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Astronomy
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Astrophysics

Evaluating Gaia performances on eclipsing binaries

IV. Orbits and stellar parameters for SV Cam, BS Dra and HP Dra

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Abstract. This is the fourth in a series of papers that aim both to provide reasonable orbits for a number of eclipsing binaries and to evaluate the expected performance of Gaia of these objects and the accuracy that is achievable in the determination of such fundamental stellar parameters as mass and radius. In this paper, we attempt to derive the orbits and physical parameters for three eclipsing binaries in the mid-F to mid-G spectral range. As for previous papers, only the H_P, V_T, B_T photometry from the Hipparcos/Tycho mission and ground-based radial velocities from spectroscopy in the region 8480−8740 Å are used in the analyses. These data sets simulate the photometric and spectroscopic data that are expected to be obtained by Gaia, the approved ESA Cornerstone mission to be launched in 2011. The systems targeted in this paper are SV Cam, BS Dra and HP Dra. SV Cam and BS Dra have been studied previously, allowing comparisons of the derived parameters with those from full scale and devoted ground-based investigations. HP Dra has no published orbital solution. SV Cam has a β Lyrae type light curve and the others have Algol-like light curves. SV Cam has the complication of light curve anomalies, usually attributed to spots; BS Dra has non-solar metallicity, and HP Dra appears to have a small eccentricity and a sizeable time derivative in the argument of the periastron. Thus all three provide interesting and different test cases.

Key words. surveys – stars: fundamental parameters – binaries: eclipsing – binaries: spectroscopic

1. Introduction

Gaia is a Cornerstone mission re-approved by ESA in May 2002. It is intended to perform three important tasks: (a) micro-arcsec astrometry; (b) photometry in 4 broad and 11 intermediate passbands and (c) $R \sim 11\,500$ resolution spectroscopy in the $\lambda\lambda$8480−8740 Å wavelength region. The completeness limit for both astrometry and photometry is anticipated to be $V \sim 20$ mag. Each target star is expected to be measured around a hundred times during the five year mission life-time, in an operational mode similar to that of *Hipparcos*. The astrophysical goals and technical specifications of the mission can be found, among others, in ESA's *Concept and Technology Study* (ESA SP-2000-4), Gilmore et al. (1998), Perryman et al. (2001) and in the proceedings of Gaia conferences edited by Straižys (1999), Bienaymé & Turon (2002), Vansevićius et al. (2002), Munari (2003) and Turon & Perryman (2004).

In Paper I of this series, Munari et al. (2001), we began the process of evaluating the expected performance by Gaia in dealing with eclipsing binaries and the accuracy with which fundamental stellar parameters such as masses, radii and temperatures can be determined. The number of eclipsing binaries to be discovered by Gaia is expected to be $\sim 10^6$, of which $\sim 10^5$ are likely to be double-lined. This is orders of magnitude larger than all the SB2 eclipsing binaries so far investigated from ground-based observations (e.g. Andersen 1991, 2002), with the addition of stunningly precise astrometric parallaxes to be used in close-loop iterative refinement of parameters involved in the orbital modeling. Furthermore, Gaia's discoveries will be a boon to ground-based observatories by providing opportunities to follow up discoveries with synoptic, multi-wavelength campaigns for many decades thereafter. It is therefore of great interest to test Gaia's capabilities for eclipsing binary investigations, with the aim of contributing to the fine tuning of mission planning and preparing analysis strategies for the massive data flow that will follow.

Paper I outlined the framework of the project and adopted methodologies, and the reader is referred to it (and references therein) for further details. In short, Hipparcos/Tycho

Table 1. Eclipsing binary targets. Data from the Hipparcos Catalogue. $B_{\rm T}$ and $V_{\rm T}$ are Tycho mean and $H_{\rm P}$ are median magnitude values.

Names		Sp.	$H_{\rm P}$	$B_{\rm T}$	$V_{\rm T}$	$\alpha_{\rm J1991.25}$ (h m s)	$\delta_{\rm J1991.25}$ (° ′ ″)	Parallax (mas)	μ_α^* (mas yr^{-1})	μ_δ (mas yr^{-1})
SV Cam	HIP 32015	G5	9.4377	10.204	9.411	06 41 18.89	+82 16 03.8	11.77 ± 1.07	+41.58 ± 0.95	−152.91 ± 1.17
BS Dra	HIP 98118	F5	9.2320	9.638	9.183	19 56 28.79	+73 36 57.6	4.80 ± 0.74	−7.95 ± 0.68	−5.06 ± 0.72
HP Dra	HIP 92835	G5	8.0888	8.679	8.032	18 54 53.46	+51 18 29.1	12.45 ± 0.72	+23.35 ± 0.77	+83.40 ± 0.90

photometry is adopted as a fair representation of typical Gaia photometric data, and devoted ground-based observations obtained with the Asiago 1.82 m telescope are used to simulate expected Gaia spectroscopic data. The latter are obtained in the same Gaia wavelength region ($\lambda\lambda$8480−8740 Å), at a higher resolution ($R = 20\,000$) than is planned for the satellite ($R = 11\,500$) to compensate for the lower number of recorded radial velocity points (~30 vs. the ~100 expected from Gaia). Gaia data will obviously largely surpass the Hipparcos/Tycho photometry adopted here in terms of number of epochs, number and diagnostic capabilities of the photometric bands, and therefore even better performance than we have found here can be expected from the satellite.

