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LETTER

Letter to the Editor

The central star of the Planetary Nebula NGC 6537

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Abstract. The fact that Space Telescope WFPC2 images of the planetary nebula NGC 6537 fail to show the central star is used to derive a limit to its magnitude: it is fainter than a magnitude of 22.4 in the visible. This is used to derive a lower limit to the temperature of the star. The Zanstra temperature is at least 500 000 K. The Energy Balance temperature is found to be consistent with this value, as is the ionization state of the nebula. Assuming a reasonable range of distances for the nebula, the radius of the star can be found. It is consistent with the mass-radius relation of a white dwarf of 0.9 $M_{\odot}$ or higher.

Key words: stars: fundamental parameters – ISM: planetary nebulae: general – ISM: planetary nebulae: individual: NGC 6537

1. Introduction

Determining the temperature of a hot planetary nebula central star is difficult. The methods used are well known, the most reliable being the Zanstra method, followed by the Energy Balance method. All the methods have been critically discussed by Stasinska and Tylenda (1986), (hereafter ST) using idealized nebular models. We shall apply them to the case of NGC 6537.

To measure the Zanstra temperature it is necessary to know, in addition to the hydrogen and helium nebular line flux, the stellar continuum at some low energy wavelength. Usually the magnitude of the star in the visual is used. But as a star becomes hotter, the visual magnitude of the star becomes fainter compared to the nebular emission. At some point the star can no longer be distinguished from the nebular emission. The standard technique is to use a filter which can exclude the stronger nebular lines, but the nebular continuum always remains. An image should be made in very good seeing.

This has been done for NGC 6537 by Gathier and Pottasch (1988) and Jacoby and Kaler (1989). Neither of these groups was able to detect the central star. Gathier and Pottasch report that it must be fainter than m_v=18.9, corresponding to a HeII Zanstra temperature of 210 000 K. Jacoby and Kaler find a very similar limit to the magnitude, 18.78. These latter authors predict that a 'crossover' magnitude, (that magnitude for which the H and the HeII Zanstra temperatures will be the same), is 19.67, corresponding to a stellar temperature of 250 000 K. Heap et al (1990) also fail to detect the star in conditions of very good seeing. They report that the star must be fainter than m_v=20.0.

The Hubble Space Telescope (HST) permits a much improved measurement of the magnitude. This is because the stellar image is an order of magnitude smaller, due to the fact that there is no seeing to broaden the image. This greatly increases the contrast, by about a factor of 100. We shall report on these measurements here.

2. Measurements

HST images of NGC 6537 were obtained on 12 Sept. 1997. A total of 18 images were obtained with WFPC2 in program 6502 (B.Balick, P.I.). Most of the images are not ideal for our purpose, since they were taken with filters which include strong nebular lines. One image was taken with the filter F547M, which passes visible light containing only weak nebular lines and the nebular continuum. The exposure time was 40 seconds. Some of the other images had longer exposure times, up to 500 seconds. The results are interesting: no central star is visible in any of the images including that taken with the F547M filter. This is corraborated by Balick (private communication, 2000) who states that none of the images, including the F547M image, 'show any trace of a central star'.

To obtain a quantitative estimate of the upper limit to the magnitude we have proceeded as follows. NGC 6537 has been compared to Me2-1, which has been chosen because the two nebulae are very similar, except that the central star of the latter nebula is clearly seen. Me2-1 is slightly larger (diameter about 9$''$) than the central region of NGC 6537 where almost all the emission is concentrated (diameter about 7$''$). Me2-1 has a total Hβ flux of -11.34 (log erg cm^{-2}s^{-1}) compared to -11.66 for NGC 6537. The average surface brightness is therefore very similar, but because the central regions of NGC 6537 (where presumably the central star is located) is clearly less bright than its outer regions, the central surface brightness in NGC 6537 is less than it is in Me2-1.

