

A Survey of Radio Recombination Lines from H I Regions and Associated H II Regions

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Summary. Recombination line spectra of fifteen H II regions were observed at 1.4 GHz and/or 1.6 GHz for emission from a partially ionized medium which may be associated with the H II region. Carbon lines were detected toward six of the fifteen H II regions: W 33, M 17, W 40, W 48, W 49A, DR 21. Hydrogen recombination line spectra of DR 21, which cover the frequency range from 8.6 GHz to 1.42 GHz, display unusual line width and radial velocity characteristics which can be explained by a two component model of the H II region(s). The apparently low helium abundance in DR 21 probably results from geometric properties inherent to the structure of the H II region.

Key words: C II region — H I region — H II region — radio recombination lines

Recombination lines of hydrogen, carbon, and heavier elements which originate in a partially ionized medium have previously been observed in the vicinity of several H II regions. The carbon lines are the most common, but this may simply reflect the sensitivity of the observations since the C-lines are usually the strongest. The stars which ionize the H II region are probably also responsible for the partial ionization of the surrounding neutral medium—at least for carbon and the heavier elements such as silicon, sulfur, magnesium, and iron. Although we refer to the partially ionized medium as H I, the neutral hydrogen may be molecular (H_2) in a significant fraction of the volume of these clouds.

The recombination lines from the H I gas have three characteristics which distinguish them from lines from the H II region:

i) The lines from the H I region have a different frequency dependence than lines from the H II region. In particular the lines from the H I region become

stronger relative to the H II lines at lower radio frequencies.

ii) The velocity of the H I region often differs from the velocity of the H II region by a few km s^{-1} . The velocity of the recombination lines from the H I gas usually agrees very well with the velocity of the molecular cloud near the H II region.

iii) The widths of the lines from the H I region are usually significantly smaller than the widths of the H II region lines. These three characteristics are most important for distinguishing between hydrogen lines from the H I region, $Hn\alpha(H I)$, and lines from the H II region, $Hn\alpha(H II)$, since these lines are usually blended.

We surveyed 15 H II regions for recombination line emission from an associated H I medium. We chose a frequency (~ 1400 MHz) where the lines from the H I region should be relatively strong, and we used the 100-m telescope at Effelsberg for sensitivity. Our source list was based on the strength of the continuum temperature of the H II region at 6-cm (Reifenstein et al., 1970). We omitted those H II regions where carbon lines have been unambiguously detected and line parameters have been quoted at more than one frequency. Thus Orion A, NGC 2024, W 3, W 51A, and W 51B were not observed.

The Observations

Observations were made primarily of the 166α spectrum, but because of time limitations on the initial observations and because of the desire to check interesting features in certain 166α spectra, subsequent observations were made at 158α .

166α

The 166α (1425 MHz) observations were made in August 1974. The half power beam width (HPBW) of the 100-m telescope was $8.5'$, and the beam efficiency was 0.7. The receiver was a cooled paramp with a system temperature of ~ 50 K on cold sky. The spectrometer was a 384^* channel autocorrelator. Reference spectra were obtained by switching the receiver against a cold load

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Table 1. Observational Results

