WHITE DWARF CENTRAL STARS

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Planetary nebula nuclei on lower luminosity, diagonal tracks in the HR Diagrams are degenerate dwarf stars close to their final radii. For several reasons, these stars have until recently been difficult to identify and study. With the advent of new techniques and technologies, both hydrogen–rich and hydrogen–poor atmospheric sequences have been found.

1. Introduction

It has long been realized that the nuclei of planetary nebulae (PNN) are becoming white dwarfs when their luminosities start to fall. Nonetheless, it has traditionally been very difficult to study central stars which fall on diagonal portion of a post–asymptotic giant branch (AGB) track in an HR Diagram. These are stars of rather low luminosity, and hence quite faint in apparent magnitude at the typical distances of planetary nebulae. Also, they are quite hot, so that spectral absorption features are likely to be weak and shallow. As they grow dimmer, these nuclei are more easily masked by the nebular radiation, though this is counterbalanced by the fact that the nebulae are likely to be old and low in surface brightness. Planetary nebulae are traditionally far enough away and concentrated to the Galactic plane, so that reddening may be a problem. Until recently, therefore, only a few planetary central stars were shown to have white dwarf gravities from direct studies of their spectra.

Due to some exciting developments the past several years, many more white dwarf central stars have been discovered and studied in some detail. The first reason for this is the employment of CCD detectors to obtain accurate, high signal–to–noise (S/N) ratio line profiles and spectrophotometry. Secondly, these can now be analyzed using improved, NLTE, line–blanketed model atmospheres and synthetic spectrum codes. Finally, a most important development has been the discovery of larger planetary nebulae of very low surface brightness – the "senile" planetaries (Ishida and Weinberger 1987). It comes as no surprise that this oldest group of nebulae often harbors white dwarf central stars. In fact, several weak nebulae have now been found around previously–discovered hot white dwarfs.

What can we learn from studying the white dwarf central stars and their nebulae? First, these various discoveries have in effect extended the planetary nebula luminosity function and age distribution. We want to match up the formation rates of the PNs with those of the white dwarfs in order to find out what subset of the latter pass through a PN phase. The potential problem with the respective birthrates is reviewed in Phillips (1988). In addition, it is of interest to see whether the well–established H–rich and H–poor PNN sequences evolve directly into the DA and non–DA white dwarf sequences. Does each composition group evolve as a continuous sequence, or do they change from one dominant atmospheric composition to another? A critical question for establishing the PN formation rate is whether

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the post–AGB evolutionary ages of the PNN can be reconciled with the expansion ages of the nebular shells: for cooling–dominated stars, this may be a severe test.

At this point, only very preliminary and partial answers to these questions are possible. The main reason for this is that – despite the great advances in atmospheric modelling and in the spectrophotometric data – it is not clear in many cases that accurate enough atmospheric and stellar parameters can be determined, for example, to place the stars in an HR Diagram for quantitative comparison with evolutionary tracks. Ironically, the temperature determinations for the H–poor sequence with their complicated and mixed atmospheric abundances of He and CNO elements may presently be more accurate than those of the H–rich sequence. We shall therefore discuss the two groups separately.

2. High Gravity Planetary Nuclei with Hydrogen-poor Atmospheres

The most extreme, hydrogen-poor nuclei are generally luminous objects with Wolf–Rayet (WC) spectra featuring broad emission due to helium and CNO ions. Because of the prominence of an O VI doublet in the optical ultraviolet, they are sometimes called "O VI" nuclei. The sequence apparently includes extremely hot stars, some of which may have dropped from their maximum luminosities, for which the emission lines are much weaker. The spectra are dominated by absorption features due to carbon, oxygen, usually helium and sometimes nitrogen, often with the cores reversed into emission. In the PNN spectral classification system of Mendez et al. (1986), these would be called O(C) or hgO(C), designations which denote the appearance of strong helium and carbon features. These stars range in temperature from 100,000 K to perhaps 170,000 K, as determined from the analyses cited below.

Some stars showing this kind of spectrum are pulsationally-unstable, with complicated mode structures of non-radial g modes. The prototype of this class of pulsators is PG 1159–035 or GW Vir (McGraw et al. 1979). Though the early discoveries belonging to this group were field stars in the Palomar Green (PG) Survey – and these appear to lack even "senile" nebulae – Grauer and Bond (1984) discovered that the nucleus of K 1–16 is a similar pulsator. That it's similar absorption lines were sharper indicated a higher luminosity and the implication that the apparent pulsational instability strip extends to somewhat higher luminosities. Several pulsating PNN, all with similar spectra, have subsequently been found. Several key features of the spectra are illustrated in Werner (1992) which includes a table of known objects of this "PG 1159" spectroscopic class.

