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New colour and Zanstra temperatures for 15 central stars of planetary nebulae★

J. A. de Freitas Pacheco, S. J. Codina and L. Viadana
CNPq-Observatório Nacional, Departmento de Astronomia, Rua General Bruce, 586-São Cristovão, Rio de Janeiro, Brazil

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Summary. Spectrophotometric observations of the continuum emission from 15 nuclei of planetary nebulae are presented. From these data, colour and Zanstra temperatures are derived. The characteristics of each object are briefly discussed and the results are compared with previous studies.

1 Introduction

The hot central star of a planetary nebula is believed to be the remnant of a red giant which has thrown off its outer envelope. Such a core evolves rapidly to become a white dwarf, presenting a large variety of spectral types (Aller 1976). Therefore, in order to understand these late phases of stellar evolution and the possible relation with other hot subluminous stars, it is necessary to determine the position of the central stars in the HR diagram. Such a task requires a knowledge of distances and effective temperatures.

Many efforts have recently been made in order to derive a trustworthy distance scale for planetary nebulae (Weidemann 1977; Maciel & Pottasch 1980; Daub 1982; Milne 1982), but such a problem has not yet been satisfactorily solved.

In this paper, we will be concerned with the other HR variable, namely, the effective temperature.

Most of the methods used so far to derive effective temperatures of central stars involve, to a great measure, the knowledge of the physical conditions prevailing inside the surrounding nebula. The energy-balance method (Stoy 1933; Preite-Martinez & Pottasch 1983) involves the knowledge of the relative intensity of all important collisionally excited lines. The so-called Zanstra method (Zanstra 1931; Harman & Seaton 1966) uses the recombination lines of hydrogen and helium to derive the rate of ionizing photons emitted by the star, under the assumption that the nebula is optically thick to such radiation. If for example one also assumes that the stars radiate like blackbodies and if the stellar continuum is measured at any wavelength, then the star's temperature can be calculated.

A rather different type of approach uses stellar observations directly. Pottasch *et al.* (1978)

★Based on observations made at the Observatório Astrofísico Brasileiro.

derived stellar temperatures using intermediate-band photometry in the UV obtained through the *ANS* satellite and broad band (*UBV*) photometry in the optical region. Colour temperatures of young planetaries were also derived from optical narrow band photometry by Martin (1981). In these works only continuum observations were used. The fitting of stellar absorption lines of hydrogen and helium allowed Méndez *et al.* (1981, 1985) to derive effective temperatures and surface gravities for several central stars, as well as the He/H abundance ratio in the atmosphere.

In this work we present new spectrophotometric data for 15 central stars. Colour temperatures for these objects are derived combining our optical data with the *ANS* measurements. We also present new *V*-magnitudes derived from our data and we recalculate the Zanstra temperatures for the stars in our sample. In the following sections, we discuss our observations and data analysis; we analyse each object, briefly, comparing our results with other studies.

2 The observations

The observations were carried out at the Brazilian Astrophysical Observatory (OAB) during several periods in 1984 and 1985. We used a photoelectric scanner built at the National Observatory in Rio (Codina *et al.* 1985) attached either to the 1.6-m telescope (most of the time) or to the 0.62-m Zeiss reflector., With the 1.6-m telescope the resolution was 40 Å, while with the 0.62-m reflector we used an exit slot of 80 Å in order to reduce the integration time.

The absolute calibration was made through observations of spectrophotometric standards given by Stone & Baldwin (1983) and Taylor (1984). The standard stars were observed several times per night so as to provide reliable atmospheric extinction coefficients and flux calibration.

The central wavelength of the continuum windows were selected inspecting the detailed spectrum of NGC 7027 (Kaler *et al.* 1976a). We expect a line contribution to our flux measurements of less than 1 per cent of the Hβ emission, except inside the band at 3780 Å, where it could attain a maximum contribution of about 5 per cent of the Hβ emission with respect to the continuum.

Table 1 gives the observed flux, including the continuum contribution inside the diaphragm.

