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H166α EMISSION FROM LOW-DENSITY GAS ASSOCIATED WITH SOUTHERN H II REGIONS

I.N. Azcárate,[1] J.C. Cersosimo[1], and F.R. Colomb[1]

Instituto Argentino de Radioastronomía
Argentina

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RESUMEN

Se han realizado observaciones en la línea de recombinación H166α y el continuo en 1.4 GHz, del gas ionizado extendido asociado a las siguientes regiones H II: NGC 6334, RCW 97, G 316.8–0.1, NGC 3603, RCW 116 and RCW 131. Se obtuvieron de las observaciones temperaturas electrónicas y otros parámetros físicos. Los mismos se han comparado con resultados de observaciones de líneas de recombinación en más alta frecuencia. En general, las regiones H II relativamente extendidas presentan una región central pequeña y de alta densidad y una envoltura extendida de baja densidad.

ABSTRACT

H166α line and 1.4 GHz continuum observations have been made of the extended ionized gas associated with the following H II regions: NGC 6334, RCW 97, RCW 116, G 316.8–0.1, NGC 3603, and RCW 131. Electron temperatures and other physical parameters were obtained from the observations. Comparisons have been made with results from higher frequency radio recombination line observations. In general the H II regions present a small and compact central region and an extended envelope of low density.

Key words: **NEBULAE-H II REGIONS – RADIO LINES-RECOMBINATION**

I. INTRODUCTION

The purpose of this paper is to study the extended and ionized gas associated with NGC 6334, RCW 97, RCW 116, NGC 3603, G 316.8–0.1, and RCW 131.

Let us consider first NGC 6334, This region has been observed previously in H109α (Wilson *et al.* 1970), H76α (Mc Gee and Newton 1981), CO in emission (Gillespie *et al.* 1977), H_2CO in absorption (Whiteoak and Gardner 1974), and OH (Caswell and Robinson 1974). Molecular line velocities range from –5 to –6.5 km s^{-1}. Radio recombination line velocities (LSR)[2] range from –3.2 to –6.5 km s^{-1}. Some optical observations (Hα, [N II] and [S II] lines) appear to indicate the presence of large and unusual motions within some parts of the nebula (Meaburn and White 1982).

RCW 97, region centered at galactic coordinates $\ell = 327^\circ.3$, $b = -0^\circ.5$, has been observed in H109α (Wilson *et al.* 1970), H76α (Mc Gee and Newton 1981) and in molecular lines of H_2CO, OH and CO. Observations of CO (J → 0) were made by Gillespie *et al.* (1977). H_2CO was observed in absorption by Whiteoak and Gardner (1974). OH was observed in absorption by Caswell and Robinson (1974).

Molecular line velocities are in general $\simeq -49$ km s^{-1}, in good agreement with recombination line velocities. RCW 116 was observed previously in H109α (Wilson *et al.* 1970), and molecular lines, like H_2CO in absorption (Whiteoak and Gardner 1974). The velocity from H109α is –14.6 km s^{-1}. Molecular line velocities range from –12 to –13 km s^{-1}. NGC 3603, with center at galactic coordinates $\ell = 291^\circ.6$, $b = -0.5$, has been observed in H109α (Wilson *et al.* 1970), H76α, (Mc Gee and Newton 1981), and H_2CO in absorption (Whiteoak and Gardner 1974), OH (Caswell and Robinson 1974). The H109α velocity is = 9.4 km s^{-1} while molecular lines velocities range from 3 to 12 km s^{-1}.

G 316.8–0.1 was observed previously in H109α, H76α, and molecular lines like H_2CO, CO, OH. The references for recombination lines and molecular lines are the same as those given for the previous regions. Molecular velocities are in general $\simeq -38$ km s^{-1}, in good agreement with recombination line velocities. RCW 131, (G 353.2+0.9) has been observed in the H109α and H76α lines, CO (Gillespie *et al.* 1977), H_2CO (Whiteoak and Gardner 1974). Molecular line velocities are in the range from –3.6 to –7 km s^{-1}. Recombination line velocities are $\simeq -4$ km s^{-1}.

We will describe in the next section observations

1. Member of the Carrera del Investigador Científico y Tecnológico del Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) de Argentina.

2. Throughout this paper, all velocities are referred to the LSR.

carried out on the H 166α line and 1.4 GHz continuum, of the extended ionized gas associated to the six nebulae.

II. OBSERVATIONS

a) *The H166α Line*

The observations were made with the 30 meter-diameter antenna of the Instituto Argentino de Radioastronomía. The noise temperature of the system was about 85 K for a cold sky background and the antenna beam was 34 arcmin at 1420 MHz. The frequency-switching technique was used for the observations. A filter bank of 112 filters each of 10 kHz width gave a velocity resolution of 2 km s^{-1}.

Nine positions were observed for each H II region at a separation of 0°.5. The total integration time was about 3-4 hours for each position. This resulted in an "rms" noise of 0.02 K. The final profiles were obtained by removing the instrumental baselines using in most cases a second order polynomial.

