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TWO PLANETARY NEBULA CANDIDATES AROUND HOT DA WHITE DWARFS

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ABSTRACT

Two possible planetary nebulae have been found during a search around hot H-rich white dwarfs. These are located close to Ton 320 and RE 1738+665. Both are extremely faint, but are rather brighter in [N II] than Hα. This would bring the total number of nebulae found around independently identified hot DA white dwarfs to four, with one other around a PG 1159 star. In addition, we failed to detect any around six PG 1159 stars. We suggest that this lack is very difficult to explain if all white dwarfs undergo essentially the same evolution, each passing through a PG 1159 stage. Furthermore, the most widely quoted alternative, in which ~25% undergo a late He-shell flash causing a brief return to the AGB, can successfully explain this only if it produces a substantially greater delay than is currently assumed.
Subject headings: planetary nebulae: general – stars: AGB and post-AGB — white dwarfs

1. INTRODUCTION

The desirability of detecting planetary nebulae around hot white dwarfs arises because new information is obtained about the prior evolution. This is in spite of the complicated nature of the nebulae—essentially all of them interact substantially with the ISM, and only exploratory calculations exist in the literature (e.g., Soker et al. 1992)—since even their presence or absence can be instructive. For example, the presence of the nebula Sh 2-174 around the white dwarf GD 561 implies that the star is far younger than suggested by standard post-AGB or post-EHB evolutionary models (Tweedy & Napiwotzki 1994).

It is therefore natural to look to planetary nebulae as a possible way to discriminate between the two main evolutionary scenarios for the hottest white dwarfs. The most straightforward is that all post-AGB white dwarfs evolve along the same path (e.g., Fontaine & Wesemael 1987), regardless of whether they eventually have H-rich (DA) or H-poor (DB) atmospheres—this is the single channel hypothesis. The strongest supporting evidence is that almost all of those that are hotter than 80,000 K are H-poor. However, the space density of these H-poor stars is insufficient by a factor of ~8 to account for the cooler white dwarfs. It is not clear, either, that this can explain the unusual elemental abundances of H-poor stars. Both problems are readily explained if ~25% undergo a late He shell flash, which would remove the outer H (e.g., Iben et al. 1983; Iben 1984). This is the most well defined of the two-channel scenarios, in which the H-poor minority undergo a different evolution to the rest. In this case, the relative absence of hot H-rich white dwarfs remains a problem. Assuming that a higher fraction undergo a late He shell flash merely revives the objection to the single-channel scenario—the space density of H-poor objects observed is too low.

If the single-channel hypothesis for post-AGB white dwarfs is correct, then planetary nebulae should be far more easily detected around the hot PG 1159 stars than around the hottest of the DAs, because the PG 1159 stars are much younger. This can be illustrated by taking representative timescales, for example from the recent models of Vassiliadis & Wood (1994). An H-poor white dwarf will cool through 140,000 K (the temperature of PG 1159−035 and PG 1520+525;Werner, Heber, & Hunger, 1990) between 3000 and 25,000 yr after leaving the AGB, depending on the mass and metallicity. They will cool through 100,000 K (typical of NGC 7293; Napiwotzki 1994) after 70,000 to 120,000 yr essentially independently of whether they are H-rich or H-poor, and will cool through 70,000 K (e.g., Ton 320, Bergeron et al. 1994) after ~600,000 yr. In the two channel case, exact details depend on the models. For example, Vassiliadis & Wood suggest that the evolutionary timescale is the same for H-rich white dwarfs as for H-poor ones, so that nebulae should be equally easy (or difficult) to detect around either class. By contrast, Iben (1984) shows a much faster evolution for the H-rich class, so nebulae will still exist around stars much further down the cooling sequence than for the H-poor objects.

