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HR 4657 – evidence for a thick-disk field blue straggler*

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Abstract. Observational evidence for mass and angular momentum transfer from a companion that is now a white dwarf is presented for the nearby HR 4657 (F5V), a single-lined spectroscopic binary of the Milky Way's thick-disk population. With an orbital period of ~850 days the results support the possible importance of long period, low radial velocity amplitude binaries as a viable mechanism, among others, for the blue-straggler phenomenon.

Key words: stars: fundamental parameters – stars: individual: HR 4657 – stars: blue stragglers – stars: white dwarfs

1. Introduction

HR 4657 (=HD 106516) is among the most metal-poor objects that can be found in the Bright Star Catalogue. Its early registration as a high-velocity star (Keenan & Keller 1953, Roman 1955) and Wallerstein's (1961) ambiguous spectroscopic results gave rise to many subsequent studies of this object (cf. Cayrel de Strobel et al. 1997). In the late eighties, Carney & Latham (1987) announced the status of binarity for HR 4657, followed by detailed orbital parameters in Latham et al. (1992).

In a spectroscopic study of F and G stars of the solar vicinity HR 4657 came to our attention since it has many features of a typical *thick-disk* star, viz., an iron abundance [Fe/H]~ -0.7, an -0.4 dex [Fe/Mg] deficiency and a considerable rotational lag ($V_\odot = -72$ km s^{-1}), whereas evolutionary tracks imply an age less than 8 Gyr, i.e. rather typical for old *thin-disk* stars. Interestingly the star shows also an unexpected high projected rotational velocity, $v\sin i \sim 7$ km s^{-1}, that provokes the suspicion as to whether angular momentum transfer from the unseen companion, that is, from an object that must have later on evolved to a *white dwarf*, might have occurred in the past. Although we have not found any spectroscopic abnormality of s-process elemental abundances, we will show in what follows that HR 4657 possesses a number of compelling characteristics for a *blue straggler*.

* Based on observations at the German Spanish Astronomical Center, Calar Alto, Spain

Table 1. Stellar parameters of HR 4657. ζ_{RT} is the *adopted* value for the radial-tangential macroturbulence. $\mathrm{d_{HIP}}$ and $\mathrm{d_{sp}}$ denote the astrometric (Hipparcos) and spectroscopic distance, respectively

T_{eff}	:	6197	$\pm$	80	[K]
$\log g$	:	4.28	$\pm$	0.10	[cgs]
[Fe/H]	:	-0.74	$\pm$	0.08	
ξ_t	:	1.29	$\pm$	0.20	[km s^{-1}]
[Fe/Mg]	:	-0.44	$\pm$	0.05	
ζ_{RT}	:	5.2			[km s^{-1}]
$v\sin i$	:	6.8	$\pm$	0.9	[km s^{-1}]
V	:	6.108	$\pm$	0.010	[mag]
M_{bol}	:	4.21	$\pm$	0.07	[mag]
BC_V	:	-0.13	$\pm$	0.05	[mag]
Mass	:	0.90	$\pm$	0.05	[$M_\odot$]
Radius	:	1.11	$\pm$	0.05	[$R_\odot$]
$\mathrm{d_{HIP}}$	:	22.55	$\pm$	0.53	[pc]
$\mathrm{d_{sp}}$	:	23.13	$\pm$	3.17	[pc]

2. Observations and basic atmospheric parameters

Two spectra of HR 4657 at $\lambda/\Delta\lambda \sim 60000$ from about 4300 to 9300 Å were obtained in June 1998 at the Calar Alto Observatory with the fiber optics Cassegrain échelle spectrograph FOCES (Pfeiffer et al. 1998). The basic atmospheric parameters are derived in the same manner as described in Fuhrmann (1998), except for the mass and age determinations, which follow the prescriptions in Bernkopf (1998), but also allow for HR 4657's [Fe/α] deficiency. All relevant data are summarized in Table 1 along with the photometric V magnitude (Mermilliod et al. 1997), the absolute bolometric magnitude based on the Hipparcos parallax and the bolometric correction following Alonso et al. (1995), and the astrometric and spectroscopic distance scale. The comparison of the latter shows an excellent agreement (Δd=2.6%) and is thereby a good base for the assumption that the spectra of HR 4657 are not contaminated by the light of the companion.

