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HST photometry of the stars near the center of PN NGC 650

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Abstract. Colours and magnitudes of the central star of NGC 650 and its two companions have been obtained from HST images. The spectral types of the companions, which have been deduced from the colours, suggest a probable distance to the companions of between 5 and 6 kpc. Using the spectral and photometric characteristics of the central star, which are very similar to the very well studied PN PG 1159, we show that its distance is probably close to 1.2 kpc. Thus it appears unlikely that the central star is physically related to the two visible companions.

Key words: planetary nebulae: individual: NGC 650

1. Introduction

The planetary nebula (PN) NGC 650 is a large nebula showing a remarkable spatial structure. The brighter part looks like a bipolar outflow with a NE-SW axis, while the fainter parts also show a bipolar structure, but the symmetry axis is perpendicular to the axis of the brighter part. The catalogue of Manchado et al. (1996) shows a photograph of the PN, which clearly illustrates this. The nebular spectrum shows quite a high excitation, indicating a high temperature for the central star (Sect. 5 gives a more detailed discussion of the temperature). Analysis of the abundances shows a somewhat high He/H ratio (0.13 compared to 0.10 average PN value, Kwitter & Henry, 1996) and a higher than average N/O ratio (0.42 compared to 0.14 average PN value, Kwitter & Henry, 1996). These abundances may be indicative of a rather high mass star, and for this reason the nebula is classified as Type I. The central star, while faint, stands out against the nebula and was reported by Cudworth (1973) to be a double with a separation of $1\farcs4$. The northern component was found by Cudworth to be somewhat brighter, and probably bluer, indicating that this is the exciting star. For several other possible binary central stars, Cudworth was able to obtain proper motions, but for NGC 650 he only had single epoch plates so that it was impossible to say anything about a physical association of the stars. Bond et al. (1995) first reported that the secondary is itself a double star, using the same HST data available to us. The distance to NGC 650 is poorly known. There are statistical distances, which place it quite nearby. For example, Cahn et al. (1992) give 0.75 kpc. This might be expected for such a large, bright nebula. Acker (1978) gives a distance of 1.2 kpc on kinematic grounds. However, planetary nebulae, being older objects, often show considerable departure from circular rotation (e.g. Pottasch, 1984) so that this determination is also uncertain. If there were a physical association between the central star and its companions, it would be possible to obtain a distance to the planetary nebula from the spectral type of the companions. Because the distance is such an important parameter for discussing nebular evolution, we attempt in this paper to use the Hubble Space Telescope (HST) measurements of the central part of the nebula to determine the spectroscopic distance to the companion stars.

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2. Observations

Several images with the central part of NGC 650 centred on the PC1 ("Planetary Camera") chip of the WFPC2 camera aboard HST were obtained on August 5, 1995. Two images (U2SA0203T and U2SA0204T), with exposure times of 80^s and 160^s, were made through the F555W filter, which closely resembles the Johnson-V band. Additional exposures (U2SA0201T and U2SA0202T) were made with the F814W filter. Exposure times were 300^s and 500^s, respectively. All images are "well exposed" with a typical DN1200 (out of DN4096; gain 15 $\overline{e}$/DN; T = −88C). Both filters adopted are extremely well characterised (Burrows, 1995; Holtzman et al. 1995), and we extract information on zero-points and colour transformations from those publications.

3. Data-analysis

Cosmic rays were removed by comparing the multiple images per filter before we constructed the image shown as Plate 1. However, owing to the short exposure times, particle hits did not significantly disturb any of the stellar images of interest to us. Consequently, we applied the standard photometric and astrometric *iraf* tasks tasks to each of the four available images individually. This provided us with valuable information on consistency and repeatability. The accuracy of the individ-

Table 1. HST/WFPC2 observations of the three resolved stellar components

Nos.	Comment	V	I	RA(2000)	Dec(2000)	$\rho_{1,\mathrm{No.}}('')$	$\theta_{1,\mathrm{No.}}(^\circ)$
1	Centr. star NGC650	17.48	17.69	1:42:19.656	51:34:32.79	–	–
2	Poss. double	18.36	17.30	1:42:19.643	51:34:31.47	1.33	185
3	Comp. to No.2	19.20	18.08	1:42:19.630	51:34:31.38	1.43[1]	190
	Total:	16.94	16.45				

