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Magnitudes of central stars of planetary nebulae

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Summary. Magnitudes have been measured for 44, mostly faint central stars of planetary nebulae by imaging the star and nebula on a CCD detector. The nebular lines are suppressed by using a continuum filter. The remaining nebular continuum is then subtracted as background as long as the star can be clearly seen. This is true in 41 of the 44 cases observed. Zanstra temperatures are calculated from the observed magnitudes, and discussed.

Key words: planetary nebulae – photometry central stars – Zanstra temperatures

1. Introduction

The late stage in the evolution of intermediate-mass stars (4–8 $M_\odot$) is rather uncertain. Such stars make important contributions to galactic enrichment but their ultimate fate as supernovae or white dwarfs is both controversial and unclear. The recent discovery of very hot central stars of planetary nebulae (PN) (Pottasch, 1981; Reay et al., 1984) and their association with progenitor stars of intermediate mass raises the possibility that the PN phase may extend to at least some stars in this mass range. Since this may be a short-lived phenomenon, the identification of all possible central stars of very high temperature is important to constrain the frequency with which this occurs.

The magnitude of a central star of a PN is an important parameter in studying its evolution. The magnitude is used to determine the effective temperature and luminosity of the central star, especially with the help of the Zanstra method. Previous studies of the evolution of PN have concentrated mainly on PN with well observed central stars (e.g. Schönberner, 1981; Schönberner and Weideman, 1983). From these studies it was concluded that the majority of central stars have masses of ~ 0.55 to $\approx 0.6\,M_\odot$. However, PN with very faint or even undetected central stars were generally not included in these studies.

It is expected that these faint central stars are very hot objects with temperatures up to $\sim 5\;10^5$ K (Pottasch, 1981). It is believed that these central stars have masses of $\gtrsim 0.7\,M_\odot$ and have originated from stars with masses of ~ 4 to $8\,M_\odot$. In the case of optically thick nebulae, the very high temperatures imply that the ratio of the number of ionizing photons to the stellar continuum flux in the visual is large. Since the number of ionizing photons determines the nebular flux, the ratio of nebular to stellar flux can be so large for a hot central star that the emission at the position of the star is completely dominated by nebular flux.

To make a detailed study of these PN with hot, faint central stars accurate stellar magnitudes are necessary. To avoid nebular radiation as much as possible, measurements have to be made in a spectral region where no nebular lines are present. However, nebular continuum is always present although its effect can be eliminated by mapping the continuum structure and comparing it to a map of the nebula made in the light of a Balmer line. The above method has been applied to the bright nebula NGC 7027 (Atherton et al., 1979) where it was possible to estimate the central star magnitude at $m_v \approx 19\overset{m}{.}5$. The resulting effective temperature and luminosity show that this PN is a nice example of the class of PN of interest (see Gathier, 1984).

In a similar way faint central stars of eight other PN were observed using the Image Photon Counting System (IPCS) at the Anglo Australian Telescope (AAT) (Reay et al., 1984). The results prove that the number of central stars with effective temperatures well above 10^5 K is considerable. This work has been extended by Walton et al. (1986) and Atherton et al. (1986) with the same technique.

Another method has been used since the advent of photoelectric photometry. In this method the magnitude is measured in the normal photometric manner using a diaphragm, which is usually rather large because of the uncertain position of the exciting star. The nebular component is then subtracted by measuring the Hβ flux and predicting theoretically the expected nebular radiation. This method is uncertain for small nebulae excited by faint central stars, because usually more than 95% of the measured radiation must be subtracted. As discussed by Reay et al. (1984), in these cases the *noise* from the nebula and the background night sky is as bright as a 14th magnitude star making the subtraction procedure questionable.

We report here the measurement of the magnitude of the central stars in 41 nebulae and upper limits to the brightness in 3 others. A few of these have already been discussed by Reay et al. (1984) and Walton et al. (1986). The temperatures of the stars are also derived; about 10 are higher than 150,000 K. The well known effect that the He II Zanstra temperature is substantially higher than the H temperature is also discussed in the light of these new measurements. This effect disappears in stars with temperatures above 100,000 K.

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2. Observations

Monochromatic images of each of the nebulae were obtained with two filters. The measurements were made in April 1986 (a few in June 1985) using the European Southern Observatory (ESO) 2.2 m telescope equipped with an RCA SID 501 Ex CCD camera. The field of view is 112″ × 180″ with an individual pixel size of approximately 0″.35.

