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Empirical Absolute Magnitudes, Luminosities and Effective Temperatures of SPB Variables and the Problem of Variability Classification of Monoperiodic Stars

by

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ABSTRACT

We derive semi–empirical $\log L/L_\odot$ for 27 stars classified as SPB on the basis of Hipparcos photometry and we plot these stars on the $\log T_{\rm eff}-\log L/L_\odot$ diagram. We confirm pulsations of HIP 63210 and HIP 108348 and show that luminosities and masses derived from photometry are of limited use for asteroseismology.

For HIP 69174 and 77227, two SB2 systems with an SPB primary, we compute the age of the systems, the orbital inclination – i, the large semi-axis – a, and the masses, radii, $\log T_{\rm eff}$, $\log g$ and $\log L/L_\odot$ of the components.

We discover five new multiperiodic stars classified in the literature as SPB, namely, HIP 5161, 20963, 26243, 26464 and 44996. One of these stars, HIP 26243, shows periods on the time-scales of days and hours.

Finally, we discuss classification of monoperiodic SPBs and show that photometry combined with evolutionary models can be helpful in preselecting tentative pulsators.

Key words: *Stars: early-type – Stars: oscillations – Stars: fundamental parameters*

1. Introduction

Slowly pulsating B stars (SPB) are pulsators having spectral type in the range from B3 to B9 and periods of the order of one day. They were discovered as a separate class of variable stars by Waelkens and Rufener (1985). There are about 120 stars classified as SPB, a majority discovered by the Hipparcos satellite (ESA 1997). For 70 of these stars, Waelkens *et al.* (1998) and Aerts *et al.* (1999) derived $\log T_{\rm eff}$ and $\log L/L_\odot$ from Geneva photometry. A more detailed study of 29 selected SPBs was performed by Aerts *et al.* (1999) and Mathias *et al.* (2001). These authors confirmed that most of the 29 stars are pulsators, but showed also that more than 50% are SB1 or SB2 systems and that several are in fact chemically peculiar (CP) or ellipsoidal (Ell) variables. The high percentage of SB systems and the presence of CP and Ell variables among the stars classified as SPB confirmed the suspicion of Molenda-Żakowicz (2000) that Waelkens' *et al.* (1998) classification was premature.

In this paper, we analyze stars classified as SPB in the Hipparcos Catalogue or by Waelkens *et al.* (1998). In Section 2 we use Hipparcos parallaxes to derive absolute magnitudes and semi-empirical luminosities for 27 of these stars. Then we use these luminosities and evolutionary models of Schaller *et al.* (1992) and Schaerer *et al.* (1993), computed for $Z = 0.02$ and 0.008, respectively, to derive evolutionary masses of these stars. In Section 3, we focus on two SB2 systems, HIP 69174 and 77227, for which we compute orbital inclination, separation of the components, age, masses, radii, $\log T_{\rm eff}$, $\log L/{\rm L}_\odot$ and $\log g$ for both components. In the last Section, we discuss classification of monoperiodic SPBs.

2. Luminosities

Using Hipparcos parallaxes, the V magnitudes and reddening corrections computed with the use of the UVBYBETA code (see below), we calculated absolute visual magnitudes for 27 stars classified as SPB for which the Lutz–Kelker correction for M_V can be applied, *i.e.,* stars for which the ratio σ_π/π is less than 0.175 (Lutz and Kelker 1973). Then, we derived luminosities of these stars according to the formula

$$\log L/{\rm L}_\odot = -0.4(M_V + BC - {\rm M}_{\odot,{\rm bol}}), \quad (1)$$

adopting the solar absolute bolometric magnitude, ${\rm M}_{\odot,{\rm bol}}$, as equal to 4.75 mag and computing the bolometric corrections, BC, from c_0 indices. We used the calibration of Davis and Shobbrook (1977) which is based on the scale of Code *et al.* (1976). Thus, our bolometric corrections are not obtained from integrated flux measured individually for each star. We cannot therefore refer to our luminosities as "empirical". We shall use the adjective "semi–empirical".

We list the HIP numbers of the 27 stars in the first column of Table 1. In the next two columns, we list $\log T_{\rm eff}$ and $\log g$, computed from the mean Strömgren indices of Hauck and Mermilliod (1990) or Grønbech and Olsen (1976) by means of the calibration of Napiwotzki *et al.* (1993) and the UVBYBETA code kindly provided by Dr. Napiwotzki. In the fourth column, we list the semi-empirical $\log L/{\rm L}_\odot$ with sigmas computed from σ_π given in the Hipparcos Catalogue and $\sigma_{\rm BC}$ listed by Code *et al.* (1976). In the fifth and sixth columns, we list evolutionary $M/{\rm M}_\odot$ derived from the semi-empirical $\log L/{\rm L}_\odot$, the photometric $\log T_{\rm eff}$ and the evolutionary models of Schaerer *et al.* (1993) or Schaller *et al.* (1992). We used the models computed for $Z = 0.008$ to be consistent with Niemczura (2003) who showed that the mean metallicity of SPBs is equal to $Z \simeq 0.01$. The models computed for $Z = 0.02$ were used by us for a comparison of our results with those obtained by Aerts *et al.* (1999) and Mathias *et al.* (2001). For the SB2 systems

Table 1

Parameters of the sample

HIP	$\log T_{\rm eff}$	$\log g$	$\log L/{\rm L}_{\odot}$	$M/{\rm M}_{\odot}$ (Z=0.008)	$M/{\rm M}_{\odot}$ (Z=0.02)	
19398	4.196	3.99	3.195±0.23	5.42±0.76$^{(1)}$	5.65±0.75$^{(1)}$	SPB
				5.20±0.80$^{(3)}$		
20493	4.109	4.12	2.431±0.11	3.49±0.22	3.72±0.23	
34817	4.224	4.26	3.233±0.24	5.67±0.81	5.92±0.77	
38455	4.265	4.06	3.462±0.11	6.61±0.49	6.84±0.49	Ell
40285	4.203	3.44	3.578±0.21	6.53±0.96$^{(3)}$	6.54±0.59$^{(3)}$	Ell
42726	4.220	4.10	2.956±0.07	4.94±0.28	5.26±0.29	SPB
43763	4.174	4.37	2.872±0.14	4.53±0.38	4.79±0.35	
45189	4.152	4.09	2.832±0.14	4.37±0.37	4.60±0.35	
48782	4.222	3.92	3.340±0.22	5.97±0.79$^{(1)}$	6.19±0.77$^{(1)}$	
				5.73±0.82$^{(3)}$		
59173	4.256	4.23	2.980±0.09	5.30±0.35	5.65±0.36	
61199	4.211	4.07	2.976±0.06	4.93±0.26	5.22±0.26	
63210	4.090	4.46	2.594±0.11	3.72±0.24$^{(1)}$	3.93±0.25$^{(1)}$	
				5.56±0.25$^{(3)}$		
67973	4.082	4.36	2.024±0.07	2.85±0.12	3.10±0.13	
69174	4.078	4.17	2.347±0.12	3.30±0.22*	3.52±0.23*	SPB
76243	4.152	4.17	2.472±0.10	3.71±0.21	4.00±0.22	SPB
77227	4.152	4.30	2.576±0.09	3.99±0.24*	4.21±0.22*	SPB
79992	4.177	3.93	2.894±0.06	4.59±0.22	4.59±0.22	SPB
86414	4.243	3.83	3.487±0.09	6.54±0.42$^{(1)}$	6.76±0.40$^{(1)}$	SPB
				6.31±0.39$^{(3)}$		
90797	4.104	3.59	2.808±0.11		4.38±0.28$^{(1)}$	Ell
				4.01±0.28$^{(3)}$	4.17±0.26$^{(3)}$	
93210	4.257	4.42	2.981±0.16	5.31±0.50	5.66±0.50	
95159	4.172	4.10	2.795±0.23	4.37±0.55	4.62±0.53	SPB
95260	4.157	4.24	2.561±0.09	3.87±0.21	4.16±0.21	SPB
107173	4.150	3.97	2.785±0.23	4.25±0.58	4.50±0.55	SPB
108022	4.232	3.95	2.969±0.12	5.06±0.39	5.38±0.40	SPB
108348	4.117	4.13	2.876±0.21		4.57±0.50$^{(1)}$	
				4.19±0.54$^{(3)}$	4.33±0.50$^{(3)}$	
110408	4.179	4.13	2.738±0.15	4.29±0.38	4.57±0.37	
112781	4.150	3.93	2.515±0.07	3.77±0.17	4.04±0.18	SPB

