RECOMBINATION LINES 158α AND 198β IN NINE SOUTHERN NEBULAE

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Summary

Recombination lines H 158α, He 158α, and H 198β (near λ 18 cm) have been observed in the HII regions Orion Nebula, RCW 38 and 49, η Carinae I, RCW 57, PKS 1617−50I in Norma, NGC 6334 and 6357I, and Omega Nebula. Physical parameters such as ratio of line to continuum temperatures T_L/T_c, line halfwidths, median radial velocities, and intensity ratios $I(198\beta)/I(158\alpha)$ and $I(\mathrm{He})/I(\mathrm{H})$ are given. A lack of agreement in the measured radial velocities of the H 198β and H 158α lines in three nebulae is discussed.

I. Introduction

Observations of the recombination lines H 158α, He 158α, and H 198β have been made in nine southern HII regions. These are Orion Nebula, RCW 38 and 49, η Carinae I, RCW 57, PKS 1617−50I in Norma, NGC 6334 and 6357I, and Omega Nebula.

The receiver was that normally used for work on the 1665 and 1667 MHz hydroxyl-radical lines. The results corroborate the measurements of radial velocity of the same objects made on the H 126α line by McGee and Gardner (1968). Intensity ratios of the β to α lines are listed. The discussion of possible departures from local thermodynamic equilibrium (L.T.E.) is complicated by the lack of agreement between the radial velocities of the α and β lines in the same nebulae.

Despite relatively poor signal-to-noise ratios, estimates of the helium-to-hydrogen ratios are made for the nine nebulae. The ratios are in reasonable agreement with optical values.

II. Equipment and Observations

The receiving equipment and observational techniques have been described by Batchelor, Brooks, and Sinclair (1969). In the present experiment filter bandwidths at an intermediate value between 10 and 100 kHz were desirable, and so a modification was effected to incorporate a bank of 48 filters of bandwidth 37 kHz into the new receiver.

The aerial beam was measured by making continuum observations of the standard source Hydra A. The half-power beamwidth was found to be 12′·3 arc and circular to within 0′·1 arc.

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The noise temperature of the overall system looking at cold sky was 180°K. The receiver sensitivity was monitored at regular intervals by noise lamp calibrations. The noise lamp deflection was compared with the deflection from Hydra A and a relationship established between flux density S and aerial temperature T_{a}. Using the value of 53% for aperture efficiency given by Minnett and Yabsley (1966)

$$T_{\mathrm{a}} = S/1 \cdot 59 .$$

The natural frequencies of the recombination lines were calculated with values of atomic constants published by Cohen and Du Mond (1965). They are:

1651·541 MHz for H 158α,	at this frequency $-1\ \mathrm{km\,sec^{-1}} \equiv 5\cdot509$ kHz;
1652·214 MHz for He 158α,	$-1\ \mathrm{km\,sec^{-1}} \equiv 5\cdot511$ kHz;
1669·019 MHz for H 198β,	$-1\ \mathrm{km\,sec^{-1}} \equiv 5\cdot567$ kHz.

The receiver local oscillator frequency settings were precomputed to refer radial velocities to the local standard of rest. The errors in these frequencies are discussed by Batchelor, Brooks, and Sinclair (1969); they were negligible compared with errors of ± 3 kHz in the centre frequencies of the 37 kHz filters.

Prior to making a line observation the point of maximum continuum radiation from the nebula was located and its aerial temperature T_{c} measured. Line spectra were measured by making alternate observations of the source and of a nearby cool reference point. Integration time was built up by accumulating the data in a signal analyser over a period of approximately 15 min and repeating the operation until reasonable signal-to-noise conditions were achieved.

The observed profiles were normalized and averaged in the CDC 3200 computer of the CSIRO Computer Research Division.

III. Recombination Line Profiles

(a) *H 158α Line*

The profiles appeared well above the noise level and enabled satisfactory measurements of the maximum line temperature T_{L}, the halfwidth $\Delta\nu_{\mathrm{L}}$ (the width between half-intensity points on the profile), and the median radial velocity R.V.