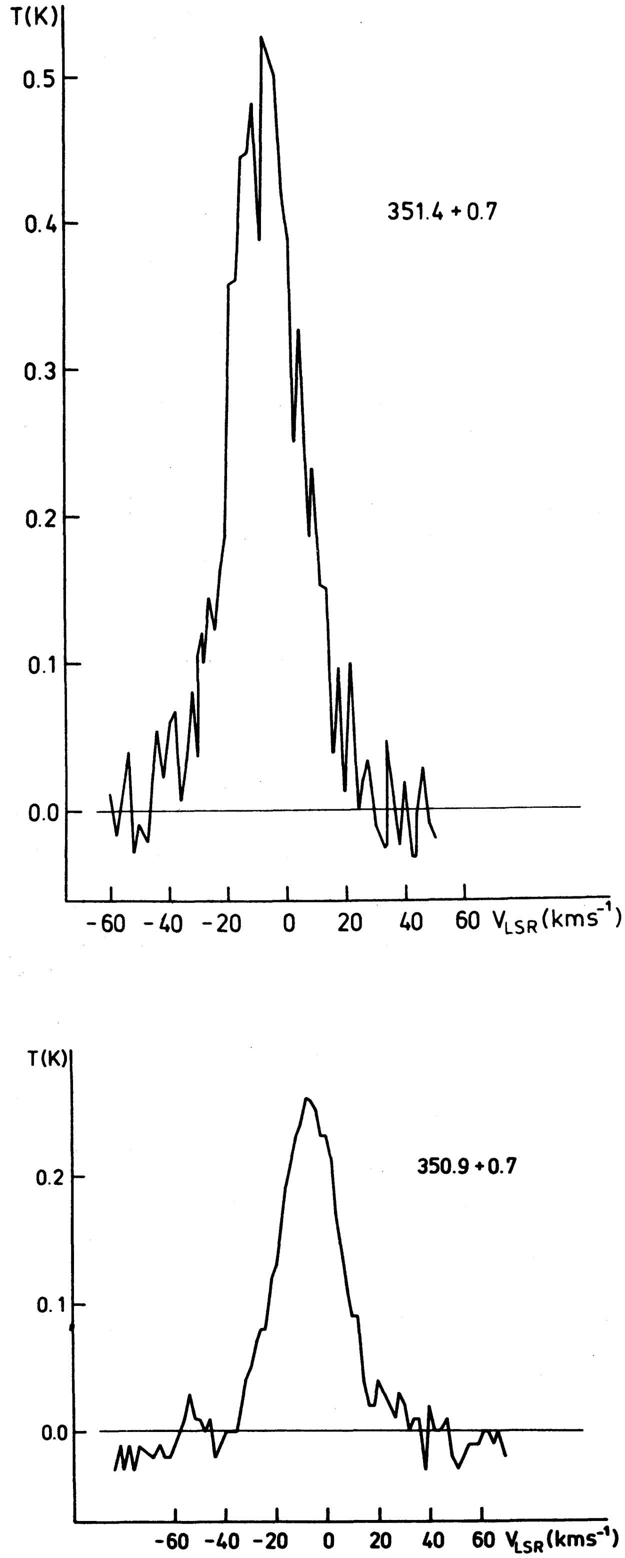
b) *The Continuum*

The six nebulae were observed in the continuum at 1420 MHz by making saveral right ascension scans spaced 0°.5 in declination. The continuum receiver covered a bandwidth of 40 MHz centered at 1420 MHz. A filter of 2 MHz centered at 1420.4057 MHz was used to eliminate the emission from galactic neutral hydrogen. The receiver was operated in the Dicke switching mode. The velocity of the right ascension scans was 0°.5/minute.

III. RESULTS

a) *NGC 6334*

Some of the observed profiles are shown in Figure 1. The profiles have centroid velocities of $\simeq -6$ km s^{-1} The full width at half maximum (FWHM) of most of the profiles is 30 km s^{-1}. The continuum map is shown in Figure 2. The positions where the line was observed are shown by X marks. The continuum flux corresponding to the NGC 6334 region of 120 arcmin of angular diameter is 2000 Jy. The obtained average electron temperature is 5700 K. By using a very simplified model with constant electron density and temperature (Schraml and Mezger 1969), we obtained a mean value for the electron density of $N_e = 12.9$ cm^{-3}, and for the emission measure EM = 1.28×10^4 pc cm^{-6}. The adopted distance is 1.7 kpc and the diameter of the spherical model is D = 59.3 pc. Higher frequency observations in the direction of G 351.4+ 0.7, which is the center of the observed region (Wilson *et al.* 1970; Mc Gee and Newton 1981), show density and emission measure values about one or two orders of magnitude greater than our values (see Table 1). This difference can be explained by the fact that at the frequency of the H166α line and with our relatively large antenna beam, the observations are more sensitive to the extended and diffuse parts of the nebula, the compact and higher emission measure regions near the center becoming optically thick at 1.4 GHz and suffering greater beam dilution.



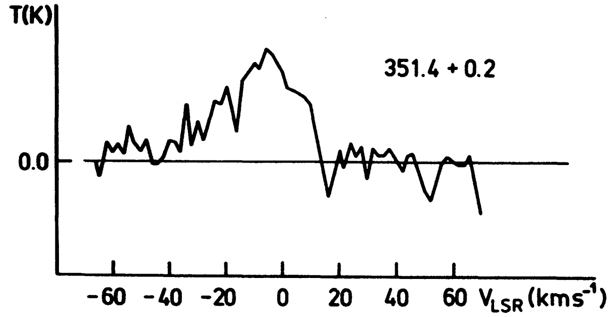


Fig. 1. Some profiles of the H166α line in the NGC 6334 region.

