THE ASTRONOMICAL JOURNAL VOLUME 108, NUMBER 3 SEPTEMBER 1994

THE PLANETARY NEBULA ABANDONED BY ITS CENTRAL STAR

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Received 1994 February 22; revised 1994 May 2

ABSTRACT

Narrowband images have been obtained of the nebula Sh 2−174, to follow up the recent claim that the white dwarf situated on one edge, GD 561, is its displaced central star. The Hα and [N II] emission originates from the cleft-hoof morphology apparent on the POSS, but the [O III] is centred on the white dwarf. This confirms that the star and the nebula are physically related. With the severely distorted morphology apparent in Hα and [N II] combined with the location of the former central star, Sh 2−174 represents the most advanced case so far of the PN–ISM interaction. Spectra taken of GD 561 suggest a surface gravity $\log g \approx 6.8$ and effective temperature $T_{\rm eff} \approx 65\,000$ K. Assuming a standard single star evolution, this would lead to an exceptionally low mass and a post-AGB age of ~ten million years, which is incompatible with the several hundred thousand years which is generally supposed to be a typical PN lifetime. We suggest instead that GD 561 is part of a close binary system, having lost its outer envelope after the termination of core H burning, and is now a small $\sim 0.3 \mathscr{M}_\odot$ degenerate He dwarf. However, this scenario requires the existence of a faint companion.

1. INTRODUCTION

The oldest planetary nebulae are characterized by significant interactions with the Interstellar Medium (ISM). It is this which increasingly determines their morphology, while at the same time the shaping produced by the original ejection mechanism becomes less important. Mild cases include Abells 34 and 61 (Tweedy & Kwitter 1994), where the interaction region appears merely as an asymmetric brightening with a lower ionization state. Later, a strong ionization stratification occurs—exemplified by Abells 31 and 62 (Tweedy & Kwitter 1994)—which may arise in part because of the severely disrupted flow in the outer region. More advanced still are those where the former central star, unaffected by the interaction with the ISM, is substantially displaced from its original position. The classic example of this is the closest known planetary nebula, Sh 2−216 (Reynolds 1985); others include the essentially one-sided nebulae, A21 (Kwitter *et al.* 1983) and Sh 2−188 (Rosado & Kwitter 1982).

Recently, Napiwotzki & Schönberner (1993a) argued that the nebulosity catalogued as Sharpless 174 is a planetary nebula, produced by the white dwarf GD 561 which is situated near its rim. Their reasoning was based on the similarity of the distance estimated to both nebula and white dwarf. Fich & Blitz (1984), in a study of H II regions, had deduced a distance of 0.3 kpc for Sh 2−174 from its radial velocity, which implies a size similar to many old planetary nebulae, but is much too small to be an H II region. Comparing the apparent magnitude of GD 561 with an approximate absolute magnitude produces a similar distance estimate. The temperature derived from a preliminary analysis of the Balmer lines—$\approx 60\,000$ K—suggests that it is hot enough to have emerged from a planetary nebula within the last few million years or so.

Although this is a fairly strong line of reasoning, neither distance estimate is of particularly high precision. Since the white dwarf is far from being central to the nebula, there is a substantial chance that the apparent proximity of the two is a line-of-sight coincidence. Narrowband imaging was therefore obtained at the Burrell–Schmidt on Kitt Peak, to ascertain whether the white dwarf is affecting the ionization structure of Sh 2−174, as would be expected if it is indeed the former central star. It thus became part of an ongoing campaign to investigate the interaction of old planetary nebulae with the interstellar medium, early results of which appear in Tweedy & Kwitter (1994).

2. OBSERVATIONS AND DATA REDUCTION

2.1 Imaging

The observations reported here were taken on various nights between 1993 May and November, at the Burrell–Schmidt telescope on Kitt Peak. This is a 36 in. instrument with 24 in. of unobscured aperture, and fast optics of $f/3.5$. Since 1989 it has been equipped with a 2048×2048 Tektronix CCD. There are two bands of hot columns which have been avoided, but apart from this the detector is cosmetically well behaved. Three filters have been used, of which one—[O III]5007—was lent by Bruce Balick at the University of Washington, and two (Hα and [N II]6584) were lent by Karen Kwitter of Williams College. The transmission at 6584 Å in the Hα filter is essentially negligible, but at 6563

Å in the [N II] filter it is ≈5%, compared to a peak value of 45%. The spatial resolution is dominated by the large angular size of the pixels, 2.07″, and is ≈4″. The data reduction was done primarily at NOAO in Tucson, using standard IRAF procedures. All images have been trimmed to 700×700 pixels, corresponding to 24′.

