# Secular contraction in extreme helium stars and the future of V4334 Sgr

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Several analyses of the optical spectrum and light curve of V4334 Sgr have made direct comparisons with the R Corona Borealis (RCrB) stars. There is evidence that V4334 Sgr is the product of a final helium flash in a hot white dwarf or planetary nebula central star (Duerbeck & Benetti, 1996). There have been suggestions that RCrBs are also products of a final helium flash (Iben et al., 1983). An evolutionary link between RCrBs and the hotter extreme helium stars (EHes: Schönberner, 1979) seems credible, although by no means proven. Despite evidence that V4334 Sgr and RCrBs have anything but a fleeting similarity in spectral type, as discussed elsewhere in these proceedings (Jeffery & Pollacco, 2001), suggestions that one is the precursor of the other are rife (e.g. Asplund et al., 1997, Kipper & Klochkova, 1997, Asplund et al., 1999, Duerbeck et al., 2000). Consequently, the logical deduction that V4334 Sgr might evolve to become an EHe should be scrutinized carefully.

This paper reports on recent measurements of contraction rates and stellar masses for extreme helium stars (Jeffery et al., 2001) and discusses whether evolution first as an RCrB and then as an EHe represents a likely future for V4334 Sgr.

## 1. Secular variability and evolution of EHes

Extreme helium stars (EHes) are very rare early-type supergiants with atmospheres typically comprising 99% helium, 1% carbon and $< 0.01\%$ hydrogen (by number, Jeffery, 1996). The principal question they pose is that of their evolutionary origin. Two principal hypotheses have

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[†] died, 1999 May 15

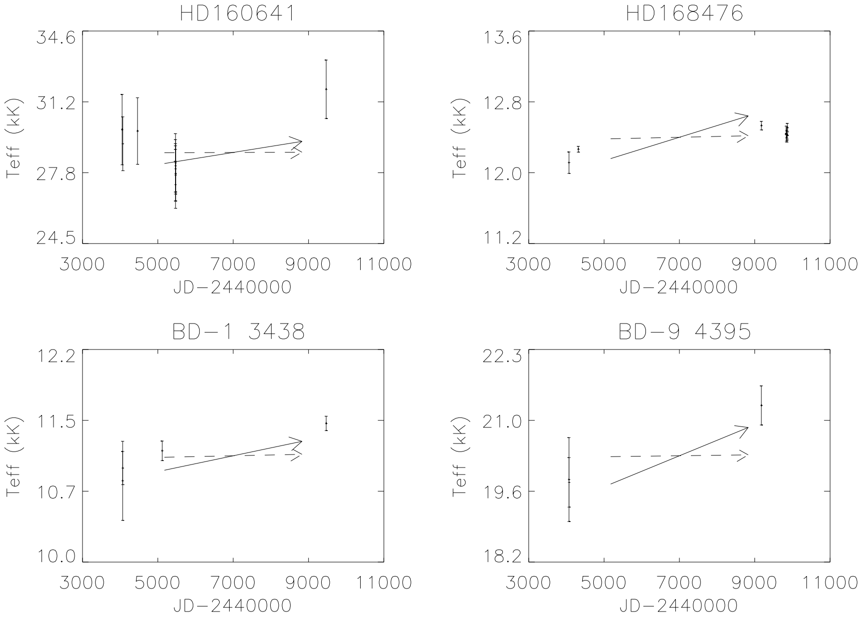

*Figure 1.* Effective temperatures of four helium stars as a function of Julian date. The vectors represent the temperature change predicted by Saio (1988) for shell helium burning stars of 0.7 $M_\odot$(dashed) and 0.9 $M_\odot$(solid) and $T_{\rm eff}$ similar to that shown.

emerged, the chief difference being whether the progenitor is a single or a binary white dwarf. The general properties of both hypotheses are discussed elsewhere (*e.g* Saio & Jeffery, 2000, Pandey et al., 2001) and are here simply referred to as the 'final flash' model (FF: Iben et al., 1983) and the 'merged binary white dwarf model' (MBWD: Webbink, 1984, Iben & Tutukov, 1985).

In both the FF or MBWD cases, the structure of the stellar core – the degenerate region below the helium-burning shell – depends on its previous history and may be reflected in its subsequent evolution. For example, to first order, the luminosity of the helium-burning shell depends on the mass and radius of the core (Jeffery, 1988, Saio, 1988). Similarly, the contraction rate of a shell-burning helium giant depends on the luminosity, the most luminous stars contracting the most quickly. Therefore, if it were possible to plot the evolution of any of these stars in terms of luminosity and radius as a function of time, it would provide an invaluable diagnostic of stellar evolution.