The reddening correction was derived from the 2200 Å feature using the ANS data by Pottasch *et al.* (1978) and our own data, forming a longer baseline. The interstellar extinction was also derived from the Balmer ratio Hα/Hβ for some nebulae without UV data, using our own flux measurements. In general, there is good agreement with those values recently compiled by Pottasch (1984) (hereinafter P84) except for NGC 1360 and A36. For NGC 1360 we found a colour excess from the Balmer decrement twice the value given by P84 on the basis of the flux at 6 cm to the Hβ flux ratio. On the other hand, for A36 our value is about half of that given by Pottasch also based on radio and optical data. Once the colour excess was derived for each object, the correction for other wavelengths was calculated using the average analytical curves by Seaton (1979).

The other important correction to be made is that due to the nebular continuum. Such a correction can be done quite accurately if we measure the Hβ flux through the observing diaphragm. Theoretical computations of the nebular continuum were performed by Brown & Mathews (1970). However, we have measured the continuum flux at wavelengths not tabulated by those authors and therefore, we have preferred to perform new calculations rather than simply interpolating their values. In our code, we included free–free emission from H^+, He^+ and He^{++}, free–bound emission from H, He and He^+ and two-quantum emission from H. We checked our code by computing rate coefficients for the different processes at the same wavelengths as those given by Brown & Mathews. The agreement was always quite good. For the H two-quantum emission, we used the analytical formulae by Nussbaumer & Schmutz (1984) for the transition probability. Clearly the most difficult problem when computing the two-quantum emission is the

Table 1.

λ	N3132	N3242	N5882	N6572	N6210	N6629	I4593
3560	–	–	–	–	–	–	−12.01
3780	−12.15	−12.02	−12.75	−12.34	−12.42	−13.42	−12.33
4225	−12.05	−12.41	−13.00	−12.74	−12.77	−13.45	−12.48
4500	−12.15	−12.40	−12.93	−12.75	−12.70	−13.53	−12.52
4800	−12.25	−12.60	−13.25	−12.84	−12.91	−13.49	−12.63
5300	−12.39	−12.71	−13.20	−12.85	−12.94	−13.43	−12.73
5646	−12.45	−12.80	−13.28	−12.93	−12.98	−13.45	−12.93
5980	–	–	–	−12.90	–	−13.41	−12.83
6200	−12.61	−12.88	−13.33	−12.97	−13.14	–	−13.00
6865	−12.64	−12.63	–	–	−13.10	−13.49	−13.04
(n)	(2)	(1)	(2)	(4)	(2)	(3)	(3)

λ	N4361	He2–131	A36	N5315	N6891	N6751
3560	–	−11.86	−12.13	–	−12.84	–
3780	−12.82	−12.11	−12.30	−12.65	−12.76	−13.25
4225	−12.99	−12.33	−12.40	–	−13.24	−13.58
4500	–	−12.43	−12.61	−13.26	−13.30	–
4800	−13.39	−12.54	−12.65	−13.56	–	−13.51
5300	−13.48	−12.64	–	−13.54	−13.99	−13.80
5646	–	−12.75	−12.97	−13.50	−13.94	−13.78
5980	–	−12.75	–	−13.44	–	–
6200	–	−12.93	–	–	–	−13.83
(n)	(1)	(2)	(1)	(1)	(1)	(1)

λ	I418*	N1360*
3580	−11.46	−12.10
3780	−11.72	−12.31
4500	−11.99	−12.55
5300	−12.32	−12.92
6200	−12.48	−13.09
6865	−12.41	−13.28
7900	−12.06	−13.71
(n)	(2)	(2)

Log fluxes are in $\mathrm{erg\,cm^{-2}\,s^{-1}\,\AA^{-1}}$.
*Measurements made with the 0.6-m Zeiss telescope.
(n)≡Number of independent measuring nights.

evaluation of the diffuse Lyman-α radiation field inside the nebula. In our calculations we have used a local approximation for the average intensity, with an escape probability for the Lyman-α photon equal to 10^{-4} and constant throughout the nebula. The electron densities and temperatures were taken from Preite-Martinez & Pottasch (1983, and references therein) and Aller & Czyzak (1983, and references therein). For the large nebulae N1360 and N4361 we have used the electron densities quoted by P84, which are the rms value determined from the Hβ or radio-flux density, the angular size and the distance (S. R. Pottasch 1985, private communication). Abundance ratios for He^{+} and He^{++} were either taken from our data or calculated from the line ratios given by Kaler (1976) and Aller & Czyzak (1983).

