Observational tests of the GAIA expected harvest on eclipsing binaries

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Abstract. GAIA observations of eclipsing binary stars will have a large impact on stellar astrophysics. Accurate parameters, including absolute masses and sizes will be derived for $\sim 10^4$ systems, orders of magnitude more than what has ever been done from the ground. Observations of 18 real systems in the GAIA-like mode as well as with devoted ground-based campaigns are used to assess binary recognition techniques, orbital period determination, accuracy of derived fundamental parameters and the need to automate the whole reduction and interpretation process.

1. Introduction

GAIA observations of eclipsing binary stars will be of utmost importance to advances in stellar astrophysics. For no other class of objects one could determine fundamental stellar parameters, i.e. absolute mass, size and surface temperature distribution with a comparable accuracy. Solutions of wide detached binaries can be used to accurately position them on the absolute H-R diagram. Identical age of both components places useful constraints on the theoretical isochrones for the given metallicity and rotational velocity which will also be derived from GAIA observations. Components in short period systems are closer and mutually disturbed, so their evolution is different from that of single stars. But accurate surface temperatures and sizes derived from binary solutions fix their luminosity and are useful to gauge their distance even for objects that are too far for the astrometric capabilities of the satellite (see Wythe & Wilson 2002).

Availability of on-board spectroscopy is vital to the study of eclipsing binaries. Semi-major axis and stellar masses could not be determined in any other way, and additional information on metallicity and rotational velocity helps in physical interpretation. One might argue that this information could be obtained by ground-based follow-up observations. In our experience this is not feasible. In Asiago we launched an intensive campaign to spectroscopically observe eclipsing binaries discovered by Hipparcos (Munari et al. 2001 [hereafter M2001], Zwitter et al. 2003). After three years we barely finished the spectroscopic coverage of the first 18 systems. Hipparcos discovered nearly 1000 systems, GAIA will see hundred thousands. These objects are distributed over the whole sky, so fiber optic spectroscopy cannot reduce the required observing time significantly.

The strength of the GAIA mission is in the numbers. GAIA will observe $\sim 4 \times 10^5$ eclipsing binaries brighter than $V = 15$, $\sim 10^5$ of these will be double-
lined systems (M2001). Even if the stellar parameters will be determined at 1% accuracy only for 1% of them this is still 25-times more than what has been obtained from all ground-based observations in the past (cf. Andersen 1991). Moreover most of the GAIA binaries will be of G-K spectral type (cf. Zwitter & Henden 2003) where there exists only a small number of systems with accurate solutions.

Astrophysical importance of eclipsing binaries is discussed in other contributions (Milone 2003, Wilson 2003, Van Hamme 2003). Here we focus on our experience obtained from real stars that were observed in the GAIA-like mode. We start with discussion of how an object is recognized to be a binary and a determination of its orbital period. Next we discuss the accuracy of derivation of its fundamental parameters and the possibility to detect intrinsic variability of stars in binaries. We close with some general remarks on the types of binaries that will be discovered. We stress that huge numbers of objects call for completely automated reduction and possibly even interpretation techniques.

2. Orbital period from multi-epoch observations

A large fraction of binary stars with orbital periods over a month that are