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TEMPERATURE DETERMINATIONS OF H II REGIONS

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ABSTRACT

The effect that temperature fluctuations inside H II regions have on the value of the temperature determined from observations is studied. New photoelectric observations of M8, M17, and three regions of the Orion Nebula are discussed; the intensity ratios of auroral to nebular forbidden lines of O^+, O^{++}, and N^+ were measured in all five regions, whereas the intensity ratio of Balmer continuum to Balmer line was obtained for the last three. The temperatures obtained by means of the forbidden lines are found to be larger than those determined from the Balmer continuum and the published radio astronomical values. It is found that at least part of this difference can be accounted for by temperature fluctuations inside H II regions.

I. INTRODUCTION

There are at least three different methods for obtaining the temperature of H II regions: (*a*) intensity ratios of auroral to nebular forbidden lines; (*b*) intensity ratios of bound-free continuum to bound-bound emission lines of hydrogen; and (*c*) intensity ratios of bound-bound emission lines to free-free continuum of hydrogen. The first two are used in the optical region, and the third one in the radio region. However, there are discrepancies between the temperatures derived from the third and first methods. To study these differences it should be kept in mind that the probable errors in the temperature values are very large, that the temperatures refer to different volumes, and that each method weights differently the subregions in the volume considered.

The large variations in density and degree of ionization existing inside a given H II region (see, e.g., Osterbrock and Flather 1959) are likely to produce spatial temperature fluctuations. We will presently study the different effects of these fluctuations on the values of the temperatures obtained by each method.

II. TEMPERATURE EQUATIONS

The forbidden-line flux $I(X^{+p},\lambda_{nm})$ received from a nebula in ergs cm^{-2} sec^{-1} is given by

$$I(X^{+p},\lambda_{nm}) = 3.09\times 10^{18}\int N(X^{+p})\,A_{nm}\frac{P(X^{+p},n)}{S(X^{+p})}\,h\nu(\lambda_{nm})\,d\Omega dl\,, \tag{1}$$

where λ_{nm} is the wavelength associated with the emission; $N(X^{+p})$ is the number of atoms in the pth state of ionization given in cm^{-3}; Ω, the observed solid angle; A_{nm}, the Einstein transition probability coefficient in sec^{-1}; $P(X^{+p},n)/S(X^{+p})$ is the fraction of the atoms $N(X^{+p})$ in the nth level; and l is the distance inside the nebula in parsecs along the line of sight. If collisional de-excitations are negligible, equation (1) can be written as

$$I(X^{+p},\lambda_{nm}) = C\int N(X^{+p},r)N_e(r)T_e(r)^{-1/2}\exp\,[-\Delta E/kT_e(r)]d\Omega dl\,, \tag{2}$$

where r is the position vector and the constant C depends on atomic parameters only, $N_e(r)$ is the local number density of electrons in cm^{-3}, ΔE is the difference of energy between the ground and the excited levels, and $T_e(r)$ is the local electron temperature.

The flux at the Balmer limit is given by (Aller 1956)

$$I(\mathrm{Bac},3646) = 1.65\times 10^{-3}\Delta\lambda\int N_i(r)N_e(r)T_e(r)^{-3/2}d\Omega dl\,, \tag{3}$$

where $\Delta\lambda$ is given in angstroms.

The flux of an optically thin nebula in Hβ, according to Aller (1956), is given by

$$I(\mathrm{H}\beta) = 7.05 \times 10^{-1} \int N_i(r) N_e(r) T_e(r)^{-3/2} b_4 \exp(X_4) d\Omega dl \,, \tag{4}$$

where b_4 is a factor measuring the degree of departure from thermodynamical equilibrium, $X_4 = hR/16kT_e(r)$, and R is the Rydberg constant. From the work by Clarke (1965) it was found that $b_4 \exp(X_4)$ can be approximated by a power of the temperature; in the range between 5000° and 15000° K equation (4) can be expressed as

$$I(\mathrm{H}\beta) = D \int N_i(r) N_e(r) T_e(r)^{-0.91} d\Omega dl \,, \tag{5}$$

where D is constant.

