Asiago eclipsing binaries program

II. V505 Persei*,**

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Received 31 July 2007 / Accepted 30 November 2007

ABSTRACT

The orbit and fundamental physical parameters of the double-lined eclipsing binary V505 Per are derived by means of Echelle high-resolution and high S/N spectroscopy, and B, V photometry. In addition, effective temperatures, gravities, rotational velocities, and metallicities of both components are also obtained from atmospheric χ2 analysis, showing an excellent match with the results of the orbital solution. An $E_{B-V} \leq 0.01$ mag upper limit to the reddening is derived from intensity analysis of interstellar NaI (5890.0 & 5895.9 Å) and KI (7699.0 Å) lines. The distance to the system computed from orbital parameters (60.6 ± 1 pc) is identical to the newly re-reduced Hipparcos parallax (61.5 ± 1.9 pc). The masses of the two components ($M_1 = 1.2693 \pm 0.0011$ and $M_2 = 1.2514 \pm 0.0012 M_\odot$) place them in the transition region between convective and radiative stellar cores of the HR diagram, with the more massive of the two already showing the effect of evolution within the main sequence band ($T_1 = 6512 \pm 21$ K, $T_2 = 6462 \pm 12$ K, $R_1 = 1.287 \pm 0.014$, $R_2 = 1.266 \pm 0.013 R_\odot$). This makes this system particularly relevant to theoretical stellar models as a test of the overshooting. We compare the firm observational results for V505 Per component stars with the predictions of various libraries of theoretical stellar models (BaSTI, Padova, Granada, Yonsei-Yale, Victoria-Regina), as well as with BaSTI models computed specifically for the masses and chemical abundances of V505 Per. We find that the overshooting at the masses of V505 Per component stars is already pretty low, but not nil, and it is described by efficiencies $\alpha_{OV} = 0.093$ and $0.087$ for the 1.27 and 1.25 $M_\odot$ components, respectively. According to the computed BaSTI models, the age of the system is $\sim 0.9$ Gyr, and the element diffusion during this time has reduced the surface metallicity from the initial $[M/H] = -0.03$ to the current $[M/H] = -0.13$, in excellent agreement with the observed $[M/H] = -0.12 \pm 0.03$.

Key words. stars: fundamental parameters – stars: binaries: spectroscopic – stars: binaries: eclipsing – star: individual: V505 Persei

1. Introduction

Double-lined eclipsing binaries (SB2 EBs) represent a primary tool for providing fundamental stellar parameters, first of all masses and radii. These parameters, when measured with high accuracy, represent a formidable benchmark for the current generation of stellar evolutionary models. In fact, they have to simultaneously fit the two stars of the binary, by adopting exactly the same age and the same initial chemical composition for them.

On the other hand, the reliability of stellar models is still partially hampered by our poor knowledge of some of the physical processes at work in real stars, such as (a) the efficiency of core convective overshoot during the core H-burning phase in intermediate-mass stars (i.e. stars with mass $M \geq 1.1$–1.2 $M_\odot$, the exact value depending on the chemical composition), (b) the way the efficiency of core convective overshoot decreases with decreasing stellar mass in the mass range where the transition between fully convective to fully radiative stellar cores occurs, or (c) the efficiency of convection in the super-adiabatic layers (cf. Ribas et al. 2000). For all these reasons, observational data from SB2 EBs provide strong constraints on the different approaches used in stellar model computations. In this context, the most suitable type of binary systems are those where the mass of at least one of the two component is $\sim 1.2$ $M_\odot$ (cf. Pietrinferni et al. 2004, hereafter P04). V505 Per is such a system, according to earlier determinations of the masses (i.e. Marschall et al. 1997, hereafter M97; Munari et al. 2001, hereafter M01).

To properly use binary systems to constrain the accuracy of current stellar evolutionary models, the properties of both components should be known at the 1–2% level and should be accompanied by accurate determination of effective temperatures and metallicities (which are not direct products of orbital solution).

Andersen (1991, 1997, 2002) lists about fifty eclipsing binary systems for which fundamental stellar parameters at the level of 1–2% have been obtained so far in the literature from the modeling of their orbits. They have been compared to predictions of stellar evolutionary models by Pols et al. (1997). Andersen (2002) argues in favor of more systems being observed
and modeled at this level of accuracy, and Pols et al. (1997) stresses how unknown metallicity for the majority of these systems with excellent orbits spoiled the potential to compare it to theoretical predictions.

