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Some physical parameters of early-type stars

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Using recent calibrations of the absolute magnitudes and temperatures and modern model atmospheres, six parameters of early-type stars have been computed. These parameters are the absolute luminosity, the radius, the flux of Lyman continuum photons, the excitation parameter, the fraction of the total energy emitted in the Lyman continuum, and the ratio of the total luminosity of the stars to the expected Lyman–alpha luminosity. The calculations have been performed for spectral types from B3 to O4 and for zero-age main sequence (ZAMS) stars, dwarfs (V), giants (III), and supergiants (I). Some of the above listed parameters have been computed also for central stars of planetary nebulae. A critical comparison with previous calculations is made. A brief discussion about the interpretation of the radio and infrared observations of HII regions and planetary nebulae is also presented.

INTRODUCTION

RECENTLY from a set of homogeneous observational data, new absolute magnitude (Conti and Alschuler 1971) and temperature (Conti 1973) scales for *O*-type stars have been derived. The temperature scale has been obtained by comparing the optical line strengths with those predicted by NLTE model atmospheres calculations (Auer and Mihalas 1972), which, according to the authors, are to be regarded as quantitatively reliable. Therefore it is worthwhile now to derive a complete set of the main physical parameters of the early-type stars, which are consistent either with the refined observational results or with the best available stellar atmosphere models.

The calculations have been performed for zero-age-main-sequence stars (ZAMS), dwarfs (V), giants (III) and supergiants (I), and cover the range of spectral types from O4 to B3. The computed parameters of each star are the absolute luminosity, the radius, and four quantities which concern a possible nebulosity surrounding a star, namely, the flux of Lyman-continuum photons, N_L, the corresponding excitation parameter, U, the fraction of the energy emitted in the Lyman continuum, P, and the ratio of the total luminosity of the star to the expected Lyman–alpha line luminosity, α_∞.

A discussion about the implications of the present results on the interpretation of the observations of H II regions is presented in the last section. Some parameters of the nuclei of planetary nebulae are also derived and their implications are discussed.

I. THE BASIC DATA

A. Absolute Visual Magnitudes

Conti and Alschuler (1971) derived an M_V-spectral type calibration for O-stars, which ranges from O4 to O9.5 for ZAMS and supergiant stars, and from O6.5 to O9.5 for dwarfs and giants. They also estimated the probable deviation from the average values to be about ± 0.5 mag. Bearing this in mind, their compilation can be considered to be in good agreement with that of Walborn (1972), even if some differences are present. On the other hand, Conti (1973) from the same set of observations, derived a temperature scale for the O-stars which is needed to obtain all the other parameters. Therefore, in order to minimize the errors arising from the use of a nonhomogeneous set of data, the Conti and Alschuler's calibration has been adopted here. The values up to O4 for dwarfs and giants have been obtained by interpolation over the corresponding values of the other luminosity classes, also taking as a reference Walborn's calibration.

The absolute magnitudes of ZAMS B-stars are those given by Morton and Adams (1968). For the other luminosity classes, the absolute magnitudes have been derived combining the compilations of Blaauw (1963), Schimdt-Kaler (1965) and Walborn (1972). The adopted values are shown in Table I.

B. The Temperatures

The temperature scale adopted here is based on Conti's calibration for O-type stars (Conti 1973) and that of Morton and Adams (1968) for the B-type stars. As pointed out by Conti, his temperature scale for O-type stars is not very dissimilar from most of the scales derived by other authors on different bases. Conti's temperature scale has been obtained from an accurate comparison of the strengths of lines sensitive to NLTE effects with those predicted from NLTE model atmospheres (Auer and Mihalas 1972). These models are indeed able to account for most of the apparent discrepancies introduced by LTE analyses of the spectra. Therefore, the temperature scale of Conti anc be regarded as reliable.

As the two scales for ZAMS stars fit smoothly with each other (Conti 1973) no adjustments are needed.

To complete the temperature scale over all the spectral types and the luminosity classes, the following assumptions have been made:

(i) The temperature of the dwarfs (V) is the same as that of ZAMS stars;

TABLE I. Temperatures, Absolute Magnitudes, Luminosities, and Radii.