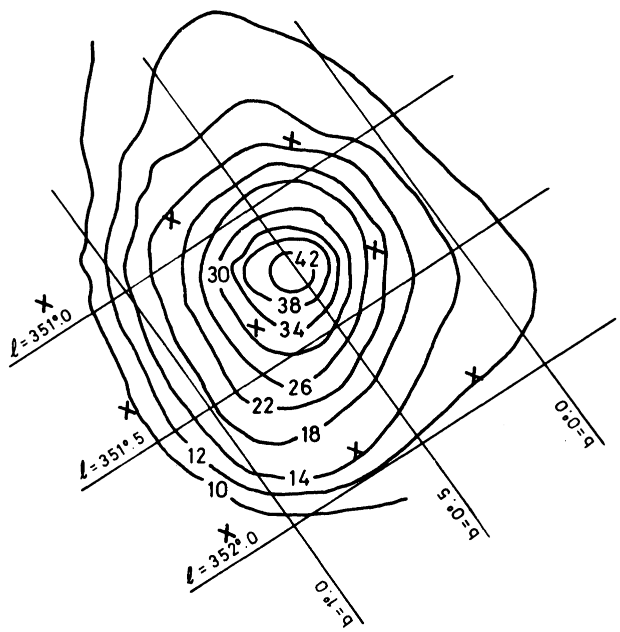


Fig. 2. Continuum map at 1420 MHz of the region associated with NGC 6334. The X marks indicate the positions where the line observations were made.

b) *RCW 97*

Some of the profiles are shown in Figure 3. Most of the profiles have centroid velocities of $\simeq$ --49 km s^{-1}. The FWHM of the profiles are $\simeq$ 30 km s^{-1}.

We show the continuum map in Figure 4. The positions where the line was observed are shown by X marks. The continuum flux associated to the RCW 97 region (with an angular diameter of 94′) is 893 Jy. The obtained average electron temperature is 5500 K.

Under the same simplifying assumptions made for NGC 6334, we computed a "rms" electron density N_e = 7.58 cm^{-3} and an emission measure EM = 8.27 X 10^3 pc cm^{-6}. The adopted distance is 3.5 kpc and the diameter, D = 98.7 pc. Values of N_e and EM (see Table 1), obtained from higher frequency recombination line observations

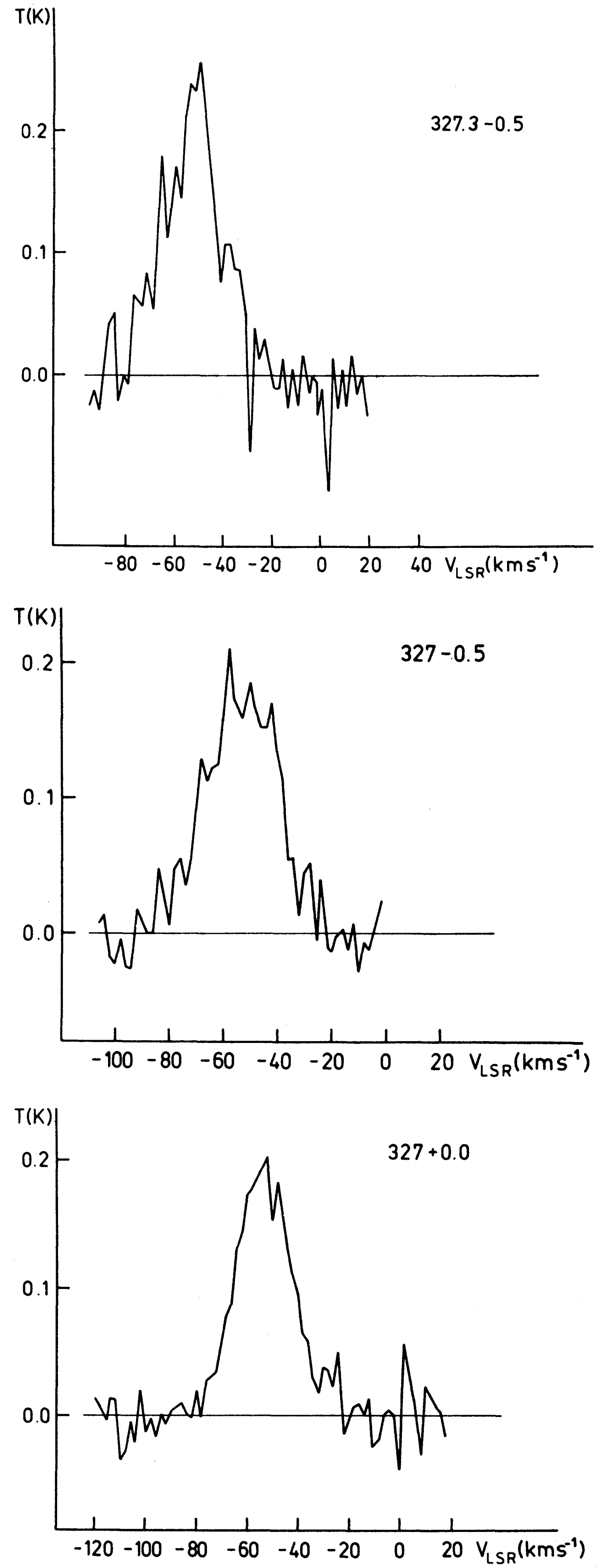


Fig. 3. Some profiles of H166α line in the RCW 97 region.

