A&A 404, 333–340 (2003)
DOI: 10.1051/0004-6361:20030446
© ESO 2003

Astronomy & Astrophysics

Evaluating GAIA performances on eclipsing binaries

II. Orbits and stellar parameters for V781 Tau, UV Leo and GK Dra

T. Zwitter[1], U. Munari[2,3], P. M. Marrese[2,4], A. Prša[1], E. F. Milone[5], F. Boschi[2], T. Tomov[6], and A. Siviero[2]

[1] University of Ljubljana, Department of Physics, Jadranska 19, 1000 Ljubljana, Slovenia
[2] Osservatorio Astronomico di Padova, Sede di Asiago, 36012 Asiago (VI), Italy
[3] CISAS, Centro Interdipartimentale Studi ed Attività Spaziali dell'Università di Padova, Italy
[4] Dipartimento di Astronomia dell'Università di Padova, Osservatorio Astrofisico, 36012 Asiago (VI), Italy
[5] Physics and Astronomy Department, University of Calgary, Calgary T2N 1N4, Canada
[6] Centre for Astronomy, Nicholaus Copernicus University, ul. Gagarina 11, 87-100 Torun, Poland

Received 7 February 2003 / Accepted 18 March 2003

Abstract. The orbits and physical parameters of three close, double-lined G0 eclipsing binaries have been derived combining H_P, V_T, B_T photometry from the Hipparcos/Tycho mission with 8480–8740 Å ground-based spectroscopy. The setup is mimicking the photometric and spectroscopic observations that should be obtained by GAIA. The binaries considered here are all of G0 spectral type, but each with its own complications: V781 Tau is an overcontact system with components of unequal temperature, UV Leo shows occasional surface spots and GK Dra contains a δ Scuti variable. Such peculiarities will be common among binaries to be discovered by GAIA. We find that the values of masses, radii and temperatures for such stars can be derived with a 1–2% accuracy using the adopted GAIA-like observing mode.

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

1. Introduction

GAIA is a challenging Cornerstone mission re-approved by ESA last May for a lunch by around 2010. It is aimed to provide micro-arcsec astrometry, 10-band photometry and medium resolution 8480–8740 Å spectroscopy for a huge number of stars, with completeness limits for astrometry and photometry set to $V = 20$ mag. Each target star will be measured around a hundred times during the five year mission life-time, in a fashion similar to the highly successful operational mode of *Hipparcos*. The astrophysical and technical guidelines of the mission are described in the ESA's *Concept and Technology Study* (ESA SP-2000-4), in the papers by Gilmore et al. (1998) and Perryman et al. (2001), and in the proceedings of conferences devoted to GAIA and edited by Straižys (1999), Bienaymé & Turon (2002), Vansevičius et al. (2002) and Munari (2003).

In Paper I of this series, Munari et al. (2001), we have started to provide reasonable orbits for a number of new eclipsing binaries and to evaluate expected performances of GAIA on eclipsing binaries with an emphasis on the achievable accuracy of derived fundamental stellar parameters like masses and radii. The expected number of eclipsing binaries to be discovered by GAIA is $\sim 4 \times 10^5$. Some 10^5 of these will be characterized as double-lined in GAIA spectral observations. This is a huge number, many orders of magnitude larger than the total of SB2 eclipsing binaries so far investigated from ground-based observations (cf. Andersen 1991; Batten et al. 1989). Perhaps the orbits and stellar parameters could be derived from GAIA observations at a few percent error only for a few percent of them. But this still represents a two-orders of magnitude increase compared to all ground-based observing campaigns during the last century. Data obtained by GAIA should be able to provide reasonable solutions as ground-based follow-up campaigns will be very time consuming. It is therefore of great interest to investigate the expected performances of GAIA on eclipsing binaries. The purpose of this series of papers is to contribute to the fine tuning of the last details in the mission planning as well as to define the strategy to analyze the massive spectroscopic and photometric data flow on eclipsing binaries that is completely unprecedented. In the meantime, this series of papers will focus on eclipsing binaries unknown or poorly studied in the literature so far.

Paper I outlines the framework of the project and adopted methods, and the reader is referred to it (and the references therein) for details. In short, Hipparcos/Tycho photometry is adopted as a fair simulation of typical GAIA photometric data. The satellite spectroscopic data is simulated by devoted ground-based observations obtained with the Asiago 1.82 m + Echelle + CCD, set up to mimic the expected GAIA spectra. Precision of the results of our investigation can be

---

Send offprint requests to: T. Zwitter,
e-mail: `tomaz.zwitter@fmf.uni-lj.si`

Table 1. Programme eclipsing binaries. Data from the Hipparcos Catalogue. H_P, B_T, V_T are out-of-eclipse median values.

Name		Spct.	H_P	B_T	V_T	α_{J2000} (h m s)	δ_{J2000} (° ′ ″)	parallax (mas)	dist (pc)	μ_α (mas yr^{-1})	μ_δ (mas yr^{-1})
V781 Tau	HIP 27562	G0	8.71	9.41	8.74	05 50 13.12	+26 57 43.4	12.31 ± 1.35	81^{91}_{73}	−0.084 ± 0.004	−0.091 ± 0.004
UV Leo	HIP 52066	G0	9.20	9.78	9.00	10 38 20.77	+14 16 03.7	10.85 ± 1.16	91^{103}_{83}	−0.007 ± 0.004	0.010 ± 0.004
GK Dra	HIP 82056	G0	8.92	9.19	8.81	16 45 41.19	+68 15 30.9	3.37 ± 0.69	297^{373}_{246}	−0.013 ± 0.002	0.014 ± 0.002

Table 2. Number of Hipparcos (H_P) and Tycho (B_T, V_T) photometric data and ground based radial velocity observations, their mean S/N and standard error for the three programme stars. Error for radial velocity is in km s^{-1}.