Being rare and unusual, several EHes were observed within the first two years of operation of the International Ultraviolet Explorer (IUE: 1978–1979) and nearly all had been observed by the mid 1980's. Upon recognising the great sensitivity of their fluxes to temperature (Dudley & Jeffery, 1993), a series of second epoch observations of EHes was made with IUE in the early 1990's.

150 low resolution observations of seventeen EHes were extracted from the IUE Final Archive and combined to form over seventy combined long-wave plus short-wave (LW+SW) spectra spanning over sixteen years of spacecraft operations. The IUE spectrophotometry was combined with optical broad-band photometry in order to establish the interstellar reddening. The IUE data alone were used to measure effective temperatures ( $T_{\rm eff}$) and angular diameters ($\theta$) for each LW+SW pair by finding the least-squares fit in a grid of model atmospheres for hydrogen-deficient supergiants. Full details of the data, methods and measurements are given by Jeffery et al. (2001).

The first object of this investigation was to compare EHe effective temperatures, obtained over a 10–15 year base line, with contraction rates predicted by Saio (1988). The latter calculated equilibrium models for luminous helium stars with degenerate carbon-oxygen cores and helium envelopes. From these, contraction rates for shell-burning helium stars were obtained as a function of mass and effective temperature. The $T_{\rm eff}$ of four EHes are shown as a function of time in Fig. 1. The panel for each star also shows the predicted change in $T_{\rm eff}$ for $0.7\,{\rm M}_{\odot}$ and $0.9\,{\rm M}_{\odot}$ helium stars over a ten-year baseline, assuming the mean measured $T_{\rm eff}$ for each star. The contraction rates for $0.7\,{\rm M}_{\odot}$ stars are an order of magnitude smaller than for $0.9\,{\rm M}_{\odot}$ stars and are barely different from zero on the scale of Fig. 1.

There is reasonable evidence that, in the four cases shown, IUE measurements have led to the direct detection of helium-star evolution and that the contraction rates detected are comparable with conservative predictions. No large secular changes have been identified in any other EHes with the exception of the possible expansion of BD+10°2179. The heating rates indicated for HD160641, HD168476, BD–9°4395 and BD−1°3438 are approximately 120, 20, 95 and 33 $\rm Kyr^{-1}$ respectively. The heating rates predicted for a $0.9\,{\rm M}_{\odot}$ helium star with the same $T_{\rm eff}$ are 105, 50, 108 and 30 $\rm Kyr^{-1}$.

## 2. Cyclic variability and pulsations of EHes

In the meantime it had been recognised that many EHes show photometric variability on timescales of hours to weeks and that the most luminous are likely to pulsate (Saio & Jeffery, 1988). Clearly, cyclic changes in flux due to pulsation would be as easy to measure but could mask any secular changes due to evolution. Such cyclic changes

