CALCULATING THE MASS OF HORIZONTAL-BRANCH STARS WITH HIPPARCOS

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ABSTRACT

Horizontal-branch stars in globular clusters turned out to have a mass of $\simeq$0.4 $M_\odot$, which followed from $T_{\rm eff}$ and log g (as derived from photometry, Balmer line spectroscopy plus Balmer profile models), the luminosity of these stars from UV + visual spectrophotometry, and the distance to the globular cluster. Such a mass value is in contradiction with values from the theory of evolution of stars.

Hipparcos parallaxes to a few field-HB stars have been used to do the same analysis. The input data are $T_{\rm eff}$ and log g from the literature, the luminosity from IUE + visual spectrophotometry, and the Hipparcos distance. Here the mean of the masses is found to be $M_{\rm HB} = 0.38 \pm 0.07$ $M_\odot$.

The masses determined for globular cluster HB stars and for field HB stars agree with each other, but deviate from stellar evolution theory. The cause for the discrepancy is discussed. The most likely cause is problems with the determination of the gravity from the comparison with theoretical Balmer profiles. An unlikely increase of the distance to the globular cluster by 0.4 mag would bring the mass of its HB-stars up to 0.6 $M_\odot$. However, the mass of the field HB stars stays fixed at 0.38 $M_\odot$, based on the Hipparcos parallaxes.

Key words: horizontal-branch stars; stellar mass; globular clusters; Cepheids.

1. BASIC STELLAR PARAMETERS

The basic parameters describing a star are mass M, luminosity L, radius R, surface temperature $T_{\rm eff}$, and surface gravity $\log g$. These parameters can be derived in various ways.

Temperature $T_{\rm eff}$.
• From a spectral index. The temperature of the stellar surface can be derived from the slope of the spectral energy distribution in a well choosen wavelength range.
• From the overall spectral distribution based on accurate model atmosphere calculations. For the hotter stars this possibility exists only since the availability of UV spectrophotometric capabilities (namely the IUE satellite).

Surface gravity, $\log g$. The gravity at the surface of the star (in the layer with optical depth $\tau = 1$) is notoriously difficult to determine.
• The continuum spectral energy distribution depends somewhat on $\log g$, but not in a decisive way. Fitting model continua gives only crude values for $\log g$, and the $\log g$ values depend then strongly on the quality of the model.
• The Balmer lines are formed near the surface of the star and the standard method is to compare the observed shapes of the Balmer lines with Balmer profiles calculated with models. Normally, a range of $T_{\rm eff}$ and $\log g$ will fit well to a given profile. Therefore, the spectro-photometrically derived $T_{\rm eff}$ is used to fix $\log g$.

Luminosity, $L_{\rm HB}$. The apparent luminosity (or the integral over the observed spectrum) $l_{\rm HB}$, can be obtained from spectrophotometry covering at least the maximum of the spectral energy distribution (for HB stars the visual and the UV). If the distance is known, $l_{\rm HB}$ can be translated to the value of $L_{\rm HB}$.

Radius, R. No direct access to radii of HB stars is possible. Radii follow from the equations when the other parameters have been determined, or radii follow from models, given a sufficient set of observationally determined surface parameters.

Mass, $M_{\rm HB}$.
• The mass can be 'measured', only if the HB star is part of a binary, of which then all further parameters must be known.
• The mass can be *calculated* once the other relevant parameters have been determined. The formalism is given in the equations below. It requires, however, that the distance to the star is known since the calculation is based on the luminosity $L_{\rm HB}$.
• The mass may follow from a comparison with models for HB stars. This comparison uses the location in the $T_{\rm eff}$ versus $\log g$ diagram. Such determinations are not unique, since evolution of HB stars follows tracks which may intersect in the mentioned parameter space.
• Evolution theory predicts that a HB-like star has a Helium core of about 0.5 $M_\odot$, surrounded by a Hydrogen envelope of up to 0.9 $M_\odot$, but which may also be vanishingly thin.