3. Evidence for a blue straggler

From an ongoing study of nearby F and G stars (cf. Fuhrmann 1998) one of the most important results is that a differentiation between thick-disk and thin-disk stars is fairly well achievable in a two-dimensional presentation of their stellar chemical properties, namely, in a diagram that makes use of iron or magnesium abundances along the abscissa and the corresponding abundance ratio perpendicular to that. With respect to the stars' kinematics, the majority of the thick-disk members is also identifiable from their considerable rotational lag. The most reliable characteristic in classifying a star as a thick-disk or thin-disk member may however come from stellar age-datings, since all our thin-disk stars turn out to be younger than ∼9 Gyr, whereas the thick-disk stars evidently exceed ∼12 Gyr. If then, there is in fact an age gap between the disk populations, HR 4657, on the other hand, is clearly discrepant: its chemical and kinematical properties suggest a thick-disk status, the evolutionary stage however implies an age of ∼7.7 Gyr, typical for old thin-disk stars.

Although it is principally imaginable to identify HR 4657 as a *lately formed* thick-disk star, we consider this possibility as very unlikely. Instead, a better understanding of what we observe may be achieved on the base of the single-lined spectroscopic binary status of HR 4657 and the fact that its projected rotational velocity is remarkably high.

As already mentioned in the preceding section, our spectroscopic analysis of HR 4657 provides no evidence for a signature of the nearby companion, which must be within ∼0.1 arcsec (see below) in the sky. Thus one possibility could be that HR 4657 has a faint M dwarf companion, i.e. both objects evolved completely independent of each other. If so, the evolutionary tracks displayed in Fig. 1 reveal HR 4657 close to its turnoff position with a corresponding age of ∼7.7 Gyr. What is at odds with this picture is HR 4657's high $v\sin i = 6.8$ km s^{-1} for analogous metal-poor dwarfs usually have negligible rotational velocities of only 1-2 km s^{-1}. With reference to Fig. 2, which displays the measured $v\sin i$'s of all our sample stars (those of our recently published analysis, as well as few, yet unpublished, objects), HR 4657 is in a region where the observed $v\sin i$'s may – at first glance – exceed values of, say, ~ 5 km s^{-1}. It is however important to note that all fast rotating stars in Fig. 2 are younger, more massive and more metal-rich compared to HR 4657. That is to say, they have throughout evolved to the left of the dividing line of low and high rotational velocities in Fig. 2. HR 4657, on the other hand, starts its track some ∼200 K *below* its actual effective temperature (cf. Fig. 1) in a region where convectively induced magnetic-dynamo braking is expected to be at work, and, most important, HR 4657 must have been in this region for several Gyr. Thus, if we prefer to designate HR 4657 as a thin-disk member and accept the young age of less than 8 Gyr, we have to explain the high rotational velocity, the low iron-to-magnesium ratio, and the high space velocities ($U_\odot/V_\odot/W_\odot = +53/-72/-61$ km s^{-1}).

Alternatively, HR 4657 may be considered as the secondary of an old (>12 Gyr) binary system, where the primary had started with $\sim 1\ M_\odot$, and, after a few billion years, evolved to a white dwarf. This scenario has several appealing features, since in this case we may expect a certain amount of mass and angular momentum transfer, which, in principle, dovetails with the prolonged turnoff stage and the high rotational velocity, respectively. Thus, we suggest the identification of HR 4657 as a field *blue straggler*, i.e. as an object whose position in the *Kiel diagram* is bluer than the turnoff point of the thick-disk population, which – according to Fig. 1 – is close to ~ 6000 K for ∼12 Gyr old stars at [Fe/H]$= -0.74$ and [Fe/Mg]$= -0.4$.