The observations reported here were from the hottest of the H-poor objects (see Werner 1993) and the hottest of the H-rich objects (see Bergeron et al. 1994). The observations cannot be claimed to be complete, but are sufficient for a pertinent discussion. However, in this program we did observe three of the four hottest white dwarfs, H1504+65, PG 1144+005 and PG 1159−035. The exception is PG 1520+525, which has already been found to have a nebula around it by Jacoby & van de Steene (1994; see also Jacoby 1994). We will discuss this important detection later.

2. OBSERVATIONS AND DATA REDUCTION

The observations reported here were taken mainly in 1994 April, with others being taken at various times from 1993 March, and were done at the Burrell-Schmidt telescope on Kitt Peak. Details of the instrumentation are given in Tweedy & Kwitter (1994a).

The objects observed and filters used are listed in Table 1. All exposure times were 30 minutes, with the exception of those for PG 1151−029, which were 10 minutes at [N II] and 20 for [O III]. Filter selection was important: for the oldest planetary

TABLE 1

OBJECTS OBSERVED

H-POOR WHITE DWARFS		H-RICH WHITE DWARFS	
Object	Ion	Object	Ion
H 1504+65	[O III], Hα	RE 1738+665	[N II], Hα
PG 1159−035	[O III], Hα	HZ 34	Hα + [N II]
PG 1144+005	Hα	PG 1342+444	Hα + [N II]
PG 1151−029	Hα, [N II]	Ton 320	Hα, [N II]
PG 1424+535	[N II]	LB 2	[N II]
		Feige 55	[N II]

nebulae the strongest line is [N II] (Tweedy & Kwitter 1994a, b), so this was usually selected. Around the hottest stars [O III] was used, since a higher ionization state would be expected, although this had the disadvantage that the sensitivity of the detector is much lower (≈20% compared to 50%), so that the resultant search is not as deep for stars like H1504 + 65 as it is for those like Ton 320.

3. PG 1159 STARS

No new nebulae were discovered around the PG 1159 stars. This is particularly critical concerning the hottest of the group, most notably the prototype PG 1159−035 and the two hotter ones, PG 1144+005 and H1504+65. This means that the only nebula discovered after the identification of the white dwarf in this group is that around PG 1520+525, by Jacoby & van de Steene (1994).

4. H-RICH WHITE DWARFS

4.1. *Post-AGB Stars*

Faint, asymmetric nebulae were found close to two of the H-rich white dwarfs, Ton 320 (Fig. 1 [Plate L4]) and RE 1738+665 (Fig. 2 [Plate L5]), whereas nothing was detected near PG 1342+444 and LB 2. All four have temperatures and gravities that are consistent with normal post-AGB evolution (Bergeron et al. 1994; Barstow et al. 1994), and the detected nebulae are sufficiently faint that the nondetections cannot be regarded as particularly significant.

Ancient planetary nebulae reveal asymmetries characteristic of the interaction with the ISM. In a few extreme cases the nebulae are essentially one-sided (e.g., Abell 21: Kwitter, Jacoby, & Lawrie 1983; Sh 2-188: Rosado & Kwitter 1982) and the white dwarfs are often displaced from the center (Borkowski, Sarazin, & Soker 1991). Convincingly identifying a nebula as an ancient planetary is therefore much more difficult than for younger systems, because of the lack of symmetry, and can therefore be more easily confused with ambient interstellar gas. Both new nebulae are brighter in [N II] than Hα, which is typical of known ancient planetaries (Tweedy & Kwitter 1994a, b). This is therefore as expected if both are being ionized by a hot white dwarf, but would be unusual for ambient interstellar material which happens to lie in the line of sight, for which [N II]/Hα ≈ 0.4 (Domgörgen & Mathis 1994) would be expected. This argument is, of course, invalid if interstellar material happens to lie within, say ∼2 pc of the white dwarfs, in which case the line emission would be essentially the same as for a planetary nebula. Such a scenario would still beg the question of how these arcs of gas originated—indeed, a planetary nebula would be the simplest explanation. The Galactic latitude of both white dwarfs is ≈32°, leading to heights above the Galactic plane of 110 pc for RE 1738+665 and 220 pc for Ton 320. These locations reduce the likelihood ambient gas compared to, say, the midplane, although the studies of dust around B stars of Gaustad & van Buren (1993) show that there is still significant interstellar material at those heights.