2. The targets

As in the previous papers in the series (Munari et al. 2001, Paper I; Zwitter et al. 2003, Paper II; and Marrese et al. 2004, Paper III), we have selected both newly discovered eclipsing binaries (i.e., those lacking spectroscopic and photometric orbit solutions in the literature), as well as binaries with already published orbital solutions (although not with data in the Gaia spectral range) to permit a comparison. In our analysis, to properly simulate Gaia, we have ignored all preexisting ground-based data, our solutions resting exclusively on Hipparcos/Tycho photometry and Gaia spectroscopy as collected in Asiago. Similarly, we have intentionally avoided selecting initial parameters for our modeling trials from published solutions. The three targets for this fourth paper in the series are SV Cam, BS Dra and HP Dra. The first one is still a controversial object in spite of hundreds of papers devoted to it, while some orbital modeling has been already attempted for the second. The third one is a relatively unstudied eclipsing system. Some basic quantities are given in Table 1.

SV Cam. This is reported in literature as a mid-F to mid-G system with 0.6 day period and a light-curve of the β Lyrae type. There is a long history of observations and analyses of this system, with extensive photometry (e.g., Kjurkchieva et al. 2000; Patkós 1982; Zeilik et al. 1988), and spectroscopy (e.g., Hempelmann et al. 1997; Kjurkchieva et al. 2002; Lehmann et al. 2002; Özeren et al. 2001; Pojmański 1998; Popper 1996; Rainger et al. 1991; Rucinski et al. 2002). Most authors have interpreted asymmetries in the light curves and the variation in them as due to spots. With the inclusion in models of high latitude, long-lasting spots, it is not surprising that there is substantial disagreement about the spectral type of the hotter component, with estimates ranging from F5 to G8 (Popper 1996). The difference in eclipse depths shows that the secondary star, as we refer to the component eclipsed at secondary minimum, is much fainter than the primary (cf. Fig. 2) and therefore it is not a surprise that it is not easily detectable and measurable in our spectra. A similar conclusion was reached by Popper (1996), based on the photometry of Zeilik et al. (1988) and by Patkós & Hempelmann (1994). Consequently we include in the analysis only the radial velocity curve of the hotter, more luminous component. This means that, from our data, the mass ratio is not independently determined by spectroscopic means, and its determination must depend on the curvature of the maxima in the light curves, which are relatively noisy. This system thus becomes an interesting test case for Gaia analyses, both because of activity and because of the low luminosity of the secondary.

BS Dra. This system is a partially eclipsing Algol system with similar components and a period of ~3.4 days. The Gaia-like spectra reveal two stars of nearly identical spectral types and luminosities. A comparison with the spectral atlases by Munari & Tomasella (1999), Marrese et al. (2003) and Zwitter et al. (2004) obtained in the same wavelength region at the same ($R = 20\,000$) resolution, indicates that the the spectral type is ~F3V and a metallicity lower than solar ([Fe/H] ~ −0.4). Previous studies were carried out by Popper (1971), Güdür et al. (1979) and by Russo et al. (1981).

HP Dra. This system was discovered as an eclipsing binary by Hipparcos, but the reported period (6.67 days) is incorrect. We find from our spectroscopic data that this Algolid system has a period of ~10.761 days. A similar value has been found also by Kurpinska-Winiarska et al. (2000). A comparison with the above cited spectral atlases suggests a spectral type of ~F9V and a solar metallicity. The lack of data at minimum light in the Hipparcos and Tycho data sets proved to be a severe problem in modeling this system, as discussed below.

3. The data

3.1. Spectroscopic observation and radial velocities

The Gaia simulating spectroscopic observations were obtained with the Echelle and CCD spectrograph on the 1.82 m telescope operated by Osservatorio Astronomico di Padova atop Mt. Ekar (Asiago), the same facility and instrument as used for the targets of the previous papers in this series. The same wavelength range (8480−8740 Å), reciprocal linear dispersion