The two filters used were ESO 1402 (continuum filter) and ESO 1403 (Hβ filter). The continuum filter is centered at $\lambda_{\rm eff} = 4793$ Å and has a width of 67.6 Å. It does not allow any important nebular line emission to pass. The Hβ filter has $\lambda_{\rm eff} = 4866$ Å with $\Delta\lambda = 34.3$ Å. Enhanced emission at the center of the nebula appearing only on the continuum image and not on the Hβ image is due to the central star. Usually the central star was clearly visible on the 4793 Å image, in case of doubt use was made of the Hβ image to check whether the enhanced continuum emission is due to the central star or the nebula.

Two doubtful cases remain: the central stars of NGC 6439 and M 1–18. For 3 cases no sign of a central star was seen: NGC 6302, 6537 and 6741. Only lower limits to the magnitudes are given in these cases.

3. Reduction

The central star intensities on the CCD images are found by subtracting the local background. The background is always an average of several regions within the nebula close to the central star.

The calibration is achieved by taking photometry of stars within the field of view on the CCD image. If no stars were present in the CCD field brighter than about 15 mag, short exposures of a partly overlapping offset field were made. This turned out to be necessary for about 25% of the nebulae.

The photometry was done using the Dutch 91 cm telescope at ESO, in the Walraven *VBLUW* system, which has the advantage of narrow, well defined bands. The system has been described and documented by Lub and Pel (1977). For some of the calibrating stars the *VBLUW* measurements of Gathier (1985) were used. Transformation from the Walraven *V* and *B* to Johnson m_v and m_B were made following Pel (1986, private communication). For typical field stars these transformation are accurate to $0^m.01$. Transformation from m_v and m_B to flux densities at 5450 Å and 4400 Å were made using the calibration of α Lyr by Tüg et al. (1977). The determination of the flux density at 4793 Å (F_{4793}) was made by a linear interpolation between the *V* and *B* effective wavelenghts. Thus a flux density for the central star could be obtained from each of the calibrating stars. The final value is the average of the individual values, which usually agree well among themselves. Only very red stars ($B-V \gtrsim 1.2$) sometimes gave deviating values.

4. Results

The resultant values of $F_{\lambda 4793}$ for 44 central stars are shown in the second column of Table 1. The error, also given in the table, is mainly determined by variations of the nebular background close to the central star. For three central stars the flux density was measured throught the Hβ filter and therefore refers to 4866 Å. The star was relatively bright to the nebula in these cases. The third column of the table converts the flux density to a magnitude, again using the calibration of α Lyr by Tüg et al. (1977). While this magnitude is precise, it is slightly unhandy to use in a comparison with other observations which are usually given in visual magnitudes (m_v). Conversion of the magnitudes in Table 1 to m_v can be done if it is assumed that the star emits like a hot blackbody between 4793 Å and the visual, and that the interstellar extinction is known. The first assumption is probably realized in practice, but the extinction is not always well known and may actually vary over the nebula (e.g. NGC 6302). For a general comparison values of m_v obtained in this way are given in column 3 of Table 2, using the extinction listed in Table 3. The differences in magnitude are small because the wavelength range is small. For calculating the Zanstra temperature it is more precise to use $F_{\lambda 4793}$.

Table 2 shows a comparison with earlier results. The results of Walton et al. (1986) and Reay et al. (1984) are made by a technique very similar to that used in the present work. The agreement with Reay et al. is very good in most cases. The central star in NGC 6537 reported by Reay et al. was a "stellar-like condensation to the east of centre" and was probably not the actual central star, which we cannot see (it is at least one half