1. Source	2. G-number	3. Position		4. Cont. Temp.	5. rms noise	6. Resol.	7. Line	8. T _L	9. V _{LSR}	10. ΔV	Notes
		R.A. (1950.0)		Dec.							
		h	m	s	°	'		(K)	(km s ⁻¹)	(km s ⁻¹)	
M 8	G 6.0–1.2	18 00 38	–24 22.8	–	0.043	2.74	H 166α He 166α	1.00(0.04) 0.09(0.05)	2.0(0.6) 4.7(6.0)	27.4(1.4) 24.7(14.3)	
W 31A	G 10.2–0.4	18 06 26	–20 19.6	–	0.044	2.74	H 166α	0.65(0.03)	13.7(1.1)	48.8(2.9)	
W 31B	G 10.6–0.4	18 07 30	–19 57.7	–	0.025	2.74	H 166α	0.22(0.02)	– 1.9(1.4)	26.4(3.3)	
W 33	G 12.8–0.2	18 11 17	–17 56.9	40	0.019	2.74	H 166α(1) H 166α(2) C 166α	0.56(0.02) 0.19(0.02) 0.08(0.04)	33.6(0.7) 62.6(1.9) 34.4(1.5)	25.9(1.7) 20.2(4.1) 6.8(3.6)	1.
M 17	G 15.1–0.7	18 17 36	–16 12.3	–	0.206	2.85	H 158α He 158α C 158α	9.5 (0.2) 1.0 (0.2) 0.8 (0.3)	16.0(0.4) 18.3(3.9) 15.0(3.3)	41.9(0.9) 30.7(10.2) 14.4(7.8)	1.
M 16	G 17.0+0.8	18 15 54	–13 47.5	–	0.022	2.74	H 166α He 166α	0.72(0.02) 0.05(0.03)	24.7(0.4) 27.7(4.9)	27.1(1.0) 20.9(12.0)	
	G 25.4–0.2	18 35 33	–06 50.2	–	0.034	2.74	H 166α(1) H 166α(2)	0.31(0.03) 0.10(0.03)	63.5(3.0) 111.7(9.5)	40.5(6.6) 38.7(20.6)	
W 40	G 28.8+3.5	18 28 49	–02 07.6	36	0.021	2.74	H 166α He 166α C 166α	0.46(0.02) 0.04(0.02) 0.09(0.05)	– 0.7(0.6) – 3.4(6.8) 6.4(1.5)	26.5(1.4) 21.3(18.0) 6.0(3.8)	
W 43	G 30.8–0.0	18 45 01	–02 00.3	–	0.042	2.74	H 166α He 166α C 166α	1.37(0.05) ~0.1 ~0.1	91.7(0.7) ~ 92 ~ 95	37.5(1.6) – –	1.
W 48	G 35.2–1.8	18 59 15	01 08.3	20	0.017	2.85	H 158α He 158α C 158α	0.26(0.02) 0.04(0.01) 0.17(0.04)	45.2(0.8) 45.7(4.7) 42.9(0.3)	27.6(2.1) 29.4(3.9) 3.1(0.8)	
				20	0.015	2.74	H 166α C 166α	0.21(0.02) 0.14(0.04)	44.1(1.5) 42.4(0.7)	22.9(3.7) 4.5(1.6)	2.
W 49A	G 43.2–0.0	19 07 54	09 01.0	57	0.018	2.74	H 166α(1) H 166α(2) He 166α C 166α(1) C 166α(2)	0.61(0.02) 0.07(0.02) 0.05(0.02) 0.15(0.03) 0.16(0.04)	9.1(0.6) 60.0(6.6) 11.3(3.8) 4.7(1.5) 13.9(1.2)	30.3(1.4) 47.7(17.3) 21.8(10.0) 8.8(3.5) 6.7(2.5)	3.
K 47	G 45.5+0.1	19 12 00	11 04.0	–	0.028	2.74	H 166α	0.21(0.02)	56.4(1.9)	34.6(4.5)	
K 3-50	G 70.3+1.6	19 59 55	33 25.0	16	0.015 0.027	4.72 2.74	H 158α H 166α	0.22(0.02) 0.16(0.03)	– 24.0(1.3) – 25.2(2.1)	23.5(3.1) 23.2(5.0)	
DR 21	G 81.7+0.5	20 37 13	42 09.0	21	0.018	2.85	H 158α C 158α	0.19(0.01) 0.10(0.06)	6.6(1.0) – 3.2(1.3)	30.2(2.6) 4.2(2.8)	
				23	0.018	2.74	H 166α C 166α	0.21(0.02) 0.10(0.05)	6.1(1.0) – 2.9(0.8)	21.2(2.4) 3.2(1.8)	
NGC 7538	G 111.5+0.8	23 11 23	61 13.0	32	0.015	4.72	H 158α	0.40(0.02)	– 60.7(0.8)	30.3(1.9)	

Values in parentheses are 3σ errors. No corrections have been made for instrumental frequency resolution.

1. Single gauss fit to profile with complex structure; parameters should be considered approx.

2. Voigt function

3. Radial velocity was fixed to the given value.

which was balanced to the signal level. The spectral resolution was 1.8 km s^{-1} .

158 α

The 158 α (1650 MHz) observations were made in March 1975. The telescope beam width was $7.8'$, and the beam efficiency was 0.65. Two cooled paramps, with system

temperatures of $\sim 55 \text{ K}$ on cold sky, accepted orthogonal polarizations. A 192 channel autocorrelator was connected to each receiver to provide two independent measurements of the same spectrum simultaneously. Reference spectra were obtained at a position away from any continuum source and were balanced to the on-source noise level. The spectral resolution was 2.9 km s^{-1} .

