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A VERY HOT, HYDROGEN-RICH, WHITE DWARF PLANETARY NUCLEUS[1]

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ABSTRACT

We report new spectrophotometry and a detailed analysis of the DA white dwarf nucleus of the planetary nebula WDHS 1 (PK 197−6°1). Based on model atmospheres fits to the Balmer line profiles, the possible T_{eff} for this star ranges from 165,000 K if the helium abundance is zero to ∼ 100,000 K if a marginally detectable abundance of $N(\mathrm{He})/N(\mathrm{H}) = 10^{-2}$ is present in the atmosphere; log $g \sim 7.6$ in either case. The nucleus of WDHS 1 is thus the hottest known high gravity star with a hydrogen-rich atmosphere.

We present CCD imaging of the nebula showing this to have an angular extent of 22′. At the distance (d) of 1.0 ± 0.25 kpc estimated from the white dwarf analysis, WDHS 1 is one of the largest known planetary nebulae with a diameter of 6.4 (d/1 kpc) pc. The implied kinematic age of the nebula is a few times 10^5 yr, which might be consistent with the post-AGB lifetime of the nucleus. We discuss the apparent paucity of objects such as the nucleus of WDHS 1 in comparison with their hydrogen-poor counterparts among planetary nuclei and field white dwarfs.

Subject headings: planetary nebulae: individual (WDHS 1) — stars: individual (WDHS 1) — white dwarfs

1. INTRODUCTION

Two atmospheric composition sequences exist among both planetary nebulae nuclei (PNNs) and white dwarfs—the hydrogen-rich and the hydrogen-poor. The latter generally have helium-dominated atmospheres, but the hottest of these may also be enriched in carbon and oxygen. However, the two types do not necessarily evolve simply as separate channels; rather, there is evidence that hydrogen-rich atmospheres may evolve into hydrogen-poor atmospheres, and vice versa (Fontaine & Wesemael 1987). For example, there are no known white dwarfs with helium-rich atmospheres (types DB or DO) between ∼30,000 K and 47,000 K (Liebert 1986; Thejll, Vennes, & Shipman 1991). It has also been found that most or all of the hottest white dwarfs with $T_{eff} \gtrsim 80{,}000$ K are hydrogen-poor (Holberg et al. 1989).

The hottest, hydrogen-rich stars with log $g \gtrsim 7$ appear to be central stars of planetary nebulae. Following the important work of Mendez et al. (1981), Napiwotzki & Schönberner (1991, NS hereafter) have been engaged in a systematic study of these objects. They have found primarily the same result as for the hottest field white dwarfs: there are now close to 10 hydrogen-rich PNNs with gravities near white dwarf values having T_{eff} of 60,000–90,000 K. These characteristically show He II λ4686 along with the stronger Balmer lines (DAO spectral class). One of the hottest of this group is LS V+46 21, the central star of S 216, with $T_{eff} \sim 90{,}000$ K, log $g \sim 7$, and $N(\mathrm{He})/N(\mathrm{H}) \sim 0.01$ (Tweedy & Napiwotzki 1992).

NS discussed a couple of curious problems. First, as already mentioned, there exist helium-rich and CNO-rich counterparts at considerably higher T_{eff} of 100,000 K to 170,000 K (Werner 1992), both with and without surrounding nebulae. Second, although the nebulae of the DAO group are characteristically large and of low surface brightness, the nebular and stellar post–asymptotic giant branch ages do not seem to agree: if one assigns distances based on the atmospheric analysis of the central star, and makes reasonable assumptions about the nebular expansion rates, the kinematic ages appear to be an order of magnitude less than the evolutionary ages of the stars, which are dominated by the onset of cooling of the degenerate cores.

One hydrogen-rich PNN was found by NS which appeared to be substantially hotter and/or higher in surface gravity than the rest, although the authors remarked that the spectrum of this faint object was too noisy for a detailed analysis. WDHS 1 (PK 197−6°1) is a "senile" planetary nebula—very large and of very low surface brightness—found by Weinberger et al. (1983). The spectrum appeared to show only very weak, broad hydrogen lines—indicative of a T_{eff} in excess of 100,000 K—but with no evidence for He II λ4686, or any of the C IV or O VI features characteristically seen in the spectra of hydrogen-poor objects hotter than ∼100,000 K. The WDHS 1 nucleus also appeared to have a higher gravity than the DAO group; they estimated log $g \gtrsim 8.5$, in contrast to the 7.0−7.5 estimated for the others.