SP	T_{eff} ZAMS-V	T_{eff} III	T_{eff} I	M_V ZAMS	M_V V	M_V III	M_V I	$\log L/L_\odot$ ZAMS	$\log L/L_\odot$ V	$\log L/L_\odot$ III	$\log L/L_\odot$ I	$\log R/R_\odot$ ZAMS	$\log R/R_\odot$ V	$\log R/R_\odot$ III	$\log R/R_\odot$ I
O4	50 000	47 500	45 000	−6.1	−6.1	−6.3	−6.5	6.11	6.11	6.12	6.13	1.18	1.18	1.23	1.29
O5	47 000	44 500	42 000	−5.6	−5.8	−6.0	−6.4	5.83	5.92	5.93	6.00	1.10	1.14	1.20	1.28
O5.5	44 500	42 500	40 000	−5.2	−5.5	−5.8	−6.3	5.60	5.74	5.78	5.89	1.03	1.10	1.16	1.27
O6	42 000	40 000	38 000	−4.9	−5.3	−5.6	−6.3	5.40	5.56	5.63	5.82	0.98	1.06	1.14	1.28
O6.5	40 000	38 000	36 000	−4.5	−5.0	−5.5	−6.3	5.17	5.37	5.50	5.75	0.91	1.01	1.12	1.29
O7	38 500	36 500	35 000	−4.2	−4.8	−5.5	−6.3	5.00	5.24	5.45	5.72	0.86	0.98	1.13	1.30
O7.5	37 500	35 500	34 000	−4.1	−4.6	−5.5	−6.4	4.92	5.11	5.41	5.73	0.84	0.94	1.13	1.33
O8	36 500	34 500	33 000	−3.9	−4.5	−5.5	−6.5	4.81	5.05	5.38	5.74	0.81	0.93	1.14	1.36
O8.5	35 500	33 500	32 000	−3.8	−4.4	−5.5	−6.6	4.73	4.97	5.35	5.75	0.79	0.91	1.15	1.39
O9	34 500	33 000	31 000	−3.7	−4.3	−5.5	−6.7	4.66	4.90	5.34	5.76	0.78	0.90	1.16	1.42
O9.5	33 000	31 500	30 000	−3.6	−4.2	−5.5	−6.7	4.58	4.82	5.30	5.73	0.78	0.90	1.18	1.44
B0	30 900	29 300	28 000	−3.3	−4.0	−5.0	−6.6	4.40	4.68	5.03	5.63	0.74	0.88	1.11	1.45
B0.5	26 200	25 000	23 600	−2.8	−3.5	−4.3	−6.6	4.04	4.31	4.57	5.48	0.71	0.85	1.02	1.52
B1	22 600	21 500	20 400	−2.3	−2.9	−3.8	−6.6	3.72	3.95	4.27	5.32	0.68	0.79	1.00	1.57
B2	20 500	19 500	18 500	−1.9	−2.5	−3.6	−6.8	3.46	3.70	4.09	5.28	0.63	0.75	0.99	1.63
B3	17 900	17 000	16 100	−1.1	−1.7	−3.1	−6.8	3.02	3.24	3.75	5.20	0.53	0.64	0.94	1.71

(ii) For supergiants with spectral type earlier than O6.5 and later than O9.5, the temperature is 0.9 times that of the ZAMS stars with the same spectral type. This relationship reproduces very well the available values in Conti's calibration and should give the appropriate temperatures for the other spectral types;

(iii) The effective temperatures of giants (III) have been taken as 0.95 times the temperature of ZAMS stars with the same spectral type.

The adopted values are summarized in Table I.

II. COMPLEMENTARY THEORETICAL DATA

A. The Bolometric Correction

To derive the bolometric correction, three sets of model atmospheres are available in the literature, namely:

(i) LTE unblanketed models (Mihalas 1969, Hummer and Mihalas 1970b);

(ii) LTE blanketed models (Hickock and Morton 1968, Bradley and Morton 1969, Van Citters and Morton 1970);

(iii) NLTE unblanketed models (Auer and Mihalas 1972).