The brightness line temperature T_L and the line width $\Delta\lambda$ of the low-energy hydrogen bound-bound lines emitted in the radio region are related to the excitation temperature of the line T_e^* by the following equation due to Kardashev (1959)

$$\Delta\nu T_L = \frac{1.67 \times 10^6}{\Omega} \int N_i(r) N_e(r) T_e^*(r)^{-3/2} d\Omega dl \,, \tag{6}$$

in which $\Delta\nu$ is given in Hz. In this equation it has been assumed that the nebula is optically thin in the line, that the line shape is Gaussian, and that the correction factor for stimulated emission is $h\nu/kT_e^*$. For the time being we will assume that T_e^* is equal to T_e. This hypothesis will be dealt with later on.

An expression for the continuum brightness temperature, T_C, due to Oster (1961) is

$$T_C = \frac{3.014 \times 10^{-2}}{\Omega} \int T_e(r)^{-0.5} \nu^{-2.0}$$
$$\times [\ln(4.955 \times 10^{-2} \times \nu^{-1}) + 1.5 \ln T_e(r)] N_i(r) N_e(r) d\Omega dl \,, \tag{7}$$

in which ν is given in GHz. This equation is for the optically thin case and can be written as

$$T_C = a(\nu, T_e) \, \nu^{-2.1} \frac{8.235 \times 10^{-2}}{\Omega} \int T_e(r)^{-0.35} N_i(r) N_e(r) d\Omega dl \,. \tag{8}$$

The factor $a(\nu, T_e)$ has been tabulated by Mezger and Henderson (1967), and from their table it can be seen that for a given frequency $a(\nu, T_e)$ is a very slowly varying function of temperature. In the following discussion we shall adopt $a(\nu, T_e) = 1$.

From equations (2), (3), (5), (6), and (8) it is noticeable that the observed parameters depend on different functions of the electron temperature weighted by the square of the density times the volume considered; and if there are temperature fluctuations in such a volume, the observed temperatures will, in general, differ from the average temperature. We will forthwith analyze these differences.

The average temperature weighted by the square of the density over the volume considered is given by

$$T_0(N_i, N_e) = \frac{\int T(r) N_i(r) N_e(r) d\Omega dl}{\int N_i(r) N_e(r) d\Omega dl} \,, \tag{9}$$

and for the case of forbidden lines N_i is replaced by $N(X^{+p})$. When the temperature is derived from a parameter that depends on the αth power of the local temperature, we have

$$\langle T^\alpha \rangle = \frac{\int T^\alpha(r) N_e(r) N_i(r) d\Omega dl}{\int N_e(r) N_i(r) d\Omega dl} \,, \tag{10}$$

which, for the case of small fluctuations, can be expanded in a Taylor series about the mean temperature thereby yielding a temperature

$$T_\alpha = \langle T^\alpha \rangle^{1/\alpha} \approx T_0 \left(1 + \frac{\alpha - 1}{2} t^2\right), \qquad \alpha \neq 0, \qquad t^2 \ll 1, \tag{11}$$

where terms of higher order in t have been neglected. Here t is the root mean square temperature fluctuation and is given by

$$t^2 = \left\langle \left[\frac{T(r) - T_0}{T_0}\right]^2 \right\rangle = \frac{\int T^2(r) N_e(r) N_i(r) d\Omega dl - T_0^2 \int N_e(r) N_i(r) d\Omega dl}{T_0^2 \int N_e(r) N_i(r) d\Omega dl}. \tag{12}$$

To obtain a value of the temperature we need to use a ratio of two parameters integrated over the volume considered. Of course no value of the temperature could be derived if the temperature dependence of these two parameters were the same, since the ratio would be independent of the temperature. Therefore, either the ratio of two forbidden lines of the same atom and different ΔE or that of equations (3) and (5) or (6) and (8) is needed.