Unfortunately we are not aware of any systematic studies of comparable depth at this Galactic latitude to assess the space density of such material— two surveys by Reynolds (1983, 1987) are close to the Galactic plane—so we can offer only anecdotal comments. In a study of old planetary nebulae (Tweedy & Kwitter 1994a, b), a few (≈20%) do show ambient gas in addition to the nebula, although they are fairly close to the Galactic plane (within 12°). The most severe example was actually around the isolated hot white dwarf BD +28°4211, 200 pc distant (e.g., Napiwotzki 1993) and 20° (70 pc) below the plane. The surrounding region has considerable faint filamentary material, some of which has a morphology similar to what might be expected for an asymmetric nebula left behind by a white dwarf. In this case, although detectable in [N II], it was substantially brighter in Hα, and the proper motion of BD +28°4211 (7″.7 century^{-1} at 216°; Hall 1953) turned out to be incompatible with this scenario.

We therefore conclude that there is a strong likelihood that the nebulosities associated with Ton 320 and RE 1738+665 are their planetary nebulae, but cannot demonstrate this conclusively.

4.2. *Non–post-AGB White Dwarfs*

In their study of DAO white dwarfs, Bergeron et al. (1994) conclude that most cannot be explained by post-AGB evolution, and suggest that departure from the EHB is more likely. As such, the appropriate comparison is not with the PG 1159 stars, but between post-EHB evolution and the He degenerate/M dwarf binary scenario of Iben & Tutukov (1986), invoked to explain GD 561/Sh 2-174 by Tweedy & Napiwotzki (1994). Two stars were observed here, Feige 55 and HZ 34, and in neither case was a nebula detected. The atmospheric parameters of HZ 34 are consistent with post-EHB evolution, leading to an age $\sim 10^7$ yr; so it is somewhat reassuring that no nebula was detected! Less easily comprehensible is the lack of one around Feige 55; like GD 561, it is much lighter than is compatible with departure from the EHB, and a similar binary scenario might be invoked. If so, using the Iben & Tutukov (1986) evolutionary track to explain the temperature and gravity suggests an age not much in excess of that of GD 561, which has an age of $\sim 10^6$ yr. Thus failure to detect a nebula is somewhat surprising. However, the Iben & Tutukov model is an example calculation for a single system without consideration of the characteristics of the secondary, and a mass somewhat higher for GD 561 than Feige 55 might explain the presence of a nebula only around GD 561.

5. DISCUSSION

The detection of nebulae around Ton 320 and RE 1738+665 is surprising only in the contest of the failure to find any around the PG 1159 stars. RE 1738+665 was the hottest H-rich white dwarf without a previously identified planetary nebula, at T_{eff} = 88,000 K, log g = 7.7 (Barstow et al. 1994). It is thus slightly hotter and more massive than the central star of Sh 2-216 (Tweedy & Napiwotzki 1992; Napiwotzki 1994). At T_{eff} = 69,000 K log g = 7.7 (Bergeron et al. 1994), Ton 320 is cooler than other H-rich post-AGB central stars, but there are