	Hip		*Tyc*			*RV*		
	N	$\sigma(H_\mathrm{P})$	N	$\sigma(B_\mathrm{T})$	$\sigma(V_\mathrm{T})$	N	S/N	$\sigma(RV)$
V781 Tau	61	0.014	81	0.18	0.15	41	35	8
UV Leo	96	0.015	150	0.21	0.17	29	30	10
GK Dra	124	0.017	179	0.15	0.15	35	45	3

considered as a lower limit to the accuracy obtainable from GAIA at the given source S/N, because (a) GAIA will observe in many more photometric bands than Hipparcos/Tycho and with far higher accuracy even in the narrow bands, thus both increasing light-curve mapping as well as accuracy of information on stellar temperature, limb-darkening and reddening; and (b) GAIA will acquire at least twice as many spectra per star than considered here due to obvious limitations in the telescope access time.

2. Target selection

Similar to Paper I we have selected both some brand-new eclipsing binaries (i.e. without a spectroscopic or photometric orbit solution in the literature) as well as binaries with already published orbital solutions (however not in the GAIA spectral range) that can serve as an external comparison. Their basic properties are quoted in Table 1.

V781 Tau. This is a G0 over-contact (∼23%) binary ($P \sim 0.4$ days) with stars of unequal temperature. It is known to undergo period changes (Donato et al. 2003, in preparation), interpreted by Liu & Yang (2000) as shrinkage of the secondary. A spectrophotometric orbit of moderate quality has been published by Lu (1993).

UV Leo. This is a G0 short period binary ($P = 0.6$ days) showing intrinsic variations caused by cool spots on the secondary component (cf. Mikuž et al. 2002). Orbital parameters have been derived from *UBV* photometric data by Frederik & Etzel (1996) and from 4430–6800 Å spectroscopic observations by Popper (1997).

GK Dra. This is a newly discovered eclipsing binary, the only existing information in the literature being *BV* photometric monitoring by Dallaporta et al. (2002). The authors showed that the photometric period listed in the Hipparcos Catalogue (∼17 days) is wrong (the actual one being 9.97 days), and that the secondary star has intrinsic variability of a $\delta-$Sct type.

3. Observations

As explained above we use Hipparcos photometry as a lower limit to the photometric information expected from GAIA. The accuracy of Hipparcos photometry is lower, but the number of observations of each star with only a limited number of points sampling the eclipses is similar. Table 2 gives details on the number of observations of each star and their accuracy.

All spectral observations were obtained in the same mode as in Paper I, i.e. at 0.25 Å/pix dispersion and ∼0.50 Å resolution over the 8480–8740 Å wavelength range (therefore a resolving power $R = \lambda/\triangle\lambda = 17\,000$).

The spectroscopic observations have been collected with the Echelle + CCD spectrograph on the 1.82 m telescope operated by Osservatorio Astronomico di Padova atop of Mt. Ekar (Asiago). A 2.2 arcsec slit width was adopted to meet the resolution requirement. The detector has been a UV coated Thompson CCD with 1024 × 1024 square pixels of 19 μm size. The GAIA spectral range is covered without gaps in a single order by the Asiago Echelle spectrograph. The actual observations however extended over a much larger wavelength interval (4550–9600 Å). Here we will limit the analysis to the GAIA spectral interval; the remaining, much larger wavelength domain will be analyzed elsewhere together with devoted multi-band photometry from ground based observations. The spectra have been extracted and calibrated in a standard fashion using IRAF software packages running on a PC under the Linux operating system. The high stability of the wavelength scale of the Asiago Echelle spectrograph has been discussed in Paper I. The results of radial velocity measurements are given in Table 3.

4. Modeling

We use an upgrade of the setup described in Paper I. The binary modeling code (Wilson 1998) was combined with van Hamme's limb darkening coefficients (van Hamme 1993), a fitting package, a graphical user interface and utilities like reddening corrections to form PHOEBE (Prša 2003). The package is able to run on any Unix platform. It may constitute the first step toward automated solution-finding routines that will be needed to interpret the vast number of binary systems to be observed by GAIA. All results were independently derived also by the WD98K93 code (Milone et al. 1992) and WD2002 code

Table 3. Journal of radial velocity data. The columns give the spectrum number (as from the Asiago 1.82 m Echelle + CCD log book), the heliocentric JD, and the heliocentric radial velocities (in km s^{-1}) for both components. An asterisk marks the spectra with a too severe blending of the lines for a meaningful measurement of radial velocities of each component. The latter have not been used in modeling of the binaries.