Table 1. Final central star fluxes and magnitudes

PN	F(λ 4793 Å) erg cm^{-2} s^{-1} Å^{-1}	m(λ 4793Å) mag.	Remarks
NGC 2022	2.22±0.16 10^{-15}	15.92±0.08	
NGC 2346	1.26±0.11 10^{-13}	11.54±0.10	
NGC 2348	6.84±0.41 10^{-16}	17.20±0.07	
NGC 2440	1.58±1.07 10^{-16}	18.8 ±0.5	
NGC 2452	4.32±0.41 10^{-16}	17.70±0.15	
NGC 2792	6.95±0.28 10^{-16}	17.18±0.04	
NGC 2818	8.07±1.59 10^{-17}	19.52±0.21	
NGC 2867	1.13±0.17 10^{-15}	16.65±0.17	
NGC 3132	4.80±0.53 10^{-13}	10.09±0.12	
NGC 3211	3.04±0.23 10^{-16}	18.08±0.08	
NGC 3242	6.08±0.08 10^{-14}	12.33±0.03	
NGC 3918	2.58±0.33 10^{-15}	15.76±0.14	
NGC 5189	6.07±0.49 10^{-15}	14.83±0.09	
NGC 5315	9.3 ±1.8 10^{-15}	14.4 ±0.2	uncertain
NGC 6072	1.1 ±0.15 10^{-16}	19.17±0.15	
NGC 6153	2.04±0.13 10^{-15}	16.01±0.07	
NGC 6302	≤2.32 10^{-17}	≥20.9	
NGC 6309	1.30±0.12 10^{-15}	16.50±0.10	
NGC 6326	9.51±1.06 10^{-16}	16.84±0.12	
NGC 6369	1.20±0.09 10^{-15}	16.59±0.08	
NGC 6439	4.45±2.35 10^{-17}	20.2 ±0.6	uncertain
NGC 6445	1.34±0.12 10^{-16}	18.97±0.10	
NGC 6537	≤8.8 10^{-17}	≥19.4	
NGC 6563	5.48±0.25 10^{-16}	17.44±0.50	
NGC 6565	4.31±1.33 10^{-17}	20.20±0.34	
NGC 6567	8.79±0.60 10^{-15}	14.43±0.07	
NGC 6572	2.83±0.51 10^{-14}	13.16±0.20	
NGC 6578	1.47±0.09 10^{-15}	16.37±0.07	
NGC 6629	2.90±0.23 10^{-14}	13.13±0.09	
NGC 6741	≤4.5 10^{-17}	≥20.2	
NGC 6772	1.43±0.08 10^{-16}	18.90±0.06	
NGC 6778	9.70±1.10 10^{-16}	16.82±0.12	
NGC 6781	8.66±0.70 10^{-16}	16.91±0.09	$\lambda_{\rm eff}$ = 4866 Å
NGC 6818	8.44±1.14 10^{-16}	16.97±0.15	
NGC 7009	3.80±0.27 10^{-14}	12.84±0.08	
IC 972	3.17±0.22 10^{-16}	18.00±0.07	$\lambda_{\rm eff}$ = 4866 Å
IC 2448	9.27±0.26 10^{-15}	14.37±0.03	
IC 4406	5.09±0.26 10^{-16}	17.52±0.06	
IC 4642	1.84±0.12 10^{-15}	16.13±0.07	
A 15	1.82±0.10 10^{-15}	16.10±0.06	$\lambda_{\rm eff}$ = 4866 Å
A 41	1.13±0.06 10^{-15}	16.66±0.06	
M 1-18	1.92±0.44 10^{-17}	21.08±0.25	Central star?
M 3-9	1.64±0.10 10^{-16}	18.75±0.07	
Me 2-1	1.36±0.27 10^{-16}	18.96±0.21	

Table 2. Comparison of magnitudes *

Nebula	This paper m(4793)	m_v	Walton et al. (1986)	Reay et al. (1984)	Shaw Kaler (1985)	Martin (1981)	Shao Liller (1972)	Anderson (1934) Curtis (1918) Hubble (1922)
NGC 2022	15.92	15.92				14.9	14.80	15.5 A
NGC 2438	17.20	17.22	18.4		17.84[1]		15.09	17.5 A
NGC 2440	18.8	18.8	18.9	>16.0	≥14.3:			19 H
NGC 2452	17.70	17.61	17.9					≥19 C
NGC 2792	17.18	17.06					13.78	
NGC 2818	19.52	19.58	19.5					
NGC 2867	16.65	16.66	16.5			14.4		
NGC 3132	10.09	9.89	10.2				10.06	
NGC 3211	18.08	18.13	17.8[2]			16.2		11.3 C
NGC 3242	12.33	12.43					12.02	11.5 A
NGC 3918	15.76	15.80	16.7			13.4	10.84	
NGC 5189	14.83	14.75		14.0				
NGC 5315	14.4:	14.3:	13.3			13.9		
NGC 6072	19.17	18.93		19.1				
NGC 6153	16.01	15.73	16.2	16.1				
NGC 6309	16.50	16.64	16.5		13.74			13 C
NGC 6326	16.84	16.84				15.2	13.49	
NGC 6369	16.59	15.91					14.66	16 C
NGC 6445	18.97	18.72		18.9				19 H
NGC 6537	≥19.4	≥18.9		19.0				
NGC 6563	17.44	17.49		17.0				18 C
NGC 6565	20.2	20.3		19.2				
NGC 6567	14.43	14.32						14 H
NGC 6572	13.16	13.12				12.7	poss.var.	12.5 H
NGC 6629	13.13	12.82			12.77	12.67	12.29	13 H
NGC 6772	18.90	18.63		18.9				>18 C
								18.1 H
NGC 6781	16.91	16.62					14.95	16.0 A
NGC 6818	16.97	17.02				14.9	13.05	~14.0 C
IC 2448	14.37	14.47				13.95		
A 15	16.10	16.27			16.86	15.72[3]		
Me 2-1	18.96	19.02				16.4	14.19	