Me2-1 was measured by the WFPC2 on 23 Feb. 1994 in program 5107 (J. Westphal,P.I.) and has been calibrated and

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analysed by Wolff et al (2000). One of the images measured was taken with an F547M filter and is entirely equivalent to the image taken of NGC 6537, except that the exposure time was somewhat longer: 100 seconds. The visual magnitude of the central star was found to be 18.40, and the ratio of the peak stellar flux in the visual to the surrounding nebular continuum is 20. A star of this magnitude is thus easily seen. If a star could be recognized when its peak flux is 50% of the nearby nebular continuum, its flux would be lower than that of Me2-1 by a factor of 40. This is 4 magnitudes, and applies for the central star of NGC 6537 if the nebular continuum is the same as for Me2-1. This is approximately true, since, as shown above, the Hβ surface brightness of both nebulae is about the same. Because the central regions of NGC 6537 have a lower surface brightness, the star could be somewhat fainter. A possible compensation for this is the somewhat shorter exposure time of the WFPC2 image of NGC 6537. We estimate that the central star has m_v=22.4 or fainter.

This result could have been anticipated. The ground based measurement was made with a seeing of approximatel 0.8-1.0$''$(Jacoby and Kaler, 1989), while the WFPC2 measurement has a resolution of 0.1$''$, an improvement of between a factor of 64-100(about 4.5-5 magnitudes). Since Jacoby and Kaler have an upper limit of m_v=18.78, we might expect an upper limit to the WFPC2 measurement of between 23.3 and 23.8 magnitudes. That we do not go so faint may have two origins. First, Jacoby and Kaler had a longer measurement: 600 seconds. Second, we may have been conservative in estimating that a 50% change in the continuum level is necessary to recognize the central star. The effect of the longer exposure time is difficult to estimate, because the nebular background increases just as fast as the starlight. We maintain the estimate of m_v=22.4.

3. Central star temperature

3.1. Zanstra temperature

The Zanstra temperature requires only a knowledge of the stellar flux density or magnitude and the Hβ flux. The extinction plays only a minor role because these radiation fields are at almost the same wavelength. A value of log Hβ=-11.66 and E_{B-V}=1.23 (see Pottasch et al, 2001, hereafter PBF, for a discussion of these quantities). The H Zanstra temperature then becomes T_Z(H)=680 000 K and the helium Zanstra temperature T_Z(HeII)=480 000 K. The difference between these two temperatures occurs in high temperature stars because some photons which doubly ionize helium can ionize hydrogen as well, sometimes twice. It is expected that the actual temperature lies between these values. The models of ST predict this behaviour, and show that probably the true value lies closer to the value given by T_Z=500 000 K. This value is a lower limit.

3.2. Energy balance temperature

The underlying idea of this method (also called the Stoy method) is that the ratio of the sum of the collisionally excited line intensities to the intensity of a hydrogen recombination line reflects the average energy liberated per photoionization, which is a function of the stellar temperature. The method is attractive because it does not require any observation of the central star, but only of the nebular spectrum. In addition there is only a small dependence on the optical thickness of the nebula.

All the collisionally excited lines must be included to obtain the correct temperature. As ST have pointed out, there are three potentially important lines which cannot be measured with present techniques. These are Lyα, O V 1215 A, and O VI 1034 A. The intensity of these lines must be estimated.

The ratio ρ of the measured collisional excited line intensities to Hβ is ρ=105 (PBF). This includes the Ne V line at 3426 A (Rowlands et al, 1994), which isn't listed by PBF, but is reasonably strong: about 2.9 Hβ. The O V and O VI line intensities can be found by using estimates of the abundances of the appropriate ions from the same reference. The intensities of these lines turns out to be comparatively small, with ρ about unity. The Lyα line is important however. It's strength may be estimated as follows. First the amount of neutral hydrogen can be found from