The nebular continuum contribution, while almost negligible for nebulae with large angular dimensions like A36, NGC 1360 of even NGC 4361, assumes a dominant role in the visible region for compact objects of high-excitation class. A good example if NGC 6572. In this case, the resulting stellar flux depends critically on the physical conditions inside the nebula. This star was one of the worst cases in our sample where such a correction is the most uncertain. It is worth

Table 2. Stellar fluxes.

λ	N3132	N3242	N5882	N6572	N6210	N6629	I4593
3780	−12.05±0.04	–	−12.27±0.04	–	–	−12.39±0.04	−12.28±0.04
4225	−11.96±0.04	−12.38±0.04	−12.62±0.04	−12.38±0.04	−12.78±0.04	−12.51±0.04	−12.44±0.04
4500	−12.06±0.04	−12.37±0.04	−12.55±0.04	−12.43±0.04	–	−12.66±0.04	−12.48±0.04
4800	−12.17±0.04	−12.73±0.04	−13.08±0.06	−12.71±0.05	−13.03±0.05	−12.70±0.04	−12.60±0.04
5300	−12.33±0.04	−13.02±0.05	−13.07±0.06	−12.90±0.05	−13.10±0.06	−12.75±0.04	−12.72±0.04
5646	−12.40±0.04	−13.39±0.06	−13.28±0.06	–	−13.18±0.05	−12.86±0.04	–
5980	–	–	–	–	–	−12.87±0.04	−12.84±0.04
6200	−12.40±0.04	–	−13.51±0.07	q–	−13.61±0.07	–	−13.04±0.05
6865	−12.62±0.04	–	–	–	–	−13.16±0.05	−13.09±0.05
(*n*)	(2)	(1)	(2)	(4)	(2)	(3)	(3)

λ	N4361	He2–131	A36	N5315	N6891	N6751	N1360*	I418*
3560	–	–	−11.75 ±0.04	–	–	–	–	–
3780	−12.58 ±0.05	−11.88 ±0.04	−11.93 ±0.04	−11.94 ±0.04	−12.53 ±0.04	–	−12.13 ±0.05	−11.38 ±0.05
4225	−12.78 ±0.05	−12.13 ±0.04	−12.06 ±0.04	–	−13.11 ±0.05	−13.10 0.04	–	–
4500	–	−12.25 ±0.04	−12.28 ±0.04	−12.76 ±0.06	−13.20 ±0.06	–	−12.39 ±0.05	−11.72 ±0.05
4800	−13.29 ±0.07	−12.38 ±0.04	−12.35 ±0.04	−13.46 ±0.07	–	–	–	–
5300	−13.43 ±0.08	−12.52 ±0.04	–	−13.70 ±0.08	–	−13.46 ±0.04	−12.79 ±0.05	−12.20 ±0.06
5646	–	−12.67 ±0.04	−12.73 ±0.04	−13.74 ±0.09	–	−13.48 ±0.05	–	–
5980	–	−12.69 ±0.04	–	−13.60 ±0.01	–	–	–	–
6200	–	–	–	–	–	−13.57 ±0.05	−12.99 ±0.05	−12.54 ±0.06
6825	–	–	–	–	–	–	−13.19 ±0.06	−12.44 ±0.07
(*n*)	(1)	(2)	(1)	(1)	(1)	(1)	(2)	(2)

Log fluxes are in $\mathrm{erg\,cm^{-2}\,s^{-1}\,Å^{-1}}$.
*Measurements made with the 0.6-m Zeiss telescope.
(*n*)≡Number of independent measuring nights.

mentioning that the *ANS* fluxes were all corrected by such a procedure also. Table 2 gives the programme objects and the derived dereddened stellar fluxes with the estimated errors.

3 The temperature of the stars

Since reliable models for the atmosphere of central stars are still lacking, we have derived colour temperatures by fitting blackbody spectra to our data, including also *ANS* measurements when available.

The data were fitted through an equation of the form

$$\log F_\lambda = \log W + \gamma \log B_1(T),$$

where the temperature T was a free parameter. The best fit was chosen for the value of T

Table 3.