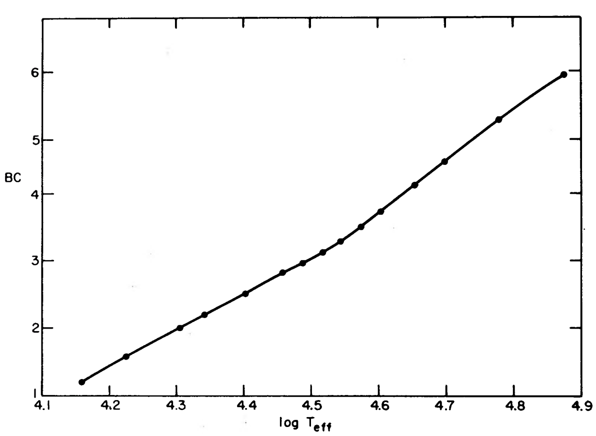

FIG. 1. Bolometric correction as a function of the temperature. The dots indicate the values from actual model atmospheres.

A comparison of these models with each other leads to the following results:

(1) For a given set of models, the optical fluxes remain the same, within a few percent, when the gravity is changed;

(2) When the blanketing of UV lines is not included [sets (i) and (iii)], the optical fluxes are essentially the same, either with or without the LTE assumption;

(3) The blanketed models give optical fluxes which are systematically higher than those of the unblanketed models.

It is then possible to conclude that the model atmospheres of Morton and co-workers should provide the best available prediction of the actual optical fluxes. Furthermore, the effect of changing the gravity can be regarded as completely negligible in this context. Therefore, the bolometric corrections derived by Morton (1969) and Van Citters and Morton (1970) have been adopted for all the luminosity classes. The resultant curve BC versus $\log T_{eff}$ is shown in Fig. 1.

B. The Lyman-Continuum Photon Flux

The number of photons of the Lyman continuum coming from a square centimeter of stellar surface per second, $N_L{}^0$, is defined by

$$N_L{}^0 = \int_{\nu_0}^{\infty} \frac{\pi F(\nu)}{h\nu} d\nu, \tag{1}$$

where ν_0 is the frequency at the Lyman edge and $F(\nu)$ is the energy flux. The integration is extended up to infinite frequency (although a photon with $\nu \geq 1.808\nu_0$ may be absorbed by neutral helium, almost every subsequent recombination of helium leads finally to the emission of one photon which is able to ionize hydrogen but not helium). Here a comparison of the various sets of model atmospheres is worthwhile. The values of $N_L{}^0$ for the NLTE models of Auer and Mihalas (1972) as well as those of the LTE blanketed models with $\log g = 3.5$ (Bradley and Morton 1969) have been obtained by integrating over the published fluxes, while the other values have been taken directly from the papers (Morton 1969, Van Citters and Morton 1970, Hummer and Mihalas 1970a). The NLTE models with $\log g$ ranging from 3.3 to 3.5 have been assumed to be representative of a unique class of atmospheres. The resulting curves $\log N_L{}^0$ versus $\log T_{\rm eff}$ are shown in Fig. 2. For reference the curve corresponding to black body emitters is also shown. It is immediately clear that a black body spectrum would provide too high an estimate of the ionizing flux for all but the highest temperatures.

The main points which arise from a comparison of the various sets of calculations are the following:

(i) For $\log g = 4$ the NLTE models give ionizing fluxes which are greater than the corresponding values of the LTE unblanketed models but are smaller than those of the LTE blanketed models. These differences, which at the lowest temperatures are conspicuous, are decreasing as the temperature increases and all the values are virtually the same for temperatures above 40 000°K. This means that for this value of gravity the blanketing effects of UV lines is dominant over the NLTE effects, both becoming smaller and smaller as the temperature increases;

(ii) For $\log g = 3.3$–3.5 the behavior is reversed: in this case the NLTE models are those which give the highest fluxes of ionizing photons. In fact, a lower gravity implies a lower average density in the atmosphere and it is not surprising that the NLTE effects are now dominant;

(iii) At the highest temperatures all the models tend to give almost equal values; also they are nearly coincident with the black-body curve.