V781 Tau				UV Leo				GK Dra			
#	HJD	RV_1	RV_2	#	HJD	RV_1	RV_2	#	HJD	RV_1	RV_2
30731*	2451153.53313	36.4	36.4	31837	2451209.51624	−151.4	199.7	31848	2451209.60066	−71.9	59.9
30788	2451154.52849	253.0	−66.6	31878	2451210.43364	166.6	−172.8	32100	2451225.52478	74.2	−59.3
30802*	2451154.61290	23.9	23.9	31952	2451216.49289	116.0	−73.3	32775	2451274.54782	80.3	−63.4
30852	2451155.49988	207.5	−15.8	31968*	2451217.46653	18.9	18.9	32817	2451275.52285	76.5	−50.3
30867*	2451155.63872	28.9	28.9	32012	2451221.51594	−156.3	171.3	32869	2451279.53257	−70.8	67.5
30913	2451156.52626	160.1	−61.6	32085	2451225.43269	179.4	−158.2	32960	2451339.41309	−72.3	63.2
31171*	2451165.47882	53.4	53.4	32658	2451269.44151	−110.2	128.3	33115	2451402.34909	27.5	−11.0
31229*	2451166.51393	49.1	49.1	32663	2451269.47415	−149.6	175.1	33978	2451564.59894	76.9	−60.0
31278	2451167.48421	−120.6	88.9	32668	2451269.50678	−164.4	206.5	34153	2451589.57475	−79.3	63.3
31327*	2451169.58493	8.0	08.0	32802	2451275.44879	−121.7	133.1	34182	2451592.56867	50.8	−39.5
31460*	2451197.50043	−0.3	−0.3	32807	2451275.48073	−147.3	183.3	34226	2451593.57209	85.7	−63.9
31462*	2451197.51640	11.8	11.8	33967	2451564.53178	99.9	−98.0	34382	2451621.43916	5.1	5.1
31622	2451201.26374	−176.8	116.1	34228	2451593.60814	−112.1	137.0	34418	2451624.51494	72.6	−54.4
31624	2451201.28454	−152.1	104.3	34410	2451624.41908	159.9	−142.5	34453	2451625.49986	46.8	−33.2
31626*	2451201.30692	8.7	8.7	34413	2451624.46813	150.9	−177.8	34503	2451626.51482	4.5	4.5
31628*	2451201.32782	31.5	31.5	34416	2451624.49141	157.4	−128.5	35762	2451798.51275		5.2
31630*	2451201.34668	46.9	46.9	34443	2451625.42998	−102.6	141.3	36093	2451895.65844	−5.0	−5.0
31632	2451201.36542	173.6	−22.8	34501	2451626.49333	−98.4	153.7	36143	2451896.68512	−34.2	33.4
31634	2451201.38402	228.4	−52.1	36082*	2451895.53608	−31.8	−31.8	36172	2451923.62582	79.5	−56.2
31636	2451201.40272	254.7	−61.8	36084*	2451895.55506	54.9	−54.3	36286	2451924.63312	48.1	−35.8
31638	2451201.42120	265.0	−66.9	36087	2451895.60196	79.4	−91.6	36413	2451951.71656	55.3	−44.3
31640	2451201.44007	239.2	−53.0	36089	2451895.62120	106.4	−106.8	36437	2451952.52896	82.0	−62.2
31642	2451201.45878	191.9	−37.0	36095	2451895.68774	153.0	−152.5	36501	2451954.61109	46.6	−30.0
31644*	2451201.48908	42.4	42.4	36133	2451896.56836	−151.1	148.9	36533	2451955.60739	−3.8	−3.8
31646*	2451201.50783	31.5	31.5	36135	2451896.58704	−169.7	155.1	36558	2451983.57775	74.2	−55.2
31648*	2451201.52638	17.7	17.7	36140	2451896.64222	−134.7	138.5	36811	2452067.40354	−72.7	59.5
31650	2451201.54527	−143.3	99.8	36142	2451896.66113	−136.5	117.1	37930	2452300.54093	44.5	−31.4
31652	2451201.56386	−169.6	120.3	36278	2451924.52603	141.9	−178.4	37955	2452302.58732	77.8	−64.0
31654	2451201.58275	−187.5	128.3	36386	2451951.51048	156.3	−199.1	38392	2452361.47712	82.8	−63.4
31667	2451202.28749	−188.7	119.7					38394	2452361.50350	81.8	−61.8
31682	2451202.46289	265.5	−76.4					38518	2452387.46484	−80.4	69.2
34483	2451626.31285	227.7	−51.6					38536	2452388.48135	−56.8	46.4
34485	2451626.33501	259.7	−65.3					38543	2452389.49614	0.0	0.0
34487	2451626.35703	248.8	−61.0					38561	2452447.46833	−77.9	64.9
37488	2452242.53303	−181.8	121.1					38579	2452448.36282	−53.6	46.9
37497	2452242.70637	271.2	−67.4								
37601	2452271.35705	184.5	−71.5								
37627	2452272.38422	207.0	−61.1								
37680*	2452277.40348	15.7	15.7								
37821	2452280.46476	−191.9	133.3								
38165	2452330.49815	−176.4	112.0								

(Kallrath et al. 1998) that are briefly described in Paper I. We found that the results are in agreement.

The usual approach to binary star modeling is to use only relative photometry obtained in each filter. Depths of eclipses in different filters constrain the ratio of the stellar temperatures, while the absolute temperature scale is tuned by judging the primary star temperature from the system colour.