Object	T_{colour}	T_Z(H I)	T_Z(He II)	V	$E(B-V)$	$\log f\mathrm{H}\beta$	$\log W$
N1360	66320	37000	82500	11.25	0.10	−10.02[6]	−21.93
N4361	102000	39500	86480	13.02	0.15	−10.60[2,3,4]	−22.65
A36	70000	21000	66500	11.20	0.20†	−10.86[2]	−21.78
N3242	95000	58090	87600	12.52	0.10	− 9.78[1]	−22.42
N3132	–	67500	73000	14.64★	0.06†	−10.43[5]	−23.43★
N5882	60000	44900	61900	12.88	0.30†	−10.37[1]	−22.24
N5315	–	71599	82750	14.63	0.41†	−10.42[5]	–
N6572	53000	59130	56900	12.57	0.35	− 9.82[1]	−21.95
N6891	58950	38000	54500[a]	13.03	0.15	−10.68[5]	−22.49
N6210	44000	46500	48500	12.43	0.08	−10.08[2]	−22.25
I4593	26200	28190	–	11.11	0.04	−10.55[4]	−21.44
I418	34630	36500	–	10.08	0.20	− 9.59[1]	−20.97
He2–131	25050	31700	–	10.85	0.13	−10.17[5]	−21.19
N6629	41250	35500	–	13.07	0.60	−10.95[1]	−21.78
N6751	22900	27750	–	13.55	0.30	−11.57[5]	−22.00

★Binary system: Values estimated under the assumption that the Helium Zanstra Temperature represents the 'true' star temperature. For the parameters of the companion, see text.
†Derived from Balmer decrement.
[a]He II λ 4686 relative intensity from Heap (1977) (see text).

References:
[1]Present work.
[2]Kaler (1983).
[3]Perek (1971).
[4]O'Dell (1962).
[5]Preite-Martinez & Pottasch (1983).
[6]Pottasch *et al.* (1978).

giving $\gamma=1$. The derived colour temperatures and the geometrical dilution factors W are given in Table 3. In this table we give also our derived V-magnitude (*not corrected for reddening*) as well as the colour excess for each object obtained as already described in the previous section. The Hβ fluxes used in our computations of the Zanstra temperatures are given in Table 3. The He II λ 4686 line ratios are all from the source already mentioned in the previous section, unless referred to explicitly. The derived Zanstra temperatures are also given in Table 3. Figs 1(a), (b), (c) and (d) show the resulting energy distribution and the quality of the blackbody fit to the data.

4 Discussions

4.1 THE HIGH-EXCITATION EXTENDED NEBULAE N1360, A36, N4361

The continuum flux from the stars of the largest nebulae in our sample, N1360 and A36, are practically unaffected by the nebular emission. However, it contributes with a significant fraction, for $\lambda > 4500$ Å, to the measurements of the less extended object N4361.

N1360 and A36 exhibit the well-known fact that the He II Zanstra temperature is much higher than the H-Zanstra temperature. The derived colour temperature for these objects agree better with the T_Z(He II), indicating that the nebulae are optically thin to the hydrogen Lyman continuum radiation. The colour temperatures obtained are also in excellent agreement with the effective temperatures derived by Méndez *et al.* (1985) through line-fitting procedures and considerably smaller than the value obtained by Pottasch *et al.* (1978) for N1360, which was about 10^5 K.

For N4361 we derived a colour temperature of about 102 000 K, considerably higher than $T_Z(\text{He II}) = 86\,500$ K. In principle, it could be thought that not all the ionizing radiation shortward of 228 Å is being absorbed by the nebula which could explain such a discrepancy.