Since Sh 2−174 has a very high declination, use of the auto guider on the Schmidt produced worse results than for images taken when the telescope tracking alone was used. The images reproduced here are the best of several in each filter that were obtained, but in each case slight trailing is evident.

2.2 Spectroscopy

Spectra of GD 561 were obtained with the TWIN spectrograph attached to the 3.5 m telescope at the Calar Alto observatory in 1992 July. In the blue, the detector was a 1024×640 RCA CCD, which has 15 μm pixels; grating T05 was used, which provided 1.3 Å resolution. In the red a GEC CCD with 1155×768 22 μm pixels was attached, and the T09 grating provided 1.5 Å resolution. Wavelength calibration spectra from a HeAr lamp were obtained after each exposure. The data were processed using standard procedures in MIDAS, distributed by the European Southern Observatory.

Observations were also performed with the Multiple Mirror Telescope on Mt. Hopkins, in 1993 September. The Red Channel spectrograph was used, which is optimized for the range 5000 Å to 1 μm, but has reasonable sensitivity to 3700 Å. The detector was a Loral 1200×800 CCD. A 1200 line grating blazed at 5800 Å, giving 2 Å resolution, was used. Conditions were cloudy, although towards the north the cover was thinner. Standard IRAF procedures were used to process the spectra. Calar Alto data was used for model fitting, except for Hβ and Hγ.

3. THE RELATIONSHIP BETWEEN Sh 2−174 AND GD 561

The Hα and [N II] images [Figs. 1(a) and 1(b) (Plate 27)] both show the morphology of Sh 2−174 at much higher spatial resolution and signal to noise than on the POSS. It appears to have two distinct halves, but both have a higher surface brightness in lobes to the south-west. While the nebula in [N II] is recognizably the same as that in Hα, its morphology in [O III] [Fig. 1(c)] bears almost no resemblance to either. Since the [O III] region is located in that part of the nebula which is adjacent to GD 561, it dramatically confirms that the white dwarf and the nebula are indeed physically related.

There remains the slight possibility that GD 561 is an isolated white dwarf that happens to be wandering through the nebula. This can be addressed by finding the space density of hot white dwarfs, which gives directly the probability that any one of them could be found in the ~10 pc^3 specified by Sh 2−174. Using the luminosity function data of Fleming *et al.* (1986), the space density of white dwarfs with M_V<9.25 is 7.56×10^{-6} per 10 pc^3—which is essentially negligible. Such a coincidence would also beg the question of how a small nebula like this could exist without having a PN origin; GD 561 is the only blue star in the vicinity which could be responsible for it.

The striking spatial difference between the [O III] and [N II] is a characteristic of extremely old nebulae. This effect is sometimes observed in young, optically thick nebulae [e.g., NGC 40, NGC 7139, see Balick (1987)], but the objects here are the epitome of those that are optically thin. Tweedy & Kwitter (1994) show that a lower ionization is induced by an interaction with the ISM. This is most clearly seen in the early stages, as exhibited by Abells 34 and 61. In more advanced cases, like Abells 31 and 62, the [O III] zone is restricted to a small region around the central star, while the outer regions are dominated by emission from [N II] and [O II]. Later in the interaction, the white dwarf becomes substantially displaced from the center. This is exemplified by Sh 2−216 (e.g., Reynolds 1985), where the [O III] region has effectively moved with the former central star. GD 561/Sh 2−174 thus represents the logical conclusion of this effect: the white dwarf is now on the edge, surrounded chiefly by the [O III] region, while the bulk of the nebula has a completely different morphology and a lower ionization state.

It might be argued that the large [N II] region is not due to the interaction with the ISM, but is instead due to the fact that the white dwarf is fading, so that recombinations now exceed ionizations. Although this may have some effect, it seems unlikely that this is the full explanation. As shown below, the central star has a temperature ≈60 000 K, and has remained above that temperature for at least 10^4 years.