According to the work of Latham et al. (1992), HR 4657 is a single-lined spectroscopic binary with orbital parameters, $e = 0.046 \pm 0.029$, $K = 7.87 \pm 0.24$ km s^{-1}, $P = 853.2 \pm 8.2$ days, and $a_1 \sin i = 92.3 \pm 2.9 \times 10^6$ km. With our values for the stellar

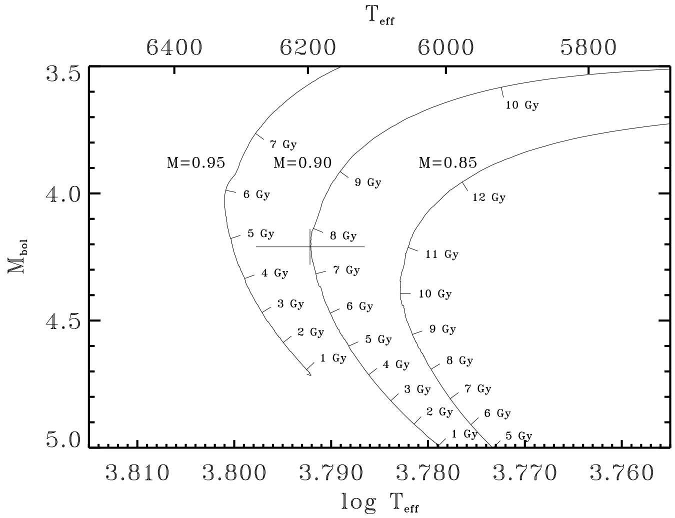

Fig. 1. Evolutionary tracks for a stellar metallicity [Fe/H]$= -0.74$, [Fe/Mg]$= -0.4$, and $M_\star = 0.95$, 0.90 and 0.85 $M_\odot$. Tick marks are given in steps of 1 Gyr. The mass and putative age for HR 4657 are found to be 0.90 $M_\odot$ and 7.7 Gyr, respectively. For an age of 12 Gyr, which may represent the *minimum* value for thick-disk stars, the turnoff is given at $\sim$ 6000 K, i.e. HR 4657's position is too *blue* by no less than 200 K

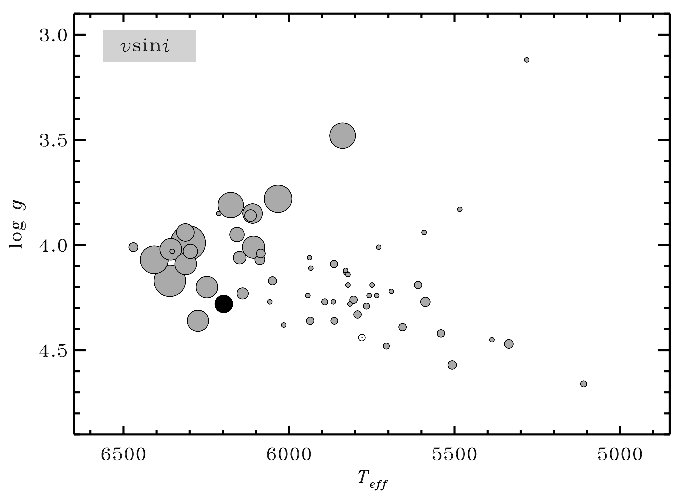

Fig. 2. Distribution of the projected rotational velocities of the sample of nearby F and G stars of Fuhrmann (1998), updated, and supplemented by some recently, yet unpublished, stars in the T_{eff}-log g *Kiel diagram*. Circle diameters are in proportion to the derived $v\sin i$, the largest circle corresponds to $v\sin i \sim 18$ km s^{-1}. The position of HR 4657 is depicted with a black circle