In the case of a temperature derived from two powers of the temperature, the ratio of the powers can be expressed in terms of series expansions about T_0 and approximated by

$$\frac{\langle T^\alpha \rangle}{\langle T^\beta \rangle} = \frac{\int T^\alpha(r) N_e(r) N_i(r) d\Omega dl}{\int T^\beta(r) N_e(r) N_i(r) d\Omega dl} \approx \frac{T_0^\alpha [1 + \frac{1}{2}\alpha(\alpha - 1) t^2]}{T_0^\beta [1 + \frac{1}{2}\beta(\beta - 1) t^2]}, \tag{13}$$

the temperature is then

$$T_{\alpha/\beta} = \left(\frac{\langle T^\alpha \rangle}{\langle T^\beta \rangle}\right)^{1/(\alpha-\beta)} \approx T_0 \left(1 + \frac{\alpha + \beta - 1}{2} t^2\right), \qquad \alpha \neq \beta, \qquad t^2 \ll 1. \tag{14}$$

The fact that α and β are added expresses the physical situation that in the case of α and β negative the two observed fluxes favor low-temperature regions and therefore the result of combining these two observations yields a temperature lower than the average.

Similarly, for the case of a temperature derived from the ratio of two forbidden lines, the flux can be written as a Taylor series about the average temperature

$$I(X^{+p}, \lambda_{nm}) \approx C T_0^{-1/2} \exp(-\Delta E / k T_0) \int N(X^{+p}, r) N_e(r)$$
$$\times \left\{1 + \left(\frac{\Delta E}{k T_0} - \frac{1}{2}\right) \frac{T(r) - T_0}{T_0} + \left[\left(\frac{\Delta E}{k T_0}\right)^2 - 3\frac{\Delta E}{k T_0} + \frac{3}{4}\right] \frac{1}{2} \left(\frac{T(r) - T_0}{T_0}\right)^2 \right\} d\Omega dl.$$

From this relation, equations (9) and (12), and the assumption of small temperature variations we obtain the following

$$\frac{I(X^{+p}, \lambda_{nm})}{I(X^{+p}, \lambda_{n'm'})} \equiv \exp\left[-\frac{\Delta E - \Delta E^*}{k T_{(\lambda_{nm}/\lambda_{n'm'})}}\right]$$
$$\approx \exp\left[-\frac{\Delta E - \Delta E^*}{k T_0}\right] \left\{1 + \frac{\Delta E - \Delta E^*}{k T_0} \left(\frac{\Delta E + \Delta E^*}{k T_0} - 3\right) \frac{t^2}{2}\right\}.$$

Therefore, the derived temperature is related to the average temperature by

$$T_{(\lambda_{nm}/\lambda_{n'm'})} \approx T_0 \left[1 + \left(\frac{\Delta E + \Delta E^*}{k T_0} - 3\right) \frac{t^2}{2}\right], \qquad \Delta E \neq \Delta E^*, \qquad t^2 \ll 1, \tag{15}$$

where ΔE and ΔE^* represent the differences in energy between the upper levels of each of the transitions and the ground level.

Assuming small fluctuations, we have from equations (3), (5), and (14):

$$T_{(\mathrm{Bac/H}\beta)} = T_0(1 - 1.70\, t^2), \tag{16}$$

and from equations (6), (8), and (14):

$$T_{(\Delta\nu T_L/T_C)} = T_0(1 - 1.42\, t^2)\,. \tag{17}$$

In the case of λ4363 and λ5007 of O^{++} from equations (2) and (15), we have

$$T_{(4363/5007)} = T_0\left[1 + \tfrac{1}{2}\left(\frac{90800}{T_0} - 3\right)t^2\right]. \tag{18}$$

If $(\Delta E + \Delta E^*)/(kT_0)$ is larger than 3, which is the case both for the temperatures encountered in H II regions and for optical lines, the forbidden-line method emphasizes the high-temperature regions while the other two methods favor the low-temperature ones.