Table 1. Field Horizontal Branch stars: Hipparcos parallaxes and distances.

Name	V	$B-V$	A_V	π (mas)	σ_π (mas)	d (pc)	$d_{\rm max}, d_{\rm min}$ (pc)	M_V	ΔM_V
HD 86986	7.99	+0.12	0.09	3.78	0.95	265	355,210	+0.79	0.55
HD 109995	7.62	+0.04	0.00	4.92	0.89	205	250,170	+1.08	0.40
HD 130095	8.13	+0.08	0.31	5.91	1.08	170	205,145	+1.68	0.40
HD 139961	8.85	+0.10	0.31	4.50	1.19	220	300,175	+1.81	0.60
HD 161817	6.96	+0.16	0.06	5.81	0.65	170	195,155	+0.72	0.25

ΔM_V given is due to the uncertainty in the parallax only.

Table 2. HB star parameters.

Name	log $l_{\rm HB}$[a] (cgs)	log $L_{\rm HB}$ ($L_\odot$)	$T_{\rm eff}$[b] (K)	$\log g$[b] (cgs)	Δ log[c] $g/T_{\rm eff}{}^4$	log $M_{\rm HB}$	Δ log $M_{\rm HB}$	$M_{\rm HB}$ ($M_\odot$)
HD 86986	−7.768	1.57	7900	3.1	0.10	−0.32	0.32	0.48
HD 109995	−7.666	1.45	8300	3.15	0.20	−0.44	0.36	0.37
HD 130095	−7.679	1.28	8800	3.4	0.15	−0.49	0.31	0.32
HD 139961	−7.788	1.39	8750	3.3	0.20	−0.48	0.44	0.33
HD 161817	−7.402	1.58	7500	2.95	0.05	−0.37	0.15	0.42

[a] $l_{\rm HB}=\int I_\lambda d\lambda$ from IUE and scanner data.
[b] $T_{\rm eff}$ and $\log g$ are best values from the literature.
[c] Δ log $(g/T_{\rm eff}{}^4)$ is total error of the product of g and $T_{\rm eff}$.
For details see de Boer et al. (1997a).

2. INTERRELATIONS

The parameters describing the surface of a star (in relation to the Sun) are given by the following equations:

$$\log\left(\frac{g_{\rm HB}}{g_\odot}\right) = \log\left(\frac{M_{\rm HB}}{M_\odot}\right) - 2\log\left(\frac{R_{\rm HB}}{R_\odot}\right) \quad (1)$$

$$\log\left(\frac{L_{\rm HB}}{L_\odot}\right) = 2\log\left(\frac{R_{\rm HB}}{R_\odot}\right) + 4\log\left(\frac{T_{\rm HB}}{T_\odot}\right) \quad (2)$$

It is possible to eliminate the radius, so that the combined equation has only the mass, the temperature and gravity, and the luminosity as variables. Thus:

$$\log\left(\frac{M_{\rm HB}}{M_\odot}\right) =$$

$$\log g_{\rm HB} - 4\log T_{\rm HB} + \log l_{\rm HB} + 2\log d + 15.11 \quad (3)$$

where $l_{\rm HB}$ is the integral of the extinction corrected spectral energy distribution as measured at the Earth, $\int I_\lambda d\lambda$, and d is the distance of the star in pc (the parallax $\pi = 1/d$, with π in arcsec). The numerical constant is determined as:

$$\log 4\pi + 2\log(3.09\times10^{18}) - \log L_\odot + 4\log T_\odot - \log g_\odot = 15.11$$

with solar values $L_\odot = 3.85\times10^{33}$ erg s^{-1}, $T_\odot = 5800$ K, and log $g_\odot = 4.44$ in cgs units. It is Equation 3 which can be used in connection with the various observationally determined parameters to calculate the mass of the stars.

3. ABSOLUTE MAGNITUDES

Parallaxes for field HB stars from the Hipparcos Input Catalogue (Turon et al. 1992) as determined by Hipparcos (ESA 1997) have been used to calculate the absolute magnitudes for the field stars de Boer et al. (1997a). A subset of the data is discussed here and presented in Table 1. Figure 1 shows that the values of M_V spread around the location of the theoretically determined horizontal branch.

