebula and a dust cloud in the presence of an infrared source close to their boundary suggests that a zone of ionized carbon may exist. At low electron densities, decameter spectroscopy proves to be more sensitive than high-frequency methods.

**Observations and results.** The methods used to observe the indicated objects were described by Konovalenko (1990); these methods are similar to the ones in the studies of Golyнкин and Konovalenko (1990). Various combinations of north–south and east–west antennas of the UTR-2 radio-telescope were used, operating near 25 MHz (principal quantum numbers of order 640). The measurements were carried out using a correlation spectrometer with a total of 160 spec-

tral channels, making it possible to observe 5 recombination lines simultaneously with an analysis bandwidth at each of about 20 kHz ( $\pm 120 \text{ km/sec}$ ). During processing, the spectra were aligned with one another according to the calculated line frequencies and then averaged. In all cases, the antenna temperature of the Galactic background ( $T_c \sim 5 \cdot 10^4 \text{ K}$ ) was significantly higher than the noise temperature of the equipment. The conditions, modes, and parameters of the observations are given in Table I.

During the measurements various methods were used to enhance the noise immunity and sensitivity of the measurements, and criteria and tests were employed to ensure reliable identification of the weak lines. The use of some of these tests is illustrated by Fig. 1, which shows the C $n\alpha$  absorption lines detected by us, reduced to the Local Standard of Rest for DR 21 [panel 6 in the figure is C166 $\alpha$  from Pankonin et al. (1977)]. Spectrum 2 (integration time  $T = 93 \text{ hr}$ ) was obtained by detuning the receiver 4 kHz relative to spectrum 1 ( $T = 77 \text{ hr}$ ). Spectrum 3 ( $T = 160 \text{ hr}$ ) was measured with an orbital Doppler shift of 1 kHz. Spectrum 4 was obtained by averaging spectra 1–3, while spectrum 5 illustrates the noise level when a wideband noise generator with a temperature equal to the antenna temperature and an integration time of about 300 hr is connected instead of the antenna.

Figure 2 shows the lines detected in the direction of S140. Panel 3 at the top is C166 $\alpha$  from Knapp et al. (1976).

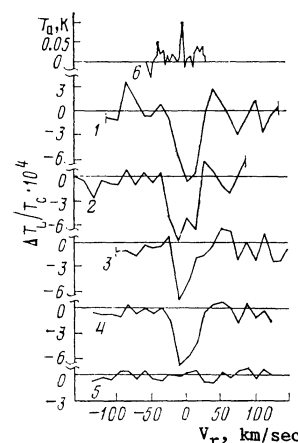


FIG. 1. Carbon recombination lines in the direction of DR 21 at 25 MHz; 1–3) spectra measured with UTR-2 at different times with different frequency shifts; 4) average of spectra 1–3; 5) spectrum of noise signal; 6) C166 $\alpha$  line at 1425 MHz (Pankonin et al., 1977).

TABLE I

| Object | Coordinates<br>$\alpha$ and $\delta$                         | Observation<br>period    | Antenna<br>mode | Re-<br>solu-<br>tion,<br>kHz | Effec-<br>tive in-<br>tegra-<br>tion | 3 $\sigma$ noise<br>level, $(\Delta T_L/T_C) \cdot 10^4$ |
|--------|--------------------------------------------------------------|--------------------------|-----------------|------------------------------|--------------------------------------|----------------------------------------------------------|
| DR-21  | 20 <sup>h</sup> 37 <sup>m</sup> 43 <sup>s</sup><br>42°09'00" | II-III.1987              | (N-S) + (W-E)   | 1                            | 330                                  | 1.5                                                      |
| S140   | 22 <sup>h</sup> 17 <sup>m</sup> 36 <sup>s</sup><br>53°04'00" | VII.1983;<br>II-III.1988 | N-S<br>W-E      | 2<br>2                       | 45<br>104                            | 2<br>1.5                                                 |

Spectrum 1 was measured by us using a north-south antenna with a  $20' \times 12''$  beam, while spectrum 2 was obtained using an east-west antenna with a beam twice as wide in the narrow direction. Clearly, the lines near 25 MHz are very wide — comparable to the analysis bandwidth — which makes it difficult to apply the frequency-shift criterion. Therefore, to increase the reliability of identification, observations with a wider analysis bandwidth (up to 50 kHz) should be carried out.

The parameters of the detected lines for the two objects are given in Table II.

These results illustrate, in addition to the possibility of detecting decameter recombination lines of carbon in the given type of interstellar formations, the attainment of high noise immunity and sensitivity of low-frequency spectral measurements. It should be noted that the observations of DR 21 described here were made in the daytime, during a period when solar activity was low and the state of the ionosphere was satisfactory. Since 1988, however, solar activity has risen sharply, and measurements have been possible essentially only at night.