To show the extent to which temperature fluctuations inside an H II region affect the observed values, predictions can be made from theoretical models. For this purpose the model by Hjellming (1966), with $T_{\rm star} = 40000°$ K, $N_e = 10$, and $N_{\rm He}/N_{\rm H} = 0.15$, was used. In order to obtain the temperatures and mean square fluctuations given in Table 1, we integrated over a volume from $0.10\, R_s < r < 0.95\, R_s$, where R_s is the Strömgren radius.

TABLE 1

PREDICTED TEMPERATURES AND FLUCTUATIONS FROM HJELLMING'S MODEL

	T_0 (°K)	t (per cent)	$T_{(\rm Bac/H\beta)}$ (°K)	$T_{(\Delta\nu T_L/T_C)}$ (°K)	$T_{(4363/5007)}$ (°K)
Integrations weighted by $N_i N_e$	5550	19 5	5200	5250	.....
Integrations weighted by $N(O^{++}) N_e$......	5500	18 9	.....	.....	6850

We were not able to predict the temperature for O^+ because the largest contribution to the integral originates in the region comprised within $0.95\, R_s < r < 1.00\, R_s$, which is not considered by Hjellming for this model; however, it can be observed from Hjellming's work that the predicted temperature would be even higher than 6850° K. The difference between the predicted forbidden-line temperature and the two predicted continuum-to-hydrogen-line values is about 1600° K; furthermore, the difference between the predicted temperatures obtained from the Balmer continuum to Hβ ratio and the radio astronomical temperatures is of only 50° K.

As can be seen from equations (16) and (17) and the previous example, the expected temperatures obtained from the Balmer continuum as well as those predicted for the radio astronomical case are very similar; moreover this difference is very insensitive to temperature fluctuations; therefore, by comparing these two temperatures it would be possible to determine the extent of the deviations from thermodynamical equilibrium of the radio lines. These deviations were first suggested by Goldberg (1966) as a plausible explanation for the difference between the observed radio and forbidden-line temperatures. On the other hand, by comparing the Balmer continuum and the forbidden-line temperatures, it will be possible to determine the extent of the spatial temperature fluctuations.

III. OBSERVATIONS AND REDUCTIONS

In the present article only the data relevant to the temperature of the photoelectric study undertaken on M8, M17, and the Orion Nebula will be discussed. The detailed photoelectric observations will be discussed elsewhere (Peimbert 1967).

The measurements were made during 1966 with the spectral scanner designed by Wampler and the Crossley telescope at Lick Observatory. The scanner is digitized and scans at preset wavelengths. It yields a dispersion of 15 Å/mm in the second order and of 30 Å/mm in the first order. For the H II regions the entrance slit used was 0.2 × 3 mm and the exit slot 0.6 × 3 mm, where these dimensions are taken along and perpendicularly to the dispersion. The entrance slit corresponds to 8″ of declination and 120″ of right ascension on the sky. The exit slot size was chosen with three requirements in mind: (1) its capacity to measure all the line, as shifts of 1 or 2 Å could be expected in the setting, (2) that it be large enough to comprise a good fraction of the continuum, and (3) that it be small enough to find several wavelength intervals without any conspicuous emission lines. For the standard stars usually a circular diaphragm of 40″ or 28″ in diameter was used, and exit slots of 1 or 0.6 mm were used. The calibration to absolute fluxes was carried out by observing the stars measured by Oke (1964) modified by more recent data. An ITT blue cell FW-130 with a modified cathode of 0.25 inch was used from λ3200 to λ7400, and an RCA 7102 cell from λ5600 to λ11000. All measurements entering directly into the temperature equations were obtained with the blue cell.

Two central points of the Orion Nebula and the regions in M8 and M17 were chosen because of their high surface brightness; a third point in the Orion Nebula was selected because its emitted flux is three times weaker than the central flux, making it a more representative region of the Orion Nebula. The coordinates for the center of the observed regions are given in Table 2.