(Wilson *et al.* 1970; Mc Gee and Newton 1981), are at least two orders of magnitude greater than those obtained by us. This fact can be explained by the same argument used for NGC 6334.

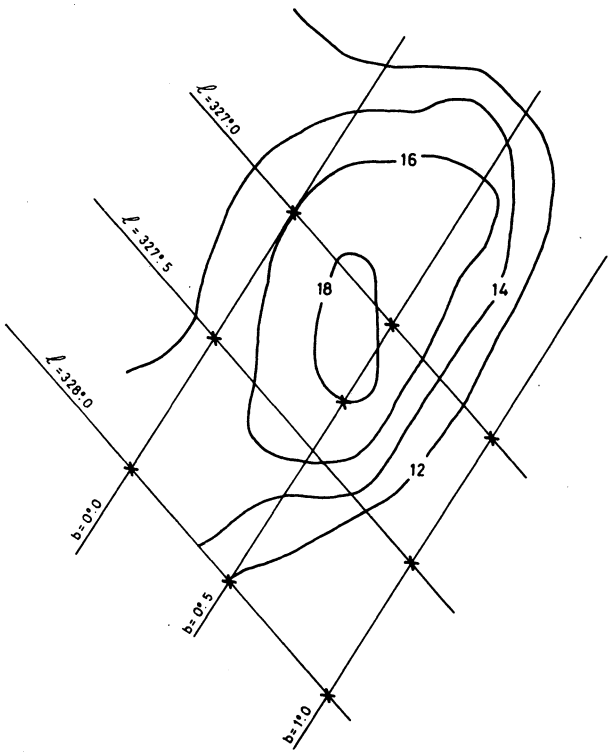


Fig. 4. Continuum map of the region associated to RCW 97. The crosses indicate the positions where the line observations were made.

c) *RCW 116*

Some of the profiles are shown in Figure 5. Most of the profiles have centroid velocities of $\simeq -18$ km s^{-1}, with a FWHM ranging from 25 to 30 km s^{-1}. We show the continuum map at 1420 MHz in Figure 6. Crosses indicate the positions where the H166α line was observed. The continuum flux corresponding to the extended region of about 84′ diameter is 288 Jy. The average electron temperature is $T_e = 6400$ K. The "rms" electron density is found to be $N_e = 7.84$ cm^{-3}. The value of the emission measure is $EM = 3.78 \times 10^3$ pc cm^{-6}. The adopted distance is 1.7 kpc and the diameter, D = 41.5 pc. Values of emission measure and density obtained from higher frequency recombination line observations (Wilson *et al.* 1970), are about two orders of magnitude larger than those obtained by us. Also the explanation already given for the other two H II regions is valid here.

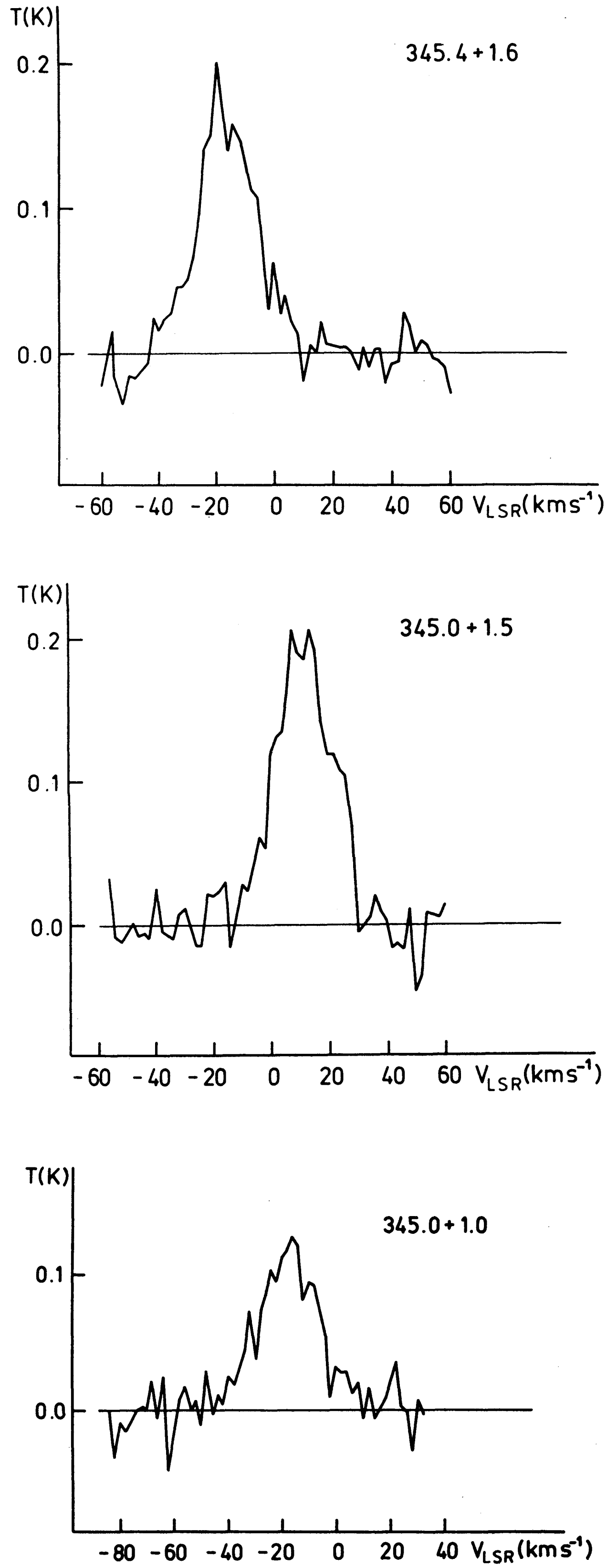


Fig. 5. Some profiles of the H166α line in the RCW 116 region.