The magnificent work by the Kiel and Munich groups has given us a quantitative understanding of this post–AGB, H–poor sequence. High S/N line profiles of He, CNO, and most recently Fe ions have been analyzed using model atmospheres which treat over 100 NLTE levels and hundreds of individual transitions. Temperatures, surface gravities, and abundances for eight PG 1159 stars including two nuclei are summarized in Werner (1993). A major surprise was the Kiel result (Werner, Heber and Hunger 1991; WHH) that carbon and oxygen mass fractions are competitive with helium in the atmospheres of these stars, while N has a significant abundance apparently only in a minority of objects. For example, the prototype PG 1159–035 has abundances of 33% He, 50% C and 17% O by mass. Even more extreme are those of the very hot object H 1504+65 – <1% He, C∼O∼50%. These abundances imply that most of the helium envelope which exists at the end of the AGB phase is lost during post–AGB evolution. WHH hypothesized that much of this mass is lost during the WC phase, at which time a high-velocity wind is observed; these stars would then be predecessors of those with PG 1159 or O(C) spectra, as first suggested by Sion, Liebert and Starrfield (1985).

The discovery last year of a spectacular mass loss event in the nucleus of Longmore 4 cements the relationship of the WC and PG1159 spectral types. This star, found to pulsate by Bond and Meakes (1990), normally exhibits an absorption–line PG 1159 spectrum. Werner et al. (1992) found that showed broad WC emission features early in 1992; these faded in strength over a period of days.

There is also a growing case that at least some of the H–deficient PNN and PG 1159 sequence lose their envelopes in a late helium shell flash (Iben et al. 1983). Abell 78 is one of three objects known to have inner nebular knots which are extremely H–deficient, and enriched in such elements as helium and carbon, but surrounded by a large nebula of "normal" abundances (cf. Jacoby and Ford 1983). The inner nebula is assumed in this hypothesis to be due to a second AGB–like phase, resulting from the ejection of the hydrogen and much of the helium envelopes due to the shell flash. Such a "born again" event may actually have been observed in V605 Aql, which was observed to have a novalike outburst in 1917–1921; it has now faded and exhibits a WC–like spectrum. This object is the central star of the old PN Abell 58. Hubble Space Telescope imaging shows what may be the ejecta of this explosion, knots of H–poor nebulosity not unlike those of Abell 78 (Bond, Liebert, Renzini and Meakes 1993, these Proceedings).

It is generally assumed that the H–deficient nuclei and PG 1159 stars cool down into the H–deficient DO white dwarfs, whose atmospheres are predominantly helium–dominated. However, the sequence can only be continuous down to a temperature of about 45,000 K, since no white dwarfs are known with He-rich spectra between 30,000 K and 45,000 K (Liebert 1985). There may also be a discrepancy between the luminosity functions of the hottest DA and DO white dwarfs, as discussed in the next section. Thus, the possibility remains that some stars evolve from one sequence to the other (see Shipman 1988 and Liebert 1988 for discussions of various hypotheses).

3. Hydrogen–rich White Dwarf Central Stars

Spectra of H–rich composition are generally dominant among both the PNN and the hot white dwarfs. Do these form a continuous sequence? It is not clear that they do. In particular, it has been difficult to identify high gravity, H–rich examples of similar temperatures (100,000–170,000 K) to the H–poor PG 1159 sequence discussed previously, or to even the hottest white dwarfs of type DO at T_{eff} 80,000 K.

Among the H–rich white dwarf nuclei are the well–studied cases of Abell 7 and NGC 7293, which may be close to or in the DO temperature range. Several H–rich central stars are known with T_{eff} ∼70,000 K, with one faint, poorly–observed star with an estimated temperature near 100,000 K (Napiwotzki and Schönberner 1991). One of the hottest, recently–reported examples is the central star to S 216 (or LS V +46 21) which has a rough temperature estimate of 90,000 K (Tweedy and Napiwotzki 1992).

The apparent paucity of H–rich objects of very hot temperatures is more dramatic for complete samples of field white dwarfs. Best studied of these is the PG Survey (Fleming, Liebert and Green 1986). Some 353 DA stars were studied in this sample to a B magnitude of typically 16.2 over 10,000 square degrees of sky at high Galactic latitude. Yet the hottest of these appear to be cooler than 80,000 K (Holberg et al. 1989); to my knowledge, there are no other field DA stars (ie. non PNN) with reported temperatures above this value. As already noted, a sequence of DO and PG 1159 stars – most lacking nebulae – extends to 170,000 K (Werner 1993; Wesemael, Green and Liebert 1985).