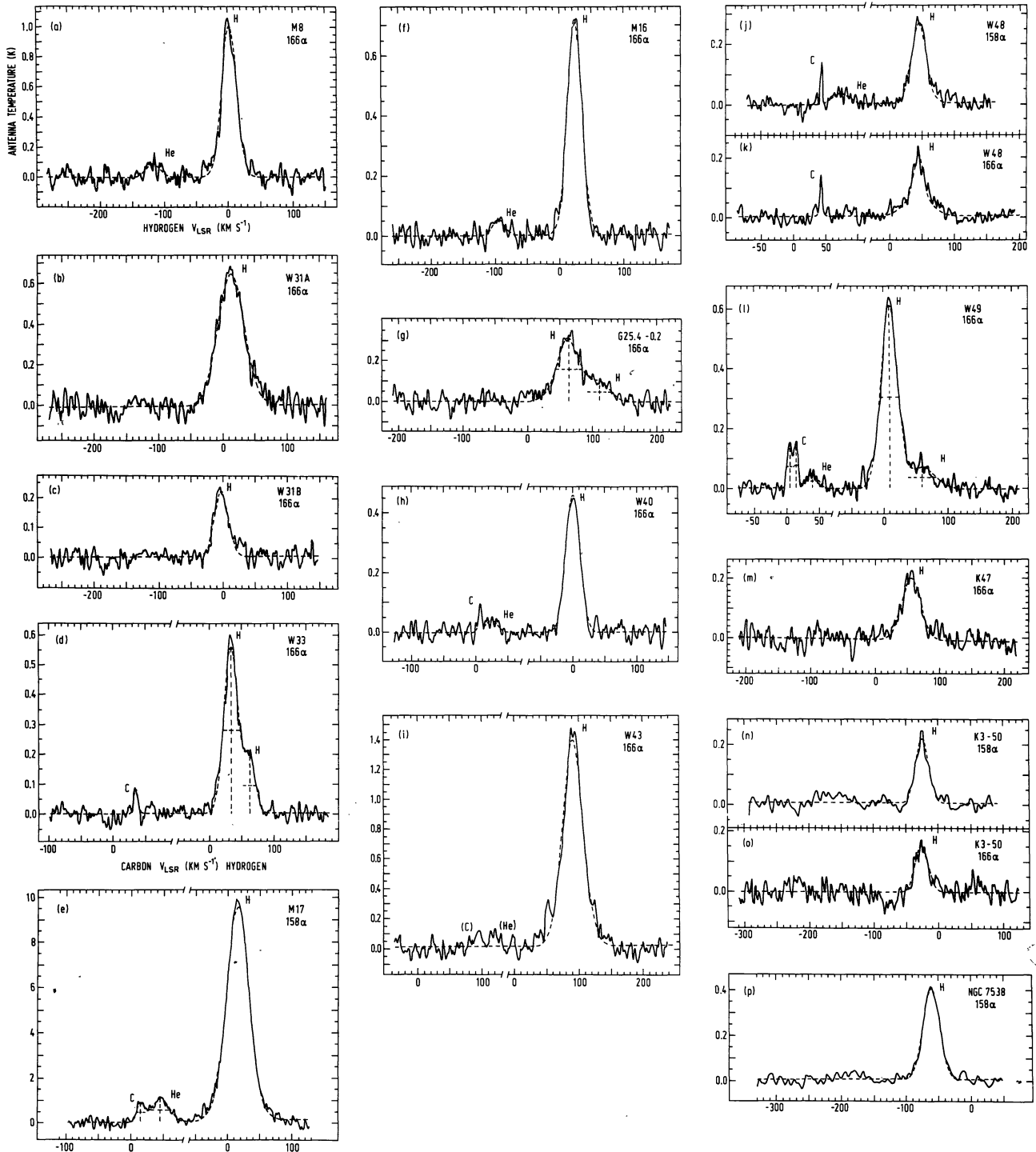


Fig. 1a–p. The 158 α and/or 166 α spectra for the H II regions listed in Table 1, except for DR 21. The spectral resolutions are given in Table 1. The velocity scale with respect to hydrogen is shown. If a carbon line was detected, the velocity scale is divided into two sections with carbon velocities on the left and hydrogen velocities on the right. To convert from hydrogen to carbon velocities add 150 km s⁻¹. The fitted functions are indicated by dashed curves. They are gaussians in all cases except for the H 166 α line from W 48 where a Voigt function was fitted. Where there are blended features, the gaussian characteristics of the individual components are indicated by dashed crosses

The observational results are summarized in Table 1:

1. the common source name, 2. the galactic coordinate number of the source, 3. the observed R.A. and dec., 4. the continuum temperature of the H II region if it was measured, 5. the *rms* noise in the spectrum, 6. the

spectral resolution; many of the spectra were Hanning smoothed, 7. the specific line observed, 8. the peak line temperature, 9. the velocity of the line with respect to the local standard of rest, 10. the full width of the line at half maximum intensity. Polynomial baselines (usually

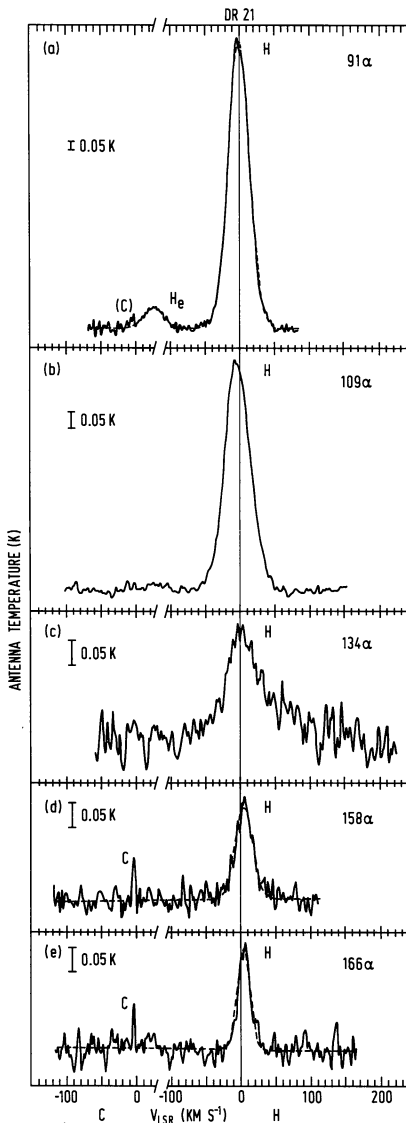


Fig. 2a-e. Five recombination line spectra of DR 21 which were obtained with the 100-m telescope. The spectral resolutions are given in Table 2. The velocity scale is divided into carbon velocities on the left and hydrogen velocities on the right

parabolas) were removed from the observed spectra. Then the line parameters were derived by fitting gaussians to the observed profiles. In most cases the fitting was limited to a single gaussian. The spectra for all of the sources except DR 21 are shown in Figure 1. The 158 α and 166 α spectra of DR 21 are shown together with additional data in Figure 2. The fitted functions which produced the line parameters listed in Table 1 are shown as dashed lines superimposed on the spectra in the figures.

Recombination Lines from H I Regions-Carbon

Our observations have added W 33, W 40, W 48 and DR 21 to the list of H II regions which have associated C II regions. Previous reports of carbon toward W 43 (C 110 α , Davies, 1971) and K3-50 (C94 α , Chaisson and Goad,

1972) were not confirmed by our observations. We did not detect carbon toward K3-50 (cf. the discussion in the appendix), and the 2.5 σ feature in the W 43 spectrum (Fig. 1i) may not be real.

