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Memorie della

Extreme horizontal branch stars

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Abstract. A review is presented on the properties, origin and evolutionary links of hot subluminous stars which are generally believed to be extreme Horizontal Branch stars or closely related objects. They exist both in the disk and halo populations (globular clusters) of the Galaxy. Amongst the field stars a large fraction of sdBs are found to reside in close binaries. The companions are predominantly white dwarfs, but also low mass main sequence stars are quite common. Systems with sufficiently massive white dwarf companions may qualify as Supernova Ia progenitors. Recently evidence has been found that the masses of some unseen companions might exceed the Chandrasekhar mass, hence they must be neutron stars or black holes. Even a planet has recently been detected orbiting the pulsating sdB star V391 Peg. Quite to the opposite,in globular clusters, only very few sdB binaries amongst are found indicating that the dominant sdB formation processes is different in a dense environment. Binary population synthesis models identify three formation channels, (i) stable Roche lobe overflow, (ii) one or two common envelope ejection phases and (iii) the merger of two helium white dwarfs. The latter channel may explain the properties of the He-enriched subluminous O stars, the hotter sisters of the sdB stars, because their binary fraction is lower than that of the sdBs by a factor of ten or more. The rivaling "late hot flasher" scenario is also discussed. Pulsating subluminous B (sdB) stars play an important role for asteroseismology as this technique has already led to mass determinations for a handful of stars. A unique hyper-velocity sdO star moving so fast that it is unbound to the Galaxy has probably been ejected by the super-massive black hole in the Galactic centre.

Key words. Stars: subluminous – Stars: atmospheres – Stars: abundances – Stars: population II – Stars: binaries – Stars: pulsations – Stars: hyper-velocity

1. Introduction

Hot subluminous stars are an important population of faint blue stars at high galactic latitudes closely related to the horizontal branch. They have recently been studied extensively because they are common enough to account for the UV excess observed in early-type galaxies (O'Connell 1999). Pulsating sdB stars became an important toy for asteroseismology (Charpinet et al. 2004), and sdB stars in close binaries may qualify as Supernova Ia progenitors (Maxted et al. 2000; Geier et al. 2007).

Subluminous B stars (sdB) have been identified as extreme horizontal branch (EHB) stars (Heber 1986); i.e. they are core helium-burning stars with hydrogen envelopes that are too thin to sustain hydrogen burning (unlike normal HB stars). Therefore they evolve directly to the white-dwarf cooling sequence by avoiding the asymptotic giant branch (AGB). While the sdB stars spectroscopically form a

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homogeneous class, a large variety of spectra is observed among their hotter sisters, the subluminous O stars (Heber 1992; Heber 2008). Most subluminous B stars are helium poor, whereas only a relatively small fraction of sdO stars are.

After a brief historical overview, the extreme horizontal branch stars in globular clusters will be discussed in section 3. Spectroscopic analyses of the field star population and the role of close binaries are addressed in sections 4 and 5. Section 6 will focus on the origin of hot subluminous stars, while section 7 summarizes the results from asteroseismology. Section 8 reports the discovery of a unique hyper-velocity sdO star. We conclude by briefly presenting ideas about the progeny and progenitors of hot subluminous stars.

2. Surveys and early results

The hot subdwarfs were and are being discovered in surveys for UV bright objects at high Galactic latitudes, starting with the Humason & Zwicky (1947) survey from which the first hot subdwarf stars were identified. Photometric (e.g. Palomar-Green) as well as objective prism surveys (e.g. the Hamburg surveys HS & HE) have now provided large samples. The Sloan Digital Sky Survey (SDSS) is a new rich source for hot subdwarf spectra (Hirsch et al. 2008). The catalog of hot subluminous stars is available by means of an online data base created and maintained by Østensen (2006).

Pioneering spectral analyses of sdB stars in the 1960s revealed strong helium-deficiencies, which at first glance seemed to challenge Big Bang Nucleosynthesis but were soon realized to be caused by atmospheric diffusion. The seminal papers by Newell (1973) and Greenstein & Sargent (1974) set the stage for the field to grow driven by new model atmospheres, improved spectroscopy and the advent of UV spectroscopy. A detailed review on the early development of the field is given by Lynas-Gray (2004).

3. The extreme horizontal branch of globular clusters

The literature on extreme or extended horizontal branches in globular clusters is vast and can not be discussed extensively here. Instead the reader is referred to the excellent reviews of Moehler (2001) and Moni-Bidin et al. (2008).