Notes: In the case of HIP 69174 and 77227, asterisks indicate the mass of the primary component (SPB). Masses derived for the core and shell hydrogen burning phases are labeled with (1) and (3), respectively.

HIP 69174 and 77227 we list the mass of the SPB primary derived in Section 3. For each of the two stars we denote the mass with an asterisk. For stars which, depending on their mass, may lie on the Main Sequence or may have already crossed

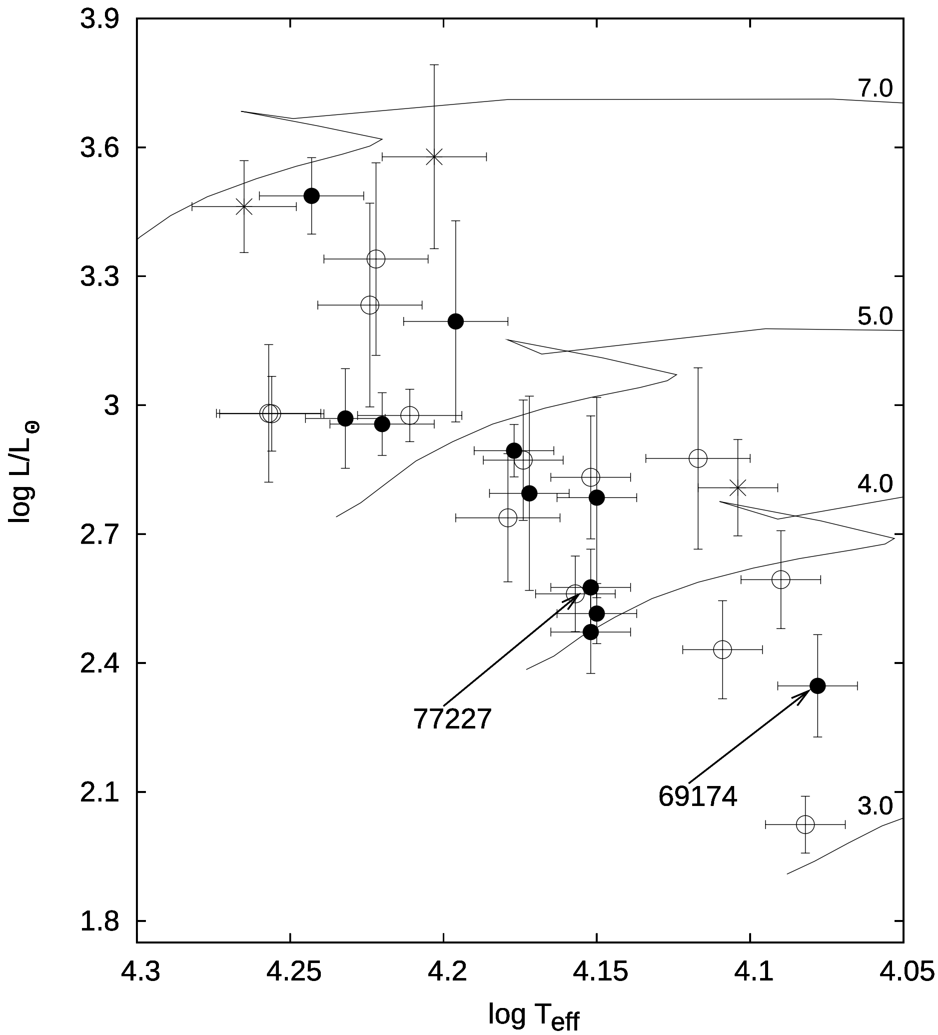

Fig. 1. The $\log T_{\rm eff} - \log L/{\rm L}_{\odot}$ diagram for stars from Table 1. Confirmed SPBs are plotted with dots, Ell stars – with crosses, unconfirmed SPBs – as open circles. The evolutionary tracks computed for $Z = 0.02$, and for 3, 4, 5, and 7 $M_{\odot}$, indicated at the right-hand end of each track, are adopted from Schaller *et al.* (1992).

TAMS, we list the mass for the core hydrogen burning phase labeled with (1) and the shell hydrogen burning phase labeled with (3). In the last column, we indicate stars which are confirmed to be SPB or Ell by Haefner (1982) (HIP 38455), Waelkens (1991) (HIP 42726, 69174 and 95159), Aerts *et al.* (1999) (HIP 19398, 40285, 76243, 77227, 90797 and 112781), Chapellier *et al.* (2000) (HIP 86414), Mathias *et al.* (2001) (HIP 95260, 107173 and 108022) or Briquet *et al.* (2003) (HIP 79992).