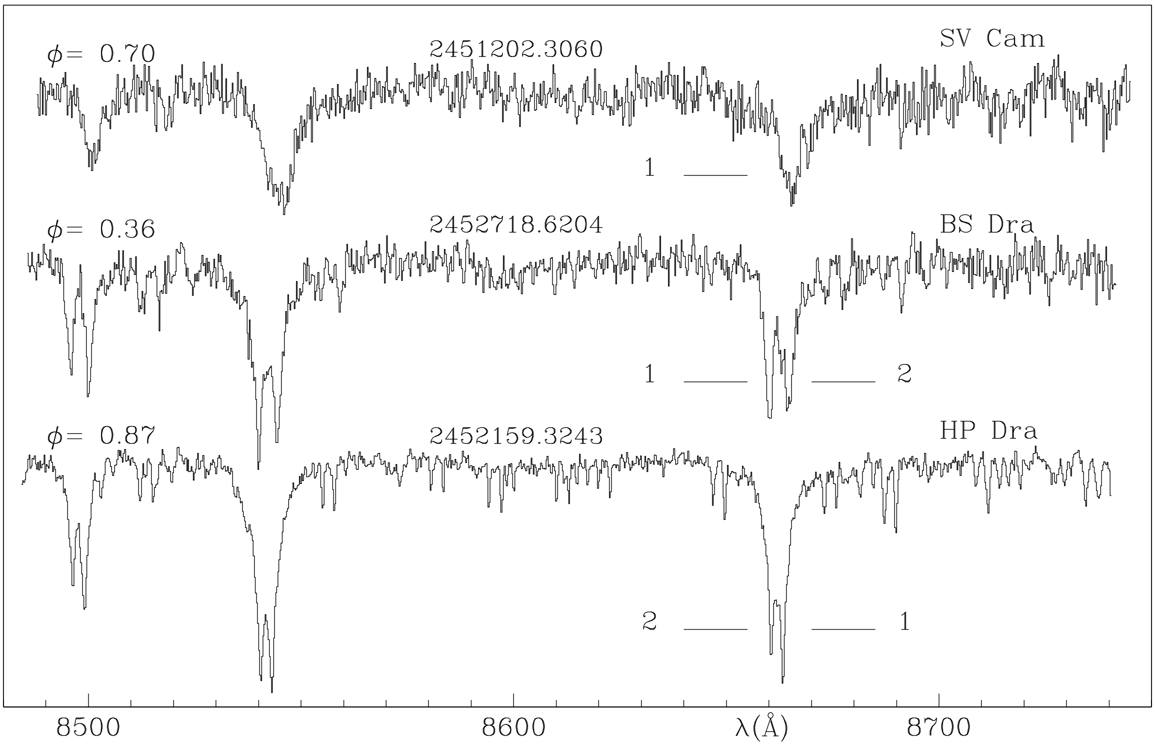

Fig. 1. Sample of the spectra of each of the variables discussed here. Note the lack of visible features of a secondary component in the SV Cam spectrum contrary to some controversial claims in literature. The spectra are shifted to heliocentric corrected wavelengths.

(0.25 Å/pix), and resolution ($R = \lambda/\Delta\lambda = 20\,000$) as for the data reported in Papers I, II, and III similarly apply. Further details of the spectrograph and the spectroscopy can be found in these earlier papers. The diary of observations of the stars discussed in this paper appear in Table 3. Sample spectra in the Ca II triplet region for each of the three systems are shown in Fig. 1. The number of spectroscopic observations and their accuracy are summarized in Table 2.

3.2. Hipparcos/Tycho photometry

Hipparcos and Tycho epoch photometry was retrieved from CDS. The conversion of Hipparcos and Tycho photometric quantities to the Johnson-Cousins system, follows, as in previous papers, the transformation equations provided in the Hipparcos Catalogue (ESA 1997):

$$V_J = V_T - 0.090 \times (B-V)_T, \tag{1}$$

$$(B-V)_J = 0.850 \times (B-V)_T. \tag{2}$$

Details on the number of observations and their accuracy are given in Table 2. The relationships among $(B-V)$, spectral type, temperature, and bolometric correction were taken from Popper (1980).

4. The modeling software

We began by using the Wilson-Devinney base program (Wilson 1998), with modifications noted by Kallrath et al. (1998) and Kallrath & Milone (1999). Since Paper I, the University of Calgary version has further evolved to wd98k93h, a Unix version which not only makes use of Kurucz stellar atmosphere models applied to each grid element, but also has sufficiently numerous grid elements that transit eclipses by objects as small as a Saturn-sized planet can be modeled. This version of wd98k93 has been incorporated into the WD2002 package that runs under Linux or Microsoft Windows. The WD2002 package permits self-iterated, damped least squares differential corrections, as did its predecessors, and now permits looping over a range of a single parameter, such as q or i, to improve optimization in highly correlated cases.

The program requires tables of the ratio of Kurucz atmospheres to black-body fluxes in each of the H_P, B_T and V_T passbands as well as in a square passband centered on the Ca II triplet region, used in connection with the radial velocity curves. In addition the limb-darkening coefficients for these passbands are needed. The former were provided by C. R. Stagg and MDW, and the latter by W. Van Hamme

Table 2. Summary of Hipparcos (H_P) and Tycho (B_T, V_T) photometric data and ground based radial velocity observations: number of data, mean S/N and mean standard error (magnitudes for photometry, km s^{-1} for radial velocities) for each of the three program stars.

	Hip		Tycho			*RV*		
	N	$\sigma(H_P)$	N	$\sigma(B_T)$	$\sigma(V_T)$	N	S/N	$\sigma(RV)$
SV Cam	113	0.021	167	0.34	0.31	35	40	10
BS Dra	88	0.016	143	0.20	0.19	27	36	6
HP Dra	81	0.012	122	0.11	0.09	29	62	3

Table 3. Journal of radial velocity data. The columns give the Heliocentric Julian Day and the radial velocities in km s^{-1} for each of the three systems discussed in this paper.