The observed absolute magnitudes fit well to the theoretical location of the Zero Age HB from models (see Figure 1). Note that the red HB appears from the Hipparcos field stars at $M_V \simeq +1$ mag.

4. MASS DETERMINATIONS

The programme of investigations of the core Helium burning sdB and HB stars carried out in Bonn aims not only at characterising the stars, but also at investigating the spatial distribution in the galaxy, including the determination of the orbits (de Boer et al. 1988, Moehler et al. 1990, Theissen et al. 1993, Theissen et al. 1995, Schmidt et al. 1997, Colin et al. 1994, de Boer et al. 1997b). In the course of the project it was realised that a verification of the mass of the HB stars was urgently needed.

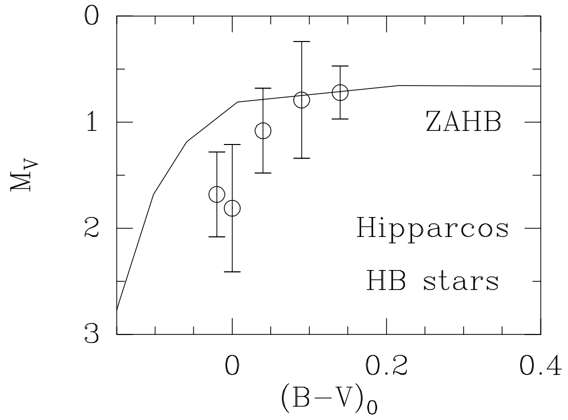

Figure 1. The absolute magnitude of the field HB stars from de Boer et al. (1997a) is presented together with the theoretical HB ([Fe/H]=−1.03, Y_{HB}=0.252) from Dorman (1992).

5. MASS OF FIELD STARS USING HIPPARCOS PARALLAXES

The mass for the field HB stars can now be calculated using the relations given above. They are plotted in Figure 2. For that, further parameters for these stars have been taken from the literature. The relevant parameters and the results are given in Table 2.

For these field HB stars, which have temperatures in the range of $7500 < T_{\rm eff} < 8800$ K, the numeric average of the individual values for the masses is 0.38 ±0.07 $M_\odot$. Note that the uncertainty in each individual value is large.

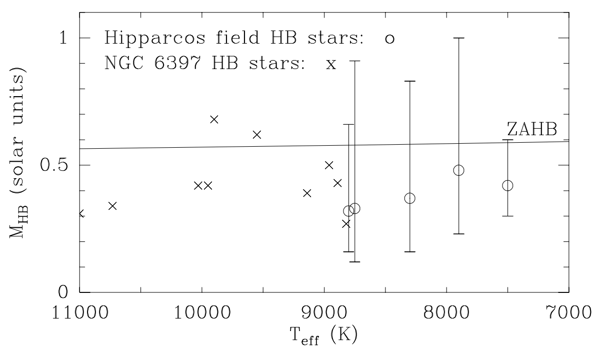

Figure 2. The mass of the field HB stars is plotted against temperature (from de Boer et al. 1997a), together with the theoretical HB (from Dorman 1992). The numeric average of the individual values is 0.38 $M_\odot$. The crosses represent the mass for some of the HB stars investigated in NGC 6397 (de Boer et al. 1995).

6. MASS OF GLOBULAR CLUSTER STARS

The investigations of HB-like stars in clusters is available from several studies (see Table 3). The trend is that the hot stars come out with masses in line with models for the sdB stars, the cool stars come out with masses clearly below the expected values. However, pAGB stars (de Boer 1985) have masses of $\simeq 0.5$ $M_\odot$ (de Boer 1987).

The value for the mass of the cluster HB stars is completely in line with the results for the field horizontal-branch stars. This must mean two things: (a) the cluster stars and the field stars behave in a very similar manner, in spite of possible differences in, e.g., age, original mass, or original metallicity; and (b) the problem with the masses lies in aspects of the analysis of the data.