In Fig. 1, we plot the stars on the $\log T_{\rm eff} - \log L/{\rm L}_{\odot}$ diagram together with the evolutionary tracks for 3, 4, 5 and 7 $M_{\odot}$ and $Z = 0.02$, adopted from Schaller *et*

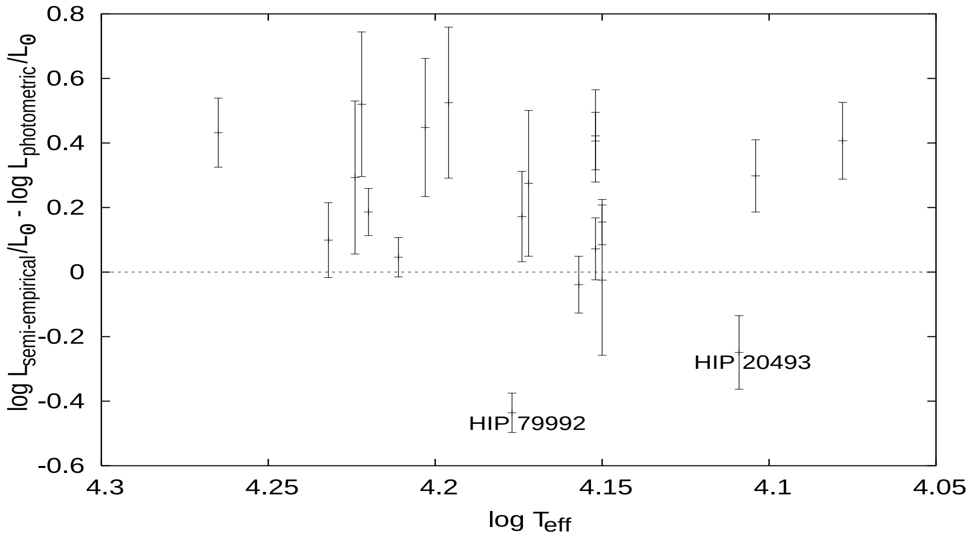

Fig. 2. $\log L_{\rm semi-empirical}/{\rm L}_\odot - \log L_{\rm photometric}/{\rm L}_\odot$ computed for 27 stars from Table 1 and plotted as a function of $\log T_{\rm eff}$ derived from Strömgren photometry. Stars labeled with HIP numbers are discussed in the text.

al. (1992). In Fig. 1 we denote confirmed SPBs with dots, confirmed Ell stars with crosses and stars classified as SPB on the basis of Hipparcos photometry alone, with open circles. Arrows indicate HIP 69174 and HIP 77227, two SB2 systems in which the primary components are SPBs. Plotting error bars of $\log L/{\rm L}_\odot$, we used sigmas listed in Table 1. For $\log T_{\rm eff}$, we used mean sigmas estimated by Jerzykiewicz (1994).

We compared our semi-empirical luminosities with luminosities derived from the Geneva photometry (hereafter "photometric" luminosities) by Aerts *et al.* (1999) (13 stars) or Waelkens *et al.* (1998) (6 stars). In the cases of two determinations we used the more recent value. In Fig. 2 we plot the difference between the semi-empirical and photometric luminosities as a function of $\log T_{\rm eff}$ derived from Strömgren photometry. The differences are mainly positive, particularly for hot stars, meaning that the photometric luminosities are too low. Only for two stars, HIP 20493 and 79992, the photometric luminosities are too high. It is not clear why discrepancies between the photometric and semi-empirical $\log L/{\rm L}_\odot$ for these two stars are so large.

Since photometric luminosities are in fact merely scaled $\log g$ values (see *e.g.,* Keenan 1963) we conclude from the predominantly positive differences in Fig. 2 that the $\log g$ values derived from Geneva photometry would be systematically too high.

Unfortunately, semi-empirical $\log g$ for the studied stars are not known. Therefore, we decided to compute $\log g$ from Geneva photometry for stars for which the semi-empirical $\log g$ are known and then compare the semi-empirical and pho-

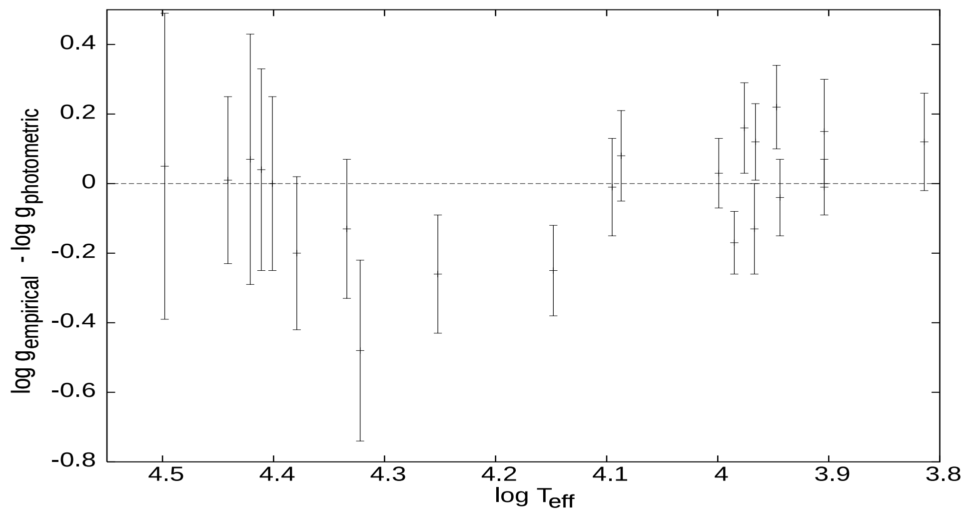

Fig. 3. $\log g_{\text{empirical}} - \log g_{\text{photometric}}$ computed for 22 stars from Table 2 of Jerzykiewicz and Molenda-Żakowicz (2000) and plotted as a function of empirical $\log T_{\text{eff}}$ from Code *et al.* (1976).

tometric values. We made the computations for 22 of the 26 stars with semi-empirical $\log g$ values from Jerzykiewicz and Molenda-Żakowicz (2000) and empirical $\log T_{\text{eff}}$ from Code *et al.* (1976). We used Geneva indices from Rufener (1988) and the CALIB code provided by Kunzli *et al.* (1997).

In Fig. 3 we plot the difference between the semi-empirical and photometric $\log g$ as a function of empirical $\log T_{\text{eff}}$. The photometric $\log g$ values agree well with the semi-empirical ones for $\log T_{\text{eff}}$ higher than 4.4 or smaller than 4.1. For stars of intermediate $\log T_{\text{eff}}$, photometric $\log g$ are indeed too high and would result in too low photometric luminosities. Analogous computations performed for these stars with the use of Strömgren photometry show that the photometric $\log g$ are too low in the whole range of $\log T_{\text{eff}}$. These results indicate that photometric luminosities and masses derived from the current calibrations are of limited use for asteroseismology.

In Fig. 4 we plot ΔM defined as the difference between the mass derived from semi-empirical luminosity and the mass derived from photometric luminosity as the function of the semi-empirical $\log L/\mathrm{L}_\odot$. We computed ΔM for 16 stars, HIP 19398, 34817, 38455, 40285, 42726, 45189, 61199, 69174, 76243, 77227, 90797, 95260, 95159, 107173, 108022 and 112781, using $M/\mathrm{M}_\odot$ from column 6 of Table 1 ($Z = 0.02$), and $M/\mathrm{M}_\odot$ listed by Aerts *et al.* (1999) or Mathias *et al.* (2001). Dots indicate stars for which we used masses listed by Aerts *et al.* (1999), crosses, by Mathias *et al.* (2001). We labeled HIP 90797 with (1) and (3) to indicate solutions obtained for the phase of core or shell hydrogen burning, respectively.