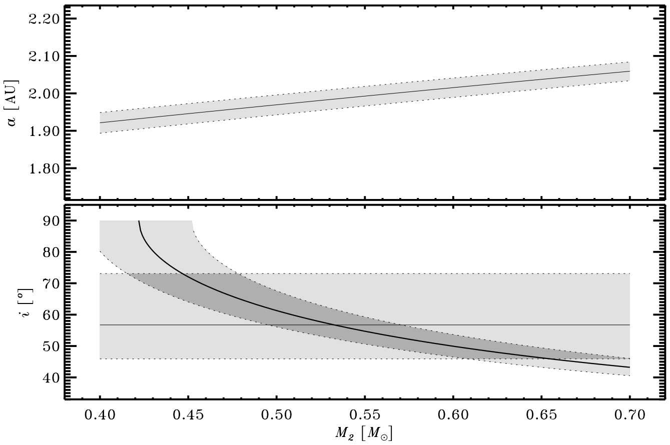

Fig. 3. Semi-major axis (*top*) and inclination angle (*bottom*) as a function of M_2, the mass of the putative white dwarf. In the lower panel the horizontal line denotes the equatorial inclination of HR 4657, whereas the thick curve is valid for the inclination of the orbital plane (dotted lines indicate calculated uncertainties of both quantities). In the very likely case of approximate coplanarity, a mass of $M_2 \sim 0.53\ M_\odot$ is read off

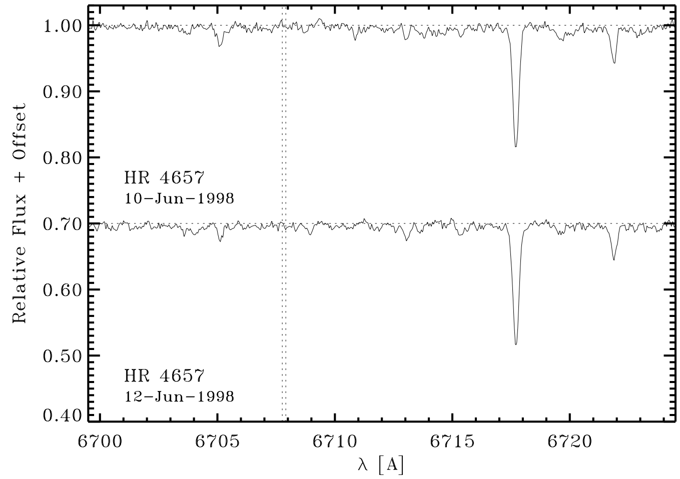

Fig. 4. Two spectra of HR 4657 in the region of the lithium resonance doublet $\lambda\lambda$6707.76/.91. As with the light element beryllium in the work of Molaro et al. (1997), there are no detectable absorption features at the indicated positions (vertical lines)

mass $M_1 = 0.90\ M_\odot$, the radius $R_1 = 1.11\ R_\odot$, the projected rotational velocity $v\sin i = 6.8$ km s^{-1}, and a mean rotation period $< P >= 6.91$ days, inferred from the modulation of chromospheric Ca II H and K fluxes (Donahue et al. 1996), we get – as a function of the mass of the unseen companion M_2 – the results displayed in Fig. 3. The data in the upper panel clearly restrict the current semi-major axis close to $\sim$2 AU (although a considerably reduced separation is also conceivable for the initial orbit). Thus, near the tip of the red giant branch the primary could have been sufficiently distended (cf. VandenBerg 1992) for mass and angular momentum transfer to take place. As a result, the stream of material might have created an orbiting disk around HR 4657, or could have been carried into the star by direct-impact accretion. Whatever flow mechanism actually occurred and whether the binary system was indeed semi-detached or not can, of course, not be stated with certainty. We content ourselves, instead, mentioning two points: first, the low eccentricity of HR 4657 may be a hint for orbit circularization as it is frequently observed in semi-detached binaries. On the other hand, and second, it is nevertheless also true that, in principle, a mere $\sim 0.07\ M_\odot$ suffices to explain HR 4657's age discrepancy (cf. Fig. 1), and this may as well be achieved even for *detached* systems via wind accretion as has been discussed in Boffin & Jorissen (1988).