In the present series of papers, fundamental physical parameters for SB2 EBs are derived by means of high-precision photometric and spectroscopic data, as well as of accurate orbital solutions via the Wilson-Devinney code (Wilson & Devinney 1971; Wilson 1998; Milone et al. 1992). Contrary to common practice, we do not assume a temperature for the primary star (deduced for example from photometric colors or spectral types) and the reddening affecting the binary, but we measure them both. Reddening comes from direct measurements of the interstellar NaI (5890 & 5896 Å) and KI (7665 & 7699 Å) doublets, using the widely-used relation between equivalent width and color excess $E_{B-V}$ calibrated by Munari & Zwitter (1997).

In addition, we perform an atmospheric analysis of both stars in the binary system by means of a $\chi^2$ fit to the Kurucz synthetic spectral library computed by Munari et al. (2005, hereafter M05) at the same $R = 20{,}000$ resolving power of Echelle spectra used in this series of papers. The $\chi^2$ fit provides temperature, gravity, metallicity, and projected rotational velocity for both components. The M05 synthetic spectral library is the same as the one adopted by Wilson & Devinney 1971, Wilson 1998: Milone et al. 1992.

3. The data

3.1. Photometry

As for Paper I in this series (Siviero et al. 2004), the photometric observations of V505 Per were obtained with a 28 cm Schmidt-Cassegrain telescope equipped with an Optec SSP5 photoelectric photometer. In all, the measurements for V505 Per consisted of 311 points in $B_I$ and 316 in $V_I$ (standard Johnson bands), secured between 2000 and 2001 and covering the whole lightcurve well. The comparison star was HD 14444 (F0 spectral type) and the check star was HD 14062 (K0 spectral type). Their adopted values were $V_I = 8.7600, (B - V)_I = +0.432$, and $V_I = 7.6585, (B - V)_I = +1.057$, respectively. They were derived from Tycho-2 $B_I, V_I$ photometry ported to Johnson’s system by means of Bessell (2000) transformations. Both comparisons and check stars lay close to V505 Per on the sky (16.42 and 28.16 arcmin, respectively) and have similar colors, so that differential atmospheric absorption is not a source of uncertainty in our photometry. The comparison star was measured against the check star at least once every observing run and was found to be stable at better than 0.01 mag level.

The whole set of photometric data is reported in Table 3 (only available electronically at the CDS). The $B_I, V_I$ lightcurves and $(B - V)_I$ color curve are plotted in Fig. 2. They do not show hints of intrinsic variability for any of the two stars. The dispersion of $B_I$ and $V_I$ points around the orbital solution plotted in Fig. 2 is $\sigma_{BB} = 0.008$ and $\sigma_{VV} = 0.007$, respectively, arguing in favor of high internal consistency in our photometric data.

3.2. Spectroscopy

Spectroscopic observations of V505 Per were carried out during a nine-year period (1998–2007) with the Echelle+CCD spectrograph mounted at the Cassegrain focus of the 1.82 m telescope, operated by INAF Osservatorio Astronomico di Padova on top of Mt. Ekar in Asiago (Italy). We obtained a total of 36 spectra, well-distributed in orbital phase and each one exposed for 1800 s. The latter corresponds to 0.5% of the orbital period, so introducing negligible smearing in orbital phase while allowing excellent $S/N$. Its mean value over different Echelle orders is given in the last column of Table 1 for all analyzed spectra. The median of these $S/N$ is 200.

Spectra up to January 2000 (HJD $\leq$ 2 451 567 in Table 1) were obtained with the same instrument set-up as adopted for Paper I: wavelength interval 4500–9480 Å, resolving power $R \sim 20{,}000$, UV-coated Thompson CCD with 1024×1024 pixel (19 μm in size), and a 2 arcsec slit oriented east-west. In 2004 (HJD $\geq$ 2 454 020) the detector changed to a thinned EEV CCD47-10 1024×1024 pixel (13 μm in size), covering the interval 3820–7290 Å. The 2 arcsec slit oriented east-west and the $R \sim 20{,}000$ resolving power were maintained.