Greenstein (1971) and Caloi (1972) were the first to identify the hot HB extension observed in very few globular cluster CMDs with the already-known field sdB stars. Various gaps on the blue HBs were found (e.g. Newell & Graham 1976) but their existence is now called into question as they may result from poor statistics and selection effects. Quantitative spectral analyses in the 1980s (e.g. Heber et al. 1986) established the similarity of GC EHB star to the field hot subdwarfs with respect to all of their atmospheric parameters ($T_{\rm eff}$, log g and He-abundance). The low helium abundance is a consequence of gravitational settling in the high gravity atmospheres.

Deep HST photometry increased the number of Globular Clusters showing an EHB considerably, thereby sharpening the so-called "Second Parameter Problem".

The term "blue tail" was coined for the most extreme HBs. Far-UV photometry revealed yet another feature, a very hot "blue hook" which seems to extend to below the helium burning limit (D'Cruz et al. 2000).

Recent theoretical investigations relate the Horizontal Branch morphology to helium enrichment (e.g. D'Antona et al. 2005). Previous investigations invoked helium mixing induced by internal rotation (Sweigart 1997). The recently discovered multiple main sequences in ω Cen have been attributed to helium enriched sub-populations (Bedin et al. 2004) pointing towards a primordial origin of helium enrichment.

The formation of EHB stars in globular clusters may be very different from that in the Galactic field due to the dense environment in globular clusters. Dynamical interactions might play an important role for the sdB formation through stellar collisions, merging or encounters of binary stars (Bailyn et al. 1992).

Observational evidence is ambiguous. On the one hand, more concentrated or denser globular clusters have bluer HBs and longer blue tails (Buonanno et al. 1997) as expected if dynamical interaction is important. On the other hand, however, no radial gradients have been found even in those clusters which have the most strongly populated EHBs (Bedin et al. 2000, e.g.). In fact, there is no correlation between HB morphology and dynamical state of a globular cluster. Pairs of clusters with similar HB morphology are dynamically different and, vice versa, others which are dynamically similar have very different HBs (Ferraro et al. 1997; Crocker et al. 1988). From this point of view, dynamical interaction does not seem to be an important channel for EHB production in globular clusters (but see section 5).

4. Hot subluminous stars in the field

As many of the field stars are much brighter than their sisters in GCs, they have been studied in greater detail. The spectral classification ends up in a zoo of different subtypes. The O-type class, in particular, is very inhomogeneous showing vastly different H/He-line spectra, from no helium lines to no Balmer lines detectable. A similar situation is found for the metal line spectra at higher spectral resolution. As a consequence no proper classification scheme has ever been established for the hot subluminous stars.

Appropriate model atmospheres have been developed for quantitative spectral analyses allowing to treat on the one hand the metal line blanketing in full and on the other hand deviations from the local thermodynamical equilibrium (in particular for the O-type stars).

Quantitative spectral analyses are now available that provide atmospheric parameters of several hundreds of sdB stars (e.g. Saffer et al. 1994; Maxted et al. 2001; Edelmann et al. 2003; Lisker et al. 2005), as well as more than 100 sdO stars (Ströer et al. 2007; Hirsch et al. 2008). . These provide a sound basis to investigate the evolutionary status and origin of the stars. Metal abundance analyses, however, are still scarce, i.e. available for a few dozen stars. From UV spectroscopy with HST-STIS a detailed picture of the abundance pattern of pulsating as well as non-variable sdB stars has been derived recently (O'Toole & Heber 2006a). Abundances for 25 elements including the iron group and even heavier elements such as tin and lead have been derived. Many heavy elements of the iron group and beyond show large overabundances (by 2–3 dex.) while most notably iron does not. For the first time the lead isotopic ratios have be measured to be consistent with the solar ratios (O'Toole & Heber 2006b). These results are valuable tools to investigate the diffusion processes, i.e. the interplay of gravitational settling, radiative levitation and a stellar wind. The latter has been found to be an important ingredient (Unglaub 2006), However, it is hard to measure since the expected rates are very low. Observational evidence is meager yet (Heber et al. 2003b).

Magnetic fields may be another factor that has been ignored up to now. With the advent of the ESO VLT, spectropolarimetry has become an option and let to the first detection of ≈kG fields in a few stars (O'Toole et al. 2005b).