In our case both stars are of similar brightness and the light curves are quite noisy. This requires some modifications to the usual approach. Hipparcos observed in three filters.

Table 4. Modeling solutions. The uncertainties are formal mean standard errors to the solution. The last four rows give the standard deviation of the observed points from the derived orbital solution.

parameter (units)	V781 Tau			UV Leo			GK Dra		
Period (days)	0.34490857	±	0.0000001	0.600086	±	0.000001	9.9742	±	0.0002
Epoch (HJD)	2447962.46572	±	0.00016	2448500.560	±	0.001	2452005.56	±	0.03
a ($R_\odot$)	2.4478	±	0.002	3.957	±	0.087	28.92	±	0.35
V_γ (km s^{-1})	30.44	±	0.10	3.9	±	3.1	1.68	±	0.67
$q = \frac{m_2}{m_1}$	2.278	±	0.028	0.917	±	0.027	1.244	±	0.020
i (deg)	66.80	±	1.04	83.07	±	0.91	86.07	±	0.18
e	0.0			0.0			0.084	±	0.013
ω (deg from a)							175.4	±	1.4
T_1 (K)	6390	±	11	6129	±	67	7100	±	70
T_2 (K)	6167	±	10	5741	±	59	6878	±	57
Ω_1	5.640	±	0.05	5.024	±	0.090	12.26	±	0.21
Ω_2	5.640	±	0.05	4.093	±	0.074	13.69	±	0.24
R_1 ($R_\odot$)	0.759	±	0.007	0.973	±	0.024	2.431	±	0.042
R_2 ($R_\odot$)	1.111	±	0.007	1.216	±	0.043	2.830	±	0.054
M_1 ($M_\odot$)	0.510	±	0.006	1.210	±	0.097	1.460	±	0.066
M_2 ($M_\odot$)	1.150	±	0.027	1.110	±	0.100	1.810	±	0.109
$M_{\mathrm{bol},1}$	4.950	±	0.025	4.590	±	0.094	1.960	±	0.075
$M_{\mathrm{bol},2}$	4.280	±	0.020	4.390	±	0.113	1.770	±	0.072
$\log g_1$ (cgs)	4.380	±	0.012	4.540	±	0.053	3.830	±	0.033
$\log g_2$ (cgs)	4.410	±	0.016	4.310	±	0.055	3.790	±	0.041
$\sigma_{RV,1,2}$ (km s^{-1})	13.8			17.6			2.71		
$\sigma(B_\mathrm{T})$ (mag)	0.193			0.228			0.187		
$\sigma(V_\mathrm{T})$ (mag)	0.173			0.227			0.199		
$\sigma(H_\mathrm{P})$ (mag)	0.020			0.028			0.028		

The observations obtained in the broad band H_P filter have an acceptable accuracy, while those in the Tycho experiment's B_T and V_T bands are generally very noisy. We use the absolute system colours at quarter phase to fix the absolute temperature scale. The transformation between the Tycho and Johnson systems is the same as in Paper I:

$$V_\mathrm{J} = V_\mathrm{T} - 0.090 \times (B-V)_\mathrm{T} \tag{1}$$

$$(B-V)_\mathrm{J} = 0.85 \times (B-V)_\mathrm{T}. \tag{2}$$

Temperatures of both stars are similar, so the temperatures of the stars, T_1, T_2 and their radii R_1, R_2 are connected to the surface-weighted effective temperature of the source at quarter phase T_{1+2} by the relation:

$$R_1^2 T_1^4 + R_2^2 T_2^4 = \left(R_1^2 + R_2^2\right) T_{1+2}^4. \tag{3}$$

First the Tycho colour index at quarter phase of the model fits to the B_T and V_T light curves was transformed to the Johnson system (Eq. (2)) and the effective temperature T_{1+2} was determined. Modeling of the better quality H_P band observations yielded the temperature ratio and, by use of Eq. (3), also the absolute temperatures of the two stars. The process was reiterated several times to reach a self-consistent solution.

Some colour calibrations proposed recently (Bessell 2000) differ from Eq. (2) and cause effective temperature offsets of ~100 K. We will comment on the changes of the results if these relations were used in the Discussion.

5. Results

Table 4 quotes the derived system parameters together with their formal errors. Table 5 compares the derived distances to the astrometric results from Hipparcos. The data and the curves from the model solutions are plotted in Figs. 1–3.

We note that model fits are generally acceptable. The differences are chiefly due to noise in the data and to some degree due to intrinsic variability of the stars. A limited number of epochs and their long timespan make modeling of transient phenomena such as stellar spots unfeasible. This will generally be also the case with data obtained by GAIA. The results were obtained assuming the stars are co-rotating. Next we discuss in turn the results for each of the objects.