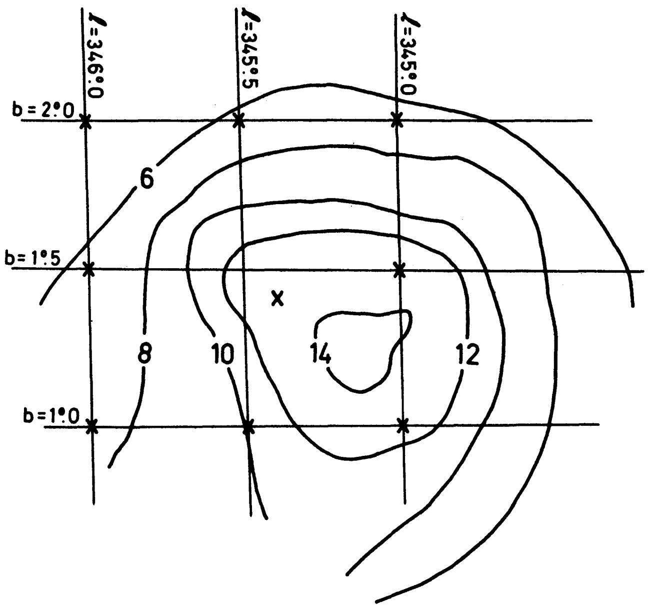


Fig. 6. Continuum map of the region associated to RCW 116. The crosses indicate the positions where the H166α line observations were made.

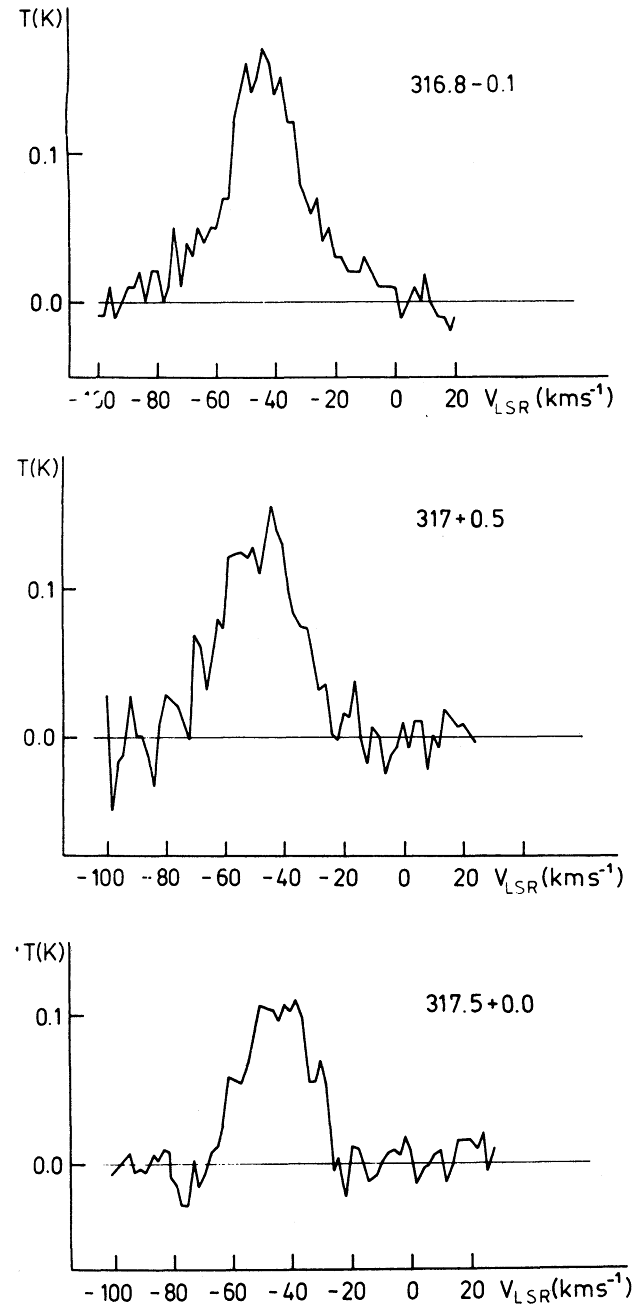


Fig. 7. Some profiles of the H166α line in the G 316.8−0.1 region.

d) *G 316.8–0.01*

Some of the H166α profiles are shown in Figure 7. The centroid velocities of the profiles are $\simeq -42$ km s^{-1}. The FWHM of most profiles ranges from 25 to 30 km s^{-1}. We show the 1420 MHz continuum map in the Figure 8. Crosses indicate the positions where the H166α line was observed. The continuum flux corresponding to the region of about 96′ diameter is 450 Jy. The average electron temperature is 7500 K. Under the same simplifying assumptions of Schraml and Mezger (1969), we obtained a "rms" electron density $N_e = 6.3$ cm^{-3} and an emission measure of 4.75×10^3 pc cm^{-6}. The distance is 2.9 kpc and the diameter is = 81 pc. Again, values of electron density and emission measure obtained from higher frequency recombination line observations (Wilson *et al.* 1970; Mc Gee and Newton 1981) are about two orders of magnitude larger than our values (see Table 1). The previous explanation is also valid here.

e) *NGC 3603*

Some of the profiles are shown in Figure 9. The centroid velocity of the central profile ($\ell = 291°.6$, $b = 0°.5$) is $\simeq 9$ km s^{-1}. The FWHM is $\simeq 48$ km s^{-1}.