$$\frac{O^0}{O^+} = \frac{9}{8}\frac{H^0}{H^+} \tag{1}$$

The values of O^0 and O^+ may be found in PBF and is

$$\frac{O^0}{O^+} = 2.9 \times 10^{-2} \tag{2}$$

Thus

$$\frac{H^0}{H^+} = 2.58 \times 10^{-2} \tag{3}$$

The ratio of the collisional Lymanα to Hβ is given by

$$\frac{I(Ly\alpha)}{I(H\beta)} = \frac{H^0 C_{12}}{H^+\alpha(H\beta)} \tag{4}$$

where the values of the electron density appearing in both the top and bottom of the equation cancel out, α(Hβ) is the effective recombination coefficient and C_{12} is the collision excitation rate. Values of the collisional excitation rate are listed by Drake (1983) and are a strong function of the electron temperature. This is given by PBF as 16 500 K or slightly higher over much of the nebula. C_{12} then is 2.1×10^{-11} cm^{3}s^{-1} and α(Hβ)=1.89×10^{-14} cm^{3}s^{-1}. The ratio of collisionally excited Lyα to Hβ is therefore 28.4. The excitation of the higher Lyman lines should be added to this. Drake gives the collisional excitation rate of Lyβ as 10% of Lyα; we therefore add 10% to the above ratio and ignore the higher Lyman lines. The total ratio of the collisionally excited l s to Hβ is approximately 140.

The predicted ρ has been discussed by Preite-Martinez and Pottasch (1983). The ratio depends not only on the stellar temperature, but also on the model atmosphere used, the abundance of the helium ions (especially doubly ionized helium) and the optical depth in the hydrogen and helium Lyman continua. We shall assume here that the star radiates as a blackbody, which is to be expected for such a hot star. The helium abundances are those appropriate to NGC 6537: He^+/H=0.062 and He^{++}/H=0.087

and are taken from PBF. The electron temperature is the same as above, but is not a critical parameter. Three cases may be distinguished. In Case I the nebula is optically thin to ionizing radiation in H, He^0 and He^+. In Case II the nebula is optically thick in He^+ and thin in the other continua. In Case III the nebula is optically thick for all ionizing continua of H and He. Case I is not realistic for NGC 6537 and we will ignore it and concentrate on the two other cases.

The results are shown in Table 1. The observed value of ρ indicates a temperature of about 370 000 K if Case II is applicable, and about 450 000 K in Case III. This confirms that the temperature of the star is very hot, and considering the possible sources of error, it is consistent with the Zanstra temperature found in the previous section.

3.3. The ionization temperature

As a star becomes hotter it produces more highly charged ionization states. This is the basis for computing an ionization temperature. In fact, this is the only temperature which exists in the literature for NGC 6537. A recent computation of the ionization temperature based on the observed Si^{+6} line is 156 000 K (Casassus et al,2000).

It is not clear how reliable such an estimate of the temperature is. ST(1986) argue quite convincingly that it is not reliable and will only give a lower limit to the temperature. This is based of a series of models made of nebulae with central star temperatures from 40 000 K to 500 000 K. The ratio of the abundance of two highly charged ions (in this case Ne^{+5}/ Ne^{+4}) was plotted against the central star temperature. As the stellar temperature increases so does this ratio, at least for temperatures below 150 000 K. Above this temperature the increase of this ratio levels off and may even decrease above 250 000 K. ST say ‘models for high excitation nebulae seem to have always been built with the lowest effective temperature compatible with the observations’. That this may also be true in the case of Casassus et al, appears from the fact that at a temperature of 156 000 K the emitting star should have m_v=19.5. A star of this magnitude would have easily been seen. Therefore it seems that the ionization temperature does not give a clear indication of the stellar temperature in this case.

4. Discussion

4.1. Uncertainty in the data and special conditions

The only parameters which enter the determination of the Zanstra temperature are the observed stellar magnitude, the observed Hβ flux and the extinction. The latter is unimportant because the other two quantities are measured at almost the same wavelength. The Hβ flux has been measured four times using diaphragms of about 40″: the same flux was measured each time. Since a substantially brighter central star would have certainly been seen in the HST measurement, we conclude that no important uncertainties in the data exist.

Are there conditions which could trick us into thinking that the Zanstra temperature is anomanously high? One possibility is that the extinction of the starlight is much greater than the extinction of the nebular light. This could be done by having a small cloud of highly absorbing material around the star. This material should have the property that it lets ionizing radiation pass freely, so that the ionization of the nebula is not impeded. Alternatively this material could be in the form of a disk placed so that it absorbs starlight in our direction but allows it to pass freely in other directions, so that the nebula will be ionized. Such a condition is not impossible: witness the dark dust lane passing through the central regions of NGC 6302. But there is nothing to see of such anomalous extinction on the HST images of NGC 6537. Other conditions could exist as well. The star could emit radiation much different than a blackbody. But none of these conditions are likely enough to ignore the possibility that the star is indeed very hot.