As can be seen from Fig. 4 for most stars the masses derived by Aerts *et al.* (1999) or Mathias *et al.* (2001) are too low and for the most luminous stars in the sample the discrepancies can exceed one solar mass. For HIP 76243 and 77227, we

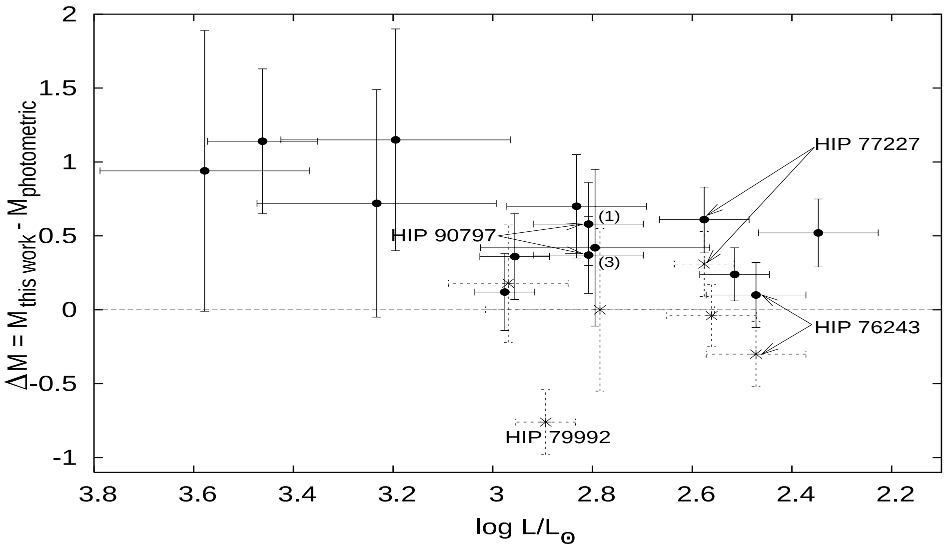

Fig. 4. Differences between $M/\mathrm{M}_\odot$ derived for 16 stars from semi-empirical and photometric $\log L/\mathrm{L}_\odot$ plotted as a function of semi-empirical $\log L/\mathrm{L}_\odot$. Stars labeled with HIP numbers are discussed in the text. The photometric $\log L/\mathrm{L}_\odot$ were derived by Aerts *et al.* (1999) (dots) or Mathias *et al.* (2001) (crosses).

plot the ΔM calculated for $M/\mathrm{M}_\odot$ of Mathias *et al.* (2001) and Aerts *et al.* (1999). Differences between ΔM from these two sources are equal to 0.4 $\mathrm{M}_\odot$ for HIP 76243 and 0.3 $\mathrm{M}_\odot$ for HIP 77227 and they are quite large if compared with the values of $\sigma_{M/\mathrm{M}_\odot}$ given for the two stars in Table 1. The discrepancies arise from different luminosities used by these authors. It is not clear why Mathias *et al.* (2001) prefer luminosities from Waelkens *et al.* (1998) to those given by Aerts *et al.* (1999) although the latter authors state that their estimates of $\log T_{\mathrm{eff}}$, $\log g$, $\log L/\mathrm{L}_\odot$ and $M/\mathrm{M}_\odot$ were derived with the use of "all the recent follow–up Geneva data (...) and should therefore be preferred above those listed by Waelkens *et al.* (1998)" (Aerts *et al.* 1999).

For HIP 79992 (see Fig. 4), the mass derived by Mathias *et al.* (2001) is 0.78 $\mathrm{M}_\odot$ higher than $M/\mathrm{M}_\odot$ derived in this paper. This discrepancy is caused by the fact that the photometric luminosity used by Mathias *et al.* (2001) was ≈ 0.5 dex higher than the semi-empirical luminosity computed in this paper. We note that our $\log L/\mathrm{L}_\odot$ is in agreement with the semi–empirical value obtained by Briquet *et al.* (2003) from Hipparcos parallaxes and Geneva photometry.

The discrepancies between $M/\mathrm{M}_\odot$ derived from different sets of photometric indices obtained in the same photometric system, and large discrepancies between $M/\mathrm{M}_\odot$ derived from photometric and semi-empirical $\log L/\mathrm{L}_\odot$, show that the masses derived from photometric $\log L/\mathrm{L}_\odot$ are very uncertain and that they would lead to incorrect identification of modes if used in asteroseismological analyzes.

3. HIP 69174 and 77227

In SB2 systems both components contribute to photometry and influence photometric indices. Therefore, the $\log T_{\rm eff}$, $\log g$ and $\log L/{\rm L}_\odot$ values derived for HIP 69174 (B9 IV) and HIP 77227 (B8 III) in Section 2 are in fact ill-defined means. For derivation of astrophysical parameters of the components and astrometric parameters of the systems, we used the observed Strömgren indices and V magnitudes which we corrected for duplicity using theoretical u, v, b, y and V magnitudes from Kurucz (1993), and evolutionary models for $Z = 0.02$ and 0.008 from Schaller *et al.* (1992) or Schaerer *et al.* (1993), respectively.

First, we expressed the observed magnitude of each system, V, as

$$V = V_1 - 2.5\log(1 + 10^{-0.4\Delta V}) \tag{2}$$

where ΔV is the difference between the magnitude of the secondary – V_2 and the primary – V_1. Then, we wrote similar equations for $(b-y)$,

$$(b-y) = (b-y)_1 - 2.5\log(1+10^{-0.4\Delta b}) + 2.5\log(1+10^{-0.4\Delta y}) \tag{3}$$

and analogous equations for m_1 and c_1. In these equations, the values of Δu, Δv, Δb, Δy and ΔV are unknown and have to be computed. To make the computations, we assumed that the components of HIP 69174 and 77227 are coeval and we used the fact that for a binary of an assumed age and orbital inclination, the $M_{1,2}\sin^3 i$ values given by De Cat *et al.* (2000) can be combined with evolutionary models and yield "preliminary" astrophysical parameters of the primary and secondary. These "preliminary" parameters, compared with theoretical magnitudes from Kurucz (1993), allow us to find Δu, Δv, Δb, Δy and ΔV values and to correct the observed indices, as well as the V magnitudes, for duplicity according to Eqs. (2) and (3), and the analogous equations written for the needed indices. We applied the calibration of Napiwotzki *et al.* (1993) to the corrected indices and we derived "actual" astrophysical parameters of the primary which should agree with the "preliminary" ones providing the assumed i and age are correct. Then, using the corrected magnitudes and Hipparcos parallaxes we computed $\log L/{\rm L}_\odot$ of the components.

We performed computations in a wide range of ages and inclinations and we selected this solution for which the "preliminary" and "actual" values of $\log T_{\rm eff}$ and $\log L/{\rm L}_\odot$ of the primary are in the best agreement. To improve precision of the final solution, we interpolated the evolutionary tracks linearly.