Conti (1973) found that $\log g \approx 4$ and $\log g \approx 3.4$ should be appropriate for dwarfs and supergiants, respectively. Therefore, the results of Morton and co-workers up to $T_{\rm eff} = 37\,500$°K and those of Auer and Mihalas for $T_{\rm eff} > 37\,500$°K and for $\log g = 4$ have been adopted to match the N_L–$T_{\rm eff}$ relationship of ZAMS and class V stars, while Auer and Mihalas' curve for $\log g = 3.3$–3.5 has been taken as representative of the supergiant stars. For temperatures higher than 40 000°K, the curve for supergiants has been extrapolated taking the black-body curve as an asymptotic limit, while for temperatures lower than 30 000°K, the curve has been assumed to be a straight line in the logarithmic plot joining the ZAMS point at $T_{\rm eff} = 14\,400$°K. As no finer grids of model atmospheres are available, the curve appropriate for giants has been assumed to be merely intermediate, at half-way in the logarithmic plot, between those of the main-sequence stars and the supergiants.

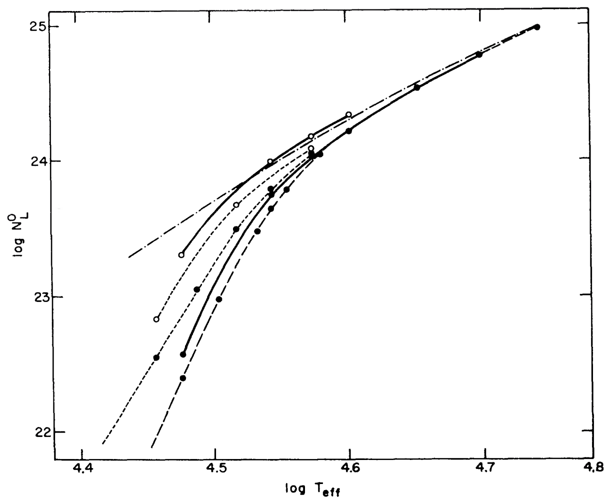

FIG. 2. The logarithm of the Lyman continuum flux (photons/cm²s) versus the logarithm of the temperature. Circles denote supergiant star models and dots main-sequence star models. Continuous lines connect the values from Auer and Mihalas (1972) models, short-dashed lines those from Morton and co-workers calculations, and long-dashed lines those from Mihalas (1969) and Hummer and Mihalas (1970a) models. For comparison, the line of a black-body spectrum is also drawn as a dashed-dotted line.

It is to be noted that the values adopted here are the highest resulting from model atmosphere calculations but still they may be somewhat underrated. In fact, an ideal NLTE blanketed model should have a Lyman-continuum flux higher than that of an LTE unblanketed model due to both the blanketing of UV lines and the NLTE effects on the Lyman-continuum opacity. As the models available in the literature have been constructed neglecting at least one of these effects, the computed Lyman continuum fluxes are underestimates. However, judging from Fig. 2, the "correct" fluxes should be higher by at most 10% or 20% (by even less at the highest temperatures). Furthermore the fluxes of Morton's models should be corrected to allow for a helium to hydrogen ratio of 0.10 instead of 0.15. This correction would have the effect of increasing the ionizing photon flux, and it should be about 15% (Rubin 1969) or even smaller (Van Citters and Morton 1970).

Finally, the possibility that the atmospheres may be extended should be taken into account. Cassinelli's calculations (1971) indicate that this effect could increase the Lyman continuous radiation sizeably, even by more than 50%, as compared with plane-parallel models. However, extended atmospheres could be a common phenomenon only for the hottest and brightest stars, that is the Of's and some of the supergiants.

In the present context I conclude that the adopted values are fairly reliable, but may be slightly underestimated.

III. THE DERIVED PARAMETERS

With the values of M_V and $T_{\rm eff}$ given in Table I and the bolometric corrections discussed in Sec. IIA, it is possible to derive two stellar parameters, namely, the absolute luminosity and the radius. The formulae are

$$\log L/L_\odot = -0.4(M_V - BC) + 1.888, \tag{2}$$

$$\log R/R_\odot = 0.5 \log L/L_\odot - 2\log(T_{\rm eff}/10^4) - 0.473. \tag{3}$$

The bolometric magnitude of the Sun has been assumed to be 4.72 and the radius of the Sun, 6.960×10^{10} cm (Allen 1963). The results are summarized in Table I.

Four other parameters can be derived, which are more strictly connected with the radiation from a nebulosity associated with a hot star, namely, the total flux of ionizing photons, $N_{\rm L}$, the corresponding excitation parameter, U, the fraction of the radiation emitted shortward of the Lyman edge, P, and the ratio of the total stellar luminosity to the expected Lyman–alpha luminosity, α_∞.