The nebula is one of the oldest known, and is a candidate for further study with sensitive CCD detectors of large format. In fact, no direct imaging with modern instrumentation is shown in Weinberger et al. (1983). Our preliminary results from direct imaging are discussed in § 2.1. Since the spectrum of the central star of WDHS 1 was obtained with the 3.5 m telescope at Calar Alto under conditions of "poor seeing" according to NS, and was regarded as of insufficient quality for an accurate, quantitative analysis, we decided to try to improve upon this situation. Our new spectrum is presented in § 2.2 and analyzed in § 3. A brief discussion of the implications follows in § 4.

2. OBSERVATIONS

2.1. *CCD Imaging*

The nebula of WDHS 1 was discovered on the POSS E plate and appears as a very faint indistinct smudge. Therefore, as part of an ongoing program of observations of old planetary nebulae, one of us (R. W. T.) obtained a 600 s exposure of the nebula at the 0.9 m Burrell-Schmidt telescope on Kitt Peak, at

[1] The spectroscopic observations reported here were obtained at the Multiple Mirror Telescope Observatory, a facility operated jointly by the Smithsonian Institution and the University of Arizona.

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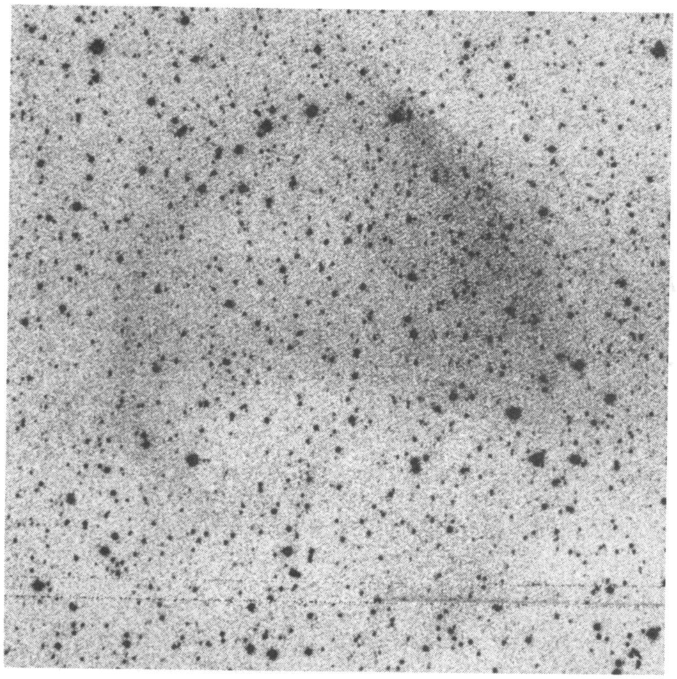

FIG. 1.—Direct CCD image of WDHS 1 covering a field of 24′ on a side, with a narrow-band Hα filter. North is up, and east is to the left.

$f/3.6$ with a 2048 × 2048 CCD detector (on loan from STScI). This observation was taken with an Hα filter which excludes [N II] λ6584, kindly lent by Karen Kwitter of Williams College, MA. The image is shown in Figure 1.

In the original paper by Weinberger et al. (1983), the nebula is described as a vague, elliptical ring. Although the nebula was only weakly detected in the current observation, the structure is rather clearer. It appears that WDHS 1 is a bipolar nebula, with an asymmetric enhancement to the west that is indicative of interaction with the ISM (Borkowski, Sarazin, & Soker 1990). The rim to the east is just visible, as is a thin arc to the north which is presumably enhanced by the ISM interaction. Nothing was detected toward the south. The central star is displaced to the north of the central bar of the nebula by ∼1′.5, rather than toward the region of strongest ISM interaction. This suggests that the ISM surrounding the nebula is not uniform, with a higher density toward the west.

The position of the central star is best understood if it originated in the central bar of a bipolar nebula and not the center of the elliptical ring described by Weinberger et al. Consequently, the dimensions reported by these authors of 17′ × 14′ need to be reevaluated. While the 17′ corresponds to the E-W bar, it is likely that the true extent of the nebula N-S is ∼22′. Deeper observations in Hα and particularly in [N II] are needed.