The observed quantities are related to the fundamental physical quantities by the relation (e.g. McGee and Gardner 1968)

$$\frac{T_{\mathrm{L}}}{T_{\mathrm{c}}}\Delta\nu_{\mathrm{L}} = \frac{C\,.\,3h^4 b_n\, u n^3 \nu^3}{16 m k e^4 T_{\mathrm{e}} \ln[\{(2k)^{3/2}/\pi m^{\frac{1}{2}} e^2 \gamma^{5/2}\}\{T_{\mathrm{e}}^{3/2}/\nu\}]}\,. \tag{1}$$

The atomic constants h, m, k, and e have their usual values, C and γ are numerical constants, $0 < b_n \leqslant 1$ (for L.T.E. $b_n = 1$), $u = 0\cdot19$ (Menzel 1968), $n = 158$, and $\nu = 1651\cdot541$ MHz. The equation may be solved for the electron temperature T_{e} provided that

(i) both the continuum background and the line radiation have low optical depth at this frequency;

(ii) the line shape is Gaussian;

(iii) the electron temperature is constant over the aerial beam and along the line of sight.

In practice it is unlikely that these conditions hold, and equation (1) merely enables a rough approximation to T_e to be made. For condition (i) it has to be assumed that the continuum background T_c is entirely thermal and that the radiation is emitted from the same object as the line radiation. Condition (ii) is probably a reasonable assumption. Condition (iii) cannot be fulfilled in practice. The very nature of HII regions is one of variations in intensity as indicated, for example, by the presence of bright filaments of dimensions small compared with the beam of a radio telescope. Therefore the value of electron temperature derived in this way is merely an average of all the contributions enclosed in the beam.

Added complications have been discussed by a number of authors. Dyson (1967) has suggested that, since it has been well established that line widths vary from place to place in a nebula, some of the averaging effects could be avoided by comparing the total energy in the line with the energy per unit frequency interval in the adjacent continuum. But of vital importance in the calculation of T_e is the knowledge of the values of b_n and $d(\ln b_n)/dn$ (Goldberg 1966). These quantities have been calculated for various electron temperatures and densities. There is evidence of departure from L.T.E. which would mean $b_n < 1$, but it would be necessary to assume some value of electron density to complete the calculations.

Recently Simpson (1968), using the latest calculations of b_n, has shown that the departure from L.T.E. does not account for all the difference between the determinations from radio observations and the optically derived values of T_e. This finding reinforces previous statements (McGee and Gardner 1968) that the observed profiles are quite often composites of two or more major sources of line radiation.

(b) *H 198β Line*

Under ideal conditions the β lines would only be one-fourth the intensity of the α lines and thus would require a factor of 16 in integration time for corresponding quality. Although only limited telescope time was available we attempted to measure the H 198β line in the six nebulae not previously observed for β transitions. (Williams (1967) has reported H 197β lines in the Orion and Omega nebulae and in NGC 6334.) The line was below the noise level in RCW 49, η Carinae I, and RCW 57. The T_L in these cases is estimated at less than $0\cdot1$°K. The line is obviously present in RCW 38, PKS 1617−50I, and NGC 6357I.

Gardner and McGee (1967) have pointed out that the ratio of the intensities of β and α lines may be used as an indicator of whether or not L.T.E. conditions are present in the populations of atomic energy levels. No knowledge of ion densities or kinetic temperatures is required by this method. Using the recent formulae for oscillator strengths (Menzel 1968) their expression for the ratio may be more accurately written

$$\frac{I(198\beta)}{I(158\alpha)} = \frac{n_{198}^3\,\nu_{200,198}^3}{n_{158}^3\,\nu_{159,158}^3} \times \frac{2\cdot633\times10^{-2}(1+3/198)}{1\cdot9077\times10^{-1}(1+1\cdot5/158)} = 0\cdot28\,. \tag{2}$$

The calculation of this value rests on the assumption of L.T.E.