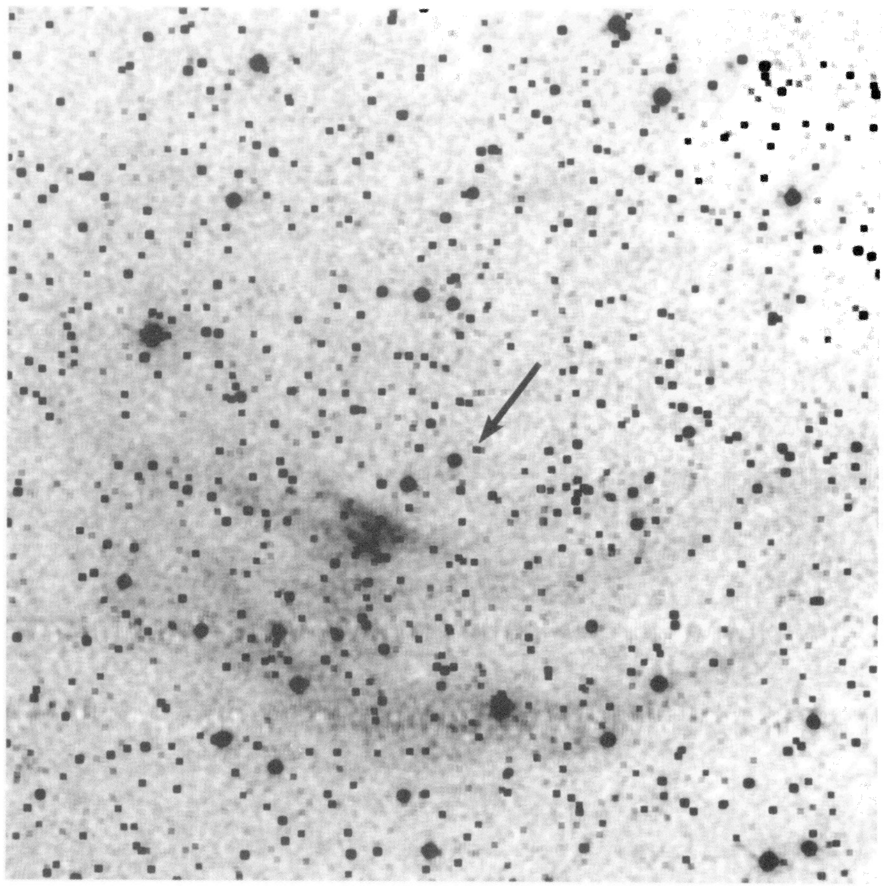

FIG. 1.—Ton 320 in [N II]. The image is 44′ on a side, with north to the top and east to the left. It has been smoothed with a 10 × 10 box to enhance the faintest features. The white dwarf is marked with an arrow.

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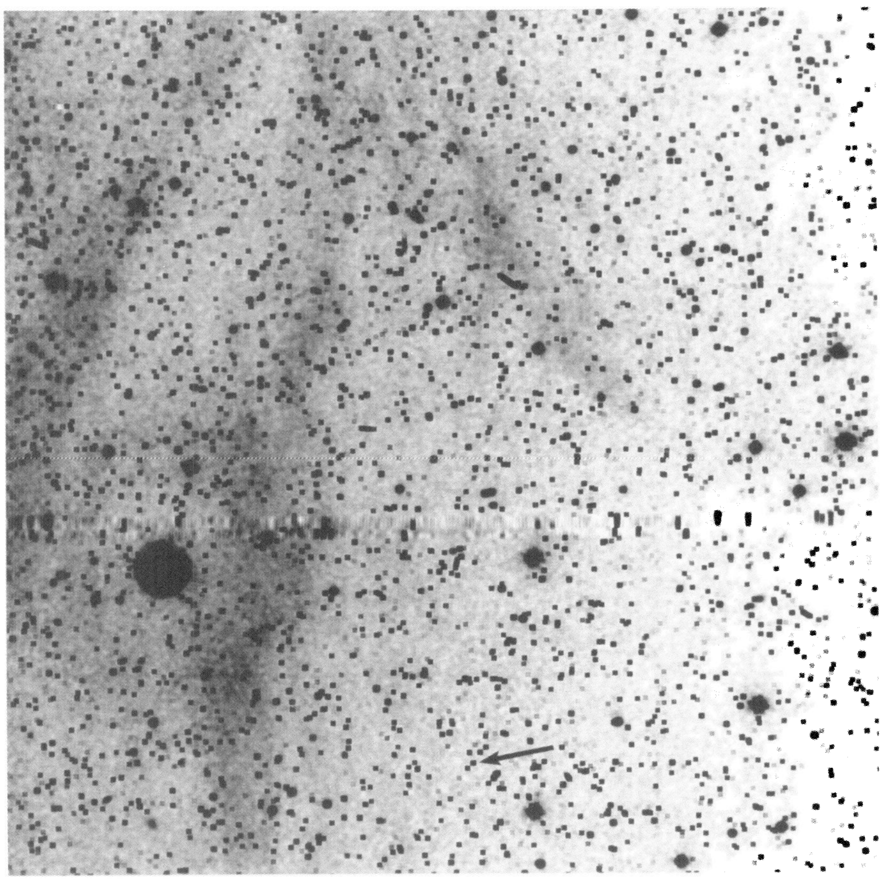