Notes: 1. Relative polar coordinates for the components 2 and 3 are $\rho_{2,3}$ = 0.16″ and $\theta_{2,3}$ = 235°.

ual positions in the HST celestial reference frame, as shown in Table 1, is estimated at 0.1 px (or 0.005 arcsec) for the central star of NGC 650 (No.1), and double that value for the companions (Nos. 2 and 3). The internal photometric errors are very small at a few thousands of a magnitude, but several additional factors need to be taken into account. In the first place, we had to use a very small extraction aperture (of 3 px, or 0.14 arcsec ⌀) to separate the components 2 and 3. In contrast, WFPC2 photometric calibrations (Holtzman et al. 1995) are based on 1 arcsec ⌀ images. We estimate the additional uncertainty introduced by this procedure, based on the PSF of the sufficiently isolated component 1, at no more than 0.03 mag. Some overlap of the PSF's occur for the stars 2 and 3, but the contribution to our extraction aperture, for which we corrected, is never more than 0.15 mag (i.e. to the I magnitude of No. 3). Finally, we converted the natural WFPC2 magnitudes to standard V and I values using the (2nd order) colour-transformation scheme of Holtzman et al. 1995. This also adds a small contribution to the error budget. We conclude that the zero-points of the magnitudes shown in Table 2 are probably correct to 0.05 mag, while the colours are a little better.

The photometry in Table 1 may be compared to values given in the literature. Cudworth (1973) gives a photovisual magnitude of 17.5 for the central star and 17.7 for the companion. Shaw & Kaler (1985) give a value of V = 15.87 ± 0.36 for the combination of stars, which is too bright. But they are measuring with a 40" diaphragm which not only allows a large amount of nebular light to enter the photometer (which they had to correct for) but measures the light of other stars in the field as well. As can be seen in Plate 1, there are several bright stars in a 40" field of view. Napiwotzki & Schönberner (1995) give V = 17.7 ± 0.3 by measuring the continuum of spectrum of the central star. This value is only marginally fainter than our measurement, which might be caused by a small tracking error during the exposure through the slit of their spectrograph.

4. Distance to the companions

From the observed colours we can derive intrinsic colours by correcting for interstellar reddening. We adopt a value of $E_{\mathrm{B-V}}$ = 0.16, which is the value that produces the intrinsic colour expected for a hot star. $(V-I)_0 = -0.47$ (Johnson, 1966). This generalised "hot star" refers to O-B stars, thus temperatures between 20,000K to 40,000K. The central star is considerably hotter, as is shown below. It is possible therefore that the intrinsic $V-I$ colour is somewhat bluer, although the effect is likely to be small. No I magnitudes are available for other PN central stars, but the effect can be seen in $B-V$ colours. Whereas the standard intrinsic colour for O-B stars is $(B-V)_\mathrm{o} = -0.31$ (Johnson, 1966), bluer colours have been measured for very hot central stars such as those of NGC 7293 and NGC 1360. In fact Kaler & Feibelman (1985) recommend the use of $(B-V)_\mathrm{o} = -0.38$. If the intrinsic $V-I$ colour is also bluer, the value of extinction would be somewhat larger. However the extinction may also be derived from the ratio of the Hβ to radio continuum, and from the nebular Balmer decrement. Cahn et al. (1992) give E_{B-V} values of 0.12 and 0.14 from these two kinds of measurements. Thus there is no clear indication that the value of extinction we have found should be increased. The intrinsic colours are shown in Table 2. Also given is the spectral type which corresponds to the intrinsic colour (Johnson, 1966). It was assumed that the companions are main sequence stars (if they were giants this would lead to an improbably large distance). Companion No. 3 would then have a value of $M_\mathrm{V} \simeq 4.7$ and a distance of $d \simeq 6$ kpc. Companion no. 2 would have $M_\mathrm{V} \simeq 4.4$ and $d \simeq 5$ kpc. If this difference is significant, and if so what it is due to, is a matter of speculation. The image of companion no. 2 shows a slight indication of being widened, so that the "binary" could be a triple system, which could explain its being overly bright. On the other hand, companion no. 3 could be sub-luminous. But the difference is small, and the conclusion may be drawn that the companions are at a distance between 5 and 6 kpc.