5. Hot subluminous stars in close binaries

The fraction of sdB stars in short period binaries (periods less than ten days) is high. Maxted et al. (2001) found 2/3 of their sdB sample were such binaries, whereas a somewhat lower fraction of 40% was found recently for the sample drawn from ESO Supernova Ia Progenitor SurveY (SPY, Napiwotzki et al. 2001). Quite to the opposite, radial velocity variable stars are rare amongst the *helium-enriched* sdOs, for which Napiwotzki et al. (2004) find that a fraction of radial velocity variables to be 4 % at most. Obviously, binary evolution plays an important role in the formation of sdB stars and possibly also in that of the sdO stars if they are formed by a merging the components of a close binary system.

This encouraged surveys for radial velocity variable sdB stars in globular clusters, which met with little success. The conclusion is that the fraction of close binary sdB stars is much lower in Globular Clusters than in the field. Moni-Bidin et al. (2008) find a binary frequency of only 4% for the EHB stars in NGC 6752 indicating that sdB formation in globular cluster may be very different from that in the field pointing to the relevance of dynamical effects, which might lead to disruption of binaries or binary mergers. Hence dynamical effects should not be disregarded despite of other observational evidence to the opposite (see section 3).

The nature of the companions is constrained via the mass function, as well as from light variation due to a reflection effect and ellipsoidal deformations. Up to now the companions have been identified only in the shortest period systems. Amongst them white dwarfs prevail, but main sequence stars of low mass are quite common.

A planetary companion to the pulsating sdB star V391 Peg has been discovered from sinusoidal variations of its pulsation frequencies (Silvotti et al. 2007). Functionally this is equivalent to the timing method used to find planets around pulsars. The discovery of planet around a post-red-giant star demonstrates that planets can survive the red-giant expansion at distances of less than 2 AU.

At the other end of the mass scale, a few very massive companions have been found recently. In the most extreme case the companion mass clearly exceeds the Chandrasekhar limit and must be a neutron star or a black hole (Geier et al. 2006). The observed fraction of such companions is much higher than predicted by binary population synthesis models. Is this a new population of "hidden" neutron stars and/or black holes?

6. Evolution and origin of hot subluminous stars

The evolutionary status of sdB stars as extreme horizontal branch stars appears to be proven beyond doubt. SdO stars, however, can not be EHB stars, and several options remain for their present state of evolution.

The origin of both sdB and sdO stars remains a puzzle. The main difficulty for every scenario is the large amount of mass that has to be lost prior to or at the start of core helium burning. Canonical evolutionary calculations have been modified by assuming large mass rates on the RGB leaving us in the dark about physical mechanism. The occurrence of delayed core helium-flashes in post-RGB evolution has been discovered as a promising mechanism to produce sdO stars in particular. The merger of two helium white dwarfs is another vital option to explain the origin of sdO stars rivaling the delayed-core-helium-flash scenario.

Non-standard evolutionary models were introduced to explain the formation of sdO stars (e.g. Sweigart 1997; Brown et al. 2001; Moehler et al. 2004). In particular, the *late hot flasher scenario* predicts that the core helium flash may occur when the star has already left the red giant branch (RGB) and is approaching the white-dwarf cooling sequence (delayed He core flash). During the flash, He and C may be dredged-up to the surface. Hydrogen is mixed into deeper layers and burnt. The remnant is found to lie close to the helium main sequence, i.e. at the very end of the theoretical extreme horizontal branch. The final composition of the envelope is helium-dominated, and enriched with carbon (or nitrogen if the hydrogen burning during the helium flash phase burns ^{12}C into ^{14}N; Sweigart 1997). Indeed, Ströer et al. (2007) found most of their observed *helium-enriched* sdO stars to lie near the model track, suggesting that this scenario may be viable. Although it can explain the helium enrichment and the line strengths of C and/or N lines as due to dredge up, it fails to reproduce the distribution of the stars in the $T_{\rm eff}$-$\log g$-diagram in detail (see Ströer et al. 2007).

The observed high fraction of short period sdB binaries made it clear that mass exchange episodes (stable Roche lobe overflow, RLOF, and common envelope ejection, CEE) in close binaries must play an important role for the origin of sdB stars. Recent binary population synthesis study (Han et al. 2003) identified three channels for forming sdB stars: (i) one or two phases of common envelope evolution, (ii) stable Roche-lobe overflow, and (iii) the merger of two helium-core white-dwarfs. The latter could explain the population of single stars. Short period binary white dwarfs will lose orbital energy through gravitational waves. With shrinking separation, the less massive object will eventually be disrupted and accreted onto its companion, leading to helium ignition. Saio & Jeffery (2000) argue, that this merger product will result in a helium burning subdwarf showing an atmosphere enriched in CNO-processed matter. This scenario therefore can explain these extremely *helium-enriched* sdOs showing strong nitrogen lines in their atmospheres.