TABLE 2

POSITIONS OF THE OBSERVED H II REGIONS

Observed Region	Reference Star	Coordinates Relative to Star	
		$\Delta\alpha$	$\Delta\delta$
Ori I. . .	θ^1 Ori	0″	+35″
Ori II. . .	θ^1 Ori	0	−35
Ori III . . .	HD 37042	0	+35
M8 I. . .	9 Sag	−175	−90
M17 I. . .	BD−16°4818	+135	+15

The nebular to auroral line ratios of N^+, O^+, and O^{++} were measured in the five points. The Balmer jump was measured only in the three Orion regions. Since the auroral lines are very weak, long integration times were necessary, each region was observed several times with sky measurements in between, and every time that a region was observed many scans were carried out. At least one continuum point at each side of the emission lines was measured to evaluate and subtract the contribution of the continuum to the emission lines.

The results for the emission lines are given in Table 3, where $F(\lambda)/F(H\beta)$ is the observed line flux compared to that of Hβ, and $I(\lambda)/I(H\beta)$ is the relative flux after correcting for reddening. The last two rows show the values of $C_{H\beta}$, the reddening logarithmic correction for Hβ (defined as c by Seaton 1960), and of $F(H\beta)$, the observed flux in ergs cm^{-2} sec^{-1}.

It is difficult to determine the intensity of the high-order Balmer lines since the continuum emission in the Orion Nebula (O'Dell and Hubbard 1965; Mendez 1965) is considerable, and a large fraction of it is due to dust-scattered starlight showing the Balmer lines in absorption. In order to estimate the underlying absorption, we assumed that the continuum is due only to atomic processes and scattered light; then computed the fraction of the continuum due to atomic processes from the work by Seaton (1960). We found that it amounted to 24 per cent for Ori I, 20 per cent for Ori II, and 12 per cent for Ori III at λ3845. From the equivalent width of λ3835 of the Trapezium stars we then estimated that the underlying absorption in the continuum at λ3835 amounted

TABLE 3

OBSERVATIONS OF LINE INTENSITIES

Wavelength	Ion	Ori I log $F(\lambda)/F(H\beta)$	Ori I log $I(\lambda)/I(H\beta)$	Ori II log $F(\lambda)/F(H\beta)$	Ori II log $I(\lambda)/I(H\beta)$	Ori III log $F(\lambda)/F(H\beta)$	Ori III log $I(\lambda)/I(H\beta)$	M8 I log $F(\lambda)/F(H\beta)$	M8 I log $I(\lambda)/I(H\beta)$	M17 I log $F(\lambda)/F(H\beta)$	M17 I log $I(\lambda)/I(H\beta)$
3726, 3729	[O II]	−0.07	+0.05	−0.07	+0.06	+0.26	+0.34	+0.12	+0.29	−0.48	+0.05
3835	H9	−1.22	−1.14	−1.25	−1.16	−1.20	−1.13	.	. .	.	. .
4102	Hδ	−0.64	−0.58	−0.65	−0.58	−0.64	−0.58	−0.67	−0.56	−0.85	−0.56
4340	Hγ	−0.36	−0.32	−0.38	−0.33	−0.35	−0.31	−0.37	−0.30	−0.51	−0.32
4363	[O III	−1.96	−1.92	−1.92	−1.88	−2.31	−2.28	−2.49	−2.42	−2.18	−1.99
4861	Hβ	0.00	0 00	0.00	0.00	0.00	0 00	0.00	0.00	0.00	0.00
5007	[O III]	+0.60	+0.59	+0.54	+0.53	+0.14	+0.13	+0.24	+0.24	+0.60	+0.55
5755	[N II]	−2.00	−2.09	−1.97	−2.06	−1.94	−2.01	−2.08	−2.19	−2.58	−2.85
6584	[N II]	−0.19	−0.38	−0.09	−0.28	+0.11	−0.06	+0.11	−0.08	−0.06	−0.55
7320, 7330	[O II]	−0.88	−1.14	−0.70	−0.96	−0.84	−1.06	−0.94	−1.28	−1.10	−1.76
$C_{H\beta}$*		+0.81		+0.81		+0.68		+ 0.50		+ 1.32	
log $F(H\beta)$†	. .	−9.20		−9.25		−9 48		−10.22		−10.63	

* $C_{H\beta}$ is the reddening logarithmic correction.