SV Cam		BS Dra			HP Dra		
HJD	RV$_1$	HJD	RV$_1$	RV$_2$	HJD	RV$_1$	RV$_2$
2451153.5702	+30.2	2451508.3202	+50.4	−45.0	2451209.6211	+23.1	−55.0
2451153.5907	+39.4	2451621.5349	−91.7	+95.1	2451225.6116	−57.2	+21.2
2451155.5316	+80.3	2451625.5801	−35.3	+39.6	2451275.5469	+47.7	−82.6
2451165.5141	+98.2	2451626.5578	+95.0	−99.4	2451339.4595	+40.4	−72.9
2451166.5492	−48.9	2451714.4217	+77.5	−78.5	2451508.2954	−55.7	+31.3
2451167.5215	−53.6	2451924.6621	−79.7	+76.6	2451621.5048	+24.5	−58.1
2451197.5554	+94.7	2452008.4671	−103.0	+96.7	2451625.5429	−78.9	+42.7
2451197.5707	+110.9	2452008.4953	−98.4	+96.5	2451626.5378	−62.1	+29.6
2451202.2627	+81.8	2452008.5268	−94.0	+101.0	2451713.5058	−38.4	+4.9
2451202.3060	+95.6	2452008.5566	−98.5	+96.7	2451714.3941	−0.8	−25.7
2451202.3281	+108.2	2452008.5825	−94.6	+96.5	2451798.5415	−67.2	+36.5
2451202.3500	+114.2	2452067.4857	+89.7	−93.1	2451895.7119	−57.1	+29.5
2451202.3722	+97.4	2452159.4621	−76.9	+74.4	2451896.7169	−31.3	−0.6
2451202.3943	+66.9	2452212.3968	+62.0	−72.7	2451923.7076	−5.5	−27.5
2451202.4171	+60.6	2452213.3489	−81.6	+83.5	2451924.6898	−44.1	+12.1
2451202.4389	+42.0	2452361.5769	−95.4	+95.4	2452035.4688	−65.2	+29.9
2451202.4823	−39.9	2452362.6732	+30.5	−30.3	2452067.3668	−67.6	+37.2
2451202.5043	−43.6	2452363.6169	+83.0	−86.5	2452159.3243	+32.9	−62.5
2451202.5264	−65.1	2452448.3906	−22.1	+17.1	2452330.5797	+48.4	−77.7
2451202.5489	−86.9	2452503.5665	−41.3	+40.6	2452330.6017	+48.0	−77.5
2451202.5709	−108.1	2452503.6137	−33.0	+32.2	2452361.5442	+33.8	−65.3
2451202.5931	−137.2	2452504.4569	+93.2	−93.4	2452447.4419	+30.6	−64.4
2451202.6152	−143.0	2452504.4697	+92.5	−94.0	2452504.3760	+13.5	−42.6
2451202.6372	−137.3	2452504.4825	+92.6	−93.9	2452504.4016	+9.5	−42.5
2451202.6591	−121.5	2452716.6742	+95.0	−100.0	2452504.4146	+9.4	−42.6
2451202.6811	−109.8	2452718.6045	−74.5	+77.7	2452504.4301	+9.5	−42.6
2451894.4084	+118.7	2452718.6304	−74.1	+73.5	2452691.6105	−69.0	+39.2
2451895.4319	−62.3				2452691.6365	−69.1	+34.8
2451895.4508	−46.1				2452719.5736	+12.0	−44.6
2451895.4672	−27.7						
2451895.4859	+6.1						
2451955.5472	+111.6						
2451955.5735	+110.4						
2451983.3746	+101.5						
2451983.4004	+110.9						

together with the correct limb darkening coefficients for appropriate effective temperatures, surface gravities and metallicities. Additionally a two-way coefficient interpolator was provided by D. Terrell.

The usual operation begins with reasonable guesses for the initial parameters based primarily on the spectrosccopic data and secondarily on the colour indices of the Tycho observations. With WD2002, we try to ascertain the correct global minimum region of parameter space, by means of simplex iterations which explore all the parameter space. Then final parameters are found by iterated damped least-squares DC runs. When convergence is achieved, the process is concluded. The uncertainties in the orbital parameters quoted in Table 4 come from final modeling check runs carried out with wd98k93h.

5. Analyses

5.1. Procedure

All modeling runs were carried out with time-ordered data, so that period and epochs were adjustable parameters. Initial periods and epochs were determined from the spectroscopy, as were the spectral types of the components (except for the undetectable secondary star of SV Cam, as we note in the previous section). Typically, the following parameters were adjusted: semi-major axis (a), systemic radial velocity (V_γ), inclination (i), temperature of the secondary star, the star at inferior conjunction at the designated primary minimum, (T_2), the modified Kopal potentials of each star ($\Omega_{1,2}$), the mass ratio ($q = M_2/M_1$), the passband luminosity in units of 4π (L_1)

Table 4. Modeling solutions. The uncertainties are formal mean standard errors of the solution. The last four rows give the rms of the observed points from the derived orbital solution. The estimation of error in the adopted temperature for the primaries is ~150 K.

parameter (units)	SV Cam	BS Dra	HP Dra
Period (days)	0.59307337±0.00000036	3.3640154±0.0000051	10.76154±0.00009
Epoch (HJD)	2447107.3024±0.0012	2448502.30336±0.00030	2447942.264±0.008
a ($R_\odot$)	3.41±0.13	12.94±0.25	26.48±0.43
V_γ (km sec^{-1})	−9.2±1.4	−0.5±1.5	−16.07±0.63
$q = \frac{M_2}{M_1}$	0.750±0.053	0.986±0.038	0.988±0.028
i (deg)	73.8±1.4	89.54±0.14	87.87±0.14
e	0.0	0.0	0.057±0.010
ω (radians)			1.14±0.15
$d\omega/dt$ (radians day^{-1})			−0.000156±0.000080
T_1 (K)	5848	6618	6000
T_2 (K)	4061±176	6626±153	6386±207
$\Delta(T_1-T_2)$ (K)	1787±93	−8±25	−386±143
Ω_1	4.29±0.33	10.14±0.14	23.81±0.65
Ω_2	3.39±0.10	10.15±0.46	31.1±2.6
$\Re_1$ ($R_\odot$)	0.98±0.10	1.415±0.022	1.172±0.034
$\Re_2$ ($R_\odot$)	1.18±0.12	1.396±0.071	0.887±0.086
M_1 ($M_\odot$)	0.862±0.099	1.294±0.079	1.099±0.023
M_2 ($M_\odot$)	0.646±0.087	1.276±0.092	1.102±0.026
$M_{bol,1}$	4.69±0.25	3.34±0.10	4.18±0.13
$M_{bol,2}$	5.86±0.29	3.37±0.15	4.51±0.24
log g_1 (cgs)	4.40±0.14	4.248±0.040	4.341±0.034
log g_2 (cgs)	4.11±0.15	4.254±0.075	4.584±0.086
σ_1 (avg.wt.)	±0.0545	±0.0109	±0.0130
$\sigma_{RV,1,2}$ (km sec^{-1})	±0.66	±0.19, 0.15	±0.17, 0.21
σ_{B_T} (mag)	±1.25		
σ_{V_T} (mag)	±0.79		
σ_{H_P} (mag)	±0.26	±0.17	±0.09

and, as already mentioned, the epoch (T_0) and period (P). Additional suites of parameter adjustments were carried out for BS Dra and HP Dra. Convective atmosphere values for gravity brightening and albedo coefficients $g = 0.32$ and $A = 0.500$, respectively, were assumed for stars similar to or cooler than the Sun, and radiative atmosphere values of 1 for both g and A were assumed for higher temperature stars. A full-precision grid number of 30 was used for all stars.