2.2. *Spectroscopy*

A new spectrum of the WDHS 1 central star was obtained with the Arizona/Smithsonian Multiple Mirror Telescope (MMT), of 4.5 m equivalent aperture, under excellent observing conditions on 1992 December 27 (U.T.). The "red channel" spectrograph was used with a 600 lines mm^{-1} grating and 1″.5 × 180″ entrance slit. This configuration yielded 7 Å spectral resolution covering 3700–5240 Å. In order to minimize any color-dependent light losses, it is desirable to maintain an orientation such that the slit is aligned with the direction of atmospheric dispersion; the altitude-azimuth nature of MMT ensures that this alignment is automatically maintained (by *not* rotating the spectrograph). Two 30 minute exposures with a thinned, Loral 1200 × 800 CCD were obtained.

The summed spectrum is shown in Figure 2 (bottom). The extremely broad and shallow Balmer lines—to an unprecedented degree in our experience—are obvious in the spectrum. The continuum is otherwise extremely flat, and an excellent signal-to-noise ratio of ∼80 was achieved. In particular, there is little evidence for the He II λ4686 line seen in nearly all hydrogen-rich, high-gravity stars with $T_{\rm eff} \gtrsim 70{,}000$ K. Illustrated for comparison at the top is a spectrum of the DAO star mentioned in § 1, LS V+46 21, which shows relatively sharper, deeper Balmer lines, and a distinct He II λ4686 feature. The middle synthetic spectrum is that of a model discussed in § 3.1.

2.3. *A ROSAT Survey Flux Limit*

Thomas Fleming has kindly informed us that the *ROSAT* PSPC Survey did not detect a source at the position of WDHS 1. The 2 σ (95.6%) confidence upper limit is less than 0.013 counts s^{-1}. Using a conversion factor appropriate for a white dwarf photosphere (T. Fleming, private communication), this yields a corresponding upper limit to the observed flux of 7.5×10^{-14} ergs cm^{-2} s^{-1}. The star also was not detected in the Wide Field Camera survey at extreme ultraviolet wavelengths. Unfortunately, this analysis was performed too late to propose this object as a target for a longer, pointed observation with the PSPC. The implications of the null detection are considered in § 4.

3. ANALYSIS

3.1. *Determination of the Atmospheric Parameters*

The averaged spectrum was analyzed using synthetic spectra and model atmospheres calculated under the assumption of Local Thermodynamic Equilibrium (LTE), as described in Wesemael et al. (1980) and Bergeron, Wesemael, & Fontaine (1991). Mixed hydrogen and helium compositions with homogeneous distributions were considered. The line profiles were normalized and fitted simultaneously following the procedure outlined in Bergeron, Saffer, & Liebert (1992). The result of our

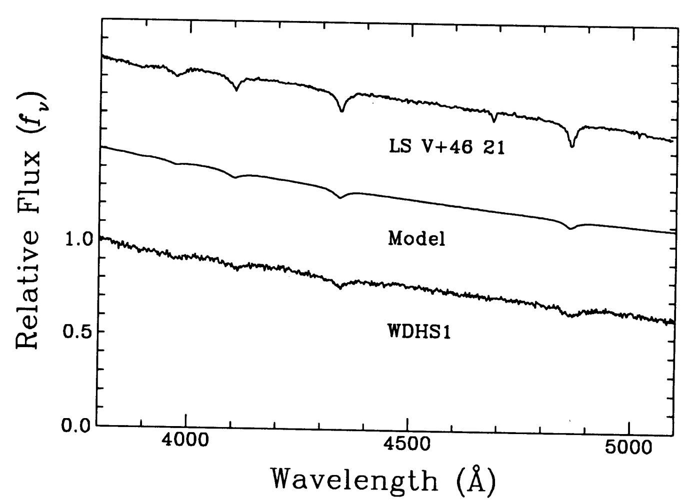

FIG. 2.—Summed spectrum of WDHS 1 (*bottom*), as described in the text, although only the 3800–5100 Å range is shown. (*middle*) Energy distribution of 165,000 K model with zero helium, which is discussed in § 3. (*top*) Spectrum of LS V+46 21, one of the hottest known DAO central stars. The vertical scales are offset by 0.5 flux units each.

fit assuming a pure hydrogen composition is shown in Figure 3*a*, where we reach an exceptionally high temperature of 165,000 ± 7500 K, with log $g = 7.56 \pm 0.14$.