**Discussion.** So far data are lacking about the spatial structure of the regions producing the detected lines. Consequently, there is some uncertainty about the ratio of solid angles of the telescope beam and the source, making it more difficult to interpret the observations and to construct a detailed model of the objects. Nevertheless, it is our opinion that it is still possible to arrive at a number of important estimates, following from an analysis of the line parameters: intensity, width, radial velocity. Note that the aforementioned uncertainty causes, first of all, some ambiguity in the estimate true intensity of the lines (optical depth), and that it affects to a much lesser extent the estimated width and radial velocity.

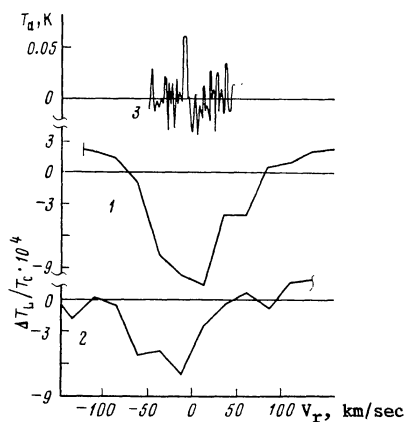


FIG. 2. Carbon recombination lines in the direction of S 140 at 25 MHz: 1) spectrum measured with north-south UTR-2 antenna; 2) the same, with east-west antenna; 3) C166 $\alpha$  line at 1425 MHz (Knapp et al. 1976).

In studies of decameter absorption lines observed against the background of distributed Galactic nonthermal radiation, their observed relative intensity is defined as

$$\left(\frac{\Delta T_L}{T_C}\right)_{\text{obs}} = \frac{\Delta T_L}{T_C} \frac{\Omega_s}{\Omega_a} \frac{T_B}{T_B + T_F} \frac{T_a}{T_a + T_n}, \quad (1)$$

where  $\Delta T_L/T_C$  is the true relative intensity in the line;  $\Omega_s$ ,  $\Omega_a$  are the solid angles of the source and the antenna beam pattern;  $T_B$ ,  $T_F$  are the brightness temperatures of the Galactic background behind the object and in front of it;  $T_a$ ,  $T_n$  are the antenna temperature of the background at the receiver input and the noise temperature of the receiver.

The true intensity in a low-frequency recombination line is

$$\Delta T_L/T_C = -\tau_L = -\tau_L^* b_n \beta_n, \quad (2)$$

where  $\tau_L$  is the optical depth of the cloud in the recombination line;  $\tau_L^* = f(N_e, T_e, S, \Delta\nu_L)$  is the equilibrium optical depth in the recombination line, as given by Shaver (1975);  $N_e$ ,  $T_e$ ,  $S$ ,  $\Delta\nu_L$  are the electron density, electron temperature, longitudinal size of the object, and line width;  $b_n$ ,  $\beta_n$  are nonequilibrium coefficients.

The radial velocity of the lines detected in the direction of DR 21 is close to zero and is in good agreement with the velocity of the high-frequency lines. However, a direct comparison of the high-frequency data with our results is not allowed, since the corresponding lines may well arise in completely different (but perhaps logically related) gaseous regions. Vallee (1987) has studied the given region in the lines C100 $\alpha$  and C125 $\alpha$ . Taking into account the results of Pankonin et al. (1977), the following model producing the high-frequency lines was proposed: electron density  $N_e \sim 300 \text{ cm}^{-3}$ , temperature  $T_e \sim 30 \text{ K}$ , effective size  $S \sim 0.01 \text{ pc}$ . The carbon lines appear in very thin layers adjacent to compact H II regions. Using the relations for the widths of the decameter recombination lines given, for instance, by Konovalenko (1990), it is easy to show that for this electron density, recombination lines cannot be observed at frequencies  $< 30 \text{ MHz}$ .

In order to estimate the parameters of the medium in which the decameter recombination lines originate, we make some assumptions: a) the region is homogeneous, isotropic, relatively compact (less than the narrow dimension of the beam), and located close to DR 21, that is, at a distance of 2.5 kpc; b) as a lower estimate of the electron temperature, we take  $T_e \geq 20 \text{ K}$ , typical of the temperatures of the molecular clouds and C II zones observed at high frequencies; c) the observed line width (3.5 kHz) is primarily collisional, which yields an estimated electron density  $N_e \leq 0.5 \text{ cm}^{-3}$ .