M 17

Carbon lines have previously been detected toward M 17: C 168 α (Simpson, 1970), C 167 α (Menon, 1970), C 157 α (Cesarsky, 1971), C 109 α and C 85 α (Churchwell, 1970), and C 76 α (Gull and Balick, 1974). The higher frequency C-lines, C 76 α and C 85 α , are consistently narrower ($\Delta V \sim 6 \text{ km s}^{-1}$), than the lower frequency lines, C 157 α and C 158 α ($\Delta V \sim 16 \text{ km s}^{-1}$). This probably indicates that there are multiple components in the low frequency profiles which have not been resolved in space and/or in frequency. There are two velocity components in the molecular cloud (~ 19 and $\sim 24 \text{ km s}^{-1}$, Lada and Chaisson, 1975), and Gull and Balick (1974) observed two distinct velocity fields in the H II gas (~ 10 and $\sim 27 \text{ km s}^{-1}$).

W 49A.

A single gaussian did not fit the observed C 166 α profile of W 49A, so we fitted two gaussian components (Fig. 1l). Scoville and Solomon (1973) have commented on the presence of two molecular clouds associated with W 49A which have velocities of ~ 3 and $\sim 14 \text{ km s}^{-1}$. There may be a C II region associated with each of these neutral clouds. There is supporting evidence for two carbon components. The width of the total C 166 α profile ($\sim 16 \text{ km s}^{-1}$) is much larger than the widths of $\sim 6 \text{ km s}^{-1}$ which are typical for carbon lines. Although the velocity of the centroid of the profile ($\sim 9 \text{ km s}^{-1}$) agrees with the velocity of the H II region, it does not agree with molecular line velocities (cf. Scoville and Solomon, 1973; T. Wilson, 1972), which is unusual for carbon lines. Chaisson and Ball (1971) reported C 85 α emission toward W 49A, and the velocity (4.4 km s^{-1}) and width (6.0 km s^{-1}) agree with the velocity and width of the lower velocity component in our C 166 α profile. Thus for W 49A, as well as M 17, there are indications of at least two C II components in the lower frequency profiles. Since the C 166 α emission is relatively strong, it is interesting that the C II regions associated with W 49A were not detected at 248 α (Pankonin, Parrish, and Terzian, 1974) or at 274 α (Parrish, Conklin, and Pankonin, 1976). The failure to detect the lines at decimeter-wavelengths indicates either that these C II regions are not geometrically placed in a way to amplify strong background continuum radiation or that quantum levels $n=248$ and $n=274$ have LTE populations, or both.

General Comments

The carbon lines toward W 48 and DR 21 were not resolved in frequency with the present observations. A "typical" width for a carbon line from a C II region which

is associated with an H II region is $\sim 6 \text{ km s}^{-1}$, but the widths range from $\lesssim 3 \text{ km s}^{-1}$ for W 48 and DR 21 to $\sim 15 \text{ km s}^{-1}$ for M 17, W 49A, and W 51A (cf. Pankonin et al., 1974, for W 51A). As discussed above, the wide carbon lines toward M 17 and W 49A may be explained by multiple components which are not resolved. Without more details on the geometry and size of the C II regions and on the frequency dependence of the line emission, further analysis into the physical characteristics of the C II regions observed in this survey is premature. Available measurements of the spectra of these sources at higher frequencies, e.g. DR 21 (Fig. 2), are generally not sensitive enough to determine the frequency dependence of the carbon line emission.

An examination of our results for the general properties of C II regions which are associated with H II region-molecular cloud complexes revealed: i) The association between C II regions and H II regions appears to be relatively common, and the correlation may become better with better observational sensitivity. ii) The observed intensity of the carbon lines, and hence the detectability, is not a function of the observed continuum temperature of the H II region, as might be expected if stimulated emission were dominating the line formation process. iii) The apparent C-line strength is not a function of the excitation parameter of the H II region (as deduced by Reifenstein et al., 1970) which should be related to the number of carbon ionizing photons. iv) The apparent intensity of the carbon emission is not a function of the distance of the source from the observer as would be the case if all of the C II regions were approximately the same size. W 49A is one of the most distant galactic H II regions, and it has a relatively strong carbon line. v) The apparent C-line strength is also not a function of the distance of the source from the galactic center as might be expected if there were a gradient in the atomic carbon abundance. vi) There are usually low excitation lines of H_2CO , OH, CO and CH at several different velocities in the line of sight to a given H II region (cf. T. L. Wilson, 1972; W. J. Wilson et al., 1974; Rydbeck et al., 1975). The velocity of the carbon line correlates very well with the velocity of the molecular cloud which is associated with the H II region. vii) For a specific line of sight, the molecular line from the neutral cloud in the vicinity of the H II region is usually stronger than the lines at other velocities, but the apparent C-line intensity is not correlated with the absolute strength of the molecular lines.

The observable characteristics of a C II region no doubt depend on a combination of: the spectral type of the exciting star(s); the relative location of the H II region, the C II region, and the observer; the distance of the source from the observer; the abundance of atomic carbon; and the density of the neutral cloud. However, the number of variables in the combination is sufficiently large that in general it appears to be impossible to predict the observable characteristics of a C II region

from the observed characteristics of an H II region or a molecular cloud.