*The magnitudes by others are reduced to visual magnitudes except those of Anderson, Curtis and Hubble which are sometimes photographic, and those of Martin which refer to 5300 Å.

[1]Kaler and Feibelman (1985)
[2]Walton (Thesis, 1987)
[3]Abell (1966)

magnitude fainter). The only other disagreement is that we find the central star of NGC 6565 to be one magnitude fainter than they do. The agreement with Walton et al. (1986) is also quite good except for two central stars which we find to be about one magnitude brighter: NGC 2438 and 3918. This difference may be caused by the seeing, which was better during our observations of these nebulae than during those of Walton. This made the background subtraction easier for us.

Columns 4–6 of the table show a comparison with magnitudes measured photoelectrically with diaphragms and filters which register some nebular light as well. The measurement of Shao and Liller (cited by Acker et al., 1982), shown in column 6, do not attempt to subtract the nebular component and consequently give magnitudes which are too high for the fainter central stars, especially in small nebulae. As can be seen from the table, the effect can be as much as 5 magnitudes. Martin (1981) and Shaw and Kaler (1985), while applying the same technique, do attempt to correct for the nebular emission on the basis of the measured Hβ flux. Thus their magnitudes are always fainter than those of Shao and Liller, but for the faint stars with bright nebulae the correction usually appears to be insufficient. The reason for this has been discussed by Reay et al. (1984) and Atherton et al. (1986). The essential difficulty is that of subtracting a large quantity from an almost equally large quantity (in the presence of noise) to get a meaningful result.

That the origin of this difficulty lies in the technique used can be seen by the comparison with the central star magnitudes listed in the last column. These are old fashioned photographic magnitudes (Anderson, 1934) or eye estimates (Curtis, 1918; Hubble, 1922). While their accuracy is limited because the measuring techniques in use 50 to 70 years ago had considerably higher errors, they are still in much better agreement with the present measurements than the photoelectric techniques which include the nebular emission. Only in the case of the very bright central stars, or fainter central stars located in nebulae of low surface brightness (in the vicinity of the central star), can photoelectric aperture photometry be expected to give reliable results.

5. Zanstra temperatures

The Zanstra temperatures can be computed in the standard way (see Harman and Seaton, 1966; summarized by Pottasch, 1984). The hydrogen Zanstra temperature, T_z (H) is given by

$$\frac{F(\mathrm{H}\beta)}{F_{4793}} = 20.58\ T_e^{-0.06}\,(T_z)^3\ G_1\,(T_z)\,(e^{3.002/T_z}-1)\,\text{Å},$$