4. THE MORPHOLOGY OF Sh 2−174

Until Napiwotzki & Schönberner (1993a), Sh 2−174 had not been regarded as a planetary nebula for two reasons—there was no central star, and its morphology is extremely distorted compared to the fairly symmetrical appearance of all but the oldest ones. Even so, it is unlike either the one-sided planetaries Sh 2−188 and A21, or the nearby Sh 2−216, which despite its bright eastern ridge preserves an essentially diffuse circular appearance elsewhere. The closest analogy to Sh 2−174 is probably Abell 31 (see Tweedy & Kwitter 1994): both are elongated, and the interaction with the ISM is strongest perpendicular to the major axis; both have strong ionization stratifications, and are still quite bright on the side of the nebula furthest from the main interaction region. It is therefore tempting to speculate that Abell 31 will eventually appear like Sh 2−174 after further evolution—although not enough is known about the development of planetaries interacting with the ISM for this to be argued convincingly.

Most of the circumference of Sh 2−174 appears to be diffuse, with the exception of the sharp edge to the NW side of the [O III] region. This is as expected, since this is in the direction of motion of the nebula and central star, where the strongest shock would be expected. Despite the unusual gross morphology, there is remarkably little internal structure—for example, the SE half appears completely featureless. The NW half appears to be slightly mottled, as might be expected for the region behind the shock visible in [O III].

The only published models of the PN–ISM interaction are those of Soker *et al.* (1991), but Sh 2−174 provides a particularly instructive comparison. Unlike Abell 31, which appears to be uniformly filled, the two halves more closely resemble the thick shell—albeit a disrupted one—assumed by Soker *et al.* Their disk model H, displayed at $t=10^5$ yr, shows the central star located close to the middle of the upstream side of the shell, and thus represents a stage a little prior to GD 561/Sh 2−174. Evolution of the galactic halo models demonstrates that the elongated shape of Sh 2−174 could have originated even from an originally circular nebula, but an important difference is that the surrounding ISM is clearly not of uniform density. It appears that the ISM variations could be approximated by a steep gradient declining from SW to NE—thus explaining the lobes in the SW corner, and the diffuse, structureless fading to the NE.

It is difficult to characterize the dimensions of this nebula, because of the peculiar morphology. The inner, bright, cleft-hoof structure has minimum and maximum sizes of 6.5′ (roughly at position angle 120°) and 9.5′ (through the NW half); including the diffuse, outer material, the size of the nebula is 9.8′ (P.A. 120°) by 15.5′ (P.A. 180°).

5. GD 561

GD 561 was one of a large number of white dwarfs discovered as a result of its extreme blue colors by Giclas *et al.* (1970), during the Lowell Proper Motion Survey. However, no proper motion was detected. Photometry by Greenstein (1974) produced $V=14.52$, $B-V=-0.33$, and multichannel spectrophotometry (Greenstein 1984)—reduced to six broad-band colors—led to a DA2 classification, implying a temperature between 20 000 and 40 000 K. Guseinov *et al.* (1983) inferred a temperature of 40 000 K, using previously published data combined with the synthetic colors of Koester *et al.* (1979). Both these determinations are significantly cooler than that obtained by Napiwotzki & Schönberner (1993a), who with 6 Å resolution spectra estimated $T_{\rm eff}$=50–60 000 K. In addition, GD 561 also exhibits He II 4686 Å, and therefore has to be reclassified as a DAO. While this work was in progress we became aware of a detailed study of DAO white dwarfs by Bergeron *et al.* (1994), of which GD 561 was one of the targets. We will discuss this interesting paper in detail below.

5.1 Optical Spectra

Analysis of the optical spectra of GD 561 was performed using a NLTE grid of model photospheres containing H and He, computed with the ALI code of Werner (1986). Full details of the models themselves are given in Napiwotzki *et al.* (1993). For comparison, we also used LTE models in which the H and He is gravitationally stratified (see, for example, Jordan & Koester 1986). The best fit models are presented in Fig. 2.