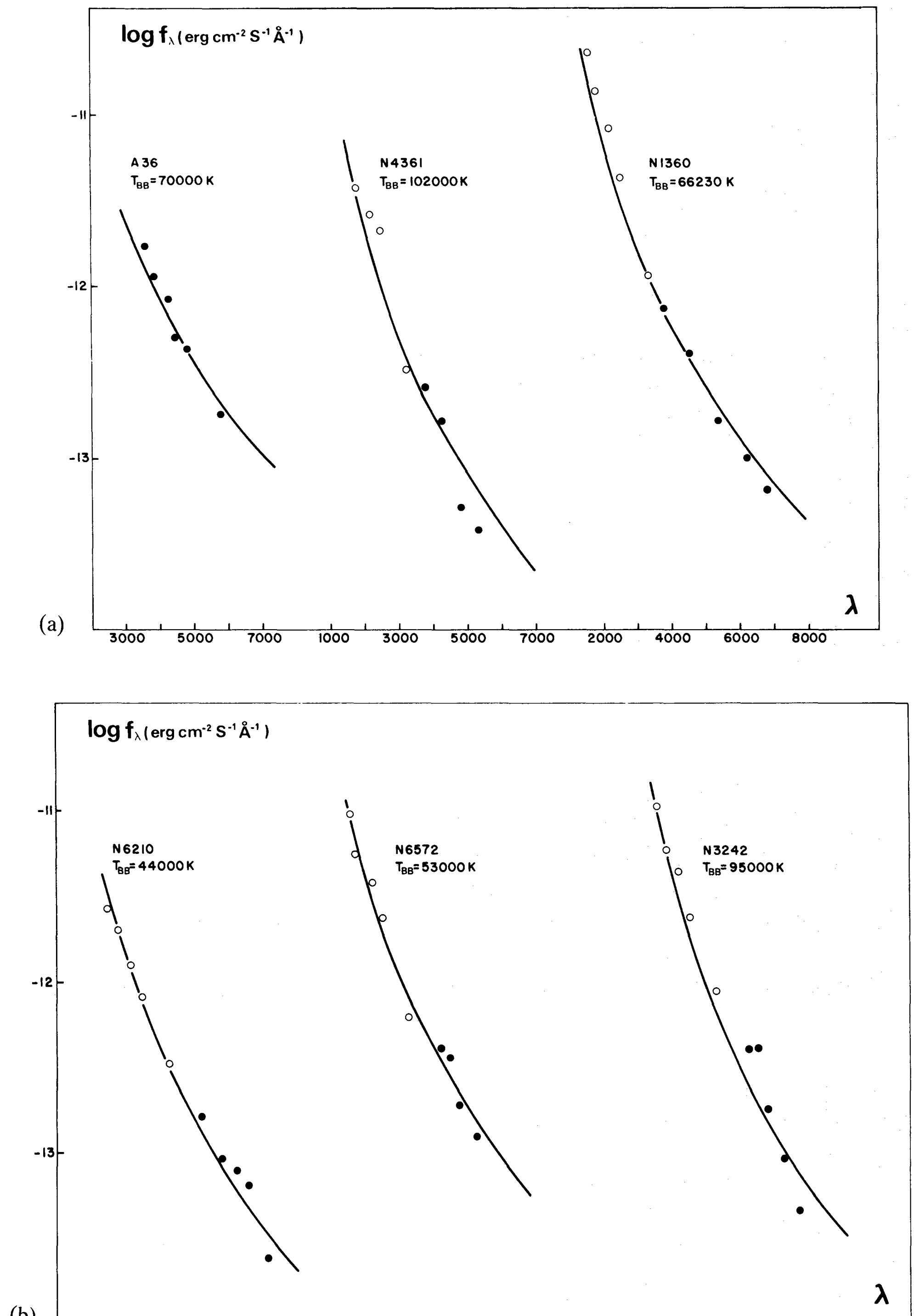
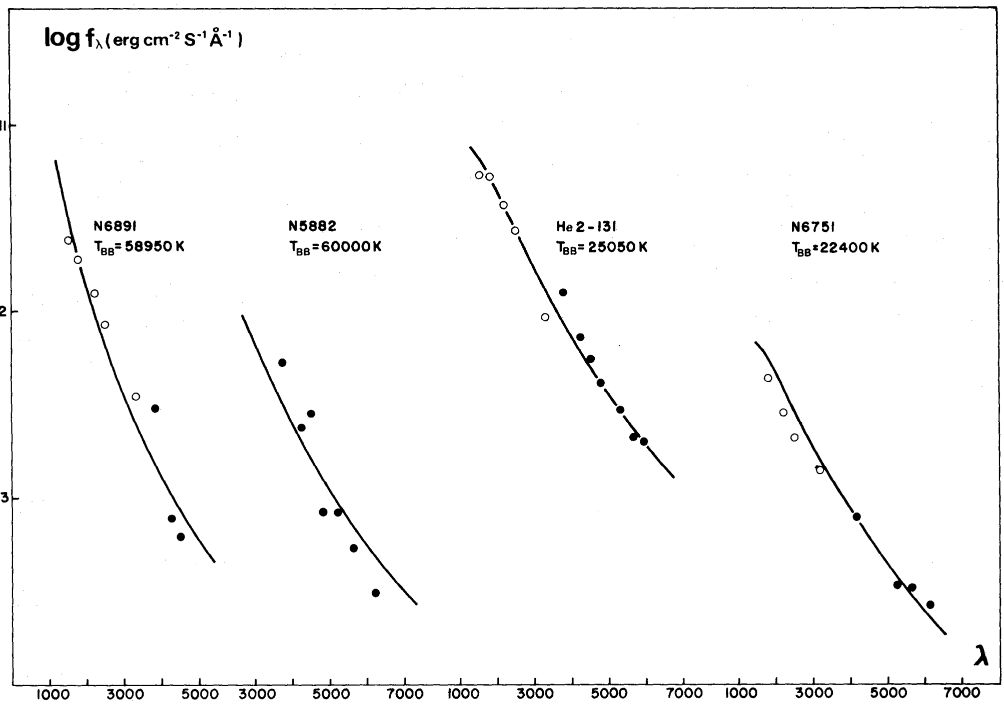