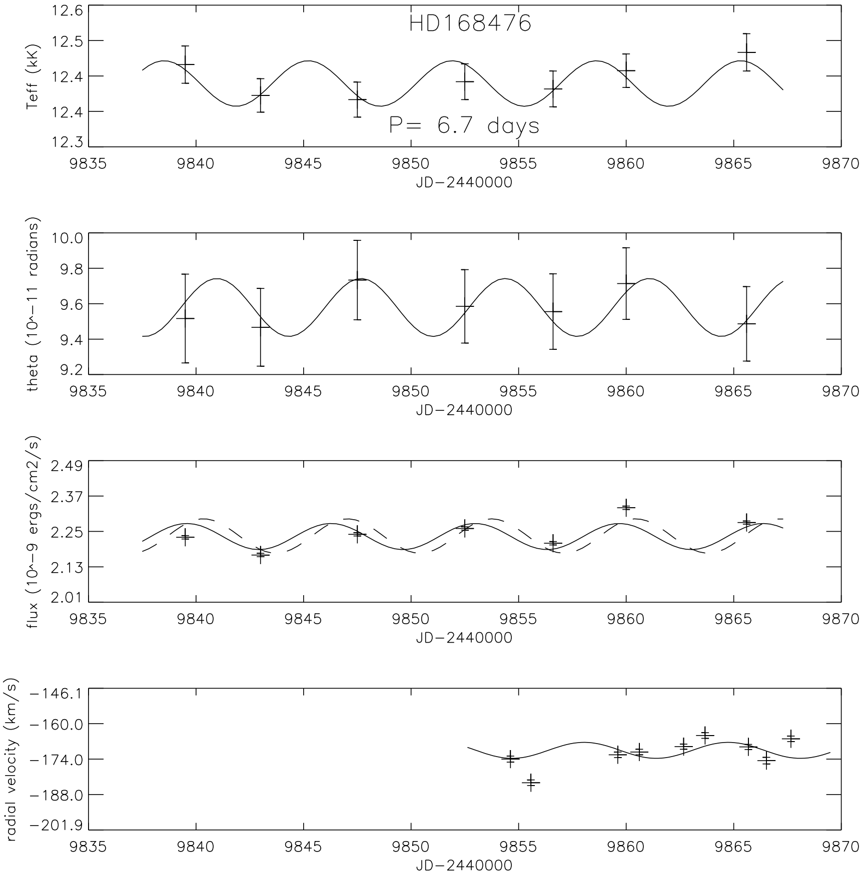

*Figure 2.* Observations of HD168476=PV Tel during a 25 day observing run with IUE and the SAAO 1.9m telescope in 1995. The four panels show the variation of $T_{\rm eff}$, $\theta$, $F_{\rm IUE}$ and radial velocity. Superimposed on each is a best-fit sine curve (solid curves); the period for all four fits is indicated in the top panel. The dashed curve for$F_{\rm IUE}$ represents the product of the fits $\theta^2$ ${T_{\rm eff}}^4$.

would, however, be useful for measuring the temperature and radius variations associated with the pulsation and could, in conjunction with radial velocity measurements, help to ascertain the radius of a pulsating helium star, independent of its distance.

Therefore IUE was used to measure $T_{\rm eff}$ and $\theta$ variations over at least one pulsation cycle of the three most accessible candidates. These were HD168476, BD+1°4381 and LS IV−1°2, which have been reported to show 'periods' of approximately 9, 20 and 11 days respectively. It was also possible to carry out optical spectroscopy nearly simultaneous with the IUE observations, which were obtained during seven shifts in

Table I. Mass estimates (in $\mathrm{M}_\odot$) for PV Tel variables from spectroscopy ($M_{\mathrm{s}}$), pulsation periods ($M_{\mathrm{p}}$) and direct measurement ($M_{\mathrm{d}}$).

| Star | $M_{\mathrm{s}}$ | $M_{\mathrm{p}}$ | $M_{\mathrm{d}}$ |
|---|---|---|---|
| HD168476=PV Tel | 0.95 | 0.85 | 0.94 |
| BD+1°4381=FQ Aqr | 1.09 | 0.93 | 0.07 |
| LS IV–1°2=V2244 Oph$^a$ | 0.66 | 0.94 | 1.99 |
| LS IV–1°2=V2244 Oph$^b$ | 0.78 | 0.94 | 0.79 |

a: log $g = 1.75$ (Pandey et al., 2001)
b: log $g = 1.35$ (Jeffery et al., 2001)

1995 May. Fig. 2 shows the ultraviolet and radial velocity behaviour of HD 168476. Variability is evident in all three targets.

Ascribing a period to the variations is difficult. It is noted that from five years of observations, (Kilkenny et al., 1999) failed to identify a unique period for either BD+1°4381 or BD–1°3438 which persisted for more than one season. It appears that EHe star variations are not regular. In the case of extremely non-adiabatic pulsations anticipated in the highly extended envelopes of luminous helium stars, it may be that the pulsations become highly chaotic. Whatever the long-term properties, it seemed reasonable here to characterise short-term behaviour by a local timescale. We made the simplifying assumption that over the small interval represented by the 1995 data, the variations can be approximated by a sine function with a single period ($\Pi$) and attempted to identify the best-fit sine function for each dataset ( $T_{\mathrm{eff}}$, $\theta$, $F_{\mathrm{IUE}}$ and radial velocity $v$). The adopted solutions are shown for HD 168476 in Fig. 2.