FIG. 2.—RE 1738+665 in [N II]. The image is 60′ on a side with north to the top, east to the left. As with the Ton 320 image, it has been smoothed with a 10 × 10 box. The white dwarf is marked with an arrow

TWEEDY & KWITTER (see 433, L94)

very few white dwarfs of this type (such as PG 1342+444 and Ton 21) that are hotter. These temperatures lead to estimates of the cooling ages of ≈200,000 and 650,000 yr, respectively. Furthermore, the morphology of the nebula around RE 1738+665—a slightly curved bar some distance from the white dwarf— is quite similar to the appearance of Sh 2-216 on the POSS (e.g., Reynolds 1985). Nonetheless, these are only the second and third nebulae found during a deliberate search around hot white dwarfs (EGB 6 was serendipitously discovered around PG 0950+139; Ellis, Grayson, & Bond 1984).

We failed to detect any nebulae around the other PG 1159 stars. Although we had embarked on this exercise in order to use the presence or absence of nebulae to descriminate between the one or two channel scenarios, the recent calculations of Vassiliadis & Wood (1994) show that the age of a DA white dwarf below 100,000 K is essentially independent of whether it is presumed to have undergone a late He-shell flash or not. (The less detailed calculations of Iben 1984 suggest that an H-poor central star will be ~4 times the age of an H-rich one at 100,000 K; Vassiliadis & Wood attribute the differences to the need to compute the prior evolution on the AGB, which was first realized by Blöcker & Schönberner 1991). Thus, irrespective of any late He-shell flashes, the absence of nebulae around stars which are apparently only ≈20,000 yr old is very surprising.

This result casts doubt on such a young evolutionary age, but does accord with the recent work on H-rich central stars of Napiwotzki (1994). It appears that many of them are much hotter than has hitherto be assumed—for example, Abell 7 is now believed to have $T_{\rm eff} = 105{,}000$ K, compared to the value of 70,000 K given in Wesemael, Green, & Liebert (1985). Most important, there is essentially agreement between Napiwotzki & Bergeron (1994) about the temperatures of the two stars in common: Sh 2-216 at ≈85,000 K and Sh 2-174 at ≈65,000 K. The detection of nebulae around two H-rich stars, with none observed around the H-poor stars, makes sense only if the evolution of the H-rich stars is very rapid compared to those that are H-poor.