The corresponding formulae are

$$N_{\rm L} = 4\pi R^2 N_{\rm L}^0 \quad \text{Photons/sec}; \tag{4}$$

$$U = 2.01\times 10^{-19}\left[\frac{N_{\rm L}}{\beta-\beta_1}\right]^{\frac{1}{3}} \text{pc cm}^{-2}; \tag{5}$$

$$P = \frac{\int_{\nu 0}^{\infty} F(\nu)\mathrm{d}\nu}{\int_0^{\infty} F(\nu)\mathrm{d}\nu}; \tag{6}$$

$$\alpha_\infty = \frac{\sigma T_{\rm eff}{}^4}{N_{\rm L}{}^0 h\nu(\mathrm{Ly}-\alpha)}. \tag{7}$$

In formula (5), $(\beta-\beta_1)$ represents the recombination rate to the excited levels of hydrogen; it has been assumed to be 3.43×10^{-13}, which corresponds to an electron temperature $T_{\rm e} = 7000$°K. To obtain the values for $T_{\rm e} = 5000$°K and 10 000°K, it is sufficient to divide ($T_{\rm e} = 5000$°K) or multiply ($T_{\rm e} = 10\,000$°K), the present values of U by a factor 1.0976.

For the calculations of P, by means of formula (6), the same selection of stellar atmosphere models as discussed in Sec. IIB has been adopted.

Formula (7), which gives the ratio of the total luminosity to the Ly–α luminosity, corresponds to the assumption that all the recombinations to the excited levels lead to an emission of a Lyman–alpha photon. This is true only when the density is much higher than 10^4 cm^{-3}. To get the correct value of α for any value of the proton density, the finite probability that a recombination to the 2-level leads to a two-photon emission via the 2s-1s transition must be taken into account. Following Gerola and Panagia (1968), it is easily found

$$\alpha \cong \alpha_\infty \frac{1.5 + 1.35\times 10^{-4} N_{\rm P}}{1 + 1.35\times 10^{-4} N_{\rm P}}, \tag{8}$$

$N_{\rm P}$ being the proton density and allowing for a ratio $He/H = 0.1$.

The computed quantities $\log N_{\rm L}$, U, P and α_∞ are shown in Table II.

IV. DISCUSSION

It should be noted that the values given in Tables I and II represent only average values of the various quantities. Conti and Alschuler (1971) and Conti (1973) gave 0$^{\rm m}$.5 and 500°K as an estimate of the intrinsic dispersion of the absolute magnitude and the temperature, respectively, for each spectral type and luminosity class. There is no quantitative estimate of the expected dispersion from the average values for B-type stars; however, the differences in the values given in the various compilations indicate about the same dispersion as for the O-type stars. Such dispersions lead to a possible logarithmic deviation from the average values

TABLE II. Fluxes of Lyman Continuum Photons, Excitation Parameters, Fractional Energy of Lyman Continuum, and Ratio of Stellar Luminosity to Lyman–alpha Luminosity.

	$\log N_{\rm L}$				U (pc cm^{-2})				P ($\times 10^2$)			α_∞		
SP	ZAMS	V	III	I	ZAMS	V	III	I	ZAMS-V	III	I	ZAMS-V	III	I
O4	49.93	49.93	49.93	49.93	126	126	126	126	66	63	61	3.5	3.7	3.1
O5	49.62	49.71	49.71	49.77	99.3	106	106	111	60	57	56	3.9	3.9	4.8
O5.5	49.36	49.50	49.53	49.66	81.3	90.2	92.3	103	54	52	52	4.2	4.3	4.1
O6	49.08	49.24	49.34	49.55	65.6	75.0	80.4	94.2	46	46	46	5.0	4.7	4.5
O6.5	48.82	49.02	49.15	49.43	53.8	62.8	69.2	86.3	40	40	40	5.4	5.4	4.9
O7	48.62	48.86	49.05	49.37	46.3	55.6	64.1	82.1	35	35	37	5.7	6.0	5.3
O7.5	48.51	48.70	49.98	49.34	42.5	49.4	60.8	80.2	31	31	32	6.1	6.5	5.9
O8	48.35	48.59	48.90	49.30	37.4	45.0	57.0	76.9	27	27	25	6.9	7.3	6.7
O8.5	48.21	48.45	48.83	49.22	33.7	40.6	54.2	73.0	23	22	19	7.9	7.9	8.1
O9	48.08	48.32	48.78	49.12	30.1	36.2	52.3	67.9	20	19	13	9.2	8.6	10.3
O9.5	47.84	48.08	48.53	48.97	25.4	30.5	43.2	60.6	14	12	6	13.2	13.9	13.7
B0	47.36	47.63	47.94	48.53	17.6	21.7	23.9	43.2	7	4	<2	26.	29.	30.
B0.5	46.23	46.50	46.80	47.60	7.3	9.1	11.5	21.0	<2	<2	···	>100	>100	>100
B1	45.29	45.52	45.87	46.78	3.5	4.3	5.6	11.2	···	···	···	···	···	···
B2	44.65	44.89	45.25	46.18	2.2	2.6	3.5	6.6	···	···	···	···	···	···
B3	43.69	43.91	44.30	45.57	1.1	1.2	1.7	4.4	···	···	···	···	···	···