5.1. V781 Tau

V781 Tau is an overcontact binary with different primary and secondary temperatures. Light curve modeling fixes the quarter phase magnitudes ($\Phi = 0.75$) to $V_\mathrm{T} = 8.56$ and $B_\mathrm{T} = 9.16$. This corresponds to the colour index $(B-V)_\mathrm{T} = 0.60$ or

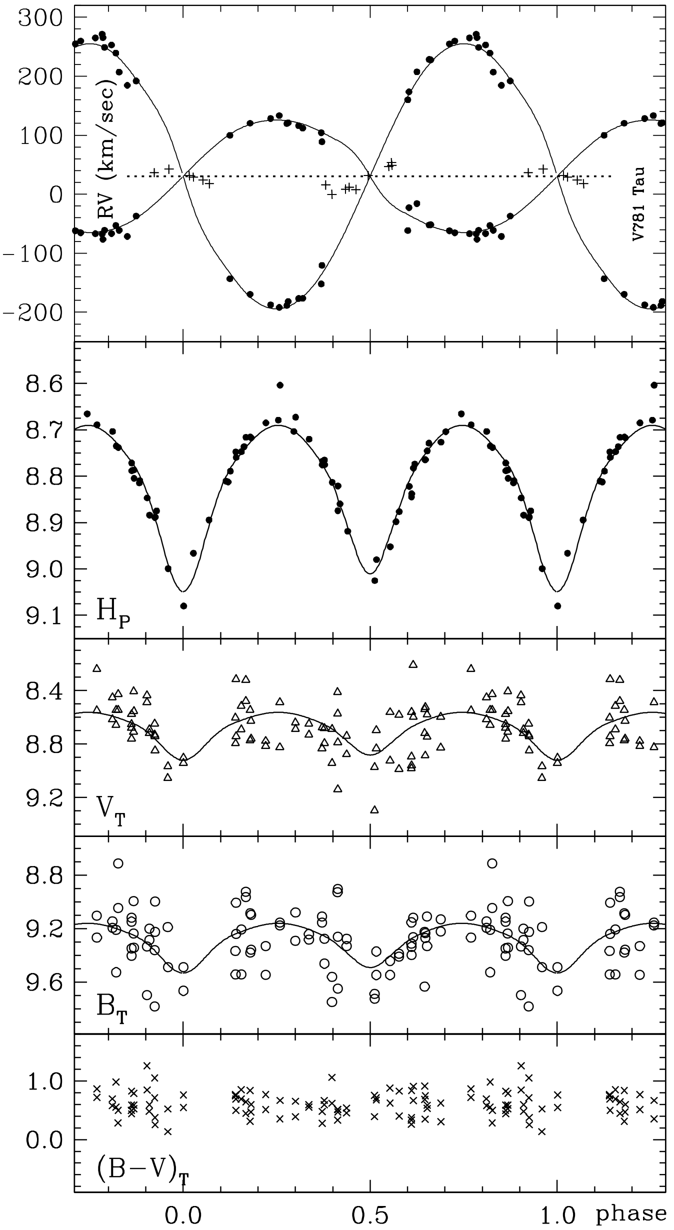

Fig. 1. Hipparcos H_P and Tycho $V_T, B_T, (B-V)_T$ lightcurves of V781 Tau folded onto the period $P = 0.34490857$ days. Radial velocity measurements in the GAIA spectral interval from Table 3 are given on the top, with "+" signs marking blended spectral lines that were not used for modeling. The curves represent the solution given in Table 4.

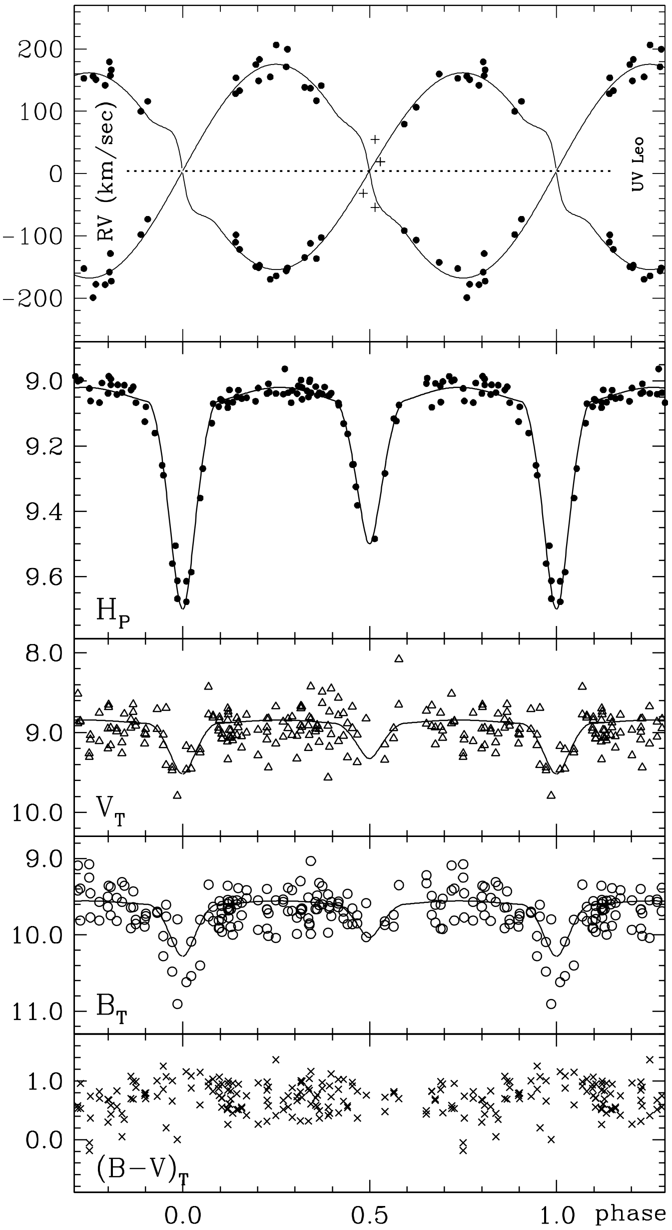

Fig. 2. Hipparcos H_P and Tycho V_T, B_T, $(B-V)_T$ lightcurves of UV Leo folded onto the period $P = 0.600086$ days. Radial velocity measurements in the GAIA spectral interval from Table 3 are given on the top, with "+" signs marking measurements around primary eclipse that were not considered in modeling. The curves represent the solution given in Table 4.