At these very high temperatures, hydrogen is almost completely ionized and the presence of trace amounts of helium may contribute significantly to the continuum (bound-free and free-free) opacity, even if the abundance is insufficient to produce a detectable line. We therefore performed another analysis with a helium abundance that produces a marginally detectable He II λ4686 line. Experiments with various helium abundances reveal that an equally good fit to the hydrogen line profiles can be reached with models having a helium abundance as high as $N(\mathrm{He})/N(\mathrm{H}) = 0.01$ while only predicting a weak He II λ4686 line. Our best fit at $T_{\mathrm{eff}} = 99{,}000 \pm 2000$ K and log $g = 7.55 \pm 0.15$ is displayed in Figure 3*b*. A non-LTE core emission reversal such as those presented by Napiwotzki & Schönberner (1993) might partially hide the absorption feature even further. Note that the log *g* values reached in both solutions are surprisingly unaffected by the additional continuum opacity; it is also likely to be substantially higher than the derived value for LS V+46 21 and most DAO stars, but lower than the preliminary NS estimate for WDHS 1.

It seems surprising at first glance that the agreement is good between the low and high Balmer lines in determining the T_{eff} (at a given helium abundance), given the problem first identified by Napiwotzki (1992; see also Napiwotzki & Schönberner 1993) for hydrogen-rich PNNs of high surface gravity. That is, the fitted T_{eff} increased with the upper level of hydrogen, with the values spreading over a range like 50,000 K to 90,000 K in some cases. The problem of discrepancies among different Balmer lines has also been reported in some cooler DAO white dwarfs (Bergeron et al. 1993). Despite the apparent association between the "Napiwotzki problem" in PNNs (and some DAO stars) and the detection of helium in these objects, it is likely that the cause is due to blanketing at extreme ultraviolet wavelengths by elements heavier than helium, unaccounted for by current models (Bergeron et al. 1993; see also Dreizler & Werner 1993). Bergeron et al. (1993) have shown, in the particular case of the DAO star Fiege 55 ($T_{\mathrm{eff}} \sim 60{,}000$ K), that the cores of the lowest Balmer lines were formed in the upper layers of the atmosphere where the temperature stratification is sensitive to additional opacities from heavy elements. Therefore, the good agreement between the observed and theoretical profiles of WDHS 1 suggests that the abundance of heavy elements, and most important, iron, are quite low. However, WDHS 1 is much hotter than Feige 55, and it is possible that the cooling brought about by the metal-line blanketing does not affect significantly the temperature stratification where the Balmer lines are formed. Detailed calculations are outside the scope of this paper.

3.2. *Potential Non-LTE Effects*

Wesemael et al. (1980) showed that non-LTE effects are not generally important for pure-hydrogen atmospheres with white dwarf gravities at most temperatures. This work included calculations of a modest grid of non-LTE models, of which the most relevant is a pure hydrogen model with $T_{\mathrm{eff}} = 150{,}000$ K at log $g = 8.0$. The Hγ line profile in the non-LTE model shows a sharper core and is ∼10% deeper, 5–10 Å from line center, in comparison with the LTE prediction (see Fig. 5 of Wesemael et al.). The difference would be close to the observational errors of the line profiles in Figure 3. However, the Wesemael et al. models treated only the continua, and not the lines, with explicit non-LTE rate equations.