Table 3. Zanstra temperatures

	-log Hβ	$\frac{\lambda 4686}{H\beta}$	E_{B-V}	T_z(H)	T_z(HeII)	Reference
NGC 2022	11.10	1.1	0.26	64100	118000	4
NGC 2438	10.97	0.43	0.25	112000	131000	5,7
NGC 2440	10.45	0.61	0.30	328000	340000	1,3
NGC 2452	11.47	0.69	0.43	83500	129500	3
NGC 2792	11.28	0.89	0.48	81500	135000	5,7
NGC 2818	11.40	0.80	0.20	175000	215000	5,7
NGC 2867	10.58	0.28	0.28	131000	130000	3,4
NGC 3211	11.06	0.74	0.21	143500	180000	4,3
NGC 3242	9.76	0.24	0.08	59000	91000	3,6
NGC 3918	10.07	0.46	0.24	150000	178000	4
NGC 5189	10.49	0.47	0.40	72500	110000	7
NGC 5315	10.40	0.09	0.38	69000	83700	3,4
NGC 6072	11.37	0.25	0.71	157500	150000	5,7
NGC 6153	10.85	0.11	0.71	80000	91200	7
NGC 6302	10.53	0.78	0.93			3
NGC 6309	11.16	0.70	0.05	72500	116000	1
NGC 6326	11.09	0.30	0.28	86500	110000	7
NGC 6369	11.24		1.38	67500		7
NGC 6439	11.59	0.22	0.53	186000	158000	5,7
NGC 6445	11.15	0.73	0.7	183000	215000	3
NGC 6537	11.46	0.72	1.10	>150000	>210000	1
NGC 6563	10.96		0.20	123000		7
NGC 6565	11.21	0.14	0.20	271000	177000	3
NGC 6567	10.95	0.02	0.42	47000	61000	7
NGC 6572	9.82	0.02	0.31	73000	71000	3,4,6
NGC 6578	11.72	0.02	0.97	45000	58500	7
NGC 6629	10.93		0.72	35000		1,4,6
NGC 6741	11.35	0.48	0.84	235000	235000	2,3
NGC 6772	11.65	0.35	0.75	111000	126000	5,7
NGC 6778	11.12	0.11	0.22	84000	93000	3
NGC 6781	11.19	0.24	0.80	83000	110000	5
NGC 6818	10.48	0.73	0.22	160000	200000	1,3
NGC 7009	9.78	0.14	0.10	68200	89000	3
IC 2448	10.85	0.30	0.08	49000	85000	4
IC 4406	10.76	0.05	0.19	150000	105000	5
A 15	12.58	1.3	0.03	28500	76000	1
Me 2-1	11.36	0.86	0.18	152000	180000	2,3,4

The references, which refer to the Hβ flux (units: erg cm^{-2} s^{-1}), the λ 4686 to Hβ ratio, and the extinction, are as follows: (1) Shaw and Kaler, 1985; (2) Kaler, 1978; (3) Preite-Martinez and Pottasch, 1983; (4) Kohoutek and Martin, 1981, (5) Kaler, 1976; (6) Freitas Pacheco et al., 1986; (7) Pottasch, 1984.

where F_{4793} is the flux density listed in Table 1, T_e is the electron temperature and F(Hβ), the total nebular flux at Hβ is listed in column 2 of Table 3. $G_1(T)$ is listed in the references cited above. Note that in both this formula and the following T_z and T_e are in units of 10^4 K.

The He II Zanstra temperature is given by

$$\frac{F(\lambda 4686)}{F_{4793}} = 41.49\, T_e^{-0.29} (T_z)^3\, G_4(T_z^3)\,(e^{3.002/T_z} - 1)\,\text{Å}.$$

$F(\lambda 4686)$ is the flux of the He II line at this wavelength and is also shown in Table 3. The fourth column of the table lists the extinction, which is not an important parameter in the temperature determination, because all of the wavelengths involved are so close that the extinction effects are minimal. The only cases where extinction will have an important effect are those where it varies strongly over the face of the nebula. For example, in NGC 6302, there is a dark lane seen optically which extends across the center of the nebula. If this lane were strongly absorbing, and the central star were imbedded in it or behind it, the extinction to the central star could be considerably higher than it is for the nebular line emission. This would cause the temperature to be overestimated. NGC 6302 is the only case of the nebulae listed in Table 3 where