5.2. Solutions

5.2.1. SV Camelopardalis

The temperature adopted for the hotter star, T_1 = 5848 K, was based on a compromise. The spectra in the Ca II triplet region indicates a temperature ~ 5800 K or cooler. The Tycho colors, however, support an slightly earlier spectral type. The star is rapidly rotating, evolved and sports numerous surface spots (cf. Kjurkchieva et al. 2002, and references therein) that are responsible for a significant uncertainty when comparing with template field stars that usually do not have spotty surfaces and rotate more slowly. The adopted 5848 K corresponds to a spectral type of G2-G3, as suggested also by Rainger et al. (1991). The temperature of the secondary component is determined solely from the light curve analysis.

The single radial velocity curve and the Hipparcos light curve provide the bulk of the modeling input information because of large scatter in the Tycho light curves. The analysis was performed fully on two different models. The first model relies on only the radial velocity and H_P measurements, while the second includes in addition Tycho B_T and V_T data. Although the formal fitting error is smaller for the first model, the determination of the mass ratio in this case depends strongly on the curvature of the light curve outside of eclipse; therefore, notwithstanding the greater scatter in the Tycho data, three light curves may provide a better determination of this critical quantity than one, with appropriate curve weights relating to the intrinsic scatter in the light curves.

The absolute parameters and other derived quantities for the adopted second model are given in Table 4 and the fittings are shown in Fig. 2. SV Cam is indeed a challenging single-lined spectroscopic binary, nevertheless we obtained a reasonable solution with accuracies of ~13% in the masses and ~10% in the radii. The cooler star contributes little to B and V light curves and even in the Ca II triplet region contributes less than 15%, according to our model, which indicates that it is very close to its Roche lobe.

The photometric solution of Albayrak et al. (2001) rests on a temperature of 6440 K for the hotter component and sets of 242 observations each for BVR passbands. While their

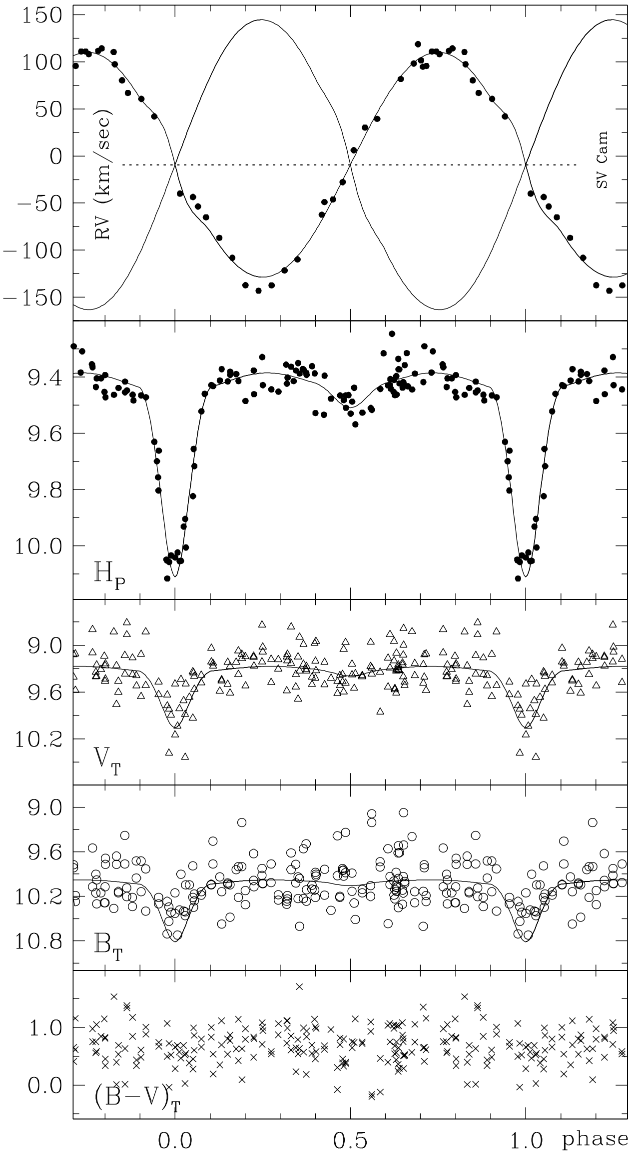

Fig. 2. Hipparcos H_P and Tycho V_T, B_T, $(B-V)_T$ lightcurves and the radial velocity curve of SV Cam folded onto a period $P \sim 0.593$ days. The lines represent the solution given in Table 4.