We show the continuum map in Figure 10. The positions where the H166α line was observed are shown by means of X marks. The continuum flux corresponding to the extended region of about 110′ of diameter is 800 Jy. The average electron temperature is $T_e = 7100$ K. Always following Schraml and Mezger (1969), we obtained a value for the electron density $N_e = 4$ cm^{-3}, and an emission measure of 6.29×10^3 pc cm^{-6}. The adopted distance is 8.2 kpc and the diameter D = 262 pc. Again we find that electron density and emission measure values obtained from higher frequency recombination line observations, (Wilson *et al.* 1970; Mc Gee and Newton 1981) are larger than our values (see Table 1). The previous explanation is also valid here.

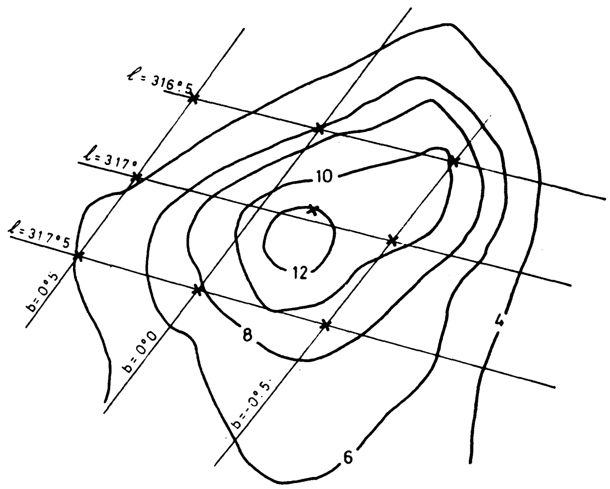
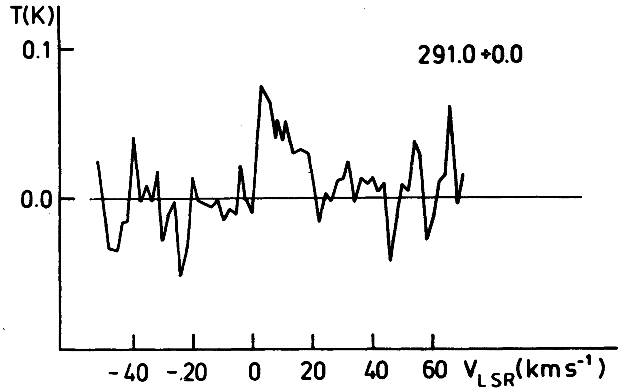
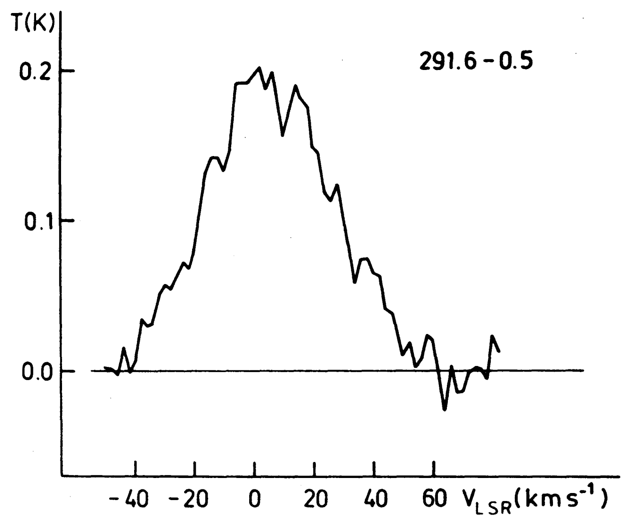


Fig. 8. Continuum map of the region associated to G 316.8−0.1. The X marks indicate the positions where the line observations were made.





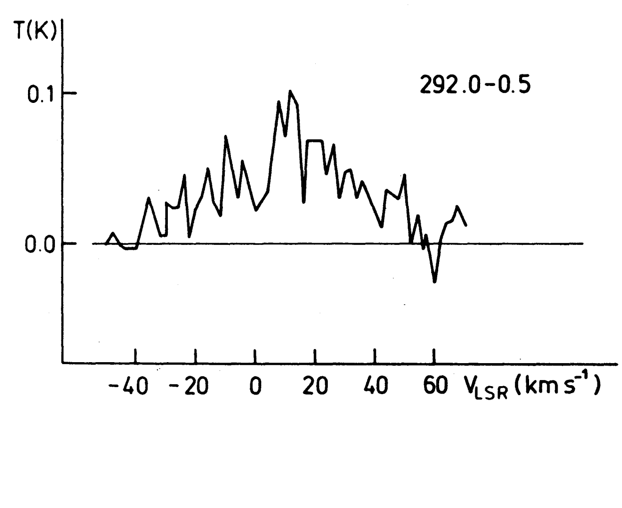


Fig. 9. Some profiles of the H166α line in the NGC 3603 region.