GD 561 reveals a classic example of the Balmer line problem, discussed in Napiwotzki & Schönberner (1993b). The inferred temperatures are systematically lower for the lower order Balmer lines—from 65 000 K for Hδ to 48 000 K for Hα. This effect occurs typically in the very hot hydrogen-rich central stars of planetary nebulae—notable examples include the central stars of Sh 2−216 and NGC 7293—and in some DAO white dwarfs—for example, Feige

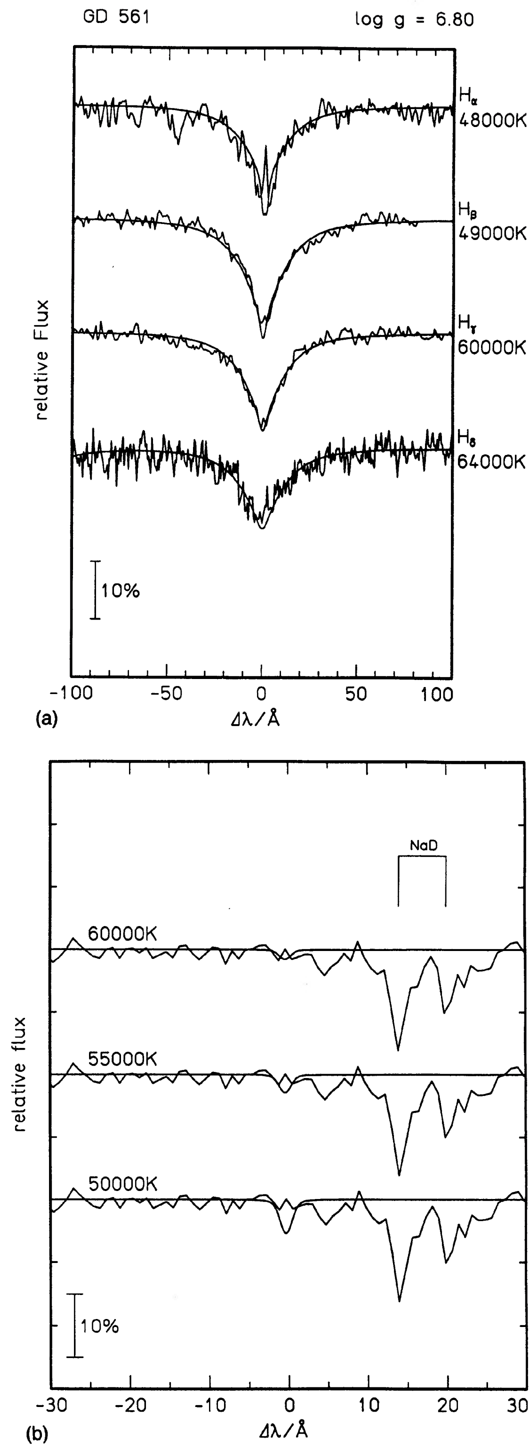

FIG. 2. Best fit synthetic spectra for (a) the Balmer lines—each of which require $\log g=6.8$, but different temperatures as indicated, and (b) the He I line at 5876 Å. The absorption lines in Fig. 3(b) are the interstellar NaD lines.

55 (Bergeron *et al.* 1993). It appears to be a temperature effect, since each best-fit line produces the same surface gravity. Furthermore, the actual effective temperature is probably close to or slightly higher than the values obtained from Hδ or Hϵ, as found from the ionization balance and comparison with the results of nebula analysis for other central stars (Napiwotzki & Schönberner 1993b). Thus the value of $\log g=6.8$ is probably reliable, and from our analysis we infer that the actual effective temperature is close to the value obtained from the Hδ line (65 000 K). However, we cannot exclude the possibility that we underestimate the temperature by 10% to 20%. The absence of any absorption at He I 5876 Å provides a lower limit of $T_{\rm eff}$=55 000 K [Fig. 2(b)].

The lines from Hβ to Hϵ were analyzed by Bergeron *et al.* (1994). Their model fitting avoided the Balmer line problem by fitting to the wings but not the core, and obtained $T_{\rm eff}=65\,000\pm2000$ K, $\log g=6.7\pm0.1$, which confirms our gravity estimate and essentially agrees with our temperature determination from Hδ. However, deviations from LTE can cause significant effects even on the Balmer line profiles of DAO white dwarfs (Napiwotzki 1993), more so than with the DAs (those without detectable He) because of their lower gravities. Thus the precise figures quoted by Bergeron *et al.* need to be treated with some caution.