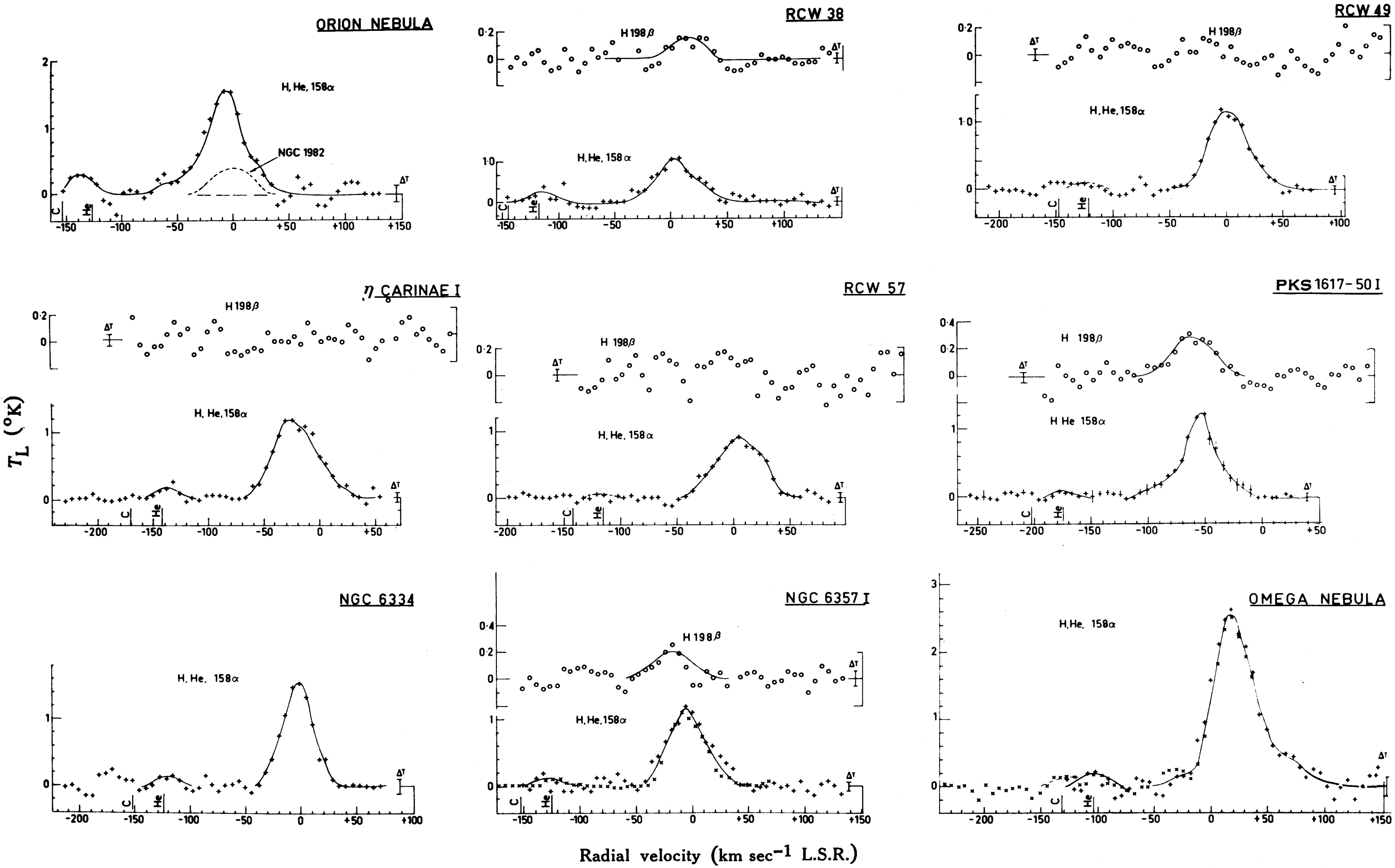

Fig. 1.—Recombination line profiles of the nine nebulae. The H 158α lines are indicated by crosses; the expected positions of the He 158α and "C 158α" lines are marked He and C respectively. The H 198β observations are shown above the corresponding α lines by open circles. The intensity scales are in aerial temperatures T_L while the radial velocity scales are referred to the local standard of rest (L.S.R.). The r.m.s. noise fluctuation level ΔT is given on the zero line of each profile.