We also imaged the nebula around PG 1520+525 as part of a concurrent study of known old planetary nebulae. Despite the decreased sensitivity of the detector at [O III], it was relatively easy to image (compared to IsWe 1 and IsWe 2, for example; see Tweedy & Kwitter 1994b), particularly with the bright interaction region to the south. However, despite a cooling age of ~20,000 yr (derived from the models of Vassiliadis & Wood 1994), its morphology is very similar to the outer nebula around the hot DA white dwarf, PG 0950+139/EGB 6. Its diameter of 11′ corresponds to a physical size of 3.2 pc, typical of the oldest known planetaries (e.g., Borkowski et al. 1991). Adopting a standard expansion velocity of 20 km s^{-1} (e.g., Weinberger et al. 1990) leads to an age ≈80,000 yr. If this age is typical of the PG 1159 stars, then it is no longer very surprising that others have not been detected—the nebula around RE 1738+665 would not have been found if the detector sensitivity at [N II] had been as low as that at [O III] (see above). Naturally, if the PG 1159 stars are as old as the hot DAs, then they cannot be their progenitors, so that there must be a two-channel scenario of some description. (It cannot be ruled out that some DAs were originally PG 1159 stars; and indeed below 40,000 K, by which all white dwarfs have become DAs, this must be true). An alternative approach would be to derive a mass for PG 1520+525, such that the evolutionary age is the same as the kinematic age. This was done by Jacoby & van de Steene, who derive a mass of ≈0.8 $M_\odot$. However, this is significantly higher than the spectroscopically derived mass of 0.57 ± 0.1 $M_\odot$ (Werner, Heber, & Hunger 1990), so that the original problem is merely cast in a different form. (Incidentally, it is this reference that is the source of the distance estimate in Jacoby & van de Steene).

The kinematic age quoted for PG 1520+525 depends on the closeness of the mean expansion velocity to the actual one for that nebula. A quick look at Weinberger (1990), for example, shows that there is a wide scatter of values about the mean. Nevertheless, the assumption that the PG1159 stars are as old as the hot DAs would readily explain why detecting nebulae around them is so difficult. There is little reasonable doubt now that the PG 1159 stars are post-AGB objects, since a sufficient number are now known to be central stars—for example NGC 246 and MWP 1 (Motch, Werner, & Pakull 1993), two of the low-gravity objects, and VV 47, Abell 21, and Jones 1, surrounding three of the white dwarfs (see, for example, Werner 1993). MWP 1 is a particularly revealing example, since it is the largest planetary nebula currently known, with a maximum dimension of 6 pc (Appleton, Kawaler, & Eitter 1993)—despite being located around a star that has yet to reach the cooling sequence (Motch, Werner, & Pakull 1993). Thus the nebula, and the absence of detected nebulae around stars like PG 1159−035, also argue for a much older age.

Although the late He-shell flash scenario (e.g., Iben 1984) is a natural way to explain the existence of the minority of white dwarfs that lack H, and furthermore also explain older ages, the ages computed from the calculations of Vassiliadis & Wood (1994) are underestimates. In particular, their 0.634 $M_\odot$ model cools through 140,000 K in 25,000 yr, and their 0.600 $M_\odot$ reaches a peak of 135,000 K after 34,000 yr (both cases quoted are solar composition). Interestingly, the more primitive calculations of Iben (1984) more naturally explain the age discrepancy of PG 1520+525 compared to the DAs, with H-rich white dwarfs passing through 100,000 K at ≈30,000 yr, while the H-poor ones do so at ≈120,000 yr. Vassiliadis & Wood speculate that differences between their models and Iben's are due entirely to their treating the prior AGB stage in detail; this seems a reasonable assumption, but in the light of the need for an age discrepancy similar to that obtained by Iben, this issue should be addressed further.

6. CONCLUSION

Two probable planetary nebulae have been detected around the hot white dwarfs RE 1738+665 and Ton 320. These are only the second and third to have been found from explicit searches for nebulae around white dwarfs. At the same time, we failed to detect nebulae around several PG 1159 stars.

Prompted by the presence of an ancient PN around PG 1520+525, discovered by Jacoby & van de Steene, we suggest that these stars are much older than implied by the cooling ages of Vassiliadis & Wood— and are perhaps generally of the same age as the post-AGB hot DAs. This necessitates some kind of two channel scenario. Since the late He-shell flash model is successful in producing both a delay in the evolution and the H-poor abundances, we suggest that the timing of the flash may need to be reconsidered in order to explain the age discrepancy.

We are particularly grateful to Pierre Bergeron, who alerted us to the likelihood of Ton 320 being a central star long before his paper reached the preprint stage. Discussions with Jim Liebert have been very beneficial. R. W. T. would like to thank

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