Data reduction was performed in a standard fashion with the IRAF package running with the Linux operating system, including modeling and subtraction of the scattered light. A lot of care was taken to ensure the highest quality wavelength calibration for the highest accuracy in radial velocity measurement.

Our Echelle spectrograph is attached at the Cassegrain focus, it moves with the telescope so it suffers from flexures. The latter are, however, quite small in amplitude. These flexures are smooth and repeatable with telescope pointing, and they do not suffer from hysteresis as studied in detail by Munari & Lattanzii (1992). Each science exposure on V505 Per was bracketed by exposures on the thorium comparison lamp, so as to remove the linear component of the flexure pattern. To check on and compensate for the presence of a (minimal) non-linear component of the flexure patten, the rich telluric absorption complexes at $\lambda \lambda$ 5880–5940, 6275–6310, 6865–7050, and 7160–7330 Å were cross-correlated on each V505 Per.
We applied it to the six adjacent Echelle orders (40–45) that cover the wavelength range λλ 4890–5690 Å. These orders (i) lie close to the optical axis of the spectograph where optical quality is the best, (ii) they are densely packed by strong and sharp absorption lines, mainly due to FeI, and (iii) the S/N of the recorded spectra reaches peak values over them. Before cross-correlation, each order was trimmed some more so as to retain the central 50%, where the instrumental response and PSF sharpness are the best.

The appropriate template spectra for cross-correlation were selected among the M05 synthetic spectra as those matching the Teff, log g, Vrot sin i, and [M/H] of V505 Per components found by y analysis (see Sect. 6 below).

Radial velocities obtained in the six trimmed orders were averaged and the resulting mean value for each given spectrum, with the corresponding error of the mean, is reported in Table 1. The columns give the spectrum number (from the Asiago Echelle log-book), the heliocentric JD (−2450000), the orbital phase, the radial velocities of the two components and the corresponding errors, and the (S/N) of the spectrum averaged over the wavelength range considered in the analysis. The median value for the errors of the mean is ∼0.4 km s−1 for both components.

As underlined by Latham et al. (1996), one of the key advantages of TODCOR compared with conventional one-dimensional cross-correlation techniques is that it greatly reduces the systematic errors in the radial velocities caused by line blending. However, Torres et al. (1997, 2000) or Torres & Ribas (2002) find that systematic errors could survive when short wavelength ranges (as in the case of the CFA speedometer they used) are cross-correlated on fast-rotating stars. We verified that our radial velocities are free from this systematic effect, thanks mainly to the wide wavelength range and multi-Echelle-order type of our spectra and, to a lesser extent, also to the slow rotation of the components of V505 Per. With this aim, we repeated the same test as carried out by Torres et al. (1997, 2000) or Torres & Ribas (2002); namely, we built synthetic binary spectra by combining, with the proper luminosity ratio, the primary and secondary templates, shifted to the appropriate velocities for each of the actual exposures as predicted by the orbital solution. These synthetic binary spectra were then fed to TODCOR in the same way as observed spectra were fed previously and the resulting velocities were compared with the input (synthetic) values. The differences (TODCOR minus synthetic), averaged over the six Echelle orders, did not show a dependence on orbital phase and never exceeded 0.2 km s−1. A further test of the accuracy of TODCOR radial velocities was carried out by comparing them with the results of radial velocities derived by measuring individual lines fitted with Gaussian profiles. We selected 42 of the strongest and more isolated absorption lines and measured them for both components on all spectra obtained close to quadratures (orbital phases 0.12 ≤ φ ≤ 0.38 and 0.62 ≤ φ ≤ 0.88). Again, the difference between TODCOR and line-by-line radial velocities does not depend on orbital phase and it is always very small, with an rms value of 0.27 km s−1.

5. Interstellar reddening

The amount of interstellar reddening is obviously critical to the determination of absolute magnitude and therefore distance to the system. Our high-resolution spectra are ideally suited to searching for and, if detected, measuring the intensity of interstellar absorption lines. In particular we searched for NaI (5890 & 5896 Å) and KI (7699.0 Å) lines that Munari & Zwitter (1997) showed to be excellent means to measure the reddening.