We list the parameters of the components of HIP 69174 and 77227 computed for $Z = 0.008$ and 0.02 in Table 2. In Fig. 5 we show the positions of the primaries (SPBs) and the cooler secondaries computed for $Z = 0.02$ and plotted on the HR diagram. We use dots to fill the regions where the SPBs and the secondaries can reside. For each system, we indicate their ill-defined mean position with a white cross. In Fig. 5 we show also evolutionary tracks for 2, 3 and 4 ${\rm M}_\odot$ adopted from

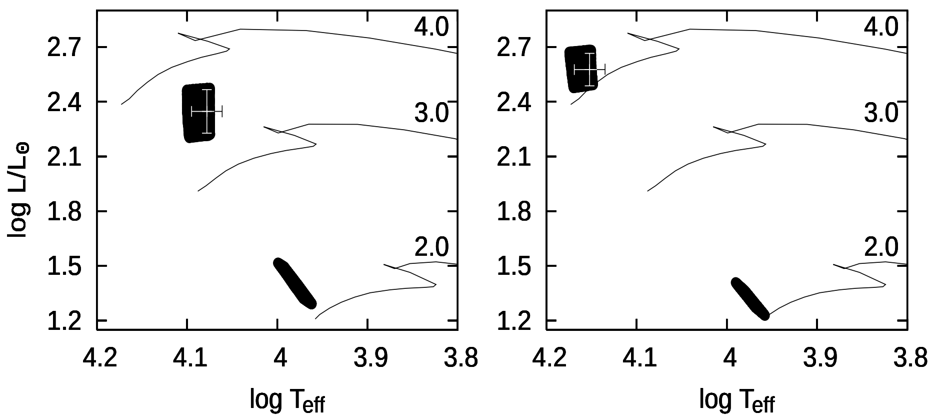

Fig. 5. *Left*: The $\log T_{\rm eff}$–$\log L/{\rm L}_\odot$ diagram with evolutionary tracks for $Z=0.02$ and for 2, 3 and 4 $M_\odot$, labeled at the right end of each track, adopted from Schaller *et al.* (1992). Regions where the primary and secondary component of HIP 69174 may reside are filled with dots. The white cross indicates the ill-defined mean position of HIP 69174 given in Table 1. *Right*: The same for HIP 77227.

Schaller *et al.* (1992). We do not show the positions of components computed for $Z=0.008$ in a separate figure, because, as it can be seen from Table 2, the computed parameters show little dependence on metallicity (respective values agree to within their error bars). Our solution shows also that in both systems the components are well-detached so that the effects of proximity, which would make the task much more complicated, can be neglected.

Table 2

Parameters of the components of HIP 69174 and 77227

	HIP 69174		HIP 77227	
	Z=0.008	Z=0.02	Z=0.008	Z=0.02
i	51.8±1.5	50.3±1.4	50.4±1.3	49.2±1.1
M_1 ($M_\odot$)	3.30±0.22	3.52±0.23	3.99±0.24	4.21±0.22
M_2 ($M_\odot$)	2.06±0.14	2.20±0.14	2.00±0.13	2.12±0.11
age ($\times 10^9$ yr)	0.22±0.03	0.17±0.05	0.11±0.02	0.07±0.03
$a/{\rm R}_\odot$	64.7±1.4	66.1±1.4	87.8±1.6	89.4±1.5
$R_1/{\rm R}_\odot$	3.4±0.7	3.3±0.7	3.2±0.6	3.1±0.5
$R_2/{\rm R}_\odot$	1.6±0.1	1.8±0.1	1.5±0.1	1.7±0.1
$\log T_{\rm eff1}$	4.087±0.013	4.087±0.013	4.165±0.013	4.161±0.013
$\log T_{\rm eff2}$	4.008±0.019	3.980±0.019	4.005±0.024	3.974±0.016
$\log L_1/{\rm L}_\odot$	2.350±0.131	2.341±0.135	2.610±0.136	2.583±0.107
$\log L_2/{\rm L}_\odot$	1.389±0.113	1.403±0.112	1.316±0.097	1.319±0.091
$\log g_1$	3.90±0.15	3.94±0.15	4.04±0.13	4.07±0.13
$\log g_2$	4.34±0.02	4.25±0.03	4.39±0.01	4.29±0.02

4. Ellipsoidal or SPB Stars

4.1. Method

The study of Aerts *et al.* (1999) showed that spectroscopic observations are crucial for checking whether we deal with an SPB or an Ell star. The multi-color photometry is another helpful tool because SPBs should show larger amplitudes on the short-wavelength side of the Balmer jump than in the Paschen continuum. However, even one-color photometry, if combined with evolutionary models, can help to find stars which cannot be Ell variables because their photometric periods would be too short to result from binarity.

With this in mind, one can check whether a star can be Ell, provided its photometric period, $\log T_{\rm eff}$, and $\log L/{\rm L}_{\odot}$ or $\log g$ are known and assuming that these parameters are measured for the primary in a binary with orbital period equal to twice the photometric one.

For computing the shortest possible orbital period, $P_{\rm min}$, the mass ratio of the components, $q = M_2/M_1$, must be set. In our analysis we decided that q should be equal to 0.1 because binaries with $q > 0.1$ would have longer $P_{\rm min}$, while binaries with $q < 0.1$ would have to be eclipsing to show the observed photometric amplitudes. In the next step we made use of the fact that a binary for which the masses and radii of components are known has the shortest orbital period when one of the components fills its critical Roche volume. Here, we assumed that the computed radius of the primary R_1 is equal to the equivalent radius $R_{\rm eq}$, defined by

$$V_{\rm crit} = \frac{4\pi R_{\rm eq}^3}{3}, \tag{4}$$

so that the separation of the components A can be computed from

$$R_1 = R_{\rm eq} = cA \tag{5}$$

where c is a decreasing function of q in the Roche model (see Kopal 1959) and the shortest orbital period can be calculated from the Kepler's III law. Computing ΔP, defined as a difference between the observed and computed orbital period,

$$\Delta P = P_{\rm orb} - P_{\rm min}, \tag{6}$$

we found stars for which this value is negative, *i.e.,* stars which cannot form binaries having the orbital period equal to $P_{\rm orb}$ and, as the result, cannot be Ell variables.