The He abundance was found by using the relatively strong line at 4686 Å. The core of the profile looks strange, so just the wings were used to obtain a He abundance of $N(\mathrm{He})/N(\mathrm{H})=0.004$. If the core were included, this would drop by a factor of 2. No nebular emission at this wavelength is evident on the image, but the MMT data reveal the same structure to the core, albeit at lower resolution. This line is also sensitive to the structure of the atmosphere, as demonstrated initially by Napiwotzki & Schönberner (1993b); Bergeron *et al.* (1994) found that only one of their DAO white dwarfs showed evidence of a stratified atmospheric structure. We find that these models indeed give a substantially worse fit than the homogeneous ones.

As we will show below, the evolutionary status and therefore the mass of GD 561 is not well known. However, it most probably lies in the range 0.2–0.6$\mathcal{M}_\odot$. Therefore we assume $\mathcal{M}\approx0.4\mathcal{M}_\odot$, and derive an absolute magnitude $M_V=6.4\pm0.7$ (where the error is a conservative estimate, which incorporates the uncertainty in both the derived surface gravity and the assumed mass). This implies a distance of 420±150 pc, a height≈150 pc above the galactic plane, and nebular dimensions (including the diffuse outer material) of 2.0 by 1.2 pc.

5.2 The Evolutionary Status of GD 561

The location of GD 561 in the $\log g$–$\log T_{\rm eff}$ diagram is plotted in Fig. 3. It clearly does not lie on any of the standard post-AGB evolutionary tracks. One possible explanation is that the actual temperature is somewhat higher than that indicated by the Hδ line, due to a particularly severe case of the Balmer line problem. This does not seem likely in view of the temperature estimate of Bergeron *et al.* (1994), who used a different fitting procedure. Therefore, if GD 561 has evolved via a standard isolated white dwarf route, then it must have an exceptionally low mass, and consequently an age of several million years [see, e.g., Schönberner (1993) for a recent review of central star ages].

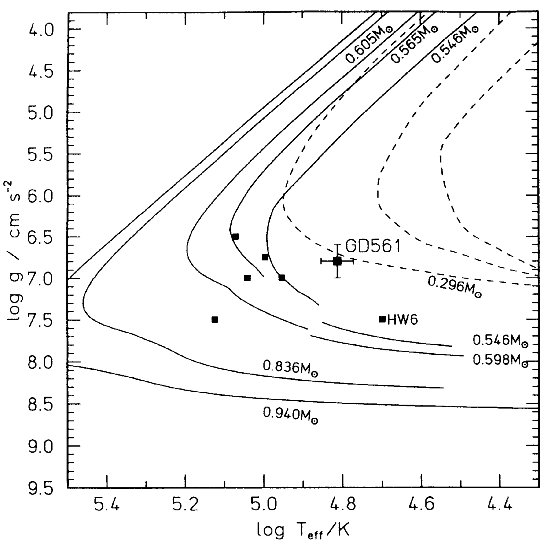

FIG. 3. Location of GD 561 in the $\log g-T_{\rm eff}$ diagram. Single star evolutionary tracks are taken from Schönberner (1983), Koester & Schönberner (1986), and Blöcker & Schönberner (1990). The dashed lines are taken from Iben & Tutkov (1986a): that on the far right represents the first descent down the cooling sequence; the middle of the three is the second descent after the first H-shell flash; the leftmost is the final descent down the cooling sequence following the second H-shell flash. The models are described in detail in the aforementioned paper. Error bars are ±10% in $T_{\rm eff}$ and ±0.2 in $\log g$. Other points are H-rich central stars taken from Napiwotzki (1994), with HW 6 labeled (discussed in the text).