To cope with the presence of two overlapped spectra in our binary, we searched for constant NaI and KI lines at different orbital phases (cf. Fig. 1). For V505 Per we did not detect any such line with an equivalent width exceeding 0.03 Å, so that the reddening affecting V505 Per is E(B−V) ≤ 0.01 mag. This corroborates the assumption by both M97 and M01 of zero reddening.
6. Analysis of stellar atmospheres

Atmospheric parameters for the two components of V505 Per were obtained via $\chi^2$ fitting to the M05 synthetic spectral library. The $\chi^2$ fitting was performed both on the single-line spectrum obtained at phase 0.497 (cf. Table 1), i.e. at the bottom of secondary eclipse, as well as on spectra at quadratures, i.e. those showing the largest line split between the two components.

The analysis of the 0.497 phase spectrum (vastly dominated by the light of the primary star alone) provided $T_{\text{eff}} = 6484 \pm 21$ K, $\log g = 4.25 \pm 0.07$, [M/H] = $-0.12 \pm 0.03$, and $V_{\text{rot}} \sin i = 15.3 \pm 1.0$ km s$^{-1}$. These values are affected by a residual, small fraction of light coming from the slightly cooler secondary star, which passes behind the primary at the secondary eclipse. We will later see from the orbital solution that the two components of the binary share very similar $\log g$ and $V_{\text{rot}} \sin i$.

Therefore the only significant correction to these $\chi^2$ values required by the residual contribution of the secondary star to the combined system light at orbital phase 0.497 concerns the effective temperature. We performed iterative orbital solutions, and at each iteration, we derived the difference in the temperature between the primary and secondary stars and the fraction of the combined system light due to the two components. Convergence was reached for $T_{\text{eff}} = 6512 \pm 21$ K for primary star, which was adopted in the orbital solution. The atmospheric parameters for the primary star derived from the phase 0.497 spectrum were confirmed by $\chi^2$ analysis of the spectra obtained in quadrature, with resulting parameters for the secondary star being $T_{\text{eff}} = 6460 \pm 30$ K, $\log g = 4.25 \pm 0.06$, $V_{\text{rot}} \sin i = 15.4 \pm 1.0$ km s$^{-1}$, and a metallicity [M/H] = $-0.12 \pm 0.03$ identical to that of the primary star. The small difference in temperature between the two stars ($T_{\text{eff,1}} - T_{\text{eff,2}} = 52$ K) agrees with the similarly small difference in eclipses depths (0.04 mag) displayed by both our and M97 photometry. The formal errors on $T_{\text{eff,1}}$ and $T_{\text{eff,2}}$ are 21 and 30 K respectively, are the error of the mean computed on the results from independent $\chi^2$ analysis of each individual Echelle spectral order. These errors are in line with typical results of $\chi^2$ and minimum-distance-method analysis from high-resolution, high S/N spectra (cf. Kovtyukh et al. 2006).

Comparison of V505 Per spectra with the high-resolution spectral atlases of Munari & Tomasella (1999) and Marrese et al. (2003) indicates a similar $\sim$F5V classification for the two components. The MK classification is a discrete one, and the range of temperatures covered by the F5V box (i.e. from F4.5V to F5.5V) is 6500 $\leq T_{\text{eff}} \leq 6650$ K according to recent calibration by Bertone et al. (2004). Similarly, the F5V box spans the color range $0.425 \leq B - V \leq 0.455$ following Popper (1980), Strain (1992) and Drilling & Landolt (2000). Our determination of the V505 Per color is $B - V = 0.410 \pm 0.023$. The 0.023 mag uncertainty is just the corresponding uncertainty in the Tycho ($B - V$)$_T$ color of the comparison star HD 14444, and does not include errors associated to the Bessel (2000) transformation from Tycho to Johnson’s system. It is worth noticing that M97 reports a $B - V = 0.43$ color for V505 Per (no uncertainty associated to the transformation from local to Johnson’s system is provided). Thus, we may conclude that spectral classification and photometric colors are mutually consistent and in agreement with results of atmospheric analysis. The wide intervals in $T_{\text{eff}}$ and color associated to a spectral type, as well as the uncertainties in color transformation from local to standard systems, argue in favor of our choice to adopt the temperature of the primary as derived by $\chi^2$ atmospheric analysis for the orbital solution. The accuracy of the latter speaks for itself, considering that it provides (a) the same surface gravity and $T_{\text{eff,1}} - T_{\text{eff,2}}$ as derived independently by the orbital solution, (b) the same metallicity as derived by fitting to theoretical isochrones and stellar evolutionary tracks, and that (c) the distance derived by adopting $T_{\text{eff,1}}$ from $\chi^2$ atmospheric analysis accurately match the Hipparcos distance.