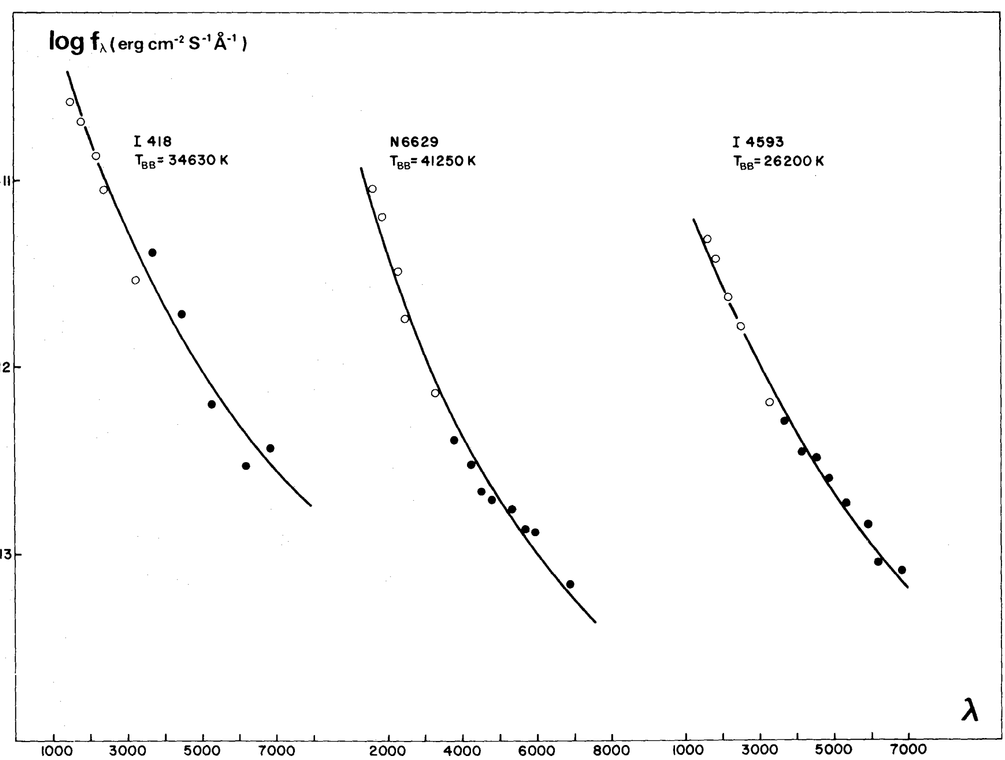