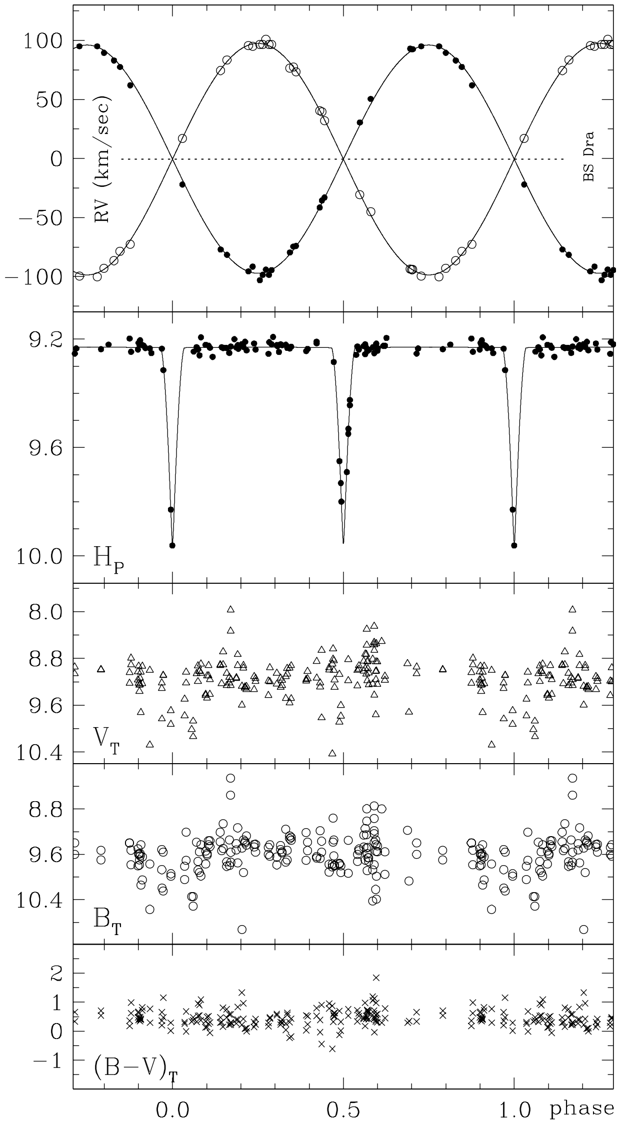

Fig. 3. Hipparcos H_P and Tycho V_T, B_T, $(B-V)_T$ lightcurves of BS Dra folded onto a period $P = 3.364$ days. The lines represent the solution given in Table 4.

period and orbital separation are quite close to ours in Table 4 (they quote $P = 0.593071$ days and $a = 3.87 \pm 0.07\ R_\odot$), their mass ratio ($q = 0.56$) and inclination ($i = 89.6 \pm 0.8$) are quite inconsistent with ours. There are many possible reasons for the differences: inclusion or exclusion of RV data, different light curve data, different limb-darkening coefficients, and the need for treatment of asymmetries. The Hipparcos/Tycho light curves present no explicit evidence of asymmetries that would justify spot modeling, which was therefore not included in our analyses, highlighting a possible shortcoming in Gaia studies of active surface, single lined eclipsing binaries.

Our assessments of the SV Cam system are based exclusively on the treatment of our adopted input data. As our anonymous referee has pointed out, these assessments are not necessarily correct. Indeed, higher quality ground-based data on SV Cam and higher resolution spectroscopy has already indicated that the secondary component has been observed and that the mass ratio is very likely 0.6 (somewhat different from our determination, described below). Although neither the precision in the Hipparcos-Tycho photometry nor the spectral resolution in our RV data match those of other studies, our modeling tools permit distortion in both curves to be treated adequately, given any discernible spot regions. Therefore our failure to find spot regions may be an indication of a relatively "quiet" interval in the system's behaviour, when the activity was below the detection level of the photometry. In such a case, a mismatch may arise because of differences in activity level at the separate epochs at which the data were acquired. The variability impacts our conclusions, and divergence from previous ground-based investigations indicates that the results for SV Cam are very important for GAIA mission planning.

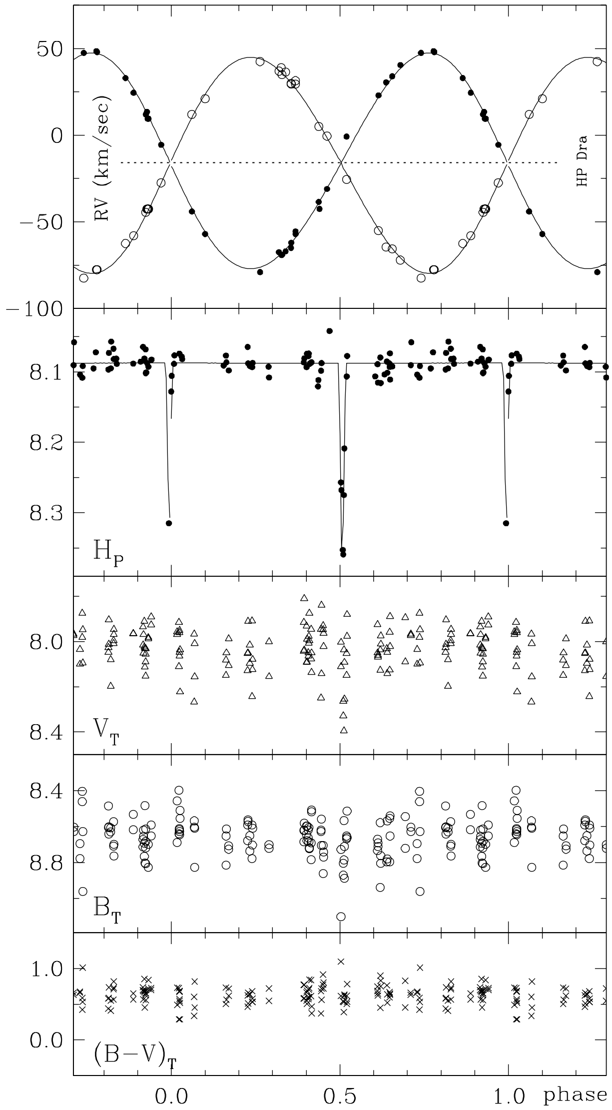

Fig. 4. Hipparcos H_P and Tycho V_T, B_T, $(B-V)_T$ lightcurves of HP Dra folded onto a period $P = 10.761$ days. The lines represent the solution given in Table 4.