Castellani & Castellani (1993) were the first to point out that helium might not be ignited in post-RGB evolution depending on the choice of the efficiency parameter for Reimer's RGB mass loss law. Indeed, there is now observational evidence that some sdB stars are not core helium burning objects. In the case of HD 188112 the mass has been determined from gravity and an accurate Hipparcos parallax to be 0.22 $M_\odot$ (Heber et al. 2003a) too low to sustain helium burning and the star is cooling down to the helium white dwarf graveyard. Its post-RGB evolutionary life time is comparable to that of EHB stars (Driebe et al. 1998).

First tests of the binary population synthesis models against observations have been performed from spectra obtained by the SPY consortium for sdB stars (Lisker et al. 2005) as well as for sdO stars (Ströer et al. 2007). There are many free parameters to be constrained from observations, the most important being the common envelope ejection efficiency parameter. The observational tests reject models with very large efficiency parameters favoured by studies of double degenerate stars. In addition there is some evidence against an uncorrelated mass distribution of the progenitor systems (see Lisker et al. 2005).

7. Pulsations of hot subluminous stars

Ten years ago, multi-periodic light variations of low amplitudes (a few mmag) and periods of a few minutes were discovered in sdB stars (Kilkenny et al. 1997) at almost the same time they were predicted by theoreticians to be caused by non-radial pulsations (Charpinet et al. 1996).

Using small telescopes (typically 1–2 m) and examining hundreds of sdBs has yielded more than 30 of these pulsators, each with amplitude < 50 mmag (for a review of these objects, now known as V361 Hya stars, see Kilkenny 2002). The periods suggest that the stars are *p*-mode pulsators, but asymptotic theory cannot be applied to the analysis of their frequency spectra. The possibility of using oscillations to probe the interiors of sdBs received another boost after the discovery of pulsations with periods of 45 min–2 hr (Green et al. 2003, now termed V 1093 Her stars). The much longer period pulsations found in these stars indicate they are *g*-modes. The stars are typically cooler than the *p*-mode pulsators. Theoretical modeling has found that the pulsations in both groups may be driven by an opacity bump due to ionization of iron (and other iron-group elements) (Charpinet et al. 2001; Fontaine et al. 2003). In order for the mechanism to work, iron must be enhanced by diffusion processes in the subphotospheric layers. Very sophisticated envelope models have been constructed and have met the observed distribution of the stars in the V346 Hya stars with great success (see Fontaine et al. 2008, for a review).

For the V1093 Her stars, however, models fail to reproduce the edges of the instability strip. Jeffery & Saio (2006, 2007) find that the results strongly depend on the choice of opacity tables and that the role of iron group elements other than iron itself has been underestimated.

Of great importance for the development of asteroseismology are the so-called hybrid pulsators which show both short period p-mode pulsations as well as long-period g-mode pulsations (e.g. Schuh et al. 2006). Two puzzling hot subdwarf pulsators have been discovered, one is a very hot sdO star (Woudt et al. 2006) and the other a sdB stars showing light variations at periods intermediate between those of the V 361 Hya stars and the V 1093 Her stars (Koen 2007). While models for the sdO pulsator are in their infancy, there is as yet no scenario around for the latter object.

The main hurdle to overcome towards asteroseismology is the identification of the observed modes. The period matching technique has already been applied to half a dozen V 361 Hya stars. Masses and envelope masses have been derived in this way. In all but one case the results are in good agreement with the predicted canonical mass of 0.47 $M_\odot$ (Randall et al. 2007). The period matching technique has its limitation as the number of modes predicted to be excited usually is larger than the number of observed frequencies.

Other methods have higher predictive power than monochromatic light curves. Multi-colour measurements would allow to constrain the mode numbers by its sensitivity to limb darkening. However, the required accuracy has not yet been reached for any star to draw conclusion (Tremblay et al. 2006).