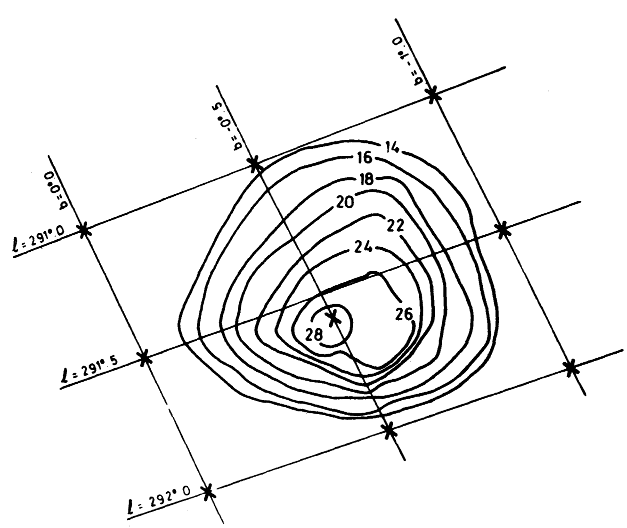
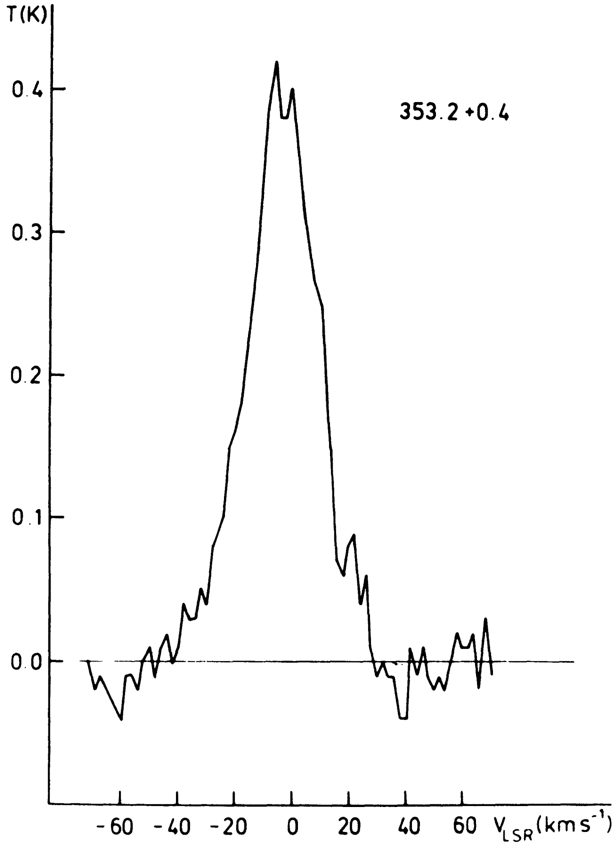


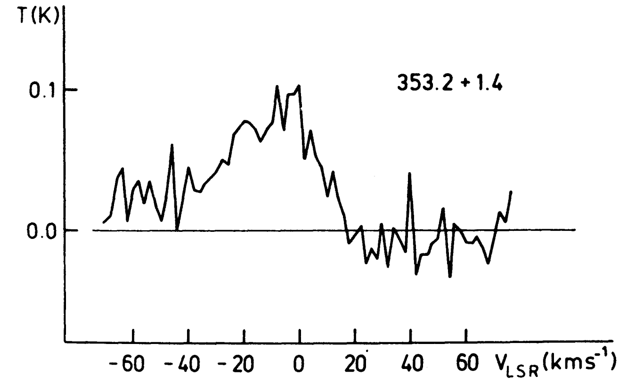
Fig. 10. Continuum map of the extended region associated to NGC 3603. The crosses indicate the positions where the line observations were made.

f) *RCW 131*

Some of the profiles are shown in Figure 11. The centroid velocities of most of the profiles are ~ -4 km s^{-1}, with a FWHM of 30 km s^{-1}.

The continuum map is shown in Figure 12. The positions where the H166α line was observed are shown by means of crosses. The continuum flux corresponding to the extended region of 75′ diameter is 857 Jy. The obtained values of density N_e and emission measure are 20 cm^{-3} and 1.4 X 10^4 pc cm^{-6}, respectively (using the same simplified model that was used for the previous arguments). The distance is 1.5 kpc and the diameter D = 32.7 pc. Electron density and emission measure values obtained from higher frequency recombination line observations (see Table 1), (Wilson *et al.* 1970; Mc Gee





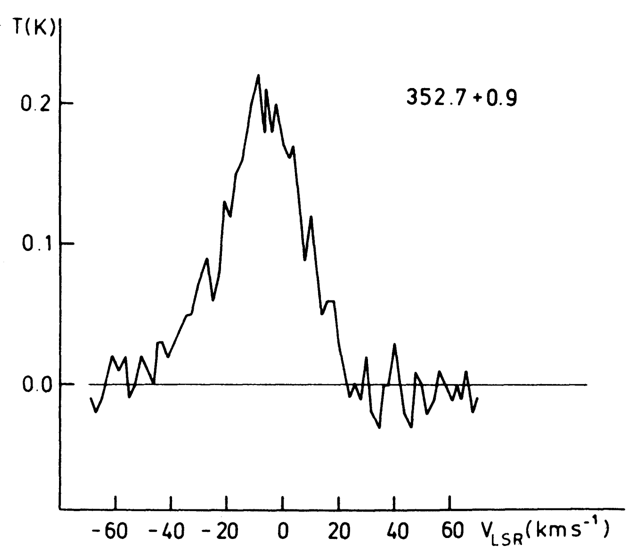


Fig. 11. Some profiles of the H166α line in the RCW 131 region.