5.2.2. BS Draconis

The inspection of the spectra of BS Dra suggests an F3 spectral type and a metallicity lower than solar. The temperature of the primary was fixed to 6619 K (Popper 1980) and the modeling was carried out with [Fe/H] = 0.0, −0.5, and −1.0 metallicities. Although scarcely significant, the fitting was seen to be slightly better for the −0.5 metallicity, as expected for its proximity with the [Fe/H] = −0.4 estimated from our spectra.

The Tycho B_T and V_T light curves are so noisy that they essentially add nothing to the modeling, and were excluded from the analysis. Dropping the information on color variation does not affect the accuracy of the solution given the almost identical temperature for the two components. Moreover, the additional information about the curvature at the light curve maxima was not important to the determination of the mass ratio, unlike the case for SV Cam. It was found that the logarithmic form of the limb-darkening appeared to improve the fits slightly, and these were retained for the analyses.

There are very few Hipparcos/Tycho photometric points covering the eclipse phases. One of the eclipses in the H_P light curve has no data points within 10% of minimum value and the other has only three points altogether, all of which are on the descending branch. Yet, if we assume symmetry, the shape and the depths are defined, even if not with great precision. The accuracy of the Hipparcos data for this star ($\sigma_{H_P} = 0.016$) is high enough to permit the few points in the light curve minima to be highly weighted to insure that the computed light curve fits them closely. All other points were individually weighted inversely to their standard errors, and scaled. The determination of the modified Kopal potentials and thus the radii depend critically on this close-fitting process.

Both the mass ratio and temperature ratios are near 1. During modeling, both the mass ratio and the temperature ratio switched repeatedly across this boundary. Solutions with either star as the primary component produce nearly the same fit error, but the adopted converged solution has the epoch given in the Hipparcos catalogue. This epoch is, however, half a cycle different from that of Popper (1971). The alternate model, where the components are interchanged, converged only with the assumption of a small eccentricity, but under this circumstance, the argument of periastron, ω, could not be determined. The stellar and system parameters are given in Table 4 for the adopted model with [Fe/H] = −0.5. Our results can be compared with those of Russo et al. (1981), who used an earlier version of the Wilson-Devinney program to analyze previously published *BV* observations, probably those of Güdür et al. (1979). Their values for period, orbital separation, inclination and modified Kopal potentials are close (even if not always within 1σ level) to our results.

5.2.3. HP Draconis

HP Dra revealed itself as the most challenging of the 12 objects in this series of papers. The HP Dra components appear to be similar in temperature and luminosity. Because of their great scatter and sparseness at minimum light, we removed the Tycho data from the modeling sets, even though the minima are weakly discernible, and modeled the Hipparcos and radial velocity data alone. There are even fewer data points in the minima for HP Dra than there are for BS Dra (9 vs. 11). The placements of the data points at minimum light are critical to the determination of the radii and potentials of the stars. Although the precision of the Hipparcos data is good ($\sigma_{H_P} = 0.012$), it still proved very difficult to achieve a final, fully convergent solution. The major trouble is that the non-coeval light and radial velocity curves (about 10 years elapsed between Hipparcos and Asiago observations) appear to be not fully compatible. If this problem is indeed connected to the non-coeval data sets, this would not be a problem for Gaia where all astrometric, photometric and spectroscopic observations will strictly share the same epochs. Several strategies were attempted to deal with this circumstance.

1. Initially, the radial velocities were modeled independently of the photometry, with assumed temperatures of ~6000 K for each component, appropriate for the spectral type (~F9)

and with equal luminosities. This yielded elements that produced an optimal fit to the radial velocity data, although the assumptions about some of the adopted parameters (such as $\Omega_{1,2}$) could not be rigorously checked. The RV modeling indicated the need to adjust the eccentricity and argument of periastron. A slight difference in mass between the components was also found. The parameters which were adjusted in these trials were: e, ω, V_γ, q, T_0, and P, which are, respectively, the eccentricity, argument of periastron, system radial velocity, mass ratio (M_2/M_1), epoch, and period.