(c) *He 158α Line*

If we make the simplifying assumption that the observed intensities of the helium and hydrogen 158α recombination lines are in the same ratio as their number densities, then $I(\mathrm{He}\,158\alpha)/I(\mathrm{H}\,158\alpha)$ represents the relative abundance and is expected to be $\sim 0\cdot 1$ (e.g. Mathis 1962).

The observations described herein do not have sufficient signal-to-noise ratio to adequately delineate the helium line. Nevertheless, indications of its presence are seen in each of the averaged profiles.

Previous observations of the helium α line at the 109 quantum level (Palmer *et al.* 1967) have been complicated by the appearance of another line in its immediate vicinity, thought to be the corresponding carbon 109α line. At the 158 quantum level we calculate that such a line would be present at a frequency equivalent to $-148\cdot 8$ km sec^{-1} on the radial velocity scale from the H 158α line. The He 158α line is displaced by $-122\cdot 2$ km sec^{-1} from the H 158α line. Thus the displacement between the helium and carbon lines would be equivalent to $\sim 4\cdot 7$ channels, i.e. between four and five points on our diagrams. In some of our observations there is possible evidence of the "C 158α line".

IV. Experimental Results

The reduced data for each of the nine nebulae are given in Figure 1. The coordinates are the aerial temperatures of the lines T_{L} in degrees Kelvin and the equivalent radial velocity in km sec^{-1}. The crosses denote the values for each of the 48 channels used to seek the 158 lines. The open circles given above some of these represent the H 198β line observations. The T_{L} scale is doubled for the latter.

The profile outlines have been sketched through the points by eye. The expected positions of the He 158α and C 158α lines are marked on the radial velocity ordinate. In this case the radial velocity is appropriate to the natural frequency of the H 158α line but at the scale in use any errors in conversion to radial velocities near -150 km sec^{-1} are negligible. The r.m.s. noise fluctuation level (ΔT) is indicated on the zero line of each profile.

The profiles have provided values of T_{L}, in degrees Kelvin, and $\Delta\nu$ in km sec^{-1} for the H 158α and 198β lines. In the case of He 158α, T_{L} only has been measured. The carbon lines appear so uncertain that no estimates are set down here. The measurements and calculations made from the profiles are presented in Table 1.

The source names and positions are stated in the first five columns of Table 1. The equatorial coordinates for 1950·0 and the galactic coordinates, l^{II} and b^{II}, have been computed from the telescope position tapes. The aerial temperatures of the continuum maximum are given in column 6. These values have an accuracy of $\pm 2\%$.

Data on the H 158α line follow: the temperature at the maximum intensity point of the line profile T_{L} in column 7; the ratio $T_{\mathrm{L}}/T_{\mathrm{c}}$ expressed as a percentage in column 8; the observed halfwidth $\Delta\nu$ in km sec^{-1} and the median value of radial velocity R.V. in km sec^{-1} in columns 9 and 10. The relation $(T_{\mathrm{L}}/T_{\mathrm{c}})\Delta\nu_{\mathrm{L}}$ (kHz) is given in column 11. The $\Delta\nu$ have been converted to frequency units and corrected for instrumental broadening here.