$(B-V)_J = 0.51$ (Eq. (2)) which gives $T_{1+2} = 6240$ K. This result was used to constrain the temperatures of the two stars through Eq. (3). Note that the magnitudes quoted in the Hipparcos catalogue (Table 1) would give somewhat different colours. However these magnitudes are just a suitable mean of all observations, also the ones close to the photometric eclipses. Therefore it is correct to use the quarter phase light curve fit and not the mean colours.

Spectroscopic observations determine absolute size of the system and individual masses as a function of the system inclination. A detailed reflection treatment was used to compute the photometric curves. The H_P light curve constrains relative sizes and temperature ratio of both stars. We found the system is actually filling its Roche lobes up to the L_1 point. The stars are of unequal temperature ($T_1 - T_2 \sim 220$ K). This difference was explained by mass transfer between the stars and the corresponding gravitational energy release (Liu & Yang 2000). A small period decrease ($dP/P = -5.0 \times 10^{-11}$) was also claimed to be an effect of mass transfer. We note that any mass lost from the system through the L_2 point would carry away roughly twice the mean value of the specific angular momentum. Mass loss through the L_2 point can therefore decrease the total angular momentum of the system, so it may be partially responsible for shortening of the orbital period. The value of the time

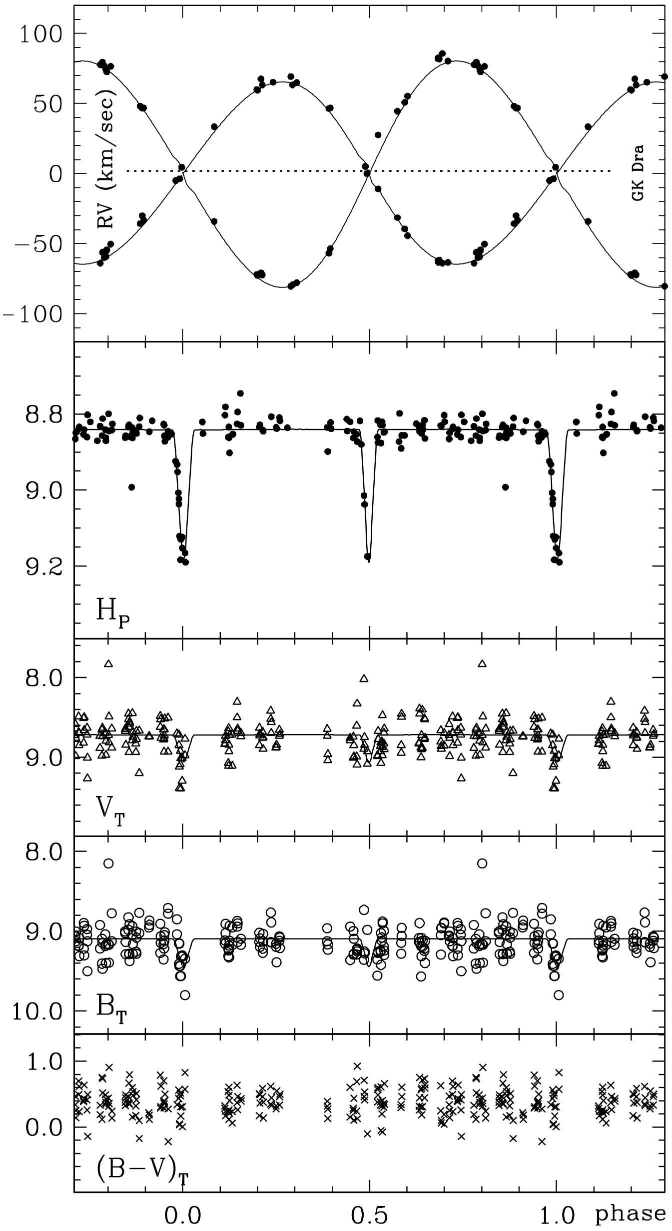

Fig. 3. Hipparcos H_P and Tycho V_T, B_T, $(B{-}V)_T$ lightcurves of GK Dra folded onto the period $P = 9.9742$ days. Radial velocity measurements in the GAIA spectral interval from Table 3 are given on the top. The curves represent the solution given in Table 4.

derivative is too small to be detectable from data used in this study.

Lu (1993) published a spectrophotometric study roughly at the same accuracy level as reported in Table 4. The values of individual parameters are generally consistent, with some differences possibly arising from the simplified software he used for modeling. In particular he adopted lower effective temperatures ($T_{1,2}$ = 5950, 5861 K) but with a large error bar of 200 K. Therefore the system in his analysis turns out to be fainter and at a smaller distance (72 pc).