It is worth noticing that the comparison of V505 Per spectra with synthetic ones and those of non-binary F5V field stars excludes the presence of emission line cores or veiling in the CaII H & K and far red CaII triplet lines. This would be the case for chromospheric active and/or spotted stellar atmospheres (e.g. Ragai et al. 2003), of the type induced by differential rotation in synchronized close binaries (e.g. Munari 2003). The wide orbital separation and slow synchronized velocities in V505 Per therefore agrees with the lack of emission cores in CaII lines.

7. Orbital solution

7.1. Orbital period stability

Our photometry provides three epochs of minima: a primary eclipse at HJD = 2 451 587.30641 ($\pm 0.00017$) and secondary eclipses at HJD = 2 451 779.40820 ($\pm 0.00016$) and 2 451 910.29094 ($\pm 0.00017$). We have combined them with the orbital ephemeris in Table 2 and the epochs of minima published by Kaiser et al. (1990), M97 and Demircan et al. (1997). The earliest of such minima dates back to 1903. No appreciable O–C trend is found, which means that the derived period is accurate and stable.

7.2. Initial parameters and modeling strategy

A simultaneous spectroscopic and photometric solution for V505 Per was obtained with the WD code (Wilson & Devinney 1971; Wilson 1998) in its WD98K93d version as developed by Milone et al. (1992), adopting the MODE-2 option, appropriate for detached binary stars. As a starting point in the iterative orbital solution, we imported the orbital parameters of M01 and the atmospheric parameters derived by $\chi^2$ analysis.
Limb darkening coefficients were taken from van Hamme (1993) for the appropriate metallicity, temperature, and gravity. A linear law for limb darkening is usually assumed for convective atmospheres (as is the case for F5V stars). Nevertheless, for check and completeness, we also re-ran full orbital solutions with logarithmic and square-root limb darkening laws as well as for metallicities $[\text{M}/\text{H}] = -1.0, -0.5, +0.0,$ and $+0.5$. The response of orbital solution to these changes was minimal, with orbital parameters varying by not more than their (quite small) formal errors. For final solution we retained the $[\text{M}/\text{H}] = -0.1$ metallicity derived by the $\chi^2$ atmospheric analysis and a linear limb-darkening law. The final adopted solution (cf. Table 2) converged to the following limb-darkening parameters (in the WD jargon):

\[
\begin{align*}
    x_{\text{bol},1} & = 0.660, \\
    x_{\text{bol},2} & = 0.666, \\
    x_{V,1} & = 0.425, \\
    x_{V,2} & = 0.426, \\
    x_{B,1} & = 0.521, \\
    x_{B,2} & = 0.522.
\end{align*}
\]

Driven by the lack of evidence of multiple reflection effects in the V505 Per lightcurve presented in Fig. 2, we ran the final orbital solution including only the inverse square law illumination. For sake of completeness, orbital solution tests were carried out including multiple reflections. Their inclusion did not improve the accuracy and convergence solution and therefore were considered no further.

Bolometric albedos ($A_{1,2}$) and exponents in the bolometric gravity brightening law ($g_{1,2}$) were set to 0.5 and 0.3, respectively, as are expected for convective envelopes (cf. Wilson 1998). Orbital solutions were carried out by testing various combinations of these parameters in the range $0.5 \leq A_{1,2} \leq 1.0$ and $0.3 \leq g_{1,2} \leq 1.0$ ($A$ and $g$ are expected to be unity for radiative envelopes), without improving accuracy.