TABLE II

| Object     | $\Delta T_L/T_C \times 10^3$ | $V_{LSR}, \text{ km/sec}$ | $\Delta v_L, \text{ kHz}$ | $\Delta v_L, \text{ km/sec}$ |
|------------|------------------------------|---------------------------|---------------------------|------------------------------|
| DR-21      | $-7 \pm 3$                   | $0 \pm 8$                 | $3.5 \pm 1.0$             | $42 \pm 12$                  |
| S140 (N-S) | $-10 \pm 3$                  | $-6 \pm 17$               | $8 \pm 2$                 | $96 \pm 2'$                  |
| S140 (E-W) | $-5 \pm 2$                   | $-36 \pm 17$              | $8 \pm 2$                 | $96 \pm 24$                  |

The optical depth in the recombination line with  $n \sim 640$  for such a region is

$$\tau_L^* \leq 5 \cdot 10^{-2} S \quad (3)$$

( $S$  in pc). At the given distance, assuming equal dimensions of the region in the line of sight and in the plane of the sky, the angular size is related to the linear size by

$$\theta_s \approx 1.4 S$$

( $\theta_s$  in arcmin and  $S$  in pc), while the solid angle

$$\Omega_s \approx 2 S^2 \text{ arcmin}^2. \quad (4)$$

Now, by substituting relations (2), (3), and (4) into (1), we arrive at an expression for the volume of the region:

$$S^3 \geq - \frac{(\Delta T_L/T_C)_{\text{obs}} \Omega_a}{0.4 b_n \beta_n} \frac{T_B + T_F}{T_B} \frac{T_a + T_n}{T_a} \text{ pc}^3. \quad (5)$$

The effective solid angle of the telescope beam when the signals from the two antennas are stunned approximately  $\Omega_a \approx 10^4 \text{ (arcmin)}^2$ . For  $n \sim 640$ ,  $T_e \sim 20 \text{ K}$ , and  $N_e \sim 0.5 \text{ cm}^{-3}$ , and the product  $b_n \beta_n$  is 0.9 (dielectronic recombination of the carbon ions can be neglected at low temperatures). For a quasihomogeneous distribution of the volume density of the nonthermal radiation,  $T_B/(T_B + T_F) = 0.8$ . The value of  $T_a/(T_a + T_m)$  was found experimentally to be  $\sim 0.8$ . Using the numerical values obtained and the experimental data, we can find from (5) the linear and angular sizes of the region:  $S \geq 5 \text{ pc}$  and  $\theta_s \geq 7'$ . It is clear that the size estimate obtained differs considerably from the size of the region producing the high-frequency recombination lines. The lines detected by us originate in extended and less dense regions of the gas and dust complex in the vicinity of DR 21.

When dielectronlike recombination takes place at  $T_e \approx 50$  to  $100 \text{ K}$ , producing "gain" in the absorption lines,  $b_n \beta_n$  may be significantly greater than unity. However, with a rise in temperature,  $\tau_L^*$  drops sharply, so that, as follows from (5), the lower estimate of the size does not change substantially.

Interestingly enough, the upper limit on the true optical depth in the line for a region with the indicated parameters is paradoxically high (as much as  $10^{-1}$ ). Moreover, these parameter values are by no means unreasonable, the only questionable factor being the attainment of the indicated electron density in a comparatively large volume of cold gas. However, a density of  $0.5 \text{ cm}^{-3}$  is an upper limit, whereas if  $N_e$  decreases, even by an order of magnitude, problems of ensuring an appropriate ionization state practically disappear.

For S 140, the radial velocities of lines measured using different antennas are found to differ, although this may be

due to errors in determining the parameters of such wide lines. Presumably, different regions are being observed, since the fan beams of the antennas used are oriented differently relative to the plane of the Galaxy (the orientation of their axes is the same). For  $l \approx 105^\circ$ , radial velocities from 0 to  $-36 \text{ km/sec}$  are quite typical. If, on the other hand, the lines are produced by a single isotropic region, then most likely it will be less than  $20'$  in size, since the intensity of lines measured with a north-south antenna is twice that obtained with an east-west antenna. The upper limit on the electron density, determined according to the line width, is  $N_e \leq 1 \text{ cm}^{-3}$ . By carrying out an analysis similar to the one for DR 21, we can show that for a distance to S 140 of the order of 1 kpc the lower limits on the linear and angular sizes are  $S \geq 2 \text{ pc}$  and  $\theta_s \geq 7'$ .

**Conclusion.** The assumptions made during the analysis (especially the assumptions concerning homogeneity, isotropy, distance, the lack of multicomponent structure, and the spread in radial velocity within the antenna beam pattern) may not correspond to reality. Nevertheless, the main conclusion following from the studies of DR 21 and S 140 should hold in any case. This conclusion can be summed up as follows: decameter recombination lines may be observed in various components of the interstellar medium, including the vicinity of emission nebulae, and these lines suggest the presence of comparatively large volumes of partly ionized cold gas, even for very low electron densities, while the corresponding model differs significantly from the model producing high-frequency recombination lines of carbon. The proposed method of estimating the linear sizes of regions (more precisely, their volumes), given the existing uncertainties, provides us with useful information almost solely from the fact that decameter recombination absorption lines are detected at all.