of ± 0.22, ± 0.10, ± 0.28, ± 0.09 for the absolute luminosity, the radius, the Lyman-continuum photon flux and the excitation parameter, respectively. These derived deviations are almost entirely due to the large dispersion of M_V and only marginally to the expected dispersion of the temperature. Then the uncertainties in the quantities P and α_0 should be small, of the order of 10%, as they depend only on the temperature (and the gravity).

Possible inaccuracies, due to insufficient theoretical data and/or computational deficiencies, may arise from the derivation of the function $N_L{}^0$ (T_{eff}, g). While for temperatures greater than 30 000°K (that is for the O-stars), it may be wrong at the most by 10%, for lower temperatures (B-stars), it can be affected by an error as large as 30% in the case of the giants and the supergiants, due to the necessity of somewhat arbitrary extrapolations. This error will affect the values of the nebular parameters, essentially N_L and U. However, the intrinsic indeterminantions remain much higher than the theoretical or computational inaccuracies. The expected intrinsic indetermination corresponds to a mismatch of the spectral type of about one subtype, in the sense that a star, which is classified as a O6 V may actually have its parameters corresponding to a labelled O5 V or O7 V star.

Several calculations of the excitation parameters are available in the literature and a comparison of them with the present results is due. For this purpose, the existing tabulations can be divided in two classes: those which approximate the stellar spectrum with a Planckian curve (Gould *et al.* 1963; Murdin and Sharpless 1968, Prentice and ter Haar 1969) and those which are derived from stellar atmosphere calculations (Rubin 1968, Churchwell and Walmsley 1973). It is immediately clear that the excitation parameters of the first class cannot be realistic, as it has been shown in Sec. IIB that the use of a black-body spectrum leads to fluxes of ionizing photons which are too high, even by orders of magnitude at the lowest temperatures.

When the present results are compared with those obtained by Rubin (1968) for main-sequence stars, these latter result to be systematically lower by about a factor 1.5. Part of the difference can be ascribed to the slightly different temperature scale, to the use of Mihalas' unblanketed-LTE models (Mihalas 1965) and to the different assumed electron temperature (10 000°K instead of 7000°K). However, the greatest discrepancy lies in the values of the stellar radii adopted by Rubin, which are smaller than those determined here by an average factor 1.8. On the other hand, the present values of the radii are in good agreement, within 20%, with the radii measured in binary system stars (Harris *et al.* 1963). The fact that the radii adopted by Rubin are underestimated was first recognized by Davidson and Terzian (1969), who suggested to apply a correction factor 1.58 to Rubin's excitation parameters. Such a correction corresponds to increasing Rubin's radii by a factor 2.

Finally, the present results can be compared with the very recent ones of Churchwell and Walmsley (1973). Their values are systematically higher, by about 30%–40%, than those derived here. This is mostly due to the different assumptions about the temperature scale. In fact they adopt a temperature scale which is consistent with LTE models and which gives temperatures somewhat too high. Furthermore they assume that for a given spectral type the temperature is the same whichever is the luminosity class, while Conti (1973) found that this does not hold. Both these facts lead to values of the excitation parameters which are too high, in the same sense as the comparison indicates.