In no case did we detect hydrogen emission which we could attribute to a cold, partially ionized medium. Apparently a restricted set of conditions must be met before $\text{H}\alpha$ (H I) emission is produced which is strong enough to be readily observed.

Recombination Lines from H II Regions

Hydrogen

High resolution continuum maps of the H II regions in our source list (e.g. Goss and Shaver, 1970, or the 6-cm map of the galactic plane with a $2.6'$ beam by Altenhoff et al., 1976) show that most of them have multiple components, each of which could contribute to the observed H 166 α and/or H 158 α profiles. For most of the sources we do not know which components, if any, are non-thermal, and we do not have sufficient information about the velocities of the individual thermal components to attempt a decomposition of the observed profiles which are not simple analytic functions, either gaussian or Voigt (pressure broadened profiles).

W 31A and W 31B are probably not physically related. The 6-cm continuum map (Altenhoff et al., 1976) shows no relationship between the two. This is supported by the obvious differences in the H 166 α profiles of the two sources (Figs. 1b and 1c). The H 166 α line of W 31A is unusually wide ($\Delta V \sim 48 \text{ km s}^{-1}$), but there are at least three discrete continuum components in our $8.5'$ beam.

M 17 and W 43 both have very complex continuum structures, and the H II gas of each has at least two velocity fields (Gull and Balick, 1974; Gardner and Thomasson, 1975). However, two gaussians would not adequately fit the hydrogen profiles which we obtained (Figs. 1e and 1i). The reason is probably pressure broadening of the line emission from at least one of the velocity components in each source.

W 33 was mapped in the H 134 α line at 11-cm by Gardner et al. (1975). The complex shape of the line profile was interpreted as emission from two H II regions with velocities of 32 km s^{-1} and 58 km s^{-1} . We obtain similar velocities with a two gaussian decomposition of the H 166 α profile (Fig. 1d) although a gaussian does not fit the lower velocity component very well.

The H 166 α profile of G 25.4-0.2 has been decomposed into two gaussians (Fig. 1g). The velocities suggest one H II region at a kinematic distance of 5 or 13 kpc (64 km s^{-1}) and a second H II region at a distance of 9 kpc (112 km s^{-1}). The 6-cm continuum map (Altenhoff et al.) shows at least four discrete sources which could be contributing to the observed H 166 α emission although one, G 25.3-0.1, is nonthermal (Dulk and Slee, 1975).

The H II region W 49A has a velocity of $\sim 10 \text{ km s}^{-1}$. A second hydrogen feature at 60 km s^{-1} , which was first detected by Parrish (1975), is present in the H 166 α

Table 2. H α observations of DR 21 with the 100-m telescope

Freq. (GHz)	HPBW (arc min)	Resolution (km s ⁻¹)	Line	T _L (K)	V _{LSR} (km s ⁻¹)	ΔV (km s ⁻¹)	Predicted ("compact" component)	
							ΔV (km s ⁻¹)	τ_c
8.6	1.5	2.2	H 91 α	1.8	-5	36	36	0.2
5.1	2.6	3.1	H 109 α	0.7	-5	43	38	0.5
2.7	4.8	2.9	H 134 α	0.2	0	>45	66	1.9
1.65	7.8	2.9	H 158 α	0.2	7	30	189	5.2
1.42	8.5	2.7	H 166 α	0.2	6	21	270	7.2

Table 3. Characteristics of "compact" and "envelope" components of DR 21

Component	T _e (K)	T _D (K)	E.M. (cm ⁻⁶ pc)	n _e (cm ⁻³)	V _{LSR} (km s ⁻¹)
"Compact"	8000	2.7 10 ⁴	3 10 ⁷	1.5 10 ⁴	-5
"Envelope"	8000	10 ⁴	10 ⁵	<10 ³	+6.5

profile (Fig. 1l). The 60 km s⁻¹ emission probably originates in a low brightness H II region which is located between the observer and W 49A (Pankonin and Downes, 1976).

DR 21. Recombination line spectra of DR 21 have been observed with the 100-m telescope at five different transitions covering the frequency range 8.6 GHz to 1.42 GHz: 91 α (Pankonin, unpublished), 109 α (Churchwell, private comm.), 134 α (Thomasson, unpublished), 158 α and 166 α (this paper). These observations are summarized in Table 2, and the spectra are shown in Figure 2. Two features should be noted about this series of spectra: i) the velocity of the peak of the line shifts from negative values at the high frequencies (H 91 α and H 109 α) through zero (H 134 α) to positive values at the lower frequencies (H 158 α and H 166 α). ii) The hydrogen profile becomes broader from H 91 α to H 109 α to H 134 α , and then it becomes narrower from H 134 α to H 158 α to H 166 α .

The recombination line characteristics of DR 21 can be explained by a simple model. Continuum observations have shown the existence of several compact H II regions in conjunction with more tenuous H II gas (Ryle and Downes, 1967; Harris, 1973). Single dish observations smooth over the details of the fine structure. Therefore, we have considered a model for the H II region of one "compact" component and one "envelope" component. The electron temperature, emission measure, and electron density of each component are given in Table 3. The electron temperature deduced by Harris (1973) was adopted, and it is assumed to be constant throughout both components. The uncertainty in the temperature is large (± 2000 K), but the method of deriving an approximate value from the line to continuum intensity ratio is unreliable here because of the

complex structure of the source. The emission measure and electron density listed for the "compact" component are averages of these values for the six components given by Harris (1973); in the average the individual values are weighted by the contribution of each component to the total flux. The "envelope" has the characteristics of component C of Ryle and Downes (1967), and this component was not detected by Harris (1973). The Doppler temperature, T_D, and the velocity of the "compact" component (Table 3) were derived from the H 91 α line; while the H 166 α line was used to obtain the Doppler temperature and the velocity of the "envelope". The gaussian half power widths of the "compact" and "envelope" components are $\sim 20''$ and $\gtrsim 3''$ respectively.