Figure 1. Observed dereddened continuum of planetary nuclei. Open circles represent *ANS* data and filled circles the present observations. Solid line is the best blackbody fit whose temperature is labelled for each object.



(c)



(d)

Figure 1 – *continued*

However, the line-fitting method gives an effective temperature of $(80^{+20}_{-10})\times10^3$ K (Méndez *et al.* 1985) closer to the He II-Zanstra temperature but still compatible with our colour value within the estimated errors. For this object we think that the blackbody spectrum is a poor representation of the true energy distribution of the star. Clearly, any blackbody spectrum which fits reasonably well the UV data, overestimates the fluxes in the optical region. Adam & Köppen (1985) fitted their *IUE* data with non-LTE model atmospheres with $T_{ef} \approx 10^5$ K. The models underestimate the fluxes shortward of 1400 Å and overestimate the fluxes in the optical region. We emphasize that the optical data used by Adam & Köppen which are *UBV* photoelectric magnitudes by Shao & Liller (1982, unpublished) and Drummond (1980), are in very good agreement with our measurements, indicating the reality of such an effect.

It is worth mentioning that N4361 and N1360 have both an abnormal photospheric He abundance (Méndez *et al.* 1985). Since some model atmospheres with a low He abundance predict a flux, shortward of 228 Å, higher than a blackbody, the significantly higher T_Z(He II) derived for N1360 with respect to the colour temperature could perhaps be explained on the basis of this fact.

4.2 THE MEDIUM-HIGH-EXCITATION NEBULAE

We shall now discuss planetaries of excitation class 6–7 which, according to Aller (1956), present a significant emission in the He II λ4686 line.

4.2.1 *N3242*

The agreement between the colour temperature and T_Z(He II) is reasonably good. The lower T_Z(H II) indicates that the nebula is probably thin to the Lyman continuum radiation. Méndez *et al.* (1985) derived through line fitting an effective temperature of $(75 \pm 20) \times 10^3$ K, consistent with our results. P84 gives a much lower value (50 000 K), also derived from a blackbody fit.

4.2.2 *N3132*

This object is a binary system (Méndez 1975) and in the optical region the light comes essentially from the companion. We have estimated the Zanstra temperatures using the star flux measured at λ1550 Å (Pottasch *et al.* 1978). We then assumed that the star radiates like a blackbody with a temperature of 73 000 K and we subtracted the expected flux from the observed one. The difference, attributed to the companion, can be represented by a blackbody of temperature of 9100 K, consistent with the spectral classification. The *V* magnitude of the companion is 10.14 and, if the star is on the main sequence, its radius will be about 2 $R_\odot$. From our blackbody fitting of the data we obtained a ratio $R/D = 9.20 \times 10^{-11}$, from which we derive a distance $D = 507$ pc for the nebula. With such a distance, the radius of the central star of N3132 is 0.042 $R_\odot$ and its luminosity is 44.6 $L_\odot$.

4.2.3 *N5882*

For this object, no *ANS* fluxes were available. Our data, covering the spectral range from 3780 to 5800 Å indicates a spectrum steeper than any reasonable blackbody. This is similar to the behaviour of N4361 already discussed. In spite of this, our best fit gives a colour temperature of 6×10^4 K, which is in excellent agreement with our derived He II-Zanstra temperature. Martin (1981) has also evaluated a T_Z(He II) quite similar to ours but he gives a colour temperature of only 2×10^4 K for the central star. We remark also that the stellar fluxes given by Martin differ substantially from our measurements.

4.2.4 N6891

The colour temperature agrees again with T_Z(He II) being both substantially higher than T_Z(H I). Heap (1977) classifies the star as an O3f object and she estimates an effective temperature of about 5×10^4 K on the basis of the observed photospheric absorption lines. In spite of such an agreement, we should remark that the He II 4686 emission is quite broad, suggesting the existence of an expanding atmosphere which is detected in fact on *IUE* spectra (see, for instance, Kaler, Mo Jing-Er & Pottasch 1985). This would indicate that the He II λ 4686 emission from the wind contributes to the total emission in this line and that the derived temperature would be only an upper limit. This point is also reinforced by the observations of the nebula by Kaler, Aller & Czyzak (1976b) since these authors do not mention the detection of the He II λ 4686 line, He being mostly singly ionized.

4.2.5 N5315

For this star, our entrance slot allows a considerable contribution from the nebular continuum and our derived stellar fluxes are quite uncertain. No good blackbody fit was obtained. It should be emphasized that this nucleus has a WR spectrum and therefore some of the broad emission lines formed in the expanding atmosphere could be contributing to our continuum flux measurements.