† $F(H\beta)$ is the observed flux in ergs cm^{-2} sec^{-1}.

to 5 per cent for Ori I and II, and to 10 per cent for Ori III. This correction was taken into account in Table 3. For the other Balmer lines listed in Table 3, this effect is negligible but for higher-order Balmer lines it should be considered.

The reddening correction for the Orion Nebula was obtained from the reddening law determined by Johnson and Borgman (1963) and by fitting the $H\beta/H\gamma$ and $H\beta/H\delta$ ratios to the Balmer decrement computed by Clarke (1965) for case B, $T_e = 10000°$ K and collisional redistribution for $n \leq 20$.

For M8 and M17 the reddening function tabulated by Seaton (1960) was used; the logarithmic value at $H\beta$ obtained for M8 showed a difference of only 0.02 from that adopted by O'Dell, Hubbard, and Peimbert (1966), but the value for M17 was 0.32 larger than the one used by O'Dell (1966).

The estimated errors in the relative line intensities after taking into account reddening corrections and errors in the absolute calibrations amounted to less than 0.04 in the logarithm, with the exception of the auroral lines in M8 and M17 for which the errors can be twice as large.

In order to obtain the temperatures from the forbidden lines, the following equations were adopted (see Aller and Liller 1967):

$$\frac{I(5007+4959)}{I(4363)} = \frac{10.3 \times 10^{14300/T_e}}{1+0.013x}, \tag{19}$$

$$\frac{I(6548+6548)}{I(5755)} = \frac{11.9 \times 10^{10900/T_e}}{1+0.37x}, \tag{20}$$

and

$$\frac{I(3726+3729)}{I(7320+7330)} = \frac{13.70}{\epsilon} \frac{1+0.13\epsilon+5.3x(1+0.60\epsilon+0.07\epsilon^2)}{1+23.8x(1+0.23\epsilon)+61.2x^2(1+0.61\epsilon+0.07\epsilon^2)} \tag{21}$$

where

$$x = 10^{-2} N_e T_e^{-1/2}\,, \tag{22}$$

and

$$\epsilon = \exp\,(-19600/T_e)\,. \tag{23}$$

For the H II regions considered, equation (19) is a function of the temperature only since the x-term is negligible. In equations (20) and (21) the x-term cannot be neglected, however, since the ionization potentials of O^+ and N^+ are very similar, we can assume that the corresponding forbidden lines originate within the same regions and treat equations (20) and (21) as two simultaneous equations on x and T_e. The temperature thus obtained depends mainly on the [N II] auroral to nebular line ratio. On the other hand, the value for x depends on the [O II] auroral to nebular line ratio, but due to the large differential reddening correction, x is not as accurate as the temperature.

The values of x obtained from our observations are the following: 0.19 for Ori I, 0.40 for Ori II, 0.16 for Ori III, 0.11 for M8 I, and 0.08 for M17 I.

Table 5 (see below) lists the temperatures for Ori I, Ori II, Ori III, M8 I, and M17 I as derived from our observations. In this same table the listed temperatures by Aller and Liller (1959) for the Orion Nebula and by O'Dell (1966) for M8 and M17 are values that we recomputed from their observational data by means of equation (19), which takes into account more recent determinations of cross-sections. The differences between the old and new cross-sections amount to a difference of several hundred degrees in the derived temperatures.