The H 91 α profile (Fig. 2a) is dominated by emission from the "compact" component; the "envelope" should contribute <15% of the observed emission. (The H 91 α profile is discussed in more detail in the appendix.) As the frequency decreases from H 91 α , two factors suppress the peak intensity of the line emission from the "compact" H II region: i) pressure broadening redistributes the energy from the center of the line into the line wings, and ii) the "compact" H II region becomes optically thick in the continuum. From the properties of the "compact" component which are given in Table 3, we estimated the line width and continuum optical depth at the observed frequencies [cf. Brocklehurst and Seaton, 1972, Eqs. (4.7) and (4.8) for the line width and Eqs. (2.5) and (2.9) for the optical depth]. The results are listed in the last two columns of Table 2. The predicted line widths deviate significantly from the measured values only for the lower frequency lines (H 158 α and H 166 α). The width of the H 134 α line could not be accurately measured because of the poor signal to noise. The "compact" component contributes most of the emission seen at H 109 α and H 134 α . (The interferometer observations of H 109 α by Wellington et al., 1976, sample only the characteristics of the "compact" H II.) Neither pressure broadening nor opacity are affecting the line emission from the "envelope". The H 158 α and H 166 α profiles are dominated by emission from the tenuous H II gas, and the emission from the H II clumps has essentially disappeared. Our simplified model of DR 21 also predicts line tempera-

tures which approximate the measured values, but the details of the source structure are not known well enough to justify a more accurate model. We emphasize that we do not know the relationship between the compact and tenuous H II regions. The five spectra in Figure 2 were not obtained with constant beam sizes; hence the observations did not sample the same region of the sky. Also the “compact” and “envelope” components may simply lie along the same line of sight, with no physical association.

Thus, we can explain the velocity shift and the unusual behaviour of the line widths from DR 21 by a simple model of two distinctly different H II components. DR 21 is not the only example of these line characteristics. Recombination line spectra of W 49A exhibit similar qualities; Pankonin et al. (1974) noted that decimeter-wavelength lines (H 221 α and H 248 α) were significantly narrower than higher frequency lines (e.g. H 166 α and H 109 α). However for W 49A the whole phenomenon occurs at a lower frequency than for DR 21. Furthermore, the “compact” and “envelope” components of W 49A have nearly the same velocity; no velocity shift is seen between H 248 α and H 166 α .

Helium

Helium recombination lines were detected at 158 α or 166 α in M 8, M 17, M 16, W 40, W 48, W 49A and possibly W 43. The apparent He⁺/H⁺ ratio was ~ 6 to 7% in all sources except W 48, and this is less than or equal to the apparent ionized helium abundances for these sources which were derived from higher frequency observations (Churchwell et al., 1974). The 158 α observations of W 48 indicate an apparent He⁺/H⁺ ratio of 16%. (At 166 α , He⁺/H⁺ is $< 20\%$). The apparent abundance is 8% at 109 α (L. F. Smith, private comm.). There is no ready explanation for the high value at 158 α , except that the signal to noise is low, making the measurement very uncertain. The apparent He⁺/H⁺ abundance ratio of DR 21 is $7 \pm 2\%$ at 91 α , but $\lesssim 4\%$ at 109 α (the upper limits for He⁺/H⁺ at 158 α and 166 α are $< 20\%$ and are therefore not significant).

The Interpretation of the Apparent Abundance of Ionized Helium

The variation in the apparent helium abundance with frequency and/or telescope beam size has been the subject of debate recently and two explanations are extant: geometric effects which are internal to the H II region (Churchwell et al., 1974), or line emission which is external to the H II region (Brown and Gomez-Gonzalez, 1975, hereafter BG). Both explanations have been applied to the apparently low helium abundance in the galactic center, particularly Sgr B2 (Brown and Lockman, 1975; Mezger and Smith, 1976; Smith and Mezger, 1976). Churchwell et al. (1974) and Mezger and

Smith (1976) develop the hypothesis that dust in the H II region selectively absorbs photons which are capable of ionizing helium, and the He II zone is smaller than the H II zone. If the He II zone is also smaller than the telescope beam, the beam will dilute the He-line emission more than the H-line emission. Because of these geometric effects the apparent helium abundance will vary with the telescope beam size. BG examined a specific example of the general phenomenon of line emission from a partially ionized medium in the vicinity of an H II region, which we have referred to as H α (H I) emission. This phenomenon was first detected experimentally by Ball et al. (1970) toward NGC 2024, and that source is currently the only unambiguous example (cf. the discussion in the appendix and Pankonin et al., 1976). In the BG model, the helium and hydrogen Ström-gren spheres coincide, but hydrogen line emission from a cold, partially ionized cloud is superimposed on the hydrogen line radiation from the H II region and alters the apparent ionized helium abundance.

General Description of the External Emission Model

The geometric model is conceptually simple and the observational consequences are clear, but this is not the case for the external emission model. We briefly summarize some of the most important aspects of the external emission model because we believe certain of the concepts discussed by BG may be misinterpreted.