TABLE 1

PHYSICAL QUANTITIES MEASURED AND DERIVED FROM H 158α, H 198β, AND He 158α LINES OF NINE NEBULAE

T_c is the aerial temperature of the continuum at the position of the source, T_L the maximum aerial temperature of the line profile, $\Delta\nu$ (km sec^{-1}) the halfwidth of the line profile uncorrected for instrumental effects, R.V. the median value of radial velocity referred to the local standard of rest, and $\Delta\nu_L$ (kHz) the line halfwidth corrected for instrumental effects

(1) Source	(2) Position (1950·0) R.A. h	m	s	(3) Dec. °	′	(4) Galactic Coordinates l^{II} °	(5) b^{II} °	(6) T_c (°K)	(7) H 158α T_L (°K)	(8) $\frac{T_L}{T_c}$ (%)	(9) $\Delta\nu$ (km sec^{-1})	(10) R.V. (km sec^{-1})	(11) $\frac{T_L}{T_c}\Delta\nu_L$ (kHz)	(12) H 198β T_L (°K)	(13) $\Delta\nu$ (km sec^{-1})	(14) R.V. (km sec^{-1})	(15) $\frac{I(198\beta)}{I(158\alpha)}$	(16) He 158α T_L (°K)	(17) $\frac{I(\text{He})}{I(\text{H})}$
Orion Nebula	05	32	50	−05	25·2	209·0	−19·4	211	1·6 ±0·12	0·8 ±0·1	37 ±5	−7	1·58	—	—	—	—	0·26 ±0·12	0·16 ±0·09
NGC 1982								(60)	0·4	(0·7)	40	−1 ±2							
RCW 38	08	57	27	−47	23·8	267·9	−1·1	97	0·7 ±0·07	0·7 ±0·1	39 ±3	+3 ±2	1·46	0·15 ±0·08	34 ±8	+13 ±4	0·21	0·16 ±0·07	0·23 ±0·12
RCW 49	10	22	19	−57	30·7	284·3	−0·3	112	1·2 ±0·06	1·1 ±0·1	38 ±3	0 ±2	2·24	<0·1 ±0·09	—	—	<0·1	0·10 ±0·06	0·08 ±0·05
η Carinae I	10	42	16	−59	20·8	287·5	−0·6	102	1·2 ±0·07	1·2 ±0·1	44 ±3	−21 ±2	2·84	<0·1 ±0·09	—	—	<0·1	0·18 ±0·07	0·15 ±0·07
RCW 57	11	12	52	−60	58·0	291·6	−0·5	110	0·9 ±0·07	0·8 ±0·1	48 ±3	+6 ±2	2·07	<0·1 ±0·09	—	—	<0·1	0·07 ±0·07	0·08 ±0·08
PKS 1617−50I	16	17	01	−50	31·8	333·1	−0·5	46	1·2 ±0·06	2·6 ±0·2	30 ±3	−53 ±2	4·16	0·3 ±0·07	41 ±6	−61 ±4	0·25	0·09 ±0·06	0·07 ±0·06
NGC 6334	17	17	07	−35	45·4	351·3	+0·7	82	1·5 ±0·11	1·8 ±0·1	33 ±5	−3 ±2	3·17	—	—	—	—	0·13 ±0·1	0·09 ±0·08
NGC 6357I	17	21	30	−34	08·6	353·2	+0·9	81	1·2 ±0·06	1·5 ±0·1	38 ±3	−5 ±2	3·06	0·2 ±0·11	38 ±8	−18 ±11	0·16	0·13 ±0·06	0·11 ±0·06
Omega Nebula	18	17	34	−16	12·7	015·0	−0·7	282	2·6 ±0·14	0·9 ±0·1	40 ±6	+20* ±2	1·93	—	—	—	—	0·18 ±0·14	0·07 ±0·06

* Peak at +18 km sec^{-1}.

The next four columns 12–15, refer to the H 198β line: T_L, $\Delta\nu$, R.V., and the intensity ratio $I(198\beta)/I(158\alpha)$ are listed. Data are complete for only three nebulae.

Information on the He 158α line, observed simultaneously with the H 158α, is given as T_L in column 16 and the ratio $I(\text{He } 158\alpha)/I(\text{H } 158\alpha)$ in column 17.

Errors in the observed quantities are stated where appropriate. Those in temperatures are in terms of r.m.s. noise. Halfwidth and radial velocity errors are estimated.