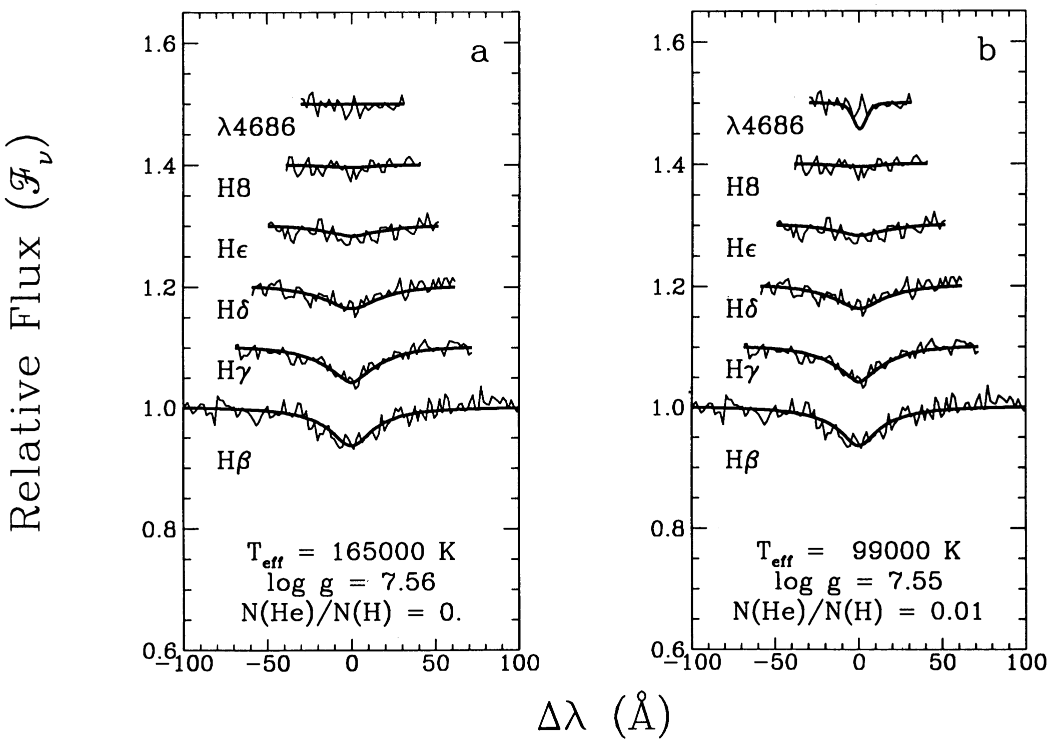

FIG. 3.—Simultaneous fits to Balmer lines and He II λ4686, for the assumptions of (*a*) zero helium, and (*b*) a helium abundance of 0.01, which yields a marginally detectable He II λ4686 line. The spectrum suggests that a weak, core emission reversal would partially hide a weak absorption line. The very different parameters of these limiting cases are also listed.

In addition to the investigation of Waesmael et al., two arguments suggest that a full non-LTE treatment will not change substantially the derived parameters of WDHS 1 (and, in any case, changes will be minor in comparison to the uncertainty caused by the unknown helium abundance). First, we might expect the cores of the lines to be affected first if LTE is violated, since these form higher in the atmosphere at the lowest densities. However, the line cores fit well, particularly the lowest transition Hβ. Moreover, there is no evidence of an emission reversal. Second, we might expect the high members of the series to be closer to LTE than the lower; yet all detected Balmer line profiles are consistent with the same solution. We are thus confident that the principal conclusions of this paper—that WDHS 1 is a DA central star of unusually high T_{eff} at a high gravity—will not be changed substantially after a comprehensive non-LTE analysis is performed.

Finally, we note that Wesemael, Green, & Liebert (1985) derived T_{eff} and log g values for the DAO central star of Abell 7 in adequate agreement with the non-LTE results of Mendez et al. (1981).

4. IMPLICATIONS

4.1. *Derived Parameters: M_V, Reddening, and Distance*

The luminosity of the central star is obviously heavily dependent on the assumed, undetected helium abundance. However, the absolute visual magnitude (M_V) is insensitive to changes in such large temperatures, since most flux is emitted in the ultraviolet. If T_{eff} were as high as 165,000 K—the pure hydrogen solution—a Schönberner evolutionary model of $\sim 0.7\ M_\odot$ would be appropriate (see Fig. 5 of NS). The radius of the star can then be obtained directly from our solution of $\log g = 7.56$, which combined to the bolometric correction (see, e.g., Wesemael et al. 1980), yields a value of $M_V = +7.01$. If the other limit of high helium and $T_{eff} = 99{,}000$ K is correct, the Schönberner model of 0.6 $M_\odot$ is appropriate, and we derive $M_V = +7.36$. Let us take $M_V = +7.2$ as a reasonable compromise.

The interstellar extinction toward WDHS 1 can be estimated by comparing the slopes of the synthetic spectra from the optimal model atmosphere with the observed energy distribution. The 165,000 K pure hydrogen model has the steeper predicted slope of our two solutions and is shown superposed on the spectrum in Figure 2. The difference between them probably is within the errors of the observation and reduction process, although we note that our practice of aligning the long-slit direction with that of atmospheric dispersion should minimize color-dependent light losses. The difference in slope between 3600 and 4500 Å (roughly $U-B$) is $\sim 4\%$ in linear flux units, in the expected sense that the model has the steeper slope. We estimate the observational error in the ultraviolet slope and the uncertainty in the mean extinction law is 5%, so that if we sum the measured difference with the observational error, the upper limit to which the observed slope may be depressed due to extinction is $\sim 10\%$.

