NLTE ANALYSES OF PG 1159 STARS: CONSTRAINTS FOR THE STRUCTURE AND EVOLUTION OF POST-AGB STARS

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1. Introduction

The majority of all stars ($M_i < 8M_\odot$) end their lives as white dwarfs (WD). On the tip of the Asymptotic Giant Branch (AGB) the star ejects its outer layers which become a Planetary Nebula and the stellar core evolves rapidly towards very high effective temperatures (T_{eff} >100 kK). When the nuclear burning in the H or He shell ceases the star enters the WD cooling sequence. The evolution starting from the AGB is separated in a H–rich and a H–deficient sequence where the latter contributes with a number fraction of $\approx$ 20%. In this paper we describe our recent effort in the analysis of one group of these stars, the PG 1159 stars.

PG 1159-035, the prototype of hot C– and O–rich pre–WDs was discovered in the Palomar Green Catalog (Green et al. 1986). It also became the prototype of a new class of variables, the GW Vir (=PG 1159-035) stars, when McGraw et al. (1979) discovered non–radial g–mode pulsations in PG 1159-035. First LTE analyses of Wesemael et al. (1985) revealed the very high T_{eff} (>100 kK) and the high surface gravity (log g$\sim$7). These stars represent corner stones in our understanding of the late phases of stellar evolution since many important effects of the post–AGB evolution can be studied here. Selected examples shall demonstrate how our analyses provide constraints for the structure and evolution of post–AGB stars.

2. Properties of PG 1159 stars

Presently 27 PG 1159 stars are known and most of them have been analyzed by our group (see Dreizler et al. 1995 and Werner et al. 1997 for latest reviews) using highly sophisticated NLTE model atmospheres (Dreizler & Werner 1993, Rauch 1997). Due to the enormous improvements in the model atmosphere techniques and also in the observation facilities we can now derive their effective temperatures, gravities, and surface abundances with high precision. These stars cover the hottest part in the post–AGB evolution in the transition between the Central Stars of Planetary Nebulae (CSPN) and the WDs with effective temperatures ranging from 65 kK to 180 kK. On the luminous end they have a broad overlap with O(He) and [WCE] CSPNe (Rauch et al. 1997, Koesterke & Hamann 1997), on the compact end with the hot He–rich DO WDs (Dreizler & Werner 1996).

The abundance pattern of PG 1159-035 (He/C/O=.5/.33/.17 by mass, H below the detection limit [H/He<1]; Werner, Heber & Hunger 1991, [WHH]) is found to be typical for PG 1159 stars. As already discussed by WHH these abundances can not be explained by standard evolutionary models which retain a H–rich envelope during the entire post-AGB phase. However, the surface abundances of PG 1159 stars are in qualitative agreement with the chemical composition in the deep intershell layers (Iben 1984) which led WHH to propose that PG 1159 stars are born–again post–AGB stars (Iben et al. 1983). In this scenario the star suffers a late He flash when it already left the AGB. The strong mass loss during the second (post–) AGB phase might be sufficient to erode the stellar surface down to the former intershell layers producing C and O rich stars. Despite the qualitative agreement between theory and observation the situation is still not satisfactory. Models consistently evolved through the numerically very difficult phase of the late He flash (Iben & MacDonald 1995) can not reproduce the observed abundance pattern since mixing processes produce significant admixtures of H and N which are not observed in this pattern in PG 1159 stars, e.g. N and H being more abundant than O. A very interesting point of view comes from recent work of Blöcker et al. (1997) who can produce the typical PG 1159 abundances already on the top of the He convection zone with a realistic treatment of the overshoot. Less drastic mass loss would be sufficient to exhibit these layers.

The GW Vir stars have also been subject to extensive photometric studies to derive asteroseismological parameters (Whole Earth Telescope, Winget et al. 1991). The spectroscopic parameters like effective temperature and surface abundance serve as constraints for these analyses in order to reduce the huge parameter space or resolve ambiguities in the solution (Kawaler & Bradley 1994, Kawaler et al. 1995). Asteroseismology can then provide otherwise inaccessible information on the structure of these stars. It is also possible to derive much lower limits on the rotation periods and magnetic fields and to obtain independently derived masses and luminosities for PG 1159 stars. A comparison between the asteroseismological and spectroscopic masses is very satisfying for those stars with reliable pulsational data (Werner et al. 1996). It is found that PG 1159 stars have a mean mass of $0.6\,M_\odot$ which is close to the CSPN and WD mean masses.

Spectroscopic results are also important to investigate the driving mechanism of the GW Vir pulsations. Starrfield et al. (1985) proposed the $\kappa-\gamma$ mechanism of C and O to cause the pulsations. The chemical composition in the driving region, which is very close to the surface, is a very important parameter for the efficiency of this mechanism. According to Stanghellini et al. (1991) and Bradley & Dziembowski (1996) this layer must be H free. Also C and O must be even more enriched then in the atmosphere. In contrast, recent calculations of Saio (1996) and Gautschy (1997) show that pulsations are possible with the presence of H in the driving zone. We therefore started an intensive search for H in PG 1159 stars. This is a difficult task since all H lines are blended by much stronger He II lines. High resolution is necessary to resolve small rest wavelength differences e.g. at Hα. Due to the faintness of these stars large telescope are required. Observations at the 3.6 m ESO and 10 m Keck telescope of 4 PG 1159 stars could reduce the upper limit to 5 % by number (Werner 1996, Dreizler et al. in prep). On the other hand we detected 4 stars with typical spectra of PG 1159 stars but with Balmer lines clearly present (Napiwotzki & Schönberner 1991, Dreizler et al. 1996). They were therefore termed hybrid PG 1159 stars. According to the results of Dreizler et al., one of them (HS 2324+3944) lies in the GW Vir instability strip. Indeed, variability was detected by Silvotti (1996) and an analysis of the light curve of Handler et al. (1997) makes this star a good candidate for a member of the GW Vir group. A multi site campaign in order to corroborate this hypothesis by resolving more frequencies is planned. Another important constraint for the pulsation theory are the boundaries of the instability strip. We therefore obtained HST spectra of 9 (4 pulsating) PG 1159 stars. A precise determination of the effective temperature should confine the blue and red edge of the GW Vir strip. This analysis is under way, however, we noticed a prominent difference between the stable and pulsating PG 1159 stars prior to detailed analyses. All cooler ($\sim$100 kK) pulsating stars clearly show the resonance doublet of N V while the stable stars do not. Whether N is relevant for the driving of pulsations has to be investigated by the pulsation experts. I any case, it is important for the evolution, since it shows that mixing processes must occur in order to produce N in the C and O rich layers (see discussion above).

The last aspect we want to investigate is rotation and mass loss in PG 1159 stars. Our high resolution Keck spectra revealed that instrumental and Stark broadening alone can not reproduce the observed line width. This could be caused by rotation (∼70 km/sec). It would, however, be quite surprising since DA WDs are slow rotators (Koester & Herrero 1987, Heber et al. 1997) with upper limits of ∼40 km/sec. However, the broadening could also be caused by mass loss (macroturbulence). In order to distinguish the two hypotheses we determined mass loss rates for all PG 1159 stars showing this additional broadening. The analysis of the very recently obtained Keck spectrum of PG 1159-035 will give further clues since it has an asteroseismologically determined rotation period.

Acknowledgement: This work is supported by the DFG by several travel grants for observation campaigns and the participation in this meeting.

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