4.2. Stars with Accurate Parallaxes

Among the 27 stars from Table 1 there are 12 which are monoperiodic and not confirmed to be SPBs. We checked whether these stars can be Ell variables with the method outlined in Section 4.1. We used the photometric $\log T_{\rm eff}$ values from Table 1, the Schaerer *et al.* (1993) or Schaller *et al.* (1992) evolutionary

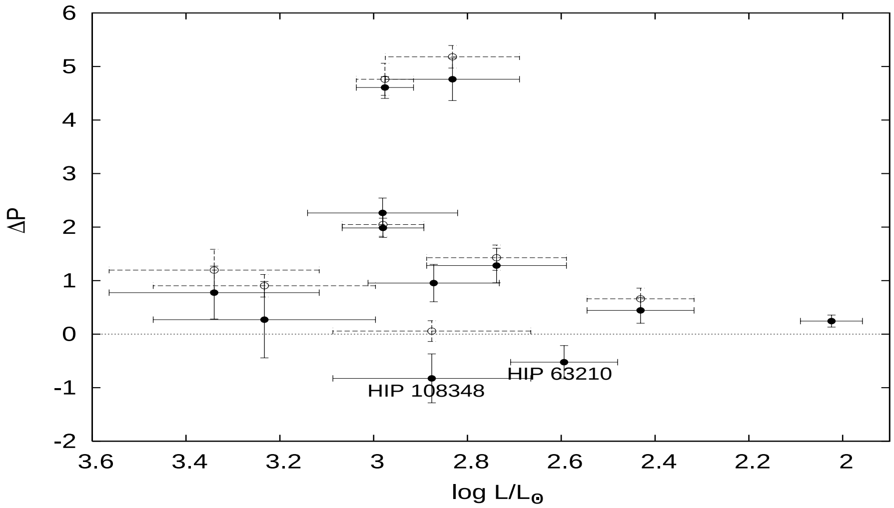

Fig. 6. $\Delta P = P_{\rm orb} - P_{\rm min}$ computed for 12 unconfirmed SPBs from Table 1, plotted as a function of $\log L/L_\odot$. Dots indicate ΔP computed from $\log L/L_\odot$, open circles – from $\log g$. Stars labeled with HIP numbers are discussed in the text.

models and the photometric periods from the Hipparcos Catalogue. For these 12 stars both $\log L/L_\odot$ and $\log g$ are known, so that we could compute the shortest orbital period – $P_{\rm min}$, using either parameter. Keeping in mind that for many stars semi-empirical $\log L/L_\odot$ are not known, we made parallel computations first using semi-empirical $\log L/L_\odot$ and then photometric $\log g$ and finally we compared the computed $P_{\rm min}$. We did not compute $P_{\rm min}$ using photometric $\log g$ for four stars, namely, HIP 43763, 63210, 67973 and 93210, which fall below ZAMS in the $\log T_{\rm eff} - \log g$ diagram. In Fig. 6 we plot ΔP as a function of $\log L/L_\odot$. We use dots to plot ΔP computed from semi-empirical $\log L/L_\odot$ and open circles to plot ΔP computed from photometric $\log g$.

Looking at Fig. 6 one can see two stars, namely, HIP 63210 and 108348, for which ΔP computed from semi-empirical $\log L/L_\odot$ is negative and which we therefore confirm as pulsators. Fig. 6 shows also that for all stars ΔP computed from $\log g$ derived from the Strömgren photometry is higher than ΔP computed from $\log L/L_\odot$. Hence we conclude that results obtained from computations based on photometry should be considered as preliminary. They can be used for preselecting suspected pulsators which may be confirmed after their $\log L/L_\odot$ become known. Such a preselection should be quite accurate because for most stars ΔP computed either from $\log g$ or $\log L/L_\odot$ agree to within their error bars which we computed from

$$\sigma_{\Delta P} = \sqrt{\sum_{i=1}^{6} \left(\frac{\partial \Delta P}{\partial x_i} \sigma x_i \right)^2} \qquad (7)$$

where x_i represent the observed V, $(b-y)$, m_1, c_1, β and π. In our computations we assumed the values of σx_i to be equal to the mean of respective sigmas listed for B-type stars by Grønbech and Olsen (1976), *i.e.*, $\sigma_V = 0.008$, $\sigma_{(b-y)} = 0.003$, $\sigma_{m_1} = 0.005$, $\sigma_{c_1} = 0.006$ and $\sigma_\beta = 0.007$. The values of σ_π we took from the Hipparcos Catalogue.

4.3. Stars without Accurate Parallaxes

Attempting to study stars that do not have accurate parallaxes, we selected 44 stars classified as SPB which were observed in the Strömgren or Geneva photometric system and computed their photometric $\log T_{\rm eff}$ and $\log g$. Ten of the stars were observed only in the Strömgren photometric system, while 16, only in the Geneva system. For the 18 remaining stars that were observed in both systems, we found that the $\log T_{\rm eff}$ and $\log g$ values derived from either Strömgren or Geneva photometry agree to within their error bars. We found discrepancies only for HIP 71666 which we discuss later in this Section.

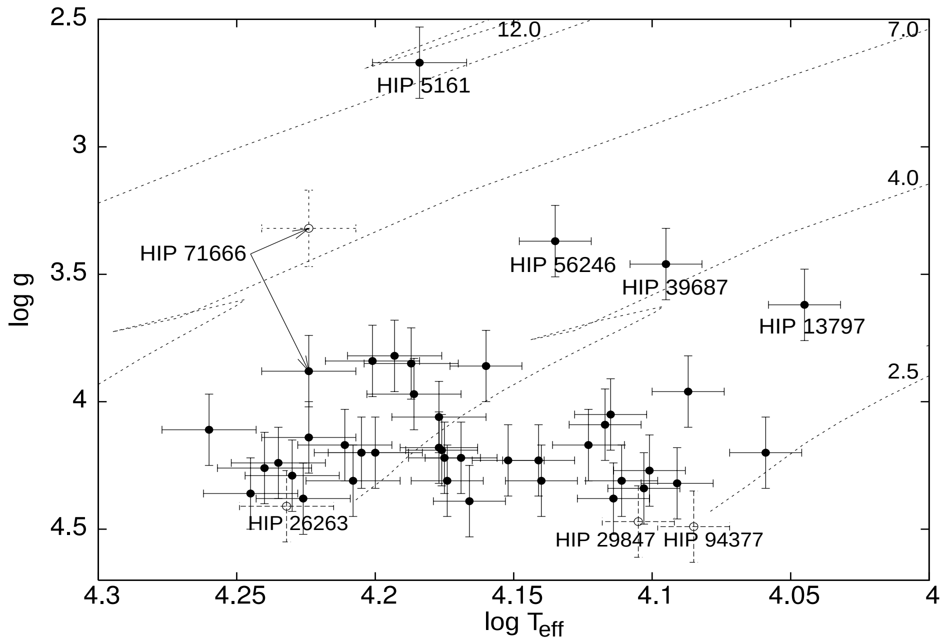

Fig. 7. The $\log T_{\rm eff}$–$\log g$ diagram constructed for 44 stars without accurate parallaxes. The evolutionary tracks ($Z = 0.008$, and 2.5, 4, 7, 12 $M_\odot$) are adopted from Schaerer *et al.* (1993). Stars indicated with their HIP numbers are discussed in the text.