Looking at the values of P, it is interesting to note that the fraction of stellar energy radiated longward of the Lyman edge is at least one-third and on the average even more than one-half the total energy. This implies that in the calculations of the IR emission from dusty H II regions the nonionizing radiation plays such an important role that it cannot be disregarded.

Furthermore the values of α_∞ indicate that for most stars the expected ratio of the total luminosity to the Ly–α luminosity exceeds 5, and only for the hottest stars can that ratio be about 4. Then the fact that in most of the 100μ sources the observed IR flux is about 5.5 times the expected Ly–α flux as derived from the radio measurements (Harper and Low 1971), *does not imply* necessarily that the dust is mixed with the ionized gas. In fact, to match the observed IR luminosity it would be sufficient to postulate a dust envelope *surrounding* the ionized region, thick enough to absorb most of the radiation coming from the central star and the nebula itself in the form of nonionizing photons. Such a model would be able to account very easily for the apparent paradox (Johnson 1973) that just for the H II regions with the lowest column densities ($N_e \times R$) the ratio of the 100μ flux to the 6 cm flux is the highest. On the other hand the rather strict coincidence, in the position and in the shape, of some 20μ sources with compact components in H II regions (Wynn-Williams *et al.* 1972, Lemke and Low 1972), seems to support the idea that at least some dust is really intimately mixed with the ionized gas. Anyhow, it is important to point out that the proof for the coexistence of ionized gas and dust is not an immediate result from a simple comparison of IR fluxes with radio fluxes. A more detailed analysis of this problem will be the argument of a future paper.

Some discussion about the expected properties of the nuclei of planetary nebulae and other possible ultraviolet stars (Hills 1972, Rose and Wentzel 1973, Katz, Malone, and Salpeter 1973) is also worthwhile. These stars are generally believed to have high effective temperatures ($T_{eff} > 50\,000$°K) and luminosities ranging from 10^2 to 10^4 solar luminosities. However, all the determinations of these quantities are usually affected by rather large errors. Therefore only those parameters which depend on the behavior of the spectrum and not on the absolute flux will be discussed here, namely,

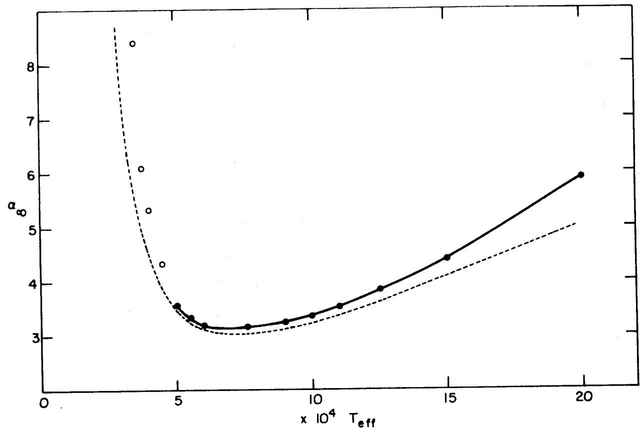

FIG. 3. The ratio of the total luminosity to the Lyman–alpha luminosity (see text) as a function of the temperature. Dots represent the values derived from Hummer and Mihalas (1970a) models. Circles correspond to main-sequence star models. The dashed line is the curve for black-body spectra.

N_L^0, P and α_∞. For the derivation of these quantities, the quite extensive set of model atmospheres of Hummer and Mihalas (1970a, 1970b) has been used.

The general trend of the above listed parameters is the following:

(1) N_L^0, which is explicitly given by Hummer and Mihalas, increases with the temperature but with a smaller gradient than it is for the O-type stars, in such a way that $d \log N_L / d \log T_{\rm eff} = \gamma \lesssim 4$;

(2) P tends rapidly to be almost 100%, being 86% at $T_{\rm eff} = 75\,000$°K;

(3) α_∞ has reversed its behavior in respect to what it was for the O-type stars, that is, here α_∞ increases as the temperature increases. This is the effect of the relatively slow increase of N_L with $T_{\rm eff}$: α_∞, which is proportional to $T_{\rm eff}^4/N_L^0$, goes like the $-(4-\gamma)$ power of the temperature, which is now definitively negative and tends to -1 when $T_{\rm eff}$ goes to infinity.