Table 2. Intrinsic stellar colours for the three resolved stellar components of NGC650 assuming $(V-I)_0 = -0.47$ for the central star corresponding to $E_{\mathrm{B-V}}$ = 0.16 and A_V = 0.5.

Nos.	V_0	I_0	$(V-I)_0$	Sp.
1	17.00	17.47	−0.47	sdO
2	17.88	17.07	0.81	G0V+?
3	18.72	17.85	0.86	G2V

5. Temperature of the central star

Before discussing the consequences of having the nebula at the distance of the visual companions, it is necessary to discuss the temperature of the central star. There are two good ways of determining the temperature: 1) from the spectrum of the central star, and 2) from the Zanstra method. The spectrum of the central star has been discussed by Napiwotzki (1993) and Napiwotzki & Schönberner (1995). Napiwotzki (1993) classifies it

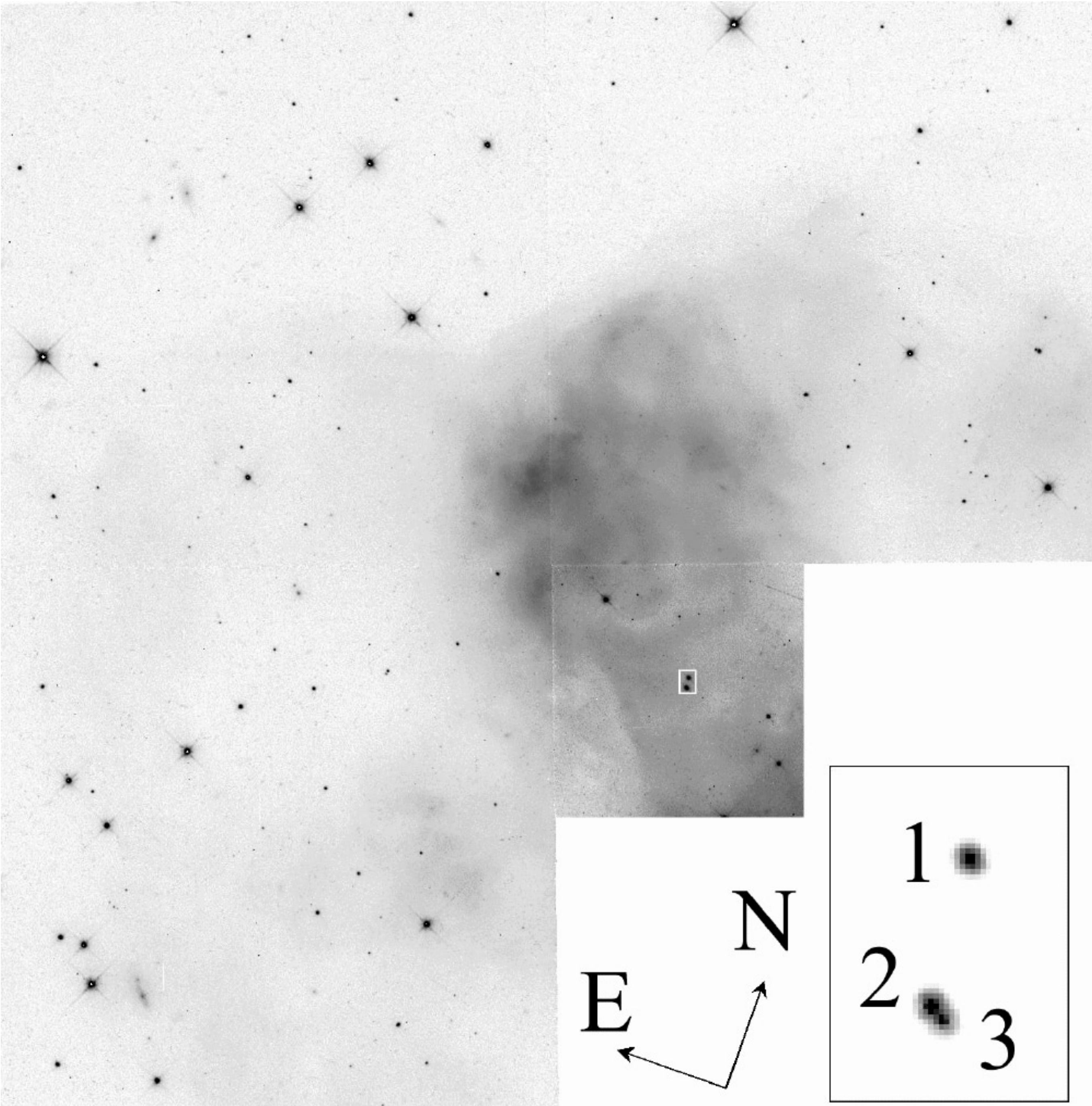

Fig. 1. This combined F555/F814 HST/WFPC2 image shows the central and north-eastern part of NGC 650. Each of the three WF chips measures $1\overset{\prime}{.}25$ on the side. The central star is centered in the PC chip, which measures $35'' \times 35''$. The central (boxed) part of this chip is shown enlarged in the insert. It includes the central star of the planetary nebula and its visual companions, clearly showing the binary nature of the latter. The object numbering corresponds to the entries in the Tables 1 and 2.

as a PG 1159 star, because of the absence of hydrogen lines and the presence of H II and C IV lines. The spectrum is very similar to spectra analysed by Werner et al. (1991). These authors find a value of temperature $T_{\rm eff} = 140,000$ K and a log g = 7.0 for these stars, which include PG 1159 itself. Napiwotzki adopts these parameters for the central star of NGC 650, which appears spectroscopically very similar to PG 1159. The uncertainty in the temperature is about 10%. Several PN central stars show a similar spectrum: A 21, Jn 1, PG 1520+525. As far as the present observations allow a comparison, they appear identical to PG 1159. Kawaler & Bradley (1994) have made a careful analysis of the non-radial pulsations in this star and have been able to derive very accurate values of temperature, luminosity and mass for this star. These values agree within the limits of error with the less accurate values of Werner et al. (1991). The temperature they find is $T_{\rm eff} = 136,000$ K. We shall return to the other parameters in Sect. 7. The Zanstra method can also be used to