7. IS THE GRAVITY DETERMINATION AT FAULT?

Of the data involved in the full parameterisation of HB stars according to Equation 3, the temperature and the integrated spectral intensity are all quite accurate. The uncertainty of the distance is solely based on the uncertainty in the parallax. The mass of the stars, which follows if the gravity is fixed, is supposed to come out in line with evolutionary expectations. HB stars are thought to have a mass ranging from 0.5 (for hot stars) to about 0.6 for HBA stars near $T_{\rm eff} = 7500$ K.

From both the field stars with temperatures between 7500 and 9000 K and the cluster stars with temperatures between 10 000 and 20 000 K the determined masses are $M_{\rm HB} \simeq 0.4$ $M_\odot$. The only way to solve this discrepancy is to admit that the gravities from spectroscopic analysis are too small (see also de Boer et al. 1995).

Taking the argument in the other direction, if one assumes the mass of the HB stars is 0.50 to 0.60 $M_\odot$ indeed (post AGB stars in globular clusters have masses between 0.54 and 0.56 $M_\odot$; de Boer 1987), then the data for the field HB stars and the stars in NGC 6397 can be brought to consistency *if the logarithmic gravities of the HB stars are made larger by 0.2.*

8. PROBLEMS WITH ATMOSPHERE MODELS?

In studies of hot Population I stars one has noted that the masses derived from spectroscopic data come out smaller than those expected from other lines of argument. Recently Lanz et al. (1996) argue, that the gravities may be at fault. They show that if one does *not* use fully blanketed non-LTE models for the calculation of the shape of the Balmer profiles, the spectroscopically derived gravities come out too small and in consequence the calculated masses are too small as well. With the HB stars we have tried to make clear that too small masses are found when spectroscopic gravities are used.

Table 3. Masses derived for globular cluster horizontal branch stars.

Cluster	d (kpc)	range of $T_{\rm eff}$	mass (K)	ref. ($M_\odot$)
M 15	10.0	20000 – 30000	0.7:	Moehler et al. 1995
		10000 – 20000	0.3:	
NGC 6397	2.0	8000 – 12000	0.39 ± 0.05	de Boer et al. 1995
NGC 6752	4.0	25000 – 30000	0.50 ± 0.04	Moehler et al. 1997
		12000 – 20000	0.30 ± 0.06	

Non-LTE fully blanketed models have to be applied to the conditions of HB star atmospheres to investigate if they lead to different Balmer profiles such that gravities and thus mass values arrived at in spectroscopic analyses are more in line with masses from evolution theory.

9. CONSEQUENCES OF A REVISED GLOBULAR CLUSTER DISTANCE SCALE

Feast & Catchpole (1997) have suggested that the period–luminosity relation for Cepheids has to be changed compared to the one of Caldwell & Laney (1991). The consequence would be, that the LMC is farther away by 10 per cent, that its RR Lyrae are farther away, and that the globular clusters are farther away. In consequence, the globular cluster NGC 6397 would be farther away, making the luminosities of its HB stars larger by a factor 1.2. Inserting this in the mass determination the mass of those stars becomes 20 per cent larger. With this change, the HB star masses in NGC 6397 now become different from those in the field, the latter being based directly on Hipparcos parallaxes, all other parameters being based on identical analysis methods.

The change of the distance scale by Feast & Catchpole thus leads to a discrepancy within the research of HB stars. We feel this is an additional argument against the proposed period–luminosity revision.

10. CONCLUSIONS

The ongoing in-depth studies of samples of horizontal-branch like stars have confirmed existing ideas of evolution in some respects, but have uncovered discrepancies in other respects. The low masses found for stars with $T_{\rm eff}$ between roughly 10^4 and 2×10^4 K point at problems with the gravities derived from spectroscopy. However, field HB stars and cluster HB stars behave identically. Adopting a revised P/L scale increases the number of problems in the field of HB star research.

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