7.3. The orbit

The final orbital solution we converged upon for V505 Per is presented in Table 2 and over-plotted to our observational data in Fig. 2. Formal errors to the solution are given. The last lines of Table 2 compare the original (ESA 1997) and revised (van Leeuwen 2007) Hipparcos trigonometric parallax and its 1σ error with the distance we derived from the orbital solution in the $E_{B-V} = 0.00$ case and $E_{B-V} = 0.01$ upper limit to the reddening affecting V505 Per. The rms of photometric data with respect to the orbital solution is 0.008 and 0.007 mag for $B_J$ and $V_J$ photometry, respectively. The rms of the measured radial velocities with respect to the orbital solution is 0.68 and 0.84 km s$^{-1}$ for the primary and secondary stars, respectively.

The final orbital solution rests on our radial velocities and photometry, augmented by inclusion of M97 photometry during eclipses (i.e. M97 photometric points from 0.95 to 0.05 and from 0.45 to 0.55 orbital phases), which helps to fill in the gaps in our lightcurves at ingress and egress from both eclipses. Inclusion of this subset of M97 data significantly reduced the formal errors on both stellar radii without altering the orbital solution. Furthermore, we better constrained $P$ and $t_0$ by importing the epoch of minimum given in M97 (HJD = 2 447 808.5998 ± 0.0001). We did not include M97 radial velocities and photometry outside eclipse phases because they would...
not improve the convergence of the orbital solution and instead would widen the formal errors (due to lower accuracy of M97 photometry and radial velocities, which are characterized by a dispersion of 0.01 mag in both photometric bands and 1.0 km s$^{-1}$ for both radial velocity curves with respect to the orbital solution). We also attempted orbital solutions by considering only $B$ or $V$ photometric data. This led to very similar orbital solutions, differing much less than their formal errors. They also both include in their error bars the adopted final orbital solution.

### 7.4. Physical parameters

All system parameters are well-constrained by the orbital solution in Table 2, particularly those most dependent on the radial velocities (i.e. $a$, $M_1$, $M_2$, $q$, and $V_γ$). Formal accuracies are 0.09 and 0.10\% on the masses, and 1.1 and 1.0\% on the radii. We found no evidence of a non-spherical shape, since $R_{\text{pole}}/R_{\text{ecl}} = 1.00$ for both stars.

The synchronized rotational velocities of the two stars would be 15.4 km s$^{-1}$ and 15.2 km s$^{-1}$. They are well within the error bars of the results of the $χ^2$ fit: $15.3 \pm 0.5$ km s$^{-1}$ and $15.4 \pm 1.0$ km s$^{-1}$ (see Sect. 6). We therefore conclude that both components of the binary rotate synchronously with the orbital motion.

Surface gravities and $T_{\text{eff}1} - T_{\text{eff}2}$ from the orbital solution (log $g_1 = 4.32 \pm 0.01$, log $g_2 = 4.33 \pm 0.01$, $T_{\text{eff}1} - T_{\text{eff}2} = 50$ K) are in excellent agreement with those from the $χ^2$ atmospheric fit (log $g_1 = 4.25 \pm 0.07$, log $g_2 = 4.25 \pm 0.06$ $T_{\text{eff}1} - T_{\text{eff}2} = 52$ K).

### 7.5. Distance to the system

To compute a distance to V505 Per from the orbital solution we adopted a bolometric correction $BC = 0.00$ for both components and a bolometric magnitude for the Sun $M_{\text{bol,0}} = 4.74$ from Bessell et al. (1998). We also assumed a standard $A_V = E_{B-V} \times 3.1$ reddening law and a color excess $E_{B-V} \leq 0.01$, as discussed in Sect. 5. The corresponding distance is $60.6 \pm 1.0$ km s$^{-1}$ for $E_{B-V} = 0.00$ and $59.7 \pm 1.0$ for $E_{B-V} = 0.01$ (cf. Table 2). The Hipparcos (ESA 1997) distance to V505 Per is given as $66 \pm 4$ pc. Recently, van Leeuwen & Fantino (2005) and van Leeuwen (2007) have performed a new reduction of the satellite data and produced a revised Hipparcos astrometric catalog. The revised Hipparcos distance to V505 Per (kindly communicated to us by van Leeuwen in advance of publication) is $61.5 \pm 1.9$ pc, in better agreement with our orbital solution than the original Hipparcos distance.