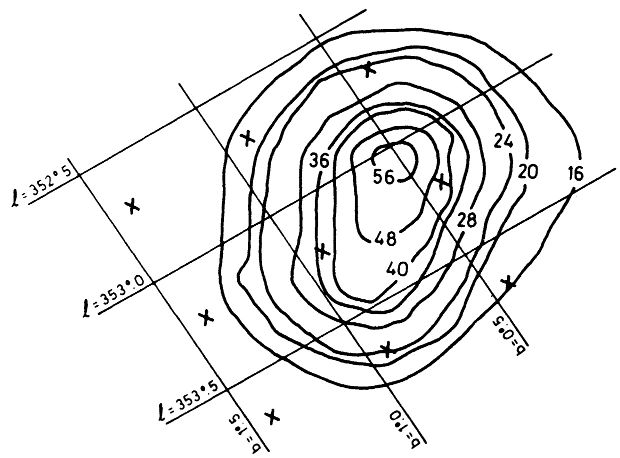


Fig. 12. Continuum map of the region associated to RCW 131. The X marks indicate the positions where the H166α observations were made.

and Newton 1981) are at least one order of magnitude greater than our values. The previous explanation given for the other regions is also valid here.

IV. DISCUSSION

For the low density ionized gas ($N_e \simeq$ 1-10 cm^{-3}), of relatively low emission measure (10^3 -10^4 pc cm^{-6}), the T_e^* obtained from H166α and 1.4 GHZ continuum observations, should differ from the actual temperature T_e by less than 20% (Dyson 1969). From Shaver's results (1980), it turns out that at 1.4 GHz and for EM = 10^3 -10^4 pc cm^{-6}, $T_e \simeq T_e^*$. In the six nebulae studied here, we investigated the possibility that departure from Local Thermodynamical Equilibrium (LTE) is present, through the expression for the ratio of the actual temperature T_e, to the value T_e^* obtained by assuming LTE:

$$\frac{T_e}{T_e^*} = \left[b_n \left(1 + \frac{\tau_c}{2} \frac{kT_e}{h\nu} \frac{d\ell_n b_n}{db_n} \Delta_n \right) \right]^{0.87}$$

TABLE 1

VALUES OF ELECTRON DENSITY, EMISSION MEASURE AND TEMPERATURE FOR THE SIX H II REGIONS, OBTAINED FROM OUR H166α OBSERVATIONS AND THOSE PREVIOUS OF H109α AND H76α MADE BY OTHER AUTHORS (WILSON *et al*, 1970; MC GEE AND NEWTON 1981)

	Parameters[a]	H166α	H109α	H76α
	T_e	5700	6100	7200
NGC 6334	EM	1.28×10^4	3.1×10^5	3.8×10^5
	N_e	12.9	377	347
	T_e	5500	6100	6770
RCW 97	EM	8.27×10^3	5.8×10^6	4.8×10^6
	N_e	7.58	2069	1834
	T_e	6400	4500	...
RCW 116	EM	3.8×10^3	7.3×10^5	...
	N_e	7.84	833	...
	T_e	7500	5900	6750
316.8–.1	EM	4.8×10^3	9.8×10^5	5.6×10^5
	N_e	6.3	332	448
	T_e	7100	6900	9400
NGC 3603	EM	6.3×10^3	7.5×10^5	9.4×10^5
	N_e	4	208	297
	T_e	8100	6500	7470
RCW 131	EM	1.4×10^4	1.1×10^6	4.3×10^5
	N_e	20	914	475

a. T_e in K, EM in pc cm^{-6} and N_e in cm^{-3}.

where τ_c is the optical depth for the continuum radiation, b_n is the population departure for the atomic level n, k is the Boltzmann's constant, h is the Planck's constant, and ν is the frequency.

Using the coefficients given by Brocklehurst (1970), we obtained values of $T_e/T_e^* \leq 1.2$, for the six regions, as expected. That would indicate that departures from LTE are negligible in our observations, and furthermore, pressure broadening is not significant. Pressure broadening does not play a dominant role because the $\Delta\nu_S/\Delta\nu_D$ ratio (Griem 1967) is unimportant for $n > 150$ when the density is $N_e \leq 10^3$ cm^{-3}. $\Delta\nu_S$ is the Stark (electron collision) broadened line half-power width, and $\Delta\nu_D$ is the Doppler half-power width.

Therefore, we may conclude that the assumption of LTE is a good approximation for the low density gas associated with these regions. For observations at low frequency and with large beamwidth the large area of the outer low density region dominates the recombination line emission over any smaller region of high density because of a combination of the effects of beam dilution and optical depth. As it is shown in previous papers (Cersosimo 1982, Cersosimo, Azcárate, and Colomb 1984, Azcárate *et al.* 1986) combined results (from high and low frequency recombination line observations), are compatible with the description of rather extended H II regions as consisting roughly of a small compact region of dense gas embedded in an extended ionized gas envelope of lower density.

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I.N. Azcárate, J.C. Cersosimo, and F.R. Colomb: Instituto Argentino de Radioastronomía, Casilla de Correo No. 5, (1894) Villa Elisa, Prov. de Buenos Aires, Argentina.