Even this modest claim leads to an interesting, and more quantitative upper limit on the interstellar reddening: $(U-B)$ slope change of 10% in linear flux units leads to an estimated $E(B-V) \leq 0.08$, or $A_V \leq 0.25$. The relationship

$$N(\text{H I} + \text{H}_2) = 5.8 \times 10^{21} E(B-V)\ \text{cm}^{-2} \quad (1)$$

(Savage & Mathis 1979) leads to an estimated column density of hydrogen of only 4.7×10^{20} cm^{-2}.

Weinberger et al. (1983) measured a photographic $V = 17.4 \pm 0.17$; the reddening-corrected magnitude might be as small as $V_0 = 16.9$. Using the above M_V value, we estimate the distance (d) in the range 870–1100 pc, depending on the correction for reddening. When one tries to allow for uncertainties in both V and M_V, our best estimate is $d = 1.0 \pm 0.25$ kpc. Along paths in the plane of the galaxy ($|b| \sim -6°$) at 1 kpc, one expects an average extinction of $E(B-V) \sim 0.61$ (Spitzer 1978), corresponding to $A_V \sim 1.9$ mag. However, WDHS 1 is located in the anticenter direction, where the mean extinction is generally lower. In this particular direction, it is dramatically lower, or our distance estimate is too high. Note that Weinberger et al. (1983) estimated a much smaller distance from the Shklovsky method of 320 pc, and also suggested that the interstellar reddening in front of WDHS 1 is extremely small, $A_V < 0.1$ mag.

4.2. *Nebular Size and Expansion Velocity*

Scaling with the uncertain distance, we can estimate the physical size of the major axis of the nebula at ~ 6.4 (d/1 kpc) pc, assuming 22′ as the angular diameter. This result leads to the conclusion that WDHS 1 is one of the largest planetary nebulae known. Our estimate compares with 1.44 pc by Weinberger et al., who assumed a smaller nebular angular diameter and much smaller distance.

A radial velocity measurement of the [N II] emission in WDHS 1 revealed doubled lines and an expansion velocity of 18 km s^{-1} in the line of sight to the central star (Gieseking, Hippelein, & Weinberger 1986; Weinberger 1989). If this were typical of the velocity of expansion transverse to the line of sight, an expansion age of 1.7×10^5 (d/1 kpc) yr is implied. As mentioned in § 1, NS found that most old planetaries with DA central stars show a severe discrepancy between the indicated post-AGB lifetime of the PNN ($\sim 10^6$ yr) and the kinematical age of the nebula (10^4–10^5 yr). WDHS 1 appears to be a case where this discrepancy is absent or less severe. However, the post-AGB lifetimes of stars in this part of the H-R diagram depend on the stellar mass, the hydrogen layer mass, and the evolutionary history (D'Antona 1989).

4.3. *Implications of the X-Ray Upper Limit*

The upper limit to any flux detected in the *ROSAT* All Sky Survey from § 2 corresponds to an X-ray luminosity of $L_X = 1.1 \times 10^{31}$ ergs s^{-1} over the 0.1–2.4 keV energy response range of the PSPC detector, assuming the distance inferred in § 4.1. This is far below the luminosities calculated for models at either extreme of T_{eff} and helium abundance: $L_X = 1.2 \times 10^{34}$ ergs s^{-1} for the 100,000 K high helium case, and 5.1×10^{35} ergs s^{-1} for 165,000 K pure hydrogen.

However, there are two ways in which the X-ray emission could be attenuated sufficiently that WDHS 1 was not detected by *ROSAT*. First, the models do not allow for the presence of heavier elements which may attenuate X-rays severely. Second, even though the evidence is that the interstellar extinction is abnormally small in the direction of WDSH 1, only a minor amount is required to attenuate the X-ray emission sufficiently. A column density near 5×10^{20} cm^{-2} (the upper limit from § 4.1) is sufficient to attenuate the PSPC spectrum of the hot DA white dwarf HZ 43 by a factor of over 500 (Fleming et al. 1993), already within a factor of 2 of that required for the 100,000 K high helium model.

Finally, we are aware of only two *ROSAT* detections of the photospheres of PNNs in the PSPC all-sky survey: NGC 246 and K1-16 (T. Fleming, private communication). (X-rays attributable to nebulae and shocked gas are discussed in Kreysing et al. 1992). Moreover, Tarafdar & Apparao (1988) have studied all observations of planetary nebulae with the Einstein Observatory Imaging Proportional Counter (IPC), the detector most similar in bandpass and sensitivity to the *ROSAT* PSPC. These authors found that only four of 19 observations resulted in detections of the central star, and one of these was marginal. No PNN was detected at a distance exceeding 600 pc, nor for which the estimated extinction exceeded $E(B-V) \sim 0.07$.