This scenario is considered in detail by Bergeron *et al.*, who suggest that isolated DAO white dwarfs are systematically less massive than those without He, the DAs. However, they distinguish between those like LS V +46 21, the central star of Sh 2−216, which have normal masses and are consistent with post-AGB evolution, and those like GD 561 and HZ 34 which require some other explanation. They reproduce three evolutionary tracks for post-EHB stars, with masses 0.471, 0.475, and 0.495$\mathcal{M}_\odot$, taken from Dorman *et al.* (1993). Such a scenario appears to be satisfactory for objects like HZ 34 and PG 0134+181, but GD 561 and Feige 55 both appear to be significantly lighter. However, evolution as a low mass single star for GD 561 leads to an unacceptably high age for one that is associated with a planetary nebula. Using the lowest mass track of Bergeron *et al.* (1994) leads to an age of $\gg 10^7$ yr, which may be compared with a typical PN lifetime of a few hundred thousand years. Since no expansion velocity has been measured for Sh 2−174, we adopt an average value from Hippelein & Weinberger (1990) of 20 km/s, taking into account the height above the galactic plane of ≈150 pc. Combined with a mean diameter of ≈12.7′, a kinematic age of 42 000 yr is produced. Admittedly, determining ages of the oldest PNe is problematic, largely because the interaction between the PN and the ISM. Nevertheless, an age discrepancy of over two orders of magnitude is severe, and cannot be lightly dismissed. Napiwotzki (1993, 1994) suggests that GD 561 is one of a number of white dwarfs which appear to be much older than their surrounding planetary nebulae—other examples include HW 6 and DHW 5. The white dwarf data of Bergeron *et al.* (1994) demonstrates the rarity of this situation: of the hot DA and DAO stars considered by these authors, only it and LS V +46 21 are surrounded by planetary nebulae. While a post-AGB evolutionary history is likely for LS V +46 21, such is not the case for GD 561, nor for the other white dwarfs which appear to be much older than their surrounding planetaries.

White dwarfs with abnormal masses and ages can in principle be produced in close binary systems. The most studied example is common-envelope (CE) evolution where the degenerate component is a carbon–oxygen white dwarf, because of its importance in the formation of most cataclysmic binaries. Livio (1993) states that all white dwarfs that are in systems with orbital periods ~1 day must necessarily have passed through the CE stage. A well known example is the pre-cataclysmic binary (PCB) Feige 24: throughout most of its four-day orbital period strong, narrow emission lines are superimposed on the white dwarf spectrum, which originate from the heated side of the secondary (e.g., Vennes *et al.* 1991). By contrast, GD 561 has been observed on several occasions—three times by ourselves and once by Bergeron *et al.*—and does not appear as a PCB. Furthermore, of the cooler DAOs considered by Bergeron *et al.*, the three which belong to PCBs are unusual in being the only ones with apparently normal masses. Finally, a low-mass CO core can be expected to evolve much more slowly than normal [see, for example, Schönberner (1993), and compare with the post-EHB models of Dorman *et al.* (1994)].

A second possibility is that GD 561 is part of a low-mass close binary system, in which mass exchange occurred when the primary had exhausted its central H, and left a degenerate He core. An example of this scenario is discussed in detail by Iben & Tutukov (1986a), who consider a star with initial and final masses $1\mathscr{M}_\odot$ and $0.296\mathscr{M}_\odot$. It is thus a much smaller system than those generally regarded as the progenitors of cataclysmic binaries—such as the stars with initial mass in the range $3\mathscr{M}_\odot<\mathscr{M}<12\mathscr{M}_\odot$, which leave CO or ONe cores, considered by Iben & Tutukov (1985). The temperature and luminosity of GD 561 is fully consistent with the He-core scenario, and would just have arrived on the final cooling track after the two H-shell flashes. It would thus have an age $\sim 4\times 10^6$ yr, an order of magnitude younger than in the post-EHB models. While this is still far too long compared to the kinematic age, it is nonetheless a substantial improvement. With the uncertainties in binary parameters and the Balmer line problem, such a discrepancy is not too disastrous. Iben and Tutukov speculate that the ejected PN in their model system is lazy, although this result depends upon the mass of the central star and the degree of orbital shrinkage. (As someone once said, laziness is sometimes very charming...). The dominant reason for the younger age compared to that of the post-EHB stars is that the maximum temperature attained in the core is much lower—$\sim 40\times 10^6$ K compared to $\sim 200\times 10^6$ K. Although the $3\mathscr{M}_\odot$ progenitor of Iben & Tutukov (1985) would produce a CO core of only $0.38\mathscr{M}_\odot$, its central temperature would be $\sim 1000\times 10^6$ K, and would require an age $>10^8$ yr for GD 561—far worse even than the post-EHB age.