To measure the Balmer continuum in the Orion Nebula, we selected eight wavelength intervals 9 Å wide, centered at λλ3504, 3520, 3570, 3620, 3742, 3780, 3810, 3845. The observed and intrinsic fluxes for the Orion Nebula are given in Table 4. All the observations were photoelectrical, adopting the same procedure and reddening corrections followed for the emission lines. Table 4 shows the average values of four photometric nights. From the work by Kaler, Aller, and Bowen (1965) on the emission spectrum of the Orion Nebula, it was estimated that less than 3 per cent of the flux in the wavelength intervals considered was due to emission lines. In order to obtain the value of the flux at 3646^- and at 3646^+, we extrapolated the values of the first and last four points, respectively. These extrapolated values show a blue gradient similar to that of the Trapezium stars, which is consistent with the fact that a large fraction of the continuum is due to dust-scattered light from the Trapezium.

TABLE 4

CONTINUUM OBSERVATIONS

WAVELENGTH	ORI I		ORI II		ORI III	
	1000 $f(\lambda)/F(H\beta)$*	1000 $i(\lambda)/I(H\beta)$†	1000 $f(\lambda)/F(H\beta)$	1000 $i(\lambda)/I(H\beta)$	1000 $f(\lambda)/F(H\beta)$	1000 $i(\lambda)/I(H\beta)$
3504	6 25	9 28	6 30	9 36	9 90	13 8
3520	6 14	9 11	6 42	9 54	9 90	13 8
3570. .	6 42	9 36	6 66	9 73	9 81	13 5
3620 . .	6 25	9 03	6 80	9 81	9.90	13 5
3646^-....	..	9 20‡	..	9 90‡	. ..	13 5‡
3646^+....	. .	3 96‡	. ..	4 32‡	. ..	7 71‡
3742	2 56	3.63	2 85	4 05	5 25	7 04
3780...	2 42	3 40	2 63	3 70	4 96	6 60
3810 ..	2 38	3 35	2 58	3 63	4 91	6.55
3845 ...	2 26	3 16	2.49	3 46	4 82	6 36

* $f(\lambda)$ is the observed flux in ergs cm^{-2} $Å^{-1}$ sec^{-1}.
† $i(\lambda)$ is the intrinsic flux in ergs cm^{-2} $Å^{-1}$ sec^{-1}.
‡ Extrapolated values.

To obtain the temperatures, we used the b_4 values computed by Clarke (1965), equations (3) and (4), and the values for the Balmer continuum obtained from Table 4 where $I(\text{Bac}, 3646) = I(3646^-) - I(3646^+)$. The results are shown in Table 5, where the errors were obtained from an estimated 0.05 probable error in the logarithm of the Balmer continuum to Hβ intensity ratio. The errors in the temperatures derived from the Balmer continuum are larger than for the forbidden-line temperatures, because this method is less sensitive to the temperature than the forbidden-line procedure.

IV. DISCUSSION

All the photoelectric observations of auroral to nebular line ratios in the literature are presented in Table 5, together with our results on the intensity ratios of auroral to nebular lines and Balmer continuum to Hβ lines. Also included are some of the best radio observations of Orion, M8, and M17. The values by Dieter (1967) refer to the 158α line and were obtained with a beam width of 31'.4 × 35'.6. Observations by Mezger and Höglund (1967) refer to the 109α line of hydrogen and a beam width of 6'.45 × 6'.3.

Since the Balmer-continuum temperature is an average over the whole volume, it has to be compared not only with the O^{++} temperature that refers mainly to the high-ionization regions, but also to the O^+ and N^+ temperatures that refer to the low-ionization ones. It is clearly shown in Table 5 that the Balmer-continuum temperatures are substantially smaller than those obtained by means of the forbidden lines, hence proving the existence of large temperature fluctuations in the regions considered.

To compare the Balmer-continuum temperature with those obtained from transitions between highly excited levels of hydrogen, the observations should refer to the same volume. In general, the solid angles observed in radio frequencies are larger and include the optical angles. However, in the Orion Nebula, the flux is highly concentrated toward the center (Osterbrock and Flather 1959; Menon 1961), and the integrated observations over the nebula refer principally to the central regions.