In Fig. 7 we plot the 44 stars on the $\log T_{\rm eff}$–$\log g$ diagram where we show also evolutionary tracks for $Z = 0.008$ from Schaerer *et al.* (1993) for 2.5, 4, 7 and 12 $M_\odot$. In Fig. 7, there are three stars, namely, HIP 26263, 29488 and 94377 (open circles) that fall below ZAMS and which we excluded from further analysis. In Fig. 7 there are also five stars, namely, HIP 5161, 13797, 39687, 56246 and 71666, that fall above TAMS. We discuss these stars below.

In Fig. 8 we show a c_0–β diagram where we plot stars from Table 1 and the 28 stars without accurate parallaxes for which we have Strömgren photometry. In

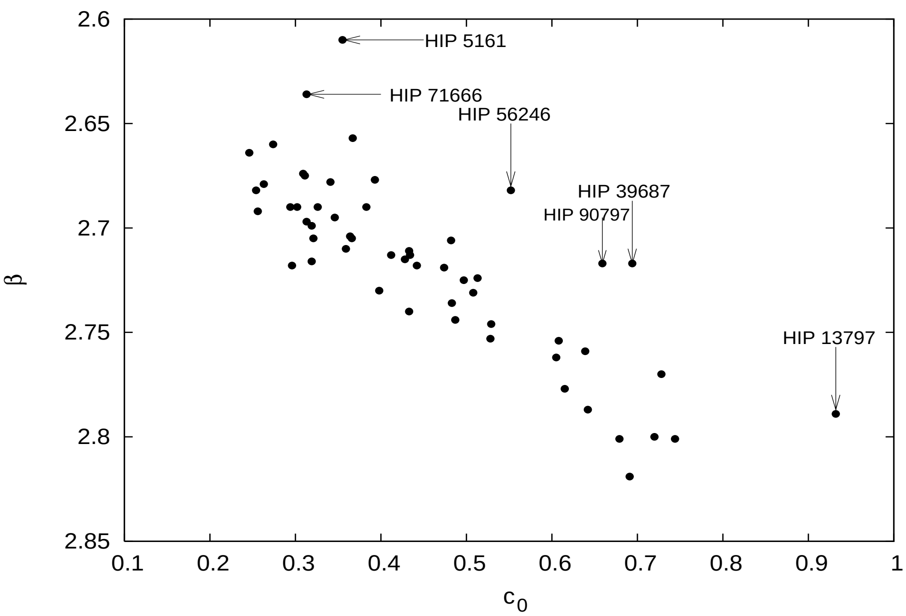

Fig. 8. $c_0-\beta$ diagram for 55 stars classified in the literature as SPB. Stars labeled with HIP numbers are discussed in the text.

Fig. 8 there are six stars, namely, HIP 5161 (B3III), 13797 (B9III), 39687 (B8V), 56246 (B7IV), 71666 (B3V) and 90797 (B8III), that fall above stars having similar c_0 indices. We suspect that all these stars show emission at Hβ. Considering HIP 5161, 13797, 39687, 56246 and 71666, that fall above TAMS in Fig. 7 we suspect that they are still in the phase of core hydrogen burning and that their photometric $\log g$ derived form the β index is spurious. In the case of HIP 71666, our suspicion is supported by the fact that its $\log g$ derived from Geneva indices, which are not sensitive to the emission at Hβ, is ≈ 0.5 dex higher than $\log g$ derived from the β index.

We performed periodogram analysis of Hp magnitudes of all the stars using the Lomb's method (Lomb 1976) modified by adding a floating mean and weights for each Hp magnitude (see Jerzykiewicz and Pamyatnykh 2000) and we prewhitened the Hp magnitudes with all detected frequencies after each run. In the result, we confirmed multiperiodicity of five stars, namely, HIP 8485, 32408, 44655, 45692 and 93808, which were discovered to be multiperiodic by Koen (2001), and we discovered five new multiperiodic variables, namely, HIP 5161, 20963, 26243, 26464 and 44996. In Table 3 we list the HIP and HD numbers of the new multiperiodic stars, the number of Hp magnitudes used for periodogram analysis, the detected frequencies and the amplitudes.

In Fig. 9 we show periodograms for the five new multiperiodic stars. In column a, we show periodograms of Hp magnitudes labeled with HIP numbers, in column b, periodograms of the data prewhitened with frequency f_1 and in column c, periodograms of the data prewhitened with frequencies f_1 and f_2. For

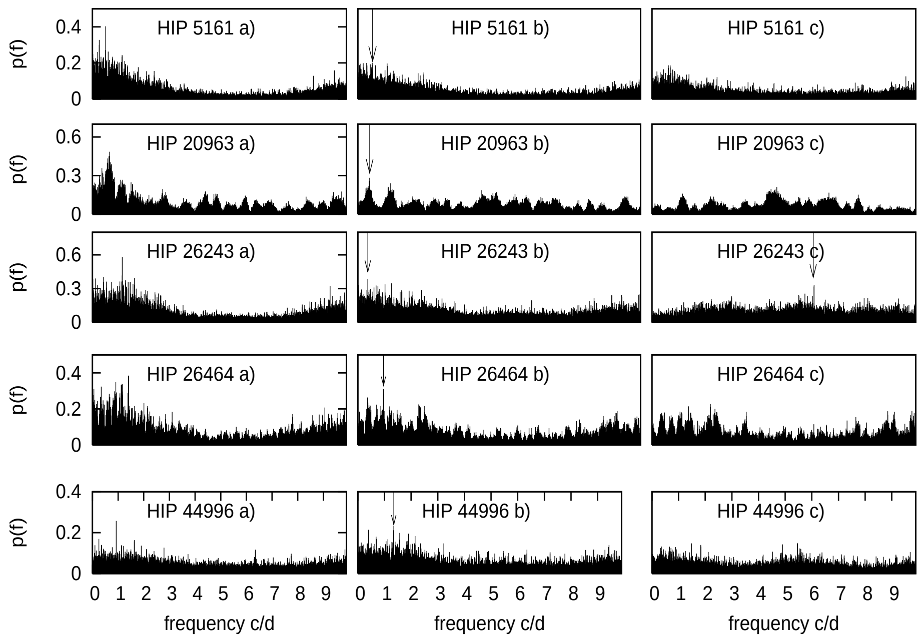

Fig. 9. Periodograms for five stars discovered in this paper to be multiperiodic. *a)* Periodograms of Hp magnitudes. The highest peak occurs at frequency f_1. *b)* Periodograms of data prewhitened with frequency f_1. Arrows indicate frequency f_2. *c)* Periodograms of data prewhitened with frequencies f_1 and f_2. In the case of HIP 26243, the arrow indicates frequency f_3.

all stars the periodograms have complicated structure and even after prewhitening with all detected frequencies they seem to contain a signal. However, in most cases the phase diagrams of the residuals plotted using the tertiary frequency show only noise. Therefore, we stop our analysis at this stage and we conclude that all the stars are clearly multiperiodic but the Hipparcos photometry is not sufficient to derive more frequencies than the ones listed in Table 3.