The external emission model requires the presence of a partially ionized H I region in the vicinity of the H II region. Thus, it is relevant in the context of our survey. The geometry which was specifically treated by BG involved a foreground layer of cold, partially ionized gas and a background H II region, in the line of sight; stimulated emission from the H I region produces the most dramatic effects. This model was first examined by Dupree and Goldberg (1969), except they did not consider the observed characteristics of superimposed line emission; i.e. line emission from the background H II region. BG illustrated the consequences of superimposed emission, especially for the situation where there is no discernible difference in the velocities of the H I and H II regions. BG considered only stimulated line emission from the H I region; they omitted the spontaneous emission term.

The quantitative effects of the external emission model depend on the details of the source structure and the variations are practically infinite. Nevertheless, the most important concepts can be summarized qualitatively as:

i) The line radiation seen by an observer is a superposition of line emission from the H II region and line emission from the H I region. If the H I region is optically thin in the line, then the superposition is linear. If the H II and H I regions have significantly different velocities, there is no problem separating the line emission. For

NGC 2024, it is possible to deconvolve the superimposed line radiation.

ii) At radio wavelengths, the continuum radiation from an H II region completely dominates over the recombination line emission. Thus, it is primarily the continuum radiation from the background source which is being amplified in the H I region; this is manifested in an enhanced H-line which originates in the H I region. As the radiation passes through the cold, partially ionized gas, the profiles of the lines (H and He) which originated in the H II region are not altered, and $Hn\alpha$ (H II) is not preferentially enhanced over $Hen\alpha$ (H II).

The consequences of the model examined by BG are:

i) As frequency decreases, e.g. from 8.6 GHz (91 α), the line emission from the H II region (H and He) is suppressed by pressure broadening and by the opacity of the continuum within the H II region.

ii) Line emission, at nearly the same velocity, which originates in the H I region becomes stronger at lower frequencies.

iii) At high frequencies where the line emission from the H I region can be neglected, the *apparent* helium abundance will be that of the H II region. At low frequencies where the line emission from the H II region has effectively disappeared, the *apparent* helium abundance will be that of the H I region. Thus, the *apparent* helium abundance will be frequency dependent.

The above discussion also applies if one simply replaces the foreground, partially ionized gas with a low density H II region in which helium is not ionized. This model is a geometric explanation of the measured helium abundance with some aspects of the external emission model. However, references to external and internal effects become confused because the model consists entirely of H II gas. The continuum from the background, high density H II region will be amplified in the lower density H II region (cf. Brocklehurst and Seaton, 1972, for a more complete treatment of this model). However, the amplification in a low density H II region is not as great as the amplification in a cold partially ionized medium, and this is the principle difference between the two situations.

Application to the Observational Results

Since we have no evidence for hydrogen emission from a cold, partially ionized cloud, our 158 α and 166 α observations of the ionized helium abundances are probably explained by geometric effects. The low frequency recombination lines are weighted to the lower electron densities of the H II regions. If the helium is not ionized in this low density structure, the ionized helium abundance may appear to be less in lower frequency observations.

DR 21. The 109 α and 91 α transitions of DR 21 should be weighted to the high density structure in the H II region; what we termed the "compact" component. The observations do not support the external emission

Table 4. The apparent ionized helium abundance in DR 21

Freq. (GHz)	Transition	HPBW (arc min)	Apparent ionized helium abundance (%)	Ref.
14.7	76 α	2.2	5	1.
10.5	85 α	2.8	4.9 ± 2.8	2.
8.6	91 α	1.5	7 ± 2	3.
5.1	109 α	2.6	$\lesssim 4$	3.

References: 1. Gull and Balick (1974); 2. Churchwell et al. (1974); 3. this paper (data from Pankonin, unpublished, and Churchwell, priv. comm.).

model for explaining the variation in the measured helium abundance at high frequencies. The carbon lines at 158 α and 166 α indicate the presence of a partially ionized medium with a velocity of $\sim -3 \text{ km s}^{-1}$. However, there is no convincing evidence for $Hn\alpha$ (H I) emission; the hydrogen emission at -3 km s^{-1} becomes weaker with decreasing frequency, while $Hn\alpha$ (H I) emission (or emission from a low density H II region) should become stronger at the lower frequencies. The origin of the H 158 α and H 166 α lines at $+6.5 \text{ km s}^{-1}$ is of no consequence to the measured helium abundances at 109 α and 91 α ; the influence of this emission, at an offset velocity, was considered, with no change in the results.

We believe that geometric effects within the H II region (with a velocity of $\sim -5 \text{ km s}^{-1}$) are the most probable explanation of the high frequency measurements of helium in DR 21. In addition to the observations reported in this paper, Gull and Balick (1974) observed helium at 76 α and Churchwell et al. (1974) measured helium at 85 α (the value in table 2 of Churchwell et al. is for 85 α and not 109 α as is listed, Churchwell, priv. comm.). The high frequency measurements of helium in DR 21 are summarized in Table 4. The observation with the smallest telescope beam, which is not the highest frequency, yields the largest apparent helium abundance. This would support a simple geometric explanation except for one major difficulty. In order for this model to explain the variation in the helium abundance between 91 α and 109 α , which are the only significantly different results in Table 4, the H II region must have a gaussian half power width of $> 60''$. This lower limit is a factor of three larger than the half power width of the high density ("compact") H II gas which was deduced from interferometer measurements of DR 21 (Harris, 1973, and references therein). What we have termed the "compact" component of DR 21 is actually composed of four clumps superimposed on (or embedded in) two envelopes (Harris, 1973). If the ionized helium were confined to one or more of the clumps and those clumps were embedded in or behind the envelopes, then the helium recombination line radiation would be attenuated as it passes through the relatively high density envelopes (free-free absorption); the attenuation in-

creases with decreasing frequency. The hydrogen line emission, on the other hand, would include the additional contribution from the envelopes. Thus, the measured ionized helium abundance would be frequency dependent, although the internal structure (geometry) of the H II region(s) would be responsible. This can explain the measured difference in He^+/H^+ between 109 α and 91 α .