2. Further attempts at modeling the combined light and RV curves with these parameters fixed were also attempted. The results gave minima which were systematically too shallow. Attempts to weight points in the minima more heavily also failed to produce convergence.
3. Adjustment of the third light, which failed to improve the fitting errors.
4. The phased $H_{\rm P}$ light curve data appear to be modulated by a rough sinusoid at maximum light. This effect is also seen in the 1989–1990 V light curve of Kurpinska-Winiarska et al. (2000). Their light curve shows relatively little scatter when phased with a similar but independently determined period. One possibility is a reflection effect of some sort. This is not likely, given the scale of the orbit and similarity of the temperatures of the component stars, but it was investigated anyway. Introduction of a more complicated reflection effect option in the Wilson-Devinney program also failed to provide adequate fittings to the $H_{\rm P}$ light curve, even when the size of the primary star was initially increased (by decreasing its potential). The computing time increases greatly when this option is adopted in treating an eccentric orbit case, such as HP Dra, so we performed only one trial with the enhanced (2-pass) reflection effect. The fitting was not quite as good as for the simple reflection case, in which the illuminating star is assumed to be a point source and only one reflection is treated.
5. Because intrinsic variation may also be affecting the light curve, we attempted to introduce a large starspot onto the visible hemisphere of the component at inferior conjunction during eclipses: either a hot spot on the “secondary” star visible at primary minimum (phase 0.0) or a cool, spot on the “primary” star visible at secondary minimum (phase 0.5). With spots centered on a longitude of 180° and with a radius of 90°, the modulation was adequately fit but a solution with this artifice still failed to converge, in either spot placement case. The existence of a spot on stars just slightly hotter than the Sun would not be surprising, but we have not found lower fit errors by assuming convective envelopes in these components (although not every model was tested), thus star spots appear to be both unnecessary and insufficient to model this system, given only the current suite of data that have been modeled.
6. An investigation of variability in the residuals failed to show periodicities differing slightly from the derived eclipsing period, viz., over the range 3.364000000 to 3.364033141 days.
7. Adjustment of dP/dt equally failed to produce an improvement.
8. On the contrary, adjustment of the dω/dt term did produce an improvement in fitting of both light curve and radial velocity curves (when modeled simultaneously). This finally yielded a converged solution that allowed us to combine into a coherent picture both photometric data and radial velocities in spite of the 10 year elapsed between them. This is the adopted solution presented in Table 4.

Even though the system seems to be at or just beyond the data-paucity limit for analysis of partially eclipsing systems, we were able to achieve a fully convergent and self-consistent solution. It is worth repeating here that the two major problems encountered in the analysis of HP Dra (i.e., non-coevality of photometric and radial velocity curves and paucity of the photometric points covering the eclipse phases) will not pertain to Gaia (cf. Katz et al. 2004). The satellite will obtain simultaneous spectroscopic and photometric data during the planned 5 year mission, the photometry at about ~355 independent epochs (cf. Munari et al. 2004) compared to the ~100 Hipparcos epochs.

Nevertheless, the resulting model cannot be said to be a truly accurate one. With only three points in one of the minima (and only one point near minimum value), it is clear that the relative surface brightnesses of the two stars cannot be obtained from the Hipparchos photometry alone, the depth providing less information than the branches of the minima, which the model must fit. In fact the light curve produced by Kurpinska-Winiarska et al. (2000) shows the secondary minimum to be the shallower. This suggests that there is indeed a temperature difference between the components, but in the opposite sense from that found here. The large uncertainty in the temperature difference is therefore reasonable. The difference in the potentials is determined largely by the phases of contact and is therefore also uncertain, but the outer contacts are not badly defined by the data. Our model indicates that there is a small orbital eccentricity, in rough agreement with a preliminary value ($e = 0.043$) found by Kurpinska-Winiarska et al. (2000). As far as we know, there has been no evidence presented for a third body in the system, but we could not achieve convergence in the modeled data set without adjustments of the apsidal motion. For HP Dra, complete light- and radial velocity curves exist and the full analysis promised by Kurpinska-Winiarska et al. (2000) is awaited with great interest. If the apsidal motion mentioned here can be confirmed, additional photometry across a range of bandpasses, times of minima, and spectroscopy, should be pursued.

It is possible that further spot modeling on a fuller data set will be able to resolve the question of the true nature of HP Dra. For now, we indicate only the possibility of apsidal motion, and the limitations for GAIA models given our current suite of tools to test that mission’s capability.

6. Conclusions

The distances derived from the orbital solutions are compared to those from the Hipparcos Catalogue in Table 5. Despite the fairly large uncertainties in the fundamental parameters, the derived distances to all three systems agree with the astrometric

Table 5. Comparison between the Hipparcos distances and those derived from the parameters of the modeling solution in Table 4 assuming an uncertainty of ±150 K in the temperature adopted for the primary in each system.

	Hipparcos (pc)	This paper (pc)
SV Cam	85_{79}^{93}	87 ± 8
BS Dra	208_{181}^{246}	183 ± 9
HP Dra	80_{76}^{85}	73 ± 4

distances from Hipparcos-Tycho within or very close to their one-sigma errors.

The overall agreement confirms similar findings in previous papers in this series and together they reinforce confidence in the overall quality and astrophysical potential of orbital modeling of eclipsing binary data to be obtained by Gaia.

As in other papers in this series, we have been discriminate in the use of the Tycho mission data, because of its limited precision, and effectively used them in the present paper only for the SV Cam system for reasons mentioned earlier. For fainter systems, the Tycho data are useful only for the limited mean color information that they provide. For the BS Dra and HP Dra systems, they proved unsuitable for modeling purposes.

Although we conclude that the results for the three systems presented here are plausible, in context with existing, higher quality data other than our adopted data suite, we note the possibility of systematic error in the analyses based on photometry only from Hipparcos and Tycho missions, even when these are coupled with spectroscopy that closely matches GAIA's. In particular, the results for SV Cam, and possibly also for HP Dra, point to the need to diagnose spot regions in systems detected by GAIA. Of course, it is possible that a system will appear "quiet" during times of data acquisition, but GAIA will acquire all its types of data at the same instant, so they will be self-consistent, at least. Moreover, the suite of photometric passbands recently selected for GAIA permits the discrimination of system properties from photometric indices of passbands across a broad region of the spectrum, making the color effects of spotted regions easier to detect.

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