The literature lacks consensus for the bolometric magnitude of the Sun, the listed values spanning $M_{\text{bol,0}} = 4.72$ (Lang 2006) to $M_{\text{bol,0}} = 4.77$ (Bowers & Deeming 1984; see also Allen 1976; Böhm-Vitense 1984; Zombeck 1990). The effect of adopting them would be to shift the distance derived from the orbital solution by $\pm 1$ pc. The scatter in the literature is even larger for the bolometric correction. Although its definition is a straightforward one, there is some confusion resulting from the choice of a zero-point, as pointed out by Bessell et al. (1998). For guidance, the V505 Per distance would decrease by less than 1 pc when assuming $BC = -0.03$ from Popper (1980).

### 8. Comparison with theoretical stellar models

One of the most important issues of current stellar models is the extension of the convective core during the central H-burning stage: how much larger the convective core extension is with respect to the canonical prediction provided by the classical Schwarzschild criterion, i.e. the amount of convective core overshooting (cf. Cassisi 2004, and references therein).

The study of open clusters has shown that stellar models must allow for the occurrence of convective core overshooting in order to provide a satisfactory match to the observed CMDs (Kalirai et al. 2001, and references therein). On the other hand, a still unsettled issue concerns how much the convective core overshooting reduces with decreasing stellar mass (cf. Woo & Demarque 2001, for a detailed discussion).

Among open clusters, only those with a turn-off (TO) mass $\sim 1.2 M_\odot$ are useful tests in this respect, with M67 the main target of current investigations, in particular those of Sandquist (2004) and Vandenberg & Stetson (2004). Their main conclusion – supported by the results shown by P04 – was that the comparison between the CMD of M67 and theoretical isochrones seems to indicate that the extension of the overshooting region already has to be almost down to zero for masses $\sim 1.2 M_\odot$, at least for metallicities around solar. Due to current uncertainties in empirical estimates about cluster distance, reddening, and heavy-element abundances (cf. Vandenberg et al. 2007), this result needs independent confirmation.

In this context a relevant contribution can be provided by binary systems whose components have a suitable mass. This approach has already been adopted in the literature for some well-studied binaries, namely V459 Cas (Sandberg Lacy et al. 2004), TZ For (Vandenberg et al. 2006, and references therein), and AI Phe (Andersen et al. 1988; P04, and references therein). The masses derived above for the V505 Per components should
Fig. 3. Comparison of evolutionary tracks from various libraries (see the text for more details), with the observed parameters for the components of the binary V505 Per (filled circles). The values of the metallicity and helium content are given for the best-fitting evolutionary tracks. The BaSTI tracks have been computed on purpose for this paper for exactly the masses of the two components (1.2693 and 1.2514 \( M_\odot \)).

Fig. 4. As in Fig. 3, but only for the BaSTI models. Selected evolutionary models computed by neglecting the occurrence of convective core overshooting are also shown. The adopted initial metallicities are labeled.

Element diffusion in stellar interiors is a relevant issue that can confuse comparison between observed values and theoretical predictions. During the lifetime of a star, heavier nuclei tend to sink deeper within the star, while lighter ones migrate toward the surface. Thus, a star that has been formed homogeneously progressively decreases its surface metallicity while living on the main sequence. The BaSTI models, computed including element diffusion, show that the initial \([M/H] = -0.03\) metallicity decreases to \([M/H] = -0.13\) at the stellar surface for the \(\sim 0.9\) Gyr age of V505 Per. The Granada and Padova tracks do not account for the element diffusion. Their \([M/H]\) values in Fig. 3 therefore pertain to a model of initial homogeneous composition, kept constant during model computations. On the other hand, the Yonsei-Yale tracks account for He diffusion but not for metal diffusion. In spite of the unknown relation between initial and current metallicity for Padova, Granada, and Yonsei-Yale tracks, their ability to reproduce the basic physical parameters measured for V505 Per is nevertheless quite reasonable.

Figure 3 also shows that the V505 Per system is a not-significantly evolved binary system: the secondary star is still near to its zero-age main sequence location, while the primary component is only slightly more evolved.

It is worth noticing that all the evolutionary tracks plotted in Fig. 3 account for a very small amount of convective core overshooting (see quoted references for more details about the overshooting efficiency adopted by the various authors). To investigate the role of overshooting in greater detail, we computed a grid of BaSTI models for exactly the masses of the two components, with element diffusion but with null overshooting (cf. Fig. 4). These models require an higher initial metallicity \((Z = 0.0183)\) to fit the position of V505 Per components, and they predict a current surface metallicity \([M/H] = -0.09\) for V505 Per. Even if marginally within the error bar, this value is offset with respect to observed metallicity. More important, these canonical models without overshooting are not able to provide a
null for the AI Phe masses and very small, but not negligible, for V505 Per ones.