It cannot be ruled out that the detected lines originate in nearby regions of the Galaxy, possibly regions of large angular dimensions (for instance, in the local interstellar medium). The lines could then be produced by high-temperature dielectronic recombination in heavy elements. However, the foregoing analysis seems to provide a more natural explanation.

In order to obtain more accurate values of the parameters of the medium and the models, it is important to study the spatial distribution of absorption in the lines (the angular resolution of the UTR-2 radiotelescope may be adequate for this) and also to carry out measurements over a wide range of frequencies.

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Translated by R. Hardin

## Decameter-wave carbon recombination lines in the dust cloud L 1407

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(Submitted July 23, 1990)

*Pis'ma Astron. Zh.* **17**, 23–29 (January 1991)

Recombination lines of highly excited carbon C635 $\alpha$  to C643 $\alpha$  have been detected near the dust cloud L 1407. The intensity of the absorption lines is  $\sim 7 \cdot 10^{-4}$  of the background level, the width of the lines is about  $\sim 1$  kHz, and the radial velocity is of the order of  $\sim 10$  km/sec. The region producing these lines and the absorption in the low-frequency continuum has an electron temperature of less than 20 K and an electron density of less than  $0.1 \text{ cm}^{-3}$ .

**Introduction.** Studies of the lowest-frequency carbon recombination lines, principally in Cas A, have engendered new capabilities for the investigation of a low-density interstellar plasma. Therefore, it would be very interesting to study in detail such lines for different classes of interstellar objects, for instance, dark dust clouds. Zones of ionized carbon may originate in these clouds, either because of the presence in them of young stars of spectral type B or due to the action of external ionization sources. However, although a greater number of high-frequency studies of dark clouds have been carried out, as noted in the review paper of Brown (1980), recombination lines have only been detected in a few. Moreover, Konovalenko (1984) has pointed out that decameter-wave observations may sometimes be preferable, since the corresponding absorption lines turn out to be more intense; a search for such lines has therefore become a timely issue.

Most such objects can only be observed against the diffuse Galactic radio background, rather than a strong compact source. This causes additional technical difficulties in identifying weak recombination lines, and it becomes questionable as to whether such objects are accessible to study, and whether sensible measurements are feasible. Thus it is no accident that so far, except for Cas A, the lowest frequency lines have been detected in a relatively small number of objects by Konovalenko (1984) and Anantharamaiah et al. (1988).

In recent years, the UTR-2 radio telescope has been used for systematic spectroscopic studies of various components of the interstellar medium. In the present paper, we report on a search for decameter-wave carbon recombination lines in the dust cloud L 1407, which has been thoroughly studied in the variable and infrared, and in molecular lines (Snell, 1981). This object is of special interest because, during a study in the continuum at low frequencies by Abramenskov (1985), absorption of the Galactic radio background was recorded at

this location. However, absorption in the continuum cannot provide an unambiguous determination of the nature of the absorbing gas, that is, it cannot establish whether it is an H II region or a weakly ionized low-temperature medium. This problem can be solved via spectroscopic observations in the decameter range, since the corresponding recombination lines cannot originate in hot and comparatively dense H II regions.

**Observations and results.** The studies were carried out with the UTR-2 radiotelescope operating near 25 MHz. The signals from the north–south and west–east antennas were summed, since this maximized the effective aperture ( $150,000 \text{ m}^2$ ) and coverage of the plane at low spatial frequencies. The directional diagram in this operating regime has a complicated form. It has a cruciform cross section with generatrices  $20' \times 12^\circ$  and  $40' \times 12^\circ$  in size. On the principal axis there is a weak  $20' \times 40'$  in width. The telescope was pointed by computer, and it tracked the source over a range of the about  $\pm 4^\circ$  from the meridian (the principal axis was oriented toward the point of maximum absorption in the continuum:  $\alpha = 4^h 26^m 30^s$ ;  $\delta = 54^\circ 17' 0''$ ).

The spectra were measured using two digital correlation spectrometers with 32 and  $4 \times 32$  channels. Thus it was possible to observe simultaneously five recombination lines, the spectra of which were then averaged, so as to increase the sensitivity and noise immunity of the measurements, while at the same time reducing baseline distortion. The line frequencies and the corresponding tuning frequencies of the receivers were selected from the interval of principal quantum numbers  $n = 635$  to 643. The analysis bandwidth around each line was  $\sim 20$  kHz ( $\pm 120$  km/sec), and the resolution was  $\sim 1.0$  kHz (12 km/sec). The measurements were Dicke-switched, with the signal from the output of the radio telescope being compared with the signal from an equivalent noise source.

The studies described here were carried out from 1987 to 1989, with observing runs 5 to 7 days long. Such extended