4.4. *WDSH 1: The Only Hydrogen-rich Star with a PG 1159 T_{eff} and Gravity?*

Despite the large uncertainty in T_{eff}, it seems likely that the WDHS 1 central star is the hottest object with a white dwarf gravity and an hydrogen-rich atmosphere yet to be recognized and analyzed in detail. The central stars of NGC 7293 and S216 (LS V +46 21) come close to or overlap the low end of the possible T_{eff} range for WDHS 1, but their surface gravities appear to be lowered by +0.5–1 dex (see Mendez et al. 1988; Tweedy & Napiwotzki 1992). Comparison with evolutionary tracks indicates that WDHS 1 is more massive and/or has an older post-AGB age than the DAO planetary nuclei studied by NS, Mendez, and collaborators. WDHS 1 appears to be the only hydrogen-rich case for which both the T_{eff} and log g are in the range of the PG 1159 stars (including perhaps H1504+651 and KPD 0005+5106).

NS have suggested that these objects provide evidence that PNNs with hydrogen-rich atmospheres really do evolve directly into DA white dwarfs, without the dominant atmospheric constituent changing. They argue for the existence of two evolutionary channels, with the hydrogen-poor PNNs evolving into non-DA white dwarfs. As mentioned in § 1, this hydrogen-poor sequence is well established, and may consist of WC (Wolf-Rayet) planetary nuclei evolving into "PG 1159" stars and then into DO white dwarfs (Werner 1993).

It is not clear, however, that the relative numbers work out for a scenario as simple as the "two channel" hypothesis. Since the distances of the PG 1159 stars are generally similar to the 1 kpc estimated for WDHS 1 (Werner 1992), the space density of the hydrogen-poor sequence at $T_{eff} \gtrsim 100{,}000$ K and log $g \gtrsim 7$ still appears to be substantially larger than the sequence represented by WDHS 1. There were in fact no WDHS 1–like stars found in the Palomar-Green Survey, nor thus far in any other survey of blue stellar objects with well-defined magnitude and color limits. Such samples are likely to be more complete and less biased than, for example, selection as planetary nuclei. WDHS 1 is a substantially fainter star, found only because of the discovery of its nebula. Yet the hydrogen-rich PNN in general appear to be at least twice as numerous as their hydrogen-poor counterparts (Mendez et al. 1986), while the hot DA white dwarfs over a wide range of T_{eff} are at least 3 times more numerous than their DB/DO counterparts (Fontaine & Wesemael 1987).

The possible deficit of hot DAs has at least three possible explanations: First, if they possess the thick ($\gtrsim 10^{-4}$ $M_\odot$) hydrogen envelopes predicted by standard post-AGB evolution calculations, the hydrogen-rich stars may evolve much more rapidly through the high-temperature region than their hydrogen-poor counterparts (Iben & Tutukov 1984). Second, with thick hydrogen envelopes, those with masses as low (~ 0.56 $M_\odot$) as the mean for DA white dwarfs may not even become as hot as 100,000 K in post-AGB evolution (D'Antona 1989; but see also the model with similar parameters in Koester & Schönberner 1986). We have already noted that the timescales of evolution at large T_{eff} depend on the total mass, the hydrogen layer mass, and the prior evolutionary history on the post-AGB. Finally, it has been proposed that most (all) DAs pass through a PG 1159 stage, after which at lower T_{eff} a thin layer of hydrogen forms by diffusion and produces a DA star (Fontaine & Wesemael 1987).

We must conclude this discussion with a caveat: it is clear that our knowledge of the parameters of the hydrogen-rich central stars remains uncertain, so that we do not know the space density of this group at all accurately. With the range of plausible temperatures for WDHS 1 introduced by the unknown He abundance, and the problem of self-consistency of Balmer line fits in DAO stars, it remains conceivable that the number of known hot DA stars in the PG 1159 temperature range will substantially increase with improved models. Until self-consistent parameters can be determined for all line profiles and other data on these DAO stars, further assessment of the "two-channel" and other scenarios may be premature.