Before concluding, it is worth noticing that SB2 EBs with a larger difference in mass between the two components and older than V505 Per would be an even more stringent test of the amount of convective core overshooting. In fact, both components of V505 Per are still close to their zero-age main sequence, when the stellar radius does not depend much on the stellar age, which limits the use of the radius-mass diagram for constraining the evolutionary scenario. This is shown in Fig. 5. The comparison between the position of the two components of V505 Per with BaSTI isochrones computed with diffusion and overshooting provides the best match for an age of 0.905 Gyr, but a similar good fit can be obtained by adopting canonical models for a slightly lower age, although the two stellar models show a significant difference in age at the fitting point in the HR diagram. In Fig. 5 we have tried to similarly estimate the age of V505 Per using also the Victoria-Regina library of stellar models provided by Vandenberg et al. (2006) that accounts for convective core overshooting but neglects the occurrence of diffusive processes. In this case, the age of V505 Per would be ~0.80 Gyr.

Acknowledgements. We would like to thank the technical staff operating the 1.82m telescope in Asiago for their skilful assistance; L.A. Marschall and D.B. Williams for kindly communicating their published observational data in electronic form, F. van Leeuwen for the revised Hipparcos parallax of V505 Per prior to publication, and M. Valentini and R. Barbon for useful discussions. We warmly thank D. Vandenberg for providing his own evolutionary models.

References

ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Kaiser, D. H. 1989, AAVSO, 18, 149
Kovtyukh, V. V., Sofian, B., Bienayme, O., Mishenina, T. V., & Belik, S. I. 2006, MNRA, 371, 879

Fig. 5. Top panel: comparison between the observed masses and radiii of the components of the eclipsing binary V505 Per (filled circles and 1σ errors), and the predictions of both an overshooting and a canonical isochrone from the BaSTI library, for the labeled choices for the metallicity and age. Bottom panel: as above, but for the overshooting isochrones provided by the Victoria-Regina library.

similar age to both components of V505 Per: the age difference between the stellar models fitting the two stars is ~0.11 Gyr. On the other hand, BaSTI stellar models that include overshooting fit the location of both V505 Per components in the HR diagram very well, their current metallicity is closer to observed value, and their age difference at the fitting point is about 0.05 Gyr. Therefore, we conclude that, at the masses of the V505 Per components, some convective core overshooting must be present.

To quantify its exact amount, we computed BaSTI models for different efficiencies of the convective core overshooting. The efficiency is usually defined in terms of the parameter \(\alpha_{OV}\) that gives the length – expressed as a fraction of the local pressure scale height \(H_P\) – crossed by the convective cells in the convective stable region outside the Schwarzschild convective boundary. The BaSTI models providing the best fit to observations have efficiencies \(\alpha_{OV} = 0.093\) and 0.087 for the 1.2693 \(M_\odot\) primary component and its 1.2514 \(M_\odot\) companion, respectively. This suggests that stars with masses \(\sim 1.2 \ M_\odot\) have an overshooting region that is already very small, supporting the conclusions by P04 for the system AI Phe and by Vandenberg et al. (2006, and references therein) for the stars belonging to the cluster M67. Even if coarsely similar, the mass of the two components of AI Phe are lighter than those of V505 Per: 1.231 +1.190 vs. 1.269 +1.251 \(M_\odot\). Both pairs are in the critical range where the efficiency of convective overshooting changes with the stellar mass\(^1\), so it could really be the case that overshooting is already

\(^1\) Regardless of the initial metallicity, P04 adopt \(\alpha_{OV} = 0.20 \times H_P\) for \(M \geq 1.7 \ M_\odot\), \(\alpha_{OV} = 0\) for \(M \leq 1.1 \ M_\odot\), and \(\alpha_{OV} = (\frac{M}{1.1 \ M_\odot} - 0.9)/4\) for 1.1 \(M_\odot\) \(\leq M \leq 1.7 \ M_\odot\).