Table 1. The ratio ρ for hot blackbodies

Temperature	Case II	Case III
200 000	84	82
250 000	102	95
300 000	120	107
350 000	136	119
400 000	151	131
500 000	176	150

4.2. The nature of the star

An upper limit to the radius of the star can be obtained, assuming it radiates as a blackbody of 500 000 K and has an m_v=22.4. The distance to the nebula must also be known but is poorly determined. The best value is that of Gathier et al (1986): 2.4 kpc. It is based on 21 cm absorption line measurements which show clear absorption feature from the local gas and from the Sagittarius arm as well. No trace of the Scutum arm is seen. The Sagittarius feature has the same optical depth as is seen in the spectrum of a very close background source. Gathier et al conclude that NGC 6537 is at the far side of the Sagittarius arm but in front of the Scutum arm. With this distance the radius of the star becomes $R_{\rm star} = 1.16 \times 10^{-2} R_\odot$[1]. This is what would be expected from a $0.7 M_\odot$ white dwarf carbon-oxygen core (Hamada and Salpeter,1961 and Suh and Mathews,2000). However the star probably has a substantial hydrogen atmosphere, making the carbon-oxygen core at least 10% and perhaps 40% smaller than the stellar radius. This would correspond to a star of $0.9 M_\odot$ to $1.0 M_\odot$. For example, the models of Blocker (1995) show a substantially bigger atmosphere for hot stars in this stage of stellar evolution. His hottest model, which has a core mass of $0.94 M_\odot$ and reaches a temperature of 400 000 K, has a radius of $1.39 \times 10^{-2} R_\odot$ on the cooling curve about a factor of 20 below maximum luminosity. This is almost 50% greater than the carbon-oxygen core of

[1] Model atmospheres of very hot stars computed by Rauch (unpublished) have been used to compute the radius

this mass. It is clear that we are dealing with an abnormally high core mass central star. This result is distance dependent: if the star is closer(as several recent statistical determinations indicate) its radius will be even smaller and the core mass even higher.

4.3. Evolution

There is good agreement between the observations and the models in one respect. The models predict that the higher core mass central stars are able to reach a much higher surface temperature than the lower mass stars, and this is what we believe we see in NGC 6537. In another respect the models do not agree with the measurements in this nebula. All models predict that the evolution occurs more quickly as the core mass increases. In the 0.94$M_\odot$ model of Blocker(1995) the evolution from the AGB to the white dwarf stage happens in less than 100 years. If the mass were higher the time would be shorter still. In NGC 6537 the evolutionary time can be estimated by noting the bright shell of material surrounding the central star at a distance of about 3 or 4$''$ from it. If this has always moved at about 18km/s, which is the accepted expansion velocity of the nebula, then its age, measured from when the shell was expelled, is 2500 years. This value is similar to other young nebulae, and gives no evidence for exceptionally fast evolution. There is a photograph of the nebula taken about 85 years ago by Curtis(1918) for which a diameter of 5$''$ is given. This is comparable to its present dimension considering the great difficulty of measuringdiameters on uncalibrated photographs. In addition, Curtis remarks that no central star was seen. If the central star had a temperature of 30 000 K 100 years ago, it would have been 10.1 magnitudes brighter in the visible if it followed the 0.94$M_\odot$ model of Blocker(1995). It would thus have had a visual magnitude of 12.3. Such a bright star would have easily been seen by Curtis, who probably could have seen a star as faint as the 17th magnitude. It must be concluded that the evolution of the central star did not take place nearly as quickly as predicted by the 0.94 $M_\odot$ model of Blocker.

5. Conclusions

The visual magnitude of the central star of NGC 6537 is 22.4 or fainter. The Zanstra temperature of the central star derived from this magnitude is 500 000 K or higher. The Energy Balance method gives a temperature consistent with this value. The temperature given by the degree of nebular ionization is lower, but there is reason to believe that it is not reliable.

From the above magnitude and temperature, the radius of the central star is found. Using the core mass-radius relation it is shown that the core mass must be high, probably about 1 $M_\odot$. The high temperature and high core mass are consistent with high mass evolutionary models except for the time of evolution, which must be at least an order of magnitude longer than predicted.

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