Appendix

It is instructive to examine the H 91 α profile of DR 21 (Fig. 2a) in some detail. We fitted a single gaussian to the observed profile, and the result is shown in Figure A1(a). The residuals of the fit, which are shown below the fitted function in the figure, indicate that a second component is present. Therefore we fitted two gaussians simultaneously to the observed profile. That result is shown in Figure A1(b), and the residuals indicate that a good fit was achieved.

We would ascribe the dominant gaussian in this two gaussian decomposition to emission from the H II region, i.e. H 91 α (H II). The line velocity is -0.5 km s^{-1} , and the line width is 37 km s^{-1} . The decomposition also produced a small line which has a velocity of -7.6 km s^{-1} and a width of 11 km s^{-1} . The width is too small for emission from an H II region. Since there are precedents for narrow hydrogen lines which originate in cold, partially ionized gas in the vicinity of H II regions (e.g. NGC 2024, Ball et al., 1970), it could be claimed that DR 21 is another example, i.e. H 91 α (H I). We should note that although it is necessary to provide the fitting routine with initial guesses for the parameters of the two gaussians, the results are not critically dependent on the initial values: We varied the initial guesses, and the fitting routine produced the same solution.

The apparent presence of H 91 α (H I) emission in DR 21 is not supported by the other recombination line spectra. There is no indication of H $n\alpha$ (H I) emission at lower frequencies, especially 158 α and 166 α , where the H $n\alpha$ (H I) should be stronger and where we do detect carbon lines. Also the molecular velocities ($\sim -3 \text{ km s}^{-1}$, cf. T. Wilson, 1972) do not agree with the velocity of the H 91 α (H I) line, although the uncertainty in the hydrogen velocity is large ($\pm 2 \text{ km s}^{-1}$).

The basic assumption in this analysis is that the the observed profile or its constituent parts have gaussian shapes. The H 91 α profile is asymmetric. (H 109 α is also asymmetric, but pressure broadening complicates the analysis of this profile.) H 91 α is dominated by emission from the compact H II region(s), but the "envelope" will make a small contribution at an offset velocity. A two gaussian fit to the H 91 α profile, with the velocity and width of the "envelope" line fixed, cannot account for the high velocity wing of the observed profile. On the other hand small systematic motions, e.g. rotation (Wellington et al., 1976), in the compact components

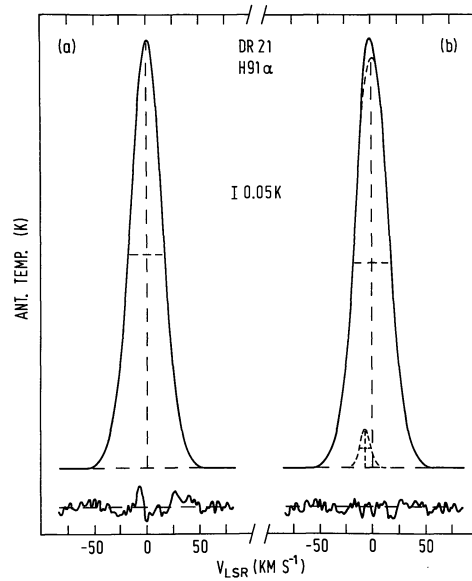


Fig. A1 a and b. Gaussian fits to the H 91 α profile of DR 21 (Fig. 2a). The solid lines show the fitted function. The characteristics of the gaussians are indicated by the dashed lines. The residuals of the data minus the fit are shown below the fitted functions. (a) One gaussian fitted to the original profile. (b) Two gaussians fitted to the original profile

can alone account for the slightly asymmetric profile. Therefore, the assumption of gaussian shaped profiles may be wrong.

C 94 α and H 94 α (H I) were reported toward K3-50 (Chaisson and Goad, 1972), but there is no indication of carbon or H $n\alpha$ (H I) in our 158 α or 166 α spectra where these lines should be stronger. Both C 94 α and H 94 α (H I) resulted from decompositions of asymmetric profiles which were dominated by emission from the H II region; C 94 α was blended with H 148 δ (H II). Thus just as in DR 21, small systematic motions within the H II region of K3-50 may produce the observed profiles rather than a blend of C 94 α and H 148 δ (H II) or of H 94 α (H I) and H 94 α (H II).

Chaisson and Lada (1974) have shown that if multiple gaussians are blended, then one must fit all of the component gaussians simultaneously in order to obtain the correct parameters of the lines. From our experiences with DR 21 and the reported sources of H $n\alpha$ (H I) emission, we conclude that one must be suspicious of the basic assumption that the line profiles have gaussian (or Voigt) shapes. A series of spectra covering a wide frequency range may be required before the source structure becomes clear.

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