Stellar surface motions can be derived from radial velocity curves. Pilot studies (e.g. O'Toole et al. 2005a) have already been successful in detecting many modes in velocity that were seen in the light curves including combination frequencies. Line profile variations can be used to deduce temperature and gravity variations on the stellar surface. Despite of the stars' faintness, such analyses have recently been carried out for three V361 Hya stars (Telting & Østensen 2004; Tillich et al. 2007). In all cases, the strongest mode has been shown to be a radial one.

8. Kinematics and population membership

As the atmospheric abundance patterns of sdB stars are governed by diffusion processes, they can not be used to establish population membership. Obviously, some sdB stars belong to the population II because they are found in globular clusters. For field stars we have to rely on their kinematical properties. This becomes now possible for a sufficiently large sample thanks to accurate radial velocity measurements, spectroscopic distance estimates and proper motions from several sources. First results indicate that most stars belong to the thin disk, with a significant fraction of thick disk stars as well as halo stars (Altmann et al. 2004; Richter et al. 2007).

Amongst the sdO stars drawn from the SDSS data base, Hirsch et al. (2005) discovered a so-called hyper-velocity star, US 708, in the Milky Way halo, with a heliocentric radial velocity of $+708\pm15\,\mathrm{kms^{-1}}$.

A quantitative NLTE model atmosphere analysis of optical spectra obtained with the KECK I telescope shows that US 708 is a normal *helium-enriched* sdO with T_{eff}=44 500 K, $\log(g)$ = 5.25. Adopting the canonical mass of half a solar mass from evolution theory the corresponding distance is 19 kpc. Its galactic rest frame velocity is at least 757 $\mathrm{kms^{-1}}$, much higher than the local Galactic escape velocity (about 430 $\mathrm{kms^{-1}}$) indicating that the star is unbound to the Galaxy. It has been suggested by Hills (1988) that such hyper-velocity stars can be formed by the tidal disruption of a binary through interaction with the supermassive black hole at the Galactic centre (GC). Numerical kinematical experiments are carried out to reconstruct the path of US 708 from the GC. US 703 needs about 36 Myrs to travel from the GC to its present position, which is shorter than its evolutionary lifetime. Hence it is plausible that the star might have originated from the GC, which can be tested by measuring accurate proper motions. A HVS survey has increased the number of known HVS to ten (Brown et al. 2007). However, US 708 remains the only bona-fide old, low mass HVS star, while all other are probably young massive stars.

9. Conclusions: progeny and progenitors

Subluminous O and B stars evolve directly towards the white dwarf cooling sequence avoiding the asymptotic giant branch (AGB Manqué). They form an important channel for low mass white dwarfs. If some sdO stars are formed by mergers, they are more massive and will evolve into heavier white dwarfs. The evolution of close sdB binaries is effected by gravitational wave emission. SdB stars with M-type dwarf companions probably evolve into cataclysmic variables. As most of the known systems have periods below the CV period gap, this might be an important channel to form short period CVs. SdB binaries with massive white dwarf companions may qualify as progenitors of type Ia Supernovae in the context of the double degenerate scenario, if their combined mass exceeds the Chandrasekhar limit. Two systems are known for which this is the case (Geier et al. 2007). An evolutionary link to the blue stragglers has been suggested for the sdB stars in the old open cluster NGC 6791.

Ever since the pioneering work by Greenstein & Sargent (1974), the helium-rich sdO stars were believed to be linked to the evolution of the hydrogen-rich subluminous B stars. Any evolutionary link between subluminous B and O stars, however, is difficult to explain since the physical processes driving a transformation of a hydrogen-rich star into a helium-rich one remain obscure.

According to the recent studies by Lisker et al. (2005) and Ströer et al. (2007) a direct evolutionary linkage of the hot sdO stars to the somewhat cooler sdB stars is plausible only for the *helium-deficient* sdO stars, i.e. the latter are the likely successors to sdB stars.

The observed distribution of *helium-enriched* sdO stars is roughly consistent with the predictions from both the late hot-flasher scenario and the helium white-dwarf merger scenario but do not match them in detail. The occurrence of both a delayed helium core flash and the merger of two helium white dwarfs may explain the helium enrichment. In these cases carbon and/or nitrogen can be dredged up to the stellar surface, which would explain the strength of the C and/or N lines in *helium-enriched* sdO stars. The lack of close binaries amongst the latter is consistent with a white dwarf merger origin.

Self-consistent models of the dredge-up processes during a delayed helium flash have become available recently (Cassisi et al. 2003). More extensive observational studies are needed to provide accurate metal abundances, in particular for C and N to test dredge-up models as well as binary merger models.

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