V. Remarks on Individual Nebulae

One of the limitations imposed by the relatively broad aerial beam is uncertainty in whether the measured continuum temperature T_c applies only to the HII region in which the recombination line parameters were observed. Confusion could be caused by interception of and blending with other radiation. Goss and Shaver (personal communication) have kindly made available their preliminary maps of the nine galactic nebulae at a wavelength of 6 cm and telescope beamwidth of only 4′·0 arc. With such information we are able to comment on how each major thermal source or group of thermal components was disposed in the 12′·3 arc beam. HII regions are characterized by small dense filaments in an apparently random arrangement and much greater radio resolution is needed before comparisons with optical temperature measurements reach common ground.

We set down notes on the radio continuum conditions and on some of the line data in Table 1 which need further remarks.

(*a*) *Orion Nebula*

The nebula was only briefly observed in view of extensive investigations by other authors (Dieter 1967; Williams 1967). When compared with the 6 cm map the present beam is seen to squarely intercept the intense central core. The nearby object NGC 1982 and the broad westerly extension have only a slight influence at the half-power width of 12′·3 arc.

The H 158α line was also observed with 10 kHz bandwidth, and in both cases good agreement was obtained with the H 126α recombination line (McGee and Gardner 1968).

The helium–hydrogen intensity ratio is in closer agreement with optical results than with the value given by Mezger and Palmer (1968) from N.R.A.O. radio measurements.

We have included an outline of the H 158α profile in the direction of NGC 1982 in Figure 1. It is estimated from the continuum maps that $\sim 40\%$ of the continuum temperature was contributed by radiation from the Orion Nebula. The line profile must be considerably influenced in a similar way. The radial velocity of -1 km sec^{-1} shows the same positive trend as reported by Gordon and Meeks (1968). They find radial velocities of $+7$ and -3 km sec^{-1} for NGC 1982 and Orion respectively with a 4′·2 arc beam and the H 94α lines.

(*b*) *RCW 38*

The main continuum core of this nebula is completely enclosed in the 12′·3 arc beam; very slight overlapping of two low intensity outlying components occurs. The

H 198β line has a radial velocity which is 10 km sec^{-1} more positive than for the H 158α line. The β profile lies within the range of the α profile.

(*c*) *RCW 49*

The 4′ arc beam of Goss and Shaver (personal communication) partly resolves the intense central contribution on which the present beam is centred. This would indicate that at least two important components have been included in the observations. Although the H 158α line is quite strong, the helium line is comparatively weak and the H 198β line remained below the noise level.

(*d*) *η Carinae I*

Although the aerial beam was centred on the maximum continuum radiation observed from η Carinae at 18 cm we find from the 6 cm continuum map that the source is resolved into two equal intensity components. Our measurement has been made at a point almost exactly between the two, 6′ arc from the maximum of η Carinae I.

The H 158α profile shape points to two or more components. The H 198β line was again lost in noise.

(*e*) *RCW 57*

Examination of the continuum maps shows the possibility of two or three major thermal components in the 12′·3 arc beam. The observed H 158α profile is very broad. The helium and Hβ lines were not detected.

(*f*) *PKS 1617—50I* (*Norma*)

The present aerial beam has taken in most of the radiation from two approximately equal components. The shape of the 6 cm contours predicts further unresolved structure. The nebula is interesting because it has produced a strong, narrow α line from a comparatively low continuum temperature. Thus the T_L/T_c ratio is very high at 2·6%. The H 198β line is very strong compared with the others and its median velocity is 8 km sec^{-1} more negative than the α line.

Two sets of averaged points of the H 158α line were available from observations made on successive days. The lengths of the verticals of the crosses in Figure 1 represent the differences in recorded intensities.

(*g*) *NGC 6334*

The beam was centred 2′·7 arc in a north-west direction from the continuum maximum seen at λ 6 cm. Evidence of finer structure exists. Observations of the H 198β line were not attempted. Williams (1967) found $I(197\beta)/I(156\alpha) = 0{\cdot}18$.

(*h*) *NGC 6357I*

The main core of the thermal radiation and some finer structure are contained in the aerial beam. Two sets of averaged points make up the α profile. The H 198β line was detected at a radial velocity 13 km sec^{-1} more negative than the α line.