The lower panel of Fig. 3 displays the data valid for the equatorial (horizontal line) and orbital inclination (thick curve). In the very likely case of approximate coplanarity (cf. Hale 1994) the intersection of both curves provides an estimate for M_2, the expected mass of the white dwarf, and shows indeed an excellent agreement with contemporary predictions from white dwarf evolutionary sequences (e.g. Salaris et al. 1997).

A good confirmation of the white dwarf + blue straggler scenario would be an observable enhancement of s-process elements in the photosphere of HR 4657. We have searched for a signature from Y II, Zr II, and Ba II lines, but in a differential comparison to adjacent thick-disk stars in the [Mg/H]-[Fe/Mg] abundance plane, such as HD 22879, HD 30649, HD 62301, HD 69611, HD 102158, HD 114762, HD 184499 and HD 204155, we were unable to find any striking abundance patterns. Recall however, that only a small amount of mass transfer is actually required for HR 4657, and this could conceivably be unaccompanied by neutron-capture elements (see Norris et al. 1997, p.377, for a more detailed discussion on this point). In addition the possibility exists that HR 4657's enhanced rotation rate induces considerable mixing of material to deep stellar layers as suggested by the observed depletion of lithium (Fig. 4) and beryllium (cf. Molaro et al. 1997, their Fig. 3). With respect to the latter observation it is interesting to note that lithium is also deficient in other field and cluster blue stragglers (Hobbs & Mathieu 1991, Pritchet & Glaspey 1991, Glaspey et al. 1994). This appears to be a general phenomenon among these objects and has been interpreted as being indicative of mass transfer across binaries as well. Thus, whichever the exact reason for the observed lithium and beryllium depletion on HR 4657 is, both, mass transfer as a primary cause or the high spin angular momentum as a "secondary" effect of binary interaction support the suggested blue straggler status.

Another indication of a white dwarf around HR 4657 could be an observable soft X-ray flux. In a sample of 86 metal-poor binary systems, Ottmann et al. (1997) analyzed *ROSAT* data from which they detected 13 X-ray sources. Interestingly, HR 4657 is among these objects, which may be explained with a coronal activity, a white dwarf companion, or even a combination of both. Insofar as the first possibility is concerned, HR 4657 is indeed known to exhibit some chromospheric activity (e.g. Noyes et al. 1984, Baliunas et al. 1995), which may well imply the existence of a corona. According to Shibata et al. (1997) the flux and spectrum observed with *ASCA* are consistent with those for an F-type star. The relatively low X-ray luminosity as well as the low hardness ratio (Ottmann et al. 1997, Hünsch et al. 1998, Shibata et al. 1997), however, are also suggestive of an accompanying white dwarf (cf. Fleming et al. 1996), a possibility that Shibata et al. obviously were not aware of. The then-existing absence of spectral signatures on low dispersion *IUE* data shortward of 1700 Å requires a cooling time of no less than ∼1 Gyr.

As a final item, we like to comment on the search for the source of GRB 930131, an intense gamma-ray burst observed in January 1993 on-board the *CGRO*. Shibata et al. (1997, and references therein) clearly demonstrate that HR 4657 is the best optical counterpart in terms of its position in the sky. The observed burst luminosity of $\sim 10^{36}$ erg s^{-1} is nevertheless very unlikely to originate from a normal F-type star. A white dwarf companion around HR 4657 certainly presents a more promising explanation. Future interferometric measurements might substantiate this assessment.

4. Conclusions

We have presented observational evidence for a thick-disk field blue straggler status of HR 4657, a single-lined spectroscopic binary ($P = 853.2$ days, $K = 7.87$ km s^{-1}) of the solar neighborhood. Among the various suggestions for the blue-straggler phenomenon that exist in the literature (e.g. Leonard 1989, Stryker 1993) our results for HR 4657 thus bring grist to the mill of those who favour the binary hypothesis and explain the lack of detections from radial velocity surveys with the long orbital periods and low radial velocity amplitudes (< 10 km s^{-1}) involved (cf. Collier & Jenkins 1984).

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