We note that the formal error bars on temperatures as given by the WD98 code can be increased due to systematic effects. True uncertainty can reach 100 K, increasing the uncertainty on the distance (Table 5) to 4.5% or 3.6 pc. Temperatures of both stars may be also influenced by reddening. V 781 Tau lies just 0.2° from the galactic plane. One may expect $E(B - V) = 0.09$, and $A_V = 0.3$ mag (Perry & Johnston 1982). In our calibration the effective temperature T_{1+2} would raise to 6540 K and the bolometric magnitude of the system would be brighter by 0.33 mag. Note that this brightening almost cancels out with the value of the total extinction. So reddening has little influence on the distance of the system reported in Table 5.

Table 5. Comparison between the Hipparcos distances and those derived from the parameters of the modeling solution in Table 4. Only formal errors quoted in Table 4 were taken into account. As explained in the text the actual distances may have a bit larger uncertainties.

	Hipparcos (pc)	this paper (pc)
V781 Tau	81^{91}_{73}	81 ± 1.0
UV Leo	91^{103}_{83}	92 ± 6
GK Dra	297^{373}_{246}	313 ± 14

5.2. UV Leo

UV Leo is a close binary with a pronounced spot activity that is expected to be common between G/K type binaries to be observed by GAIA. The spots cause vertical offsets in the brightness of the object on a time-scale of weeks to months (Mikuž et al. 2002). Such intrinsic variability may be contributing to the scatter of H_P observations in Fig. 2. Magnetic activity may be also responsible for part of the scatter of the radial velocity curves ($\sigma_{RV1,2}$ = 17.6 km s^{-1}, Table 4). In fact the Ca II lines from the secondary on JD 2 451 896 show hints of multi-component profiles, typical for spotted stars. This structure, though below the level suitable for detailed analysis in our (and usually also GAIA's) coverage of the Ca II lines, obviously increases the scatter of derived radial velocities.

The fits to the V_T and B_T curves give a quarter phase colour $(B - V)_T = 0.72$, corresponding to $(B - V)_J = 0.61$. This is consistent with the colours derived by Popper (1997). For main sequence stars this colour index translates into T_{1+2} = 5900 K. This constraint was adopted during our spectrophotometric model fitting.

Popper (1997) published a spectrophotometric solution deriving the average masses, radii and temperatures of both stars. Here we derive the parameters also for individual stars. The results are generally consistent.

5.3. GK Dra

Similar to UV Leo, GK Dra also features intrinsic variability of its components. The variability is however not caused by spots but by a likely δ-Sct variability on the secondary star (Dallaporta et al. 2002). This variability has an amplitude of ~0.05 mag, so it is partially responsible for the scatter in the H_P curve in Fig. 3. The V_T and B_T curves are very noisy. Still they provide an average quarter phase colour $(B - V)_T = 0.39$, corresponding to $(B-V)_J = 0.33$ and effective temperature $T_{1+2} = 7000$ K. The photometry to be obtained by GAIA will be of much higher accuracy ($\sigma \sim 0.001$ mag) than Tycho observations. This will provide for accurate colour information also during eclipses and therefore constrain the temperature of either star.

Hipparcos catalogue lists an orbital period of 16.96 days. Dallaporta et al. (2002) showed by a devoted ground-based observation campaign that the true period is 9.97 days. The error in the Hipparcos results can be traced to the fact that the orbital period had to be derived from only 124 points. The system is detached so only 15 point fell into either eclipse. Spectroscopic information obtained by GAIA will greatly alleviate such problems (see Zwitter 2003 for detailed simulations). This is a consequence of the fact that every radial velocity point contributes to period determination and not only those falling into eclipses as for photometric observations.

6. Discussion

Our analysis used the Tycho to Johnson colour transformation from the Hipparcos catalogue as given in Eqs. (1) and (2). The magnitude measurements themselves were obtained from the Hipparcos and Tycho-1 epoch photometry as available through the CDS. Recently Bessell (2000) published modified calibrations that would make the $(B-V)_J$ colours redder by 0.03 to 0.04 mag. The T_{1+2} temperatures for V781 Tau, UV Leo and GK Dra would be lower for 120 K, 100 K and 160 K, respectively. A modified $V_J - V_T$ vs. $(B-V)_T$ relation would also make their apparent V_J magnitudes ~0.01 mag brighter. Such small corrections cannot significantly modify the limb-darkening and other coefficients that depend on the absolute value of the temperature. But they do change the bolometric magnitudes and so distances. In our case the absolute bolometric magnitudes for V781 Tau, UV Leo and GK Dra would be 0.28, 0.19 and 0.46 mag fainter and the derived distances 14, 9 and 23% larger. The issue of absolute colour calibrations of the Tycho passbands does not seem to be a closed one. The new version of the Tycho catalogue (Tycho-2) quotes the old calibration (Eq. (2)) again. We therefore prefer to remain with the same calibration as used in Paper I with the possible modifications clearly spelled out.

7. Conclusions

The paper clearly demonstrates the potential of GAIA to derive accurate orbital solutions even for stars with intrinsic variability or for contact cases. GAIA will observe any object only around a hundred times. This will complicate the determination of orbital period of wide detached systems. Spectroscopic information will be particularly useful to determine the orbital period in such cases and also for a vast majority of binaries which are non-eclipsing. Spectroscopic information can be used also to derive orbital eccentricity as demonstrated by GK Dra.