The comparison between the temperature of Ori III and the value by Mezger and Höglund is the best that can be made because, in terms of flux, Ori III is a typical subregion of the volume measured by Mezger and Höglund. It is thus seen that temperatures obtained from the free-free to bound-bound ratio are substantially smaller than those from the forbidden lines and very similar to those from the Balmer continuum, which proves that the main difference in the Orion Nebula between radio and forbidden-line temperatures is caused by temperature fluctuations inside the nebula. Nevertheless, due

TABLE 5

TEMPERATURES OF H II REGIONS

Region	$T_{(4363/5007)}$ (°K)	$T_{(3727/7325)}$, (5755/6584) (°K)	$T_{(\mathrm{Bac}/\mathrm{H}\beta)}$ (°K)	$T_{(\Delta\nu T_L/T_C)}$ (°K)	Sources of T_e
Ori I	8900 ± 300	13700 ± 800	7100^{+1600}_{-1200}		Peimbert
Ori II	9450 ± 300	12400 ± 800	6500^{+1500}_{-1100}		Peimbert
Ori III	9450 ± 300	10500 ± 800	6100^{+1400}_{-1000}	...	Peimbert
Orion	10000 ± 300	...	...	...	Aller & Liller (1959)
Orion	...	...		6400^{+680}_{-1500}	Mezger & Höglund (1967)
Orion	...	...	...	6460 ± 500	Dieter (1967)
M8 I	8100 ± 500	9400 ± 700			Peimbert
M8	9000 ± 300	...	...		O'Dell (1966)
M8				5790^{+880}_{-1410}	Mezger & Höglund (1967)
M8	...	...	...	4570 ± 980	Dieter (1967)
M17 I	8700 ± 600	8100 ± 500			Peimbert
M17	8100 ± 300		...	...	O'Dell (1966)
M17	...		...	4910^{+520}_{-1150}	Mezger & Höglund (1967)
M17		...	...	3310 ± 460	Dieter (1967)

to the high probable errors, the radio temperatures can be smaller than the Balmer-continuum temperatures and a fraction of the difference between the radio and forbidden lines might then be attributed to deviations from thermodynamical equilibrium, as suggested by Goldberg (1966). The effect of these deviations is to overpopulate the high-energy levels of hydrogen by stimulated emission, producing stronger line emissions and consequently lower radio-measured temperatures than those obtained by means of the Balmer continuum to Hβ intensity ratio.

From Table 5 it is evident that the forbidden-line temperatures as well as those obtained from radio observations for M8 and M17 are very different. These differences are a consequence of at least four causes: (1) the temperature fluctuations present in the volumes considered; (2) the observations do not refer to the same solid angle; (3) the possible deviations from thermodynamical equilibrium of the high-energy levels of the hydrogen atoms; and (4) the differential effect of the antenna angular response on the observations of the line and the continuum as discussed by Dieter (1967).

From the equations derived in § II it is clear that the average temperature is intermediate between the forbidden line temperature and the temperatures obtained, from the intensity ratios of both the Balmer continuum to Hβ emission and the hydrogen lines to continuum in the radio region.

V. CONCLUSIONS

The effect of temperature fluctuations inside H II regions on the values determined from different physical processes was found to be very significant.

By computing observable temperatures from theoretical models it was found that there are large differences in the predicted values by each of the different methods.

From new photoelectric observations it was found that temperature fluctuations inside the Orion Nebula amount to a few thousand degrees. The existence of these temperature fluctuations was proven by comparing the Balmer-continuum and the forbidden-line temperatures.

The main fraction of the temperature difference between the forbidden-line and the radio temperatures in the Orion Nebula was found to be due to temperature fluctuations inside the nebula, and not to the effect of deviations from thermodynamical equilibrium of the high-energy levels of the hydrogen atom. This result was determined from the comparison of the Balmer-continuum and radio temperatures.

In M8 and M17 there is also a large difference between the radio and forbidden-line temperatures; however, without additional information, i.e., Balmer-continuum measurements or more radio observations with the same telescope at different frequencies, it is not possible to ascertain the relative role that spatial temperature fluctuations and deviations from thermodynamical equilibrium have on this difference.

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