determine the temperature. The resultant values differ from values given earlier in the literature because of the improved value of the V magnitude given in Table 2. Using the same extinction, an Hβ flux of log Hβ = -10.67 and a value of the ratio He II 4686/Hβ = 0.6 (Cahn et al., 1992), we find the hydrogen and He II Zanstra temperatures to be: $T_{\rm Z}$(H) = 160,000 K, and $T_{\rm Z}$(He II) = 145,000 K. The rather close agreement of these temperatures indicates that the nebula is optically thick both in hydrogen and He II ionizing radiation. We adopt $T_{\rm eff} = 140,000$ K in the following discussion.

6. The gravity distance

We make use here of the spectral similarity of the central star of NGC 650 and PG 1159. Werner et al. (1991) find spectroscopically a value of log $g = 7.0 \pm 0.5$. Kawaler & Bradley (1994) find log $g = 7.38 \pm 0.1$ and M = 0.59 $M_\odot$ from non-linear pulsations. Using the relation of Mendez et al (1988)

$$d^2 = 0.382 \frac{M}{M_\odot} F g^{-1} 10^{0.4 V_0} \qquad (1)$$

where M is the stellar mass, g is the surface gravity (cm s^{-2}), V_0 is the visual magnitude of the star corrected for extinction, and d is the distance in kpc. F is the stellar flux from a model atmosphere, and for the temperature of this star has a value of 24 in units of 10^8 erg cm^{-2} s^{-1} Å^{-1}. The distance to NGC 650 is then 1.2 kpc. If NGC 650 were placed at a distance of 5 kpc, its gravity would be log $g = 6.15$ which is too low for the spectrum found. Another way of obtaining the same result, is by making use of the distance to PG 1159 of 440 pc (Kawaler & Bradley, 1994). Since its V_0 magnitude is 14.83 compared to 17.00 for the central star of NGC 650, the distance to the latter must be 1.2 kpc if all the other characteristics of the star are the same.

7. Conclusion

We have investigated the possibility that the visual companion of the central star of NGC 650 is physically associated with the latter. Using positions, magnitudes and colours from HST images, we conclude that a physical association is unlikely. We note that the companion is itself a close binary, and possibly a triple system. As by-product of this work, the agreement between the Zanstra temperatures (H and He II) with the spectroscopic temperature, leads to the conclusion that the nebula is optically deep in H and He II ionizing radiation.

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