Absolute scale of the system provided by spectroscopic orbit can be used to derive masses and sizes of the system components at a 1–2% level (Table 4). So these stars can be absolutely placed on an H–R diagram. Exact coevality of both stars in a binary make for a useful study of stellar isochrones. Munari (2003) discusses how additional information, like metallicity, will be obtained from the GAIA data.

The distances derived from orbital solutions compete or are superior to the Hipparcos astrometric measurements. We note that the present analysis may be influenced by uncertain calibrations in the noisy photometry obtained from the Hipparcos Tycho experiment. But for the case of GAIA the errors quoted in Table 5 are realistic, as the stellar temperatures and reddening will be known with high precision from a multi-band photometry. Note also that measurement of distances from orbital solutions, especially for overcontact binaries, is limited only by relative faintness of the objects at large distances. So hot contact binaries will be a useful tool to gauge distance throughout the Galaxy and beyond.

GAIA will be able to detect also intrinsic variability of binary components. Degree of derivable physical information depends on the nature of the variability. Stellar spots will be very common but difficult to describe. These are transient phenomena, so the star will look different on each of the 100 transits during the 5-yr mission lifetime. This can be seen also in our data. Different levels of quarter phase maxima in the V781 Tau light curve (Cereda et al. 1988) were used to claim the presence of polar spots (Lu 1993). But Hipparcos light curves do not reveal such details. Also UV Leo is an object with occasional spots that change the overall system brightness. The fact that we ignored such phenomena but still derived quite accurate orbital solutions in two systems suggests that magnetic phenomena cannot jeopardize the derivation of binary star parameters to some limit of accuracy. Other types of variability, like δ-Sct variability in GK Dra (Dallaporta et al. 2002; Zwitter 2003) maintain its phase, so they will be easily detectable from GAIA data. Orbital period changes, e.g. due to passages of the third body will be quite uncommon and difficult to detect due to a limited mission lifetime.

This work reassures us of the high quality of physical information recoverable from GAIA's observations of eclipsing binaries. In future papers of this series we plan to explore more objects with intrinsic variability as well as some double lined systems with triple components.

Acknowledgements. Generous allocation of observing time with the Asiago telescopes has been vital to the present project. We would like to thank Bob Wilson who continues to provide us with the last versions of the Wilson-Devinney program and for advice on its usage. EFM acknowledges Josef Kallrath's help in further developments of spot analysis with the WD2002 code. The financial support from the Slovenian Ministry for Education, Science and Sports (to TZ and AP), of the NSERC and University of Calgary Research Grants Committee (EFM), and through the Polish KBN Grant No.5 P03D 003 20 (TT) is kindly acknowledged.

References

Andersen, J. 1991, A&ARv, 3, 91

Batten, A. H., Fletcher, J. M., & MacCarthy, D. G. 1989, Publ. Dominion Obs., 17

Bessell, M. S. 2000, PASP, 112, 961

Bienaymè, O., & Turon, C. (ed.) 2002, GAIA: a European space project (EDP Sciences)
Cereda, L., Misto, A., Poretti, E., & Niarchos, P. G. 1988, A&AS, 76, 255
Dallaporta, S., Tomov, T., Zwitter, T., & Munari, U. 2002, IBVS, 5312, 1
Frederik, M. C. G., & Etzel, P. B. 1996, AJ, 111, 2081
Gilmore, G., Perryman, M., Lindegren, L., et al. 1998, Proc SPIE Conf., 3350, 541
Kallrath, J., Milone, E. F., Terrell, D., & Young, A. T. 1998, ApJ, 508, 308
Liu, Q., & Yang, Y. 2000, A&AS, 142, 31
Lu, W. 1993, AJ, 105, 646
Mikuž, H., Dintinjana, B., Prša, A., Munari, U., & Zwitter, T. 2002, IBVS, 5338, 1
Milone, E. F., Stagg, C. R., & Kurucz, R. L. 1992, ApJS, 79, 123
Munari, U. (ed.) 2003, GAIA Spectroscopy, Science and Technology, ASP Conf. Ser., 298
Munari, U., Tomov, T., Zwitter, T., et al. 2001, A&A, 378, 477 (Paper I)
Perry, C. L., & Johnston, L. 1982, A&AS, 50, 451
Perryman, M. A. C., de Boer, K. S., Gilmore, G., et al. 2001, A&A, 369, 339
Popper, D. M. 1997, AJ, 114, 1195
Prša, A. 2003, in GAIA Spectroscopy, Science and Technology, ed. U. Munari, ASP Conf. Ser., 298, 457
Straižys, V. (ed.) 1999, GAIA, Baltic Astron. 8, 1
van Hamme, W. 1993, AJ, 106, 2096
Vansecičius, V., Kučinskas, A., & Sudžius, J. (ed.) 2002, Census of the Galaxy: challeges for photometry and spectrometry with GAIA (Kluwer)
Wilson, R. E. 1998, Computing Binary Star Observables (Univ. of Florida, Astronomy Dept.)
Zwitter, T. 2003, in GAIA Spectroscopy, Science and Technology, ed. U. Munari, ASP Conf. Ser., 298, 329