The behavior of α_∞ as a function of the temperature is shown in Fig. 3. The calculations cover the range 50 000°–200 000°K and they have been performed adopting the lowest value of the gravity for each temperature in the set of models of Hummer and Mihalas. For comparison, some values of α_∞ corresponding to main sequence O-type stars are also shown as well as the curve for black-body spectra. It is easily seen that the variation of α_∞ with $T_{\rm eff}$ is rather small; in fact it ranges from 3.1 to 6 as $T_{\rm eff}$ varies from 5×10^4 to 2×10^5 °K. Furthermore, the values for black-body spectra are nearly identical to those derived from model atmospheres. This results and the fact that $P>90\%$ for $T_{\rm eff}>75\,000$°K, imply that the infrared emission form planetary nebulae should depend primarily on the properties, the amount, and the spatial distribution of the dust present in and/or around the gaseous envelope and only marginally on the exact properties of the central star.

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REFERENCES

Auer, L. H., and Mihalas, D. (1972). Astrophys. J. Suppl. Ser. **24,** 193.
Blaauw, A. (1963). *Stars and Stellar Systems*, edited by K. Strand (U. Chicago Press, Chicago), Vol. 3, p. 383.
Bradley, P. T., and Morton, D. C. (1969). Astrophys. J. **156,** 687.
Cassinelli, J. (1971). Astrophys. Lett. **8,** 105.
Churchwell, E., and Walmsley, C. M. (1973). Astron. Astrophys. **23,** 117.
Conti, P. S. (1973). Astrophys. J. **179,** 181.
Conti, P. S., and Alschuler, W. R. (1971). Astrophys. J. **170,** 325.
Davidson, K., and Terzian, Y. (1969). Nature (Lond.) **221,** 729.
Gerola H., and Panagia, N. (1968). Astrophys. Space Sci. **2,** 285.
Gould, R. J., Gold, T., and Salpeter, E. E. (1963). Astrophys. J. **138,** 408.
Harper, D. A., and Low, F. J. (1971). Astrophys. J. Lett. **165,** L9.
Harris, D. L., III, Strand, K. Aa., and Worley, C. E. (1963). *Stars and Stellar Systems*, edited by K. Aa. Strand (U. of Chicago Press, Chicago), Vol. 3, p. 273.
Hickock, F. R., and Morton, D. C. (1968). Astrophys. J. **152,** 203.
Hills, J. G. (1972). Astron. Astrophys. **17,** 155.
Hummer, D. G., and Mihalas, D. (1970a). Mon. Not. R. Astron. Soc. **147,** 339.
Hummer, D. G., and Mihalas, D. (1970b). JILA Rept. No. 101.
Johnson, H. M. (1973). Astrophys. J. Lett. **130,** L7.
Katz, J. I., Malone, R. C., and Salpeter, E. E. (1973). In press.
Lemke, D., and Low, F. (1972). Astrophys. J. Lett. **177,** L53.
Mihalas, D. (1965). Astrophys. J. Suppl. Ser. **9,** 321.
Morton, D. C. (1969). Astrophys. J. **158,** 629.
Morton, D. C., and Adams, T. F. (1968). Astrophys. J. **151,** 611.
Murdin, P., and Sharpless, S. (1968). In *Interstellar Ionized Hydrogen*, edited by Y. Terzian (Benjamin Press, N. Y.), p. 249.
Prentice, A. J. R., and ter Haar D. (1969). Mon. Not. R. Astron. Soc. **146,** 423.
Richstone, D. O., and Davidson, K. (1972). Astron. J. **77,** 293.
Rose, W. K., and Wentzel, D. G. (1973). Astrophys. J. **181,** 115.
Rubin, R. H. (1968). Astrophys. J. **154,** 391.
Rubin, R. H. (1969). Astron. J. **74,** 994.
Schmidt-Kaler, T. (1965). In *Landolt-Börnstein New Series, Group VI*, edited by H. H. Voigt (Springer Verlag, Berlin), Vol. I, p. 301.
Van Citters, G. W., and Morton, D. C. (1970). Astrophys. J. **161,** 695.
Walborn, N. R. (1972). Astron. J. **77,** 312.
Wynn-Williams, C. G., Becklin, E. E., and Neugebauer, G. (1972). Mon. Not. R. Astron. Soc. **160,** 1.