The close binary/degenerate He dwarf scenario is therefore the only one that can reasonably explain both the low mass and age of Sh 2−174/GD 561, but it requires the existence of a secondary companion. A spectral type earlier than ~dM0 is unlikely, otherwise it would have already been detected either at the red end of the blue spectra discussed earlier, or in the colors of Greenstein (1984). In addition, an orbital period less than about 10 days is also unlikely, otherwise the blue spectra would show the emission lines characteristic of a pre-cataclysmic binary—although this constraint is somewhat dependant on the spectral type.

It is conceivable that such an explanation needs to be invoked for most or all of the non-post-AGB DAO stars. If so, they would have abnormally low masses precisely because they are all degenerate He cores that originated in short-period binaries. If such companions exist, they should be detectable as an IR excess at *JHK*. Iben & Tutukov (1986b) predicted that a low-mass population of He-core degenerates should exist, but at that stage there was no observational evidence in support of this. Since then, Bergeron *et al.* (1992) found a group of eleven with $0.3<\mathscr{M}<0.4\mathscr{M}_\odot$ in their sample of 127 DAs with $15\,000<T_{\rm eff}<40\,000$ K, which may represent the missing population. Conceivably, GD 561 and the other low-mass DAOs are the progenitors of this group.

In trying to explain the absence of low mass white dwarfs, Iben & Tutukov (1985) postulated that the merging of both components might be responsible. Indeed, Mendez *et al.* (1988) speculated that this might be true for the central stars PHL 932 and EGB 5, which are cooler and have lower gravities than GD 561—neither of which appear to have passed through the AGB. However, it is not immediately obvious that a white dwarf of unusually low mass would result; and in all cases the merger would have to occur very rapidly. These authors also discuss the He-degenerate scenario, though without coming to firm conclusions. PHL 932 and EGB 5 are both consistent with it, and would again be natural progenitors to the low mass DA white dwarfs of Bergeron *et al.*

6. CONCLUSION

The ionization structure of Sh 2−174 demonstrates that it is the planetary nebula ejected by the white dwarf GD 561. As such, it is the most extreme example yet known of one interacting with the ISM: its morphology is devoid of the symmetry present in younger nebulae, and the former central star is now located on its edge. It has some similarities with Abell 31, which may suggest that they are essentially at different stages of the same evolution, but neither bear much resemblance to the one-sided planetaries Sh 2−188 and A21. Whether this can be explained merely by the ratio of the densities of the nebula and the ISM and their relative velocity remains an open question.

GD 561 itself does not appear to have evolved by a standard single-star route. Bergeron *et al.* (1994) have argued that most DAO white dwarfs are undermassive, and infer a post-EHB evolution. GD 561 is one of the two lightest, leading to an age of a few tens of millions of years, but this requires that Sh 2−174 be unusually long lived. HW 6 and DHW 5 are two other central stars which exhibit a similar effect. We believe that the low mass of GD 561 arises because of a close binary origin, in which the degenerate component is a small ($\sim 0.3\mathscr{M}_\odot$) He core. We suggest that this may be true for all or most of the DAO stars which Bergeron *et al.* regard as post-EHB stars. It is therefore imperative to observe these objects in the near infrared to ascertain whether the predicted faint companions actually exist.

We are grateful to Pierre Bergeron for providing early access to his results. R.W.T. would like to thank Bill Schoening, Ed Carder, and the staff of NOAO/Kitt Peak National Observatory for the excellent assistance with the Burrell–Schmidt telescope and the CCD camera system, and Jeannette Barnes for making available the computer facilities at NOAO in Tucson. The Hα and [N II] filters were kindly lent by Karen Kwitter of Williams College, MA, and the [O III] filter by Bruce Balick at the University of Washington. Discussions with Jim Liebert have been particularly beneficial. R.N. thanks Thomas Rauch for providing the Calar Alto data.

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