4.2.6 N6572

As previously mentioned, the optical region of the spectrum is affected by the nebular emission but, despite the uncertainties in the derived stellar flux, the colour temperature agrees quite well with both T_Z(H I) and T_Z(He II). These results are also consistent with the energy balance temperature derived by Preite-Martinez & Pottasch (1983), who obtained $T_{EB}\simeq 56\,100$ K. Again, our results are in disagreement with those of Martin (1981), who obtained for this object a rather low colour temperature namely $T_c\simeq 17\,800$ K.

4.2.7 N6210

This object belongs to an excitation class lower than those of the others we have just discussed. Since it is the only object in our sample of excitation class 5 it is included here. The blackbody spectrum gives a quite good fit and the colour temperature agrees (as N6572) with both T_Z(H I) and T_Z(He II).

4.3 THE LOW-EXCITATION NEBULAE

4.3.1 I4593, I418 and He2–131

For all three stars our derived colour temperature agrees with the hydrogen Zanstra temperature. The visible spectra of I4593 and I418 are, according to Aller & Smith (1969), characteristic of an O7f star, presenting, in addition, emission lines of C III. The spectrum of He 2–131 is similar, but the line profiles indicate an expanding atmosphere. It is classified by Heap (1977) as an O7(f)eq object. High-resolution *IUE* spectra display P-Cygni profiles in many lines of highly ionized species in all the three objects, indicating wind terminal velocities greater than 1000 km s^{-1} (Heap 1979; Benvenuti & Perinotto 1980). Pottasch *et al.* (1978) have also derived colour temperatures for these objects. There is a good agreement between our values and these given by Pottasch *et al.*

except for I4593 for which we found a somewhat smaller value. We remark, however, that our colour temperature is in better agreement with T_Z(H I), which is 28 190 K, also obtained by P84.

4.3.2 N6629 and N6751

For N6629 a good agreement is also obtained between our colour temperature and the value derived by Pottasch *et al.* (1978). However, our hydrogen Zanstra temperature is a little smaller than the colour value. N6751 is classified by Aller & Smith (1969) as WC6 due to its broad emission lines. The blackbody spectrum gives only a reasonable fit with a rather low temperature, namely, $T_c = 22\,400$ K. For this object, we obtained a Zanstra temperature T_Z(H I) = 27 750 K. This value is somewhat smaller than that given by P84, T_Z(H I) = 36 000 K and such a difference is probably due to our brighter *V*-magnitude (13.55 compared with 13.89 given by P84) (see also comments made with respect to the other WR object in our sample, N5315).

5 Conclusions

New spectrophotometric data are presented for a sample of 15 nuclei of planetary nebulae. From these data, we derive colour and Zanstra temperatures for such a star. For the large nebulae, colour temperatures agree well with T_Z(He II), while the smaller T_Z(H I) values indicates that the shell is probably thin to the Lyman continuum radiation. Stars surrounded by medium-excitation nebulae show, in general, a rough agreement between colour temperature, T_Z(He II) and T_Z(H I). In the cases when T_Z(H I) < T_Z(He II) again the resulting temperatures from blackbody fits agree better with T_Z(He II). For the low-excitation nebulae, without He II recombination lines, there is also a good agreement between the colour temperatures and T_Z(H I).

Seven stars in our sample are common with those studied by Martin (1981) and for five objects a comparison between the derived colour temperatures can be done. His values are considerably smaller than ours (except for He2–131) and such a trend is not observed when we compare our results with those of Pottasch *et al.* (1978). The only discrepant result concerns N6891 for which we obtained a considerably higher colour temperature in comparison with those authors. For this star some contradictory data have been reported, as we mentioned previously, and we plan new observations to settle the situation. Also, the differences between our resulting colour temperatures and those by Martin are not easily understandable. A straightforward comparison between our measured fluxes with those by Kohoutek & Martin (1981) at common wavelengths shows that, on the average, our values are higher by 0.07 in log flux. The same trend is observed using the corrected fluxes. In this case, the difference in colour temperatures is probably due to the fact that we have combined our optical data with the UV data, using a total wavelength interval much more sensitive to the fitting procedure.

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