If a star is pulsating radially, the variation in its angular radius $\delta\theta$ is related to the variation in its actual radius $\delta R$ through the relation

$$\frac{\delta R}{R} = \frac{\delta\theta}{\theta}.$$

Since $\delta\theta$ and $\theta$ have already been measured and $\delta R$ may be obtained by integrating the radial velocity, $R$ is immediately available. The luminosity $L$ follows from the mean $T_{\mathrm{eff}}$ and, with a spectroscopic measurement of the surface gravity $g$, the stellar mass $M$ can also be obtained. The results are reasonable for HD168476 and LS IV–1°2, but not for BD+1°4381. This may be because BD+1°4381 is a very cool and highly reddened EHe, so that ultraviolet fluxes are not entirely suitable for measurements of $\theta$.

## 3. EHes and the future of V4334 Sgr

Table I compares mass estimates for three PV Tel variables. Spectroscopy and the core-mass shell-luminosity relation (Jeffery, 1988) provide the spectroscopic mass $M_{\rm s}$. Photometric pulsation 'periods' and linear pulsation theory (Saio & Jeffery, 1988) provide a pulsation mass $M_{\rm p}$. Angular diameter and radial-velocity measurements provide a direct mass $M_{\rm d}$. It cannot be purely coincidence that three different methods lead, in at least two cases, to mass estimates that are in surprisingly good agreement, especially taking the numerous probable sources of error into consideration.

In particular, a coherent picture emerges for the EHe HD 168476 of a 0.9 $\rm M_{\odot}$supergiant with $T_{\rm eff} \sim 12\,500\,{\rm K}$ contracting to become a white dwarf at a current rate of $\sim 20\,{\rm Kyr}^{-1}$. The contraction rate will increase to $\sim 100\,{\rm Kyr}^{-1}$ when $T_{\rm eff} \sim 30\,000\,{\rm K}$ (cf. HD160641). If it is true that RCrBs evolve to become EHes, then the overall timescale for contraction from the RCrB domain to the white dwarf domain is $\sim 10^3$ years. Such timescales are consistent with the contraction rates of shell helium burning giants in quasi-equilibrium predicted by Saio (1988).

In contrast, models for the final-flash evolution of a 0.84 $\rm M_{\odot}$ star suggest that both the expansion and contraction phases could occur on a timescale of $\sim$ 50 years or less (Blöcker & Schönberner, 1997). An even more rapid expansion is indicated for V4334 Sgr, which expanded from white dwarf to red supergiant dimensions in less than five years. Even with a conservative estimate of contraction time $\sim 10\times$ expansion time, the future contraction of V4334 Sgr is likely to be more dramatic than that of EHes. A precedent for similar evolution has been set by V605 Aql which expanded to red-giant dimensions and contracted to $T_{\rm eff} > 50\,000\,{\rm K}$ within five and 70 years respectively (Clayton & de Marco, 1997).

A direct evolutionary connection between V4334 Sgr, RCrBs and EHes appears to be untenable. The question of whether V4334 Sgr will evolve to become an RCrB remains open. However if RCrBs evolve to become EHes, it seems clear that V4334 Sgr could not be an RCrB progenitor.

## 4. Givre, 1908

The background to the slides used in presenting this paper showed a painting by Natalia Sergueevna Gontcharova entitled Givre, 1908. A dozen or so figures are seen travelling along a wooded pathway, but the detail is insufficient to see which way they are travelling. Some are

*Figure 3.* Givre, 1908; Natalia Sergueevna Gontcharova (1881-1962); ©Museum of Russia, St Petersburg. Permission to reproduce this image has been requested.

travelling singly, others in groups. It may be surmised that some share a common origin or a common destination. To one side, two figures appear to be dragging a sack towards the main path. What, one asks, is their relationship to the other travellers?

The painting illustrates the several classes of hydrogen-deficient stars (Jeffery, 1994), observed at the present epoch frozen in their positions on coincident pathways across the Hertzsprung-Russell diagram. There are few clues as to which share a common origin or, in many cases, to which way they are evolving. When a new star, such as V4334 Sgr, forces its way into the picture, extreme caution over comparisons with superficially similar stars should be exercised. In this case, the differences remain more significant than the similarities.

The subtext is that V4334 Sgr and other final-flash products are rapidly evolving and very luminous stars with surface compositions of typically 90% helium and 10% carbon (by number). They may be related to the carbon-strong sequence ( $n_{\rm C} \gtrsim 0.1$) of hydrogen-deficient post-AGB stars (Jeffery, 1994) which includes [WC] central stars of planetary nebulae, such as V605 Aql, and PG1159 stars. However, on the evidence of their evolutionary timescales, they do not appear to be related to the carbon-rich sequence ($n_{\rm C} \sim 0.01$) which includes the RCrB and EHe stars.

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