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REFERENCES

Bergeron, P., Saffer, R. A., & Liebert, J. 1992, ApJ, 394, 228
Bergeron, P., Wesemael, F., Lamontagne, R., & Chayer, P. 1993, ApJ, 407, L85
Bergeron, P., Wesemael, F., & Fontaine, G. 1991, ApJ, 367, 253
Borkowski, K. J., Sarazin, C. L., & Soker, N. 1990, ApJ, 360, 173
D'Antona, F. 1989, in IAU Coll. 114, White Dwarfs, ed. G. Wegner (Berlin: Springer), 44
Dreizler, S., & Werner, K. 1993, in White Dwarfs: Advances in Theory and Observation, NATO ASI Ser., ed. M. A. Barstow (Dordrecht: Kluwer), 205
Fleming, T. A., Barstow, M. A., Sansom, A. E., Holberg, J., Liebert, J., & Tweedy, R. 1993, in White Dwarfs: Advances in Theory and Observation, NATO ASI Ser., ed. M. A. Barstow (Dordrecht: Kluwer), 155
Fontaine, G., & Wesemael, F. 1987, in IAU Colloq. 95, 2d Conf. on Faint Blue Stars, ed. A. G. D. Philip, D. S. Hayes, & J. Liebert (Schenectady, NY: L. Davis), 319
Gieseking, F., Hippelein, H., & Weinberger, R. 1986, A&A, 156, 101
Holberg, J. B., Kidder, K., Liebert, J., & Wesemael, F. 1989, in IAU Colloq. 114, White Dwarfs, ed. G. Wegner (Berlin: Springer), 188
Iben, I., Jr., & Tutukov, A. V. 1984, ApJ, 282, 615
Koester, D., & Schönberner, D. 1986, A&A, 154, 125.
Kreysing, H. C., Diesch, C., Zweigle, J., Staubert, R., Grewing, M., & Hasinger, G. 1992, A&A, 264, 623
Liebert, J. 1986, in IAU Colloq. 87, Hydrogen-Deficient Stars and Related Objects, ed. K. Hunger, D. Schönberner, & N. K. Rao (Dordrecht: Reidel), 367
———. 1991, in Evolution of Stars: The Stellar Abundance Connection, ed. G. Michaud & A. Tutukov (Dordrecht: Reidel), 411
Mendez, R. H., Kudritzki, R. P., Gruschinske, J., & Simon, K. P. 1981, A&A, 101, 323
Mendez, R. H., Kudritzki, R. P., Herrero, A., Husfeld, D., & Groth, H. G. 1988, A&A, 190, 113
Mendez, R. H., Miguel, C. H., Heber, U., & Kudritzki, R. P. 1986, in Hydrogen Deficient Stars and Related Objects, ed. K. Hunger, D. Schönberner, & N. K. Rao (Dordrecht: Reidel), 323
Napiwotzki, R. 1992, in Proc. of Univ. of Kiel/CCP7 Workshop, Atmospheres of Early-Type Stars, ed. U. Heber & C. S. Jeffery (Heidelberg: Springer), 310
Napiwotzki, R., & Schönberner, D. 1991, in White Dwarfs, NATO ASI Ser., ed. G. Vauclair & E. M. Sion (Dordrecht: Kluwer), 39 (NS)
———. 1993, in White Dwarfs: Advances in Observations and Theory, NATO ASI Ser., ed. M. A. Barstow (Dordrecht: Kluwer), 99
Savage, B. D., & Mathis, J. S. 1979, ARA&A, 17, 73
Spitzer, L., Jr. 1978, Physical Processes in the Interstellar Medium (New York: Wiley), 318

Tarafdar, S. P., & Apparao, K. M. V. 1988, ApJ, 327, 342
Thejll, P., Vennes, S., & Shipman, H. L. 1991, ApJ, 370, 355
Tweedy, R. W., & Napiwotzki, R. 1992, MNRAS, 259, 315
Weinberger, R. 1989, A&AS, 78, 301
Weinberger, R., Dengel, J., Hartl, H., & Sabbaden, F. 1983, ApJ, 265, 249
Werner, K. 1992, in Proc. of Univ. of Kiel/CCP7 Workshop, Atmospheres of Early-Type Stars, ed. U. Heber & C. S. Jeffery (Heidelberg: Springer), 273
Werner, K. 1993, in White Dwarfs: Advances in Observations and Theory, NATO ASI Ser., ed. M. A. Barstow (Dordrecht: Kluwer), 67
Wesemael, F., Auer, L. H., Van Horn, H. M., & Savedoff, M. P. 1980, ApJS, 43, 159
Wesemael, F., Green, R. F., & Liebert, J. 1985, ApJS, 58, 379