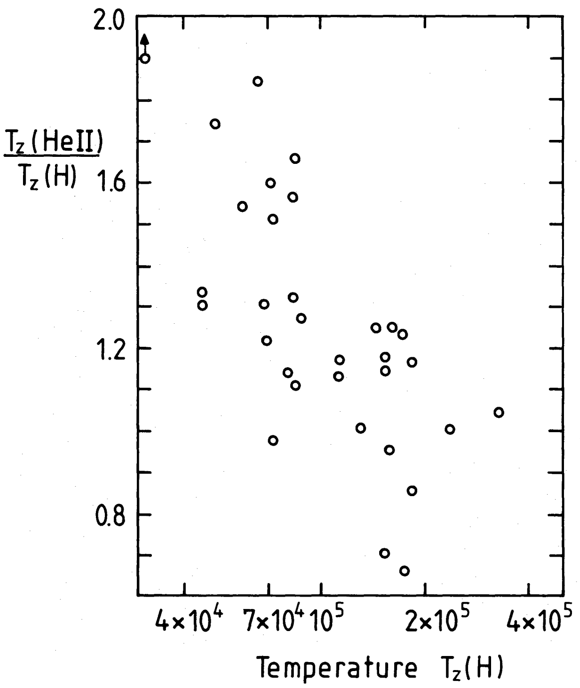

Fig. 1. The ratio of the He II Zanstra temperature to the hydrogen Zanstra temperature's is plotted as a function of the hydrogen Zanstra temperature. The ratio decreases as the temperature increases although the scatter is large

the optical observations provide such a direct indication that care must be taken in interpreting the resulting temperature. There may be other cases however.

Not all central stars listed in Table 1 have temperatures given in Table 3. This is because we have been unable to find Hβ fluxes (or radio contiuum measurements) for 5 of the nebulae which makes calculating Zanstra temperatures impossible. For 2 further nebulae (NGC 2346 and 3132) the measured magnitudes refer to companion and not the exciting star.

The resultant temperatures are listed in columns 5 and 6 of Table 3. For temperatures above 150,000 K, they have been corrected following the results of Stasinska and Tylenda (1986). This involves a lowering of T_z(H) because sometimes helium recombination provides two photons which may ionize hydrogen. Furthermore T_z(He II) can be raised because some times hydrogen absorbs a photon which was in the frequency range in which helium could be thought to do the absorbing. Because this correction is based on the assumption that the star radiates as a blackbody, it must be considered as only approximate. It is difficult to estimate an error for the temperatures given in the table. If only the uncertainty in the visual magnitude is important, the uncertainty is less than 2%. However in practice the assumptions concerning the nature of the radiation field (black body) and the optical depth totally determine the error in the effective temperature.

From Table 3 it can be seen that T_z(H) if often less than T_z(He II). This effect has been noted in the literature for some time and may be due to either (or both) of the following effects. (1) The nebula is optically thin in hydrogen ionizing radiation, in which case the correct temperature is T_z(He II), or (2) the central star does not radiate as a blackbody, in which case the higher value of T_z(He II) represents the relatively stronger emission shortward of 228 Å. In Fig. 1 we have plotted the ratio T_z(He II)/T_z(H) as a function of one of the temperatures (T_z(H)). As can be seen from the figure, the ratio is clearly highest for the lowest temperature, although a good deal of scatter is seen in the diagram. We would interpret this as supporting hypothesis (2). This is because such a relationship would not be expected in hypothesis (1). On the average the higher temperature central stars are the oldest, and might therefore be expected to occur in nebulae which are optically thin. They would thus have the highest ratio's if any effect were seen. On the other hand for hypothesis (2) we would expect the higher temperature stars to most closely resemble blackbodies, whose ratio would be unity. We therefore regard this as strong direct evidence that the difference between T_z(H) and T_z(He II) in the majority of stars is caused by departures from blackbody radiation in the central star. It must be in the sense that the radiation shortward of 228 Å is in emission, i.e. higher than would be expected from an extrapolation of the lower energy radiation. This is in accord with some of the non-LTE models presented by Husfeld et al. (1984) who find such effects in atmospheres close to the Eddington limit in the temperature range between 50,000 K and 100,000 K.

Kudritzki (1987) has also suggested that model atmospheres will produce strongly increased radiation shortward of 228 Å (by several orders of magnitude) when stellar winds are taken into account.

Recently Mendez et al. (1988) have determined T_{eff} by fitting line profiles at high spectral resolution of a number of central stars. Three of them are common to our nebulae. These are NGC 6629, NGC 7009 and IC 2448 for which they give temperatures of 47,000, 76,000, and 55,000 K respectively. For the last two stars both T_z(H) and T_z(He II) have been found. The values of Mendez et al. lie in between T_z(H) and T_z(He II) but closer to T_z(H). This also supports the idea that departures from blackbody radiation may be causing the difference. It may be premature to generalize from two cases, but these results suggest that when there is such a difference in temperature, the actual value lies in between, and possibly closer to T_z(H) than T_z(He II).

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