The only star which we find to be variable with three frequencies, HIP 26243 (B5IV/V), has the following frequencies: $f_1 = 1.16779$ c/d, $f_2 = 0.35156$ c/d and $f_3 = 6.10803$ c/d. Frequency f_3 is certainly due to pulsation. Frequencies f_1 and f_2 can also be pulsational but we cannot exclude that one of them is due to ellipticity. Thus, HIP 26243 becomes another SPB in which both low and high frequencies are excited; the first such star was HIP 45692, discovered to be variable on time–scales of days and hours by Koen (2001).

We included the multiperiodic stars in our analysis suspecting that they are similar to HIP 52043 for which the high–amplitude frequency is due to ellipticity and the low-amplitude one, to pulsation (Aerts *et al.* 1999).

Our periodogram analysis also showed that amplitudes in SPBs rarely exceed 25 mmag. We found only three monoperiodic stars, namely, HIP 37668, 47893 and 105934, which have amplitudes exceeding 40 mmag. All these stars are classified as SPB by Waelkens *et al.* (1998). The Hipparcos Catalogue classifies HIP 37668

T a b l e 3

The HIP and HD numbers, the number of Hp magnitudes, frequencies in c/d and amplitudes in mmags of five stars classified as multiperiodic variables

HIP	HD	N_{Hp}	f_1 c/d	A_1 mmag	f_2 c/d	A_2 mmag	f_3 c/d	A_3 mmag
5161	6417	172	0.51738	20.1	0.50909	14.2		
20963	28475	79	0.67450	10.0	0.41488	8.1		
26243	37104	99	1.16779	23.7	0.35156	12.3	6.10803	9.7
26464	37332	121	1.41408	20.8	0.89984	17.0		
44996	79039	142	0.93050	15.8	1.35293	10.3		

and 47893 as ACV and leaves the third star, HIP 105934, unclassified. Taking into account the monoperiodicity, the amplitudes and the type of variability listed in the Hipparcos Catalogue, we conclude that Waelkens' *et al.* (1998) classification of these stars is incorrect.

In the next step, we computed ΔP for 41 unconfirmed SPB stars. We used the Schaerer *et al.* (1993) evolutionary models for $Z = 0.008$, and $\log T_{\rm eff}$ and $\log g$ derived from Strömgren or Geneva photometry. For HIP 71666, we made parallel computations for both values of $\log g$. We show the results in Fig. 10. In Fig. 10 there are two stars, namely HIP 71666 and HIP 5161, for which ΔP is negative. For HIP 71666 (B3V), however, ΔP is negative only when it is derived from the β index which we suspect to be affected by emission. Therefore, we consider this value of ΔP to be spurious.

HIP 5161 (B3III), one of the new multiperiodic variables discovered in this paper, is the other star for which ΔP is negative. As we showed in Fig. 8 this star may have emission at Hβ and therefore we suspect that also for this star the negative ΔP is spurious. If ΔP and the location of the star in the $\log T_{\rm eff}$–$\log g$ diagram are correct, HIP 5161 would be a very peculiar SPB. Its mass, derived form the Strömgren indices and the Schaerer *et al.* (1993) evolutionary models, would be close to 13 $M_\odot$ and the star itself would be either in the shell hydrogen or core helium burning phase. Its pulsation constant – Q, would be equal to 0.05 ± 0.015 for either of the frequencies, *i.e.*, $f_1 = 0.51738$ c/d or $f_2 = 0.50909$ c/d, to within the error bars. Such a value of Q would be much smaller than the average Q of SPBs that we found to be equal to 0.5, using the data for confirmed SPBs from Table 1.

We conclude that HIP 5161 is an interesting object for future theoretical and observational study, particularly because the theory of pulsations does not predict unstable modes in this star (Daszyńska-Daszkiewicz private communication).

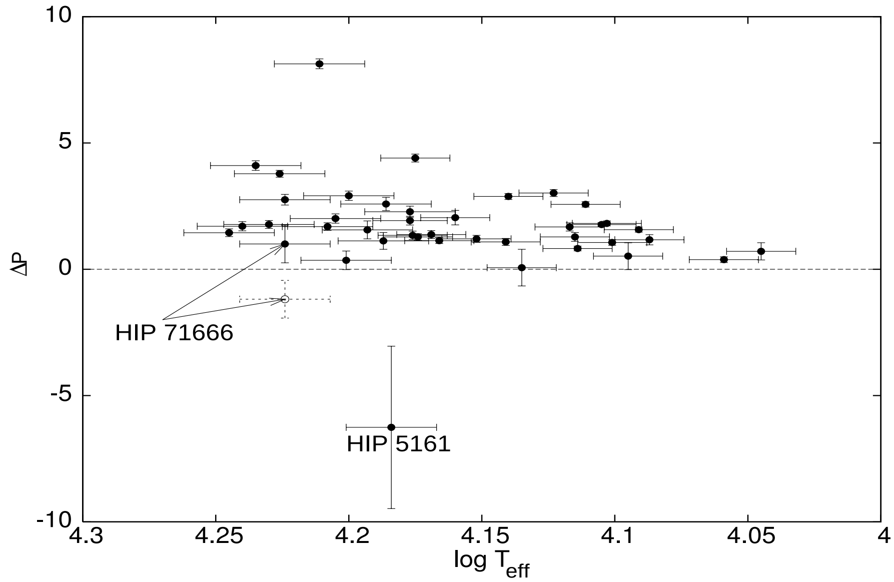

Fig. 10. $\Delta P = P_{\rm orb} - P_{\rm min}$ computed for 41 unconfirmed SPBs and plotted as a function of $\log T_{\rm eff}$. Arrows indicate ΔP computed for HIP 71666 with the use of the Geneva (dots) or Strömgren photometry (open circle).

5. Summary

Our results can be summarized as follows: from Hipparcos parallaxes and evolutionary models we: (1) derived semi–empirical luminosities and improved evolutionary masses for 27 stars classified in the Hipparcos Catalogue as SPB, (2) showed that stellar parameters derived from photometry are of limited use for asteroseismology, (3) computed astrophysical and astrometric parameters of HIP 69174 and HIP 77227, (4) confirmed pulsations of HIP 63210 and 108348, (5) discovered multiperiodicity of five stars and confirmed their classification as pulsators, (6) detected periods of the order of days and hours in HIP 26243, one of the new multiperiodic SPBs, (7) find six stars, namely, HIP 5161, 13797, 39687, 56246, 71666 and 90797, which may have their β index affected by emission, and (8) showed that photometry combined with evolutionary models may be helpful in preselecting tentative pulsators.

We note that in our analysis we did not take into account the systematic errors of Hipparcos parallaxes. These errors, however, if adopted to be equal to 0.5 mas, *i.e.*, half the systematic error observed for the Pleiades cluster (Pinsonneault *et al.* 1998), would result in an additional uncertainity of the derived $\log L/{\rm L}_\odot$ values equal to ± 0.1 dex on the average.

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