(i) *Omega Nebula*

The 6 cm continuum contours exhibit extreme steepness on the western side. Double maximum structure revealed by 2 cm observations (Zisk 1966) has not been resolved by the 4′ arc beam. Observations were restricted on Omega, since it has been so extensively investigated elsewhere. Two groups of results are superposed in Figure 1.

TABLE 2

COMPARISON OF $\bar{T}_e$ FOR H 158α AND H 126α

Nebula	$\bar{T}_e$ (°K) 158α	$\bar{T}_e$ (°K) 126α	Nebula	$\bar{T}_e$ (°K) 158α	$\bar{T}_e$ (°K) 126α
Orion Nebula	10 500	7 600	PKS 1617−50I	4 600	4 100
RCW 38	11 200	10 800	NGC 6334	5 800	4 000
RCW 49	7 700	8 800	NGC 6357I	6 000	7 200
η Carinae I	6 400	5 700	Omega Nebula	8 900	7 100
RCW 57	8 300	7 800			

VI. Discussion and Conclusions

(a) *Comparison of α Lines at Levels 126 and 158*

Comparisons are made of the ratios of T_L/T_c, the line halfwidths $\Delta\nu$, the calculated average electron temperatures, and the median radial velocities of the H 126α and H 158α lines of the nebulae.

T_L/T_c. The values in Table 1 have a range 0·7–2·6%, in good agreement with the expectation 0·5–2·5% from Figure 2 in the paper by McGee and Gardner (1968).

Halfwidths $\Delta\nu$. The halfwidths of the corresponding H 126α and H 158α lines agree to within a few per cent for Orion Nebula, PKS 1617−50I, and NGC 6334. In the other six nebulae the width is greater by 10–40% at H 158α. The influence of noise fluctuations in both sets of measurements may be at work here or the wider beam may be including contributions with a larger range of velocities.

Average electron temperature. The T_L/T_c and $\Delta\nu$ may be used in equation (1) to estimate the average electron temperature $\bar{T}_e$ of the nebulae. The values are subject to the limitations discussed at the beginning of Section III. Similar calculations have been made for the $n = 126$ line from Table 1 of McGee and Gardner (1968). The comparisons are shown in Table 2.

Radial velocities. The median radial velocities in the H 158α lines are in excellent agreement with the similar velocities of the H 126α lines. The nebulae RCW 57 and PKS 1617−50I have differences of 4 and 5 km sec^{-1} but all others have less than 2 km sec^{-1} difference.

(b) *Radial Velocities of H 198β Lines*

A puzzling feature in the observations of the three detected β lines is the lack of correspondence in median radial velocity with the α lines. Errors in the calculation of the radial velocity could not account for more than 0·1 km sec^{-1} for each nebula. The poor signal-to-noise ratio might be responsible for differences as great as

± 5 km sec^{-1}. However, differences of $+10$, -8, and -13 km sec^{-1} exist between the radial velocities of the H 198β and the H 158α lines in RCW 38, PKS 1617$-$50I, and NGC 6357I respectively. Although Williams (1967) makes no comment to this effect, the radial velocities of the H 156α and H 197β lines for the Omega Nebula, W 43, and NGC 6334 in his Figures 1, 3, and 4 show radial velocity differences of the same order ($+5$, -10, and -2 km sec^{-1} approximately).

These apparent discrepancies may be further evidence that a number of components of an HII region contribute to the recombination line profile produced by the radio telescope beam. It is possible that in some of these, β lines appear relatively strongly; in others, moving at different velocities, the β lines appear relatively weakly.

The results underline the need for caution in drawing conclusions to explain why the observed $I(198\beta)/I(158\alpha)$ ratio does not equal the theoretical value as calculated in equation (2).

(*c*) *Helium Lines*

The He 158α line is close to the noise fluctuation level in the observations of all nine nebulae. The mean ratio $I(\mathrm{He})/I(\mathrm{H})$ is 0·12, which is close to optical results.

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