Some selection effects might be envisioned for these samples which might be responsible for the apparent paucity of very hot, H–rich cases. First of all, if these stars have thick hydrogen envelopes and active hydrogen shell sources, their rate of evolution down to log L ~2 could be considerably faster than for those lacking hydrogen shells. It is controversial whether either the H–rich PNN or the DA white dwarfs have such thick shells (cf. the reviews in Schönberner 1988 and Liebert 1988).

One might then expect that any rapidly evolving H–rich stars are more likely to be enveloped in a bright PN, which could prevent the parameters from being determined by a standard photospheric analysis. For the PG Sample, it is possible to answer this concern by asking how many PNs appear in the area of sky that was surveyed, and how many of these could possibly harbor very hot nuclei. The answer to the first question is that there are only nine nebulae in the relevant field (NGC 6058, NGC 7094, A 30, A 33, A 39, H4–1, Sn–1, EGB 6 and 61+41°1). Of these, none harbor poorly-observed central stars and the only hot H–rich nucleus is that of EGB 6 / PG 0950+139; this is a 70,000 K white dwarf with unique properties (Liebert et al. 1989), but not an extremely hot star. Such extremely hot PNN, imbedded in bright and dusty nebulae do exist (cf. NGC 7027), but they are likely to be quite rare in a volume-limited sample.

We must also note that white dwarf and PNN samples may not be sampling the same stellar population. The former come from a volume very near the Sun, with a scale height of 275 pc (Boyle 1989). The scale height estimates for the nuclei are generally much smaller (see M. Peimbert, this Conference). The difference in these samples should be kept in mind in attempts to reconcile the differing formation rates.

Finally, we come to what is currently the most difficult problem of all – that the T_{eff} estimates for the H–rich white dwarfs and central stars may not currently be accurate enough to draw reliable comparisons with the H–poor sequence. No problem was apparent in prior studies of the hottest DA white dwarfs. Wesemael et al. (1980) compared LTE and NLTE, pure–H models and found the former to be adequate. Line profile fits for the series of Balmer lines and for Lyman alpha appeared to yield consistent temperatures, using just LTE models. The physics of the hydrogen atom is understood well enough to conclude that temperatures determined for the DA white dwarfs should be more accurate over a wide range than for He–rich cases.

Napiwotzki and Schönberner (1992) first showed that, above a temperature of perhaps 50,000–60,000 K, some hydrogen–rich PNN line profiles sometimes do not yield self–consistent fits. When there was a discrepancy, the temperature of the fit would increase with an increasing upper level of a Balmer transition. That is, Hα might yield a temperature as low as 50,000 K, while the Hδ fit gives 90,000 K for a given central star (Napiwotzki 1992). Most disturbing is the fact that this discrepancy appears most likely to affect the PNN and DA stars of highest temperature – so that we may not really know how hot the sequence extends! Perhaps such stars in S 216 and NGC 7293 are much hotter than the published estimates.

This lack of self–consistency in fitting a sequence of hydrogen lines for hot stars – which might be dubbed the Napiwotzki effect – can apparently extend to lower temperatures. Lamontagne et al. (1993) faced the same result in fitting the star Feige 55, for which they got a best fit temperature of about 54,000 K. Yet most of the field PG white dwarfs yield self–consistent Balmer line temperature fits up to 70,000 K, so that it is unlikely their true temperatures are much higher than the estimates.

Since this problem arises only in some stars within what appears to be a similar temperature range, there clearly is another parameter to the problem. It was initially believed that the effect was related to the appearance of helium in the atmosphere (a DAO spectrum), though He II is usually seen at least weakly in the spectra of the hottest H–rich PNN and white dwarfs. While helium might yet be part of the answer, the dominant characteristic of Feige 55 is the very strong spectrum of heavier elements – ions of carbon, nitrogen and especially iron – observed in ultraviolet spectra obtained with the it International Ultraviolet Explorer. It is argued by Lamontagne et al. (1993) that a properly treatment of the extensive blanketing in the ultraviolet might lead to better self-consistency in the hydrogen line fits and more accurate temperatures for such stars. A similar investigation of the effects of line blanketing is underway at Kiel (Dreizler and Werner 1993).

4. Conclusions

Our goal was to attempt to answer some of the interesting questions posed in the Introduction, but we are currently stopped in our tracks. Until the Napiwotzki effect is properly taken into account, no proper comparison of the H–rich and H–poor sequences is possible, and the luminosity functions and formation rates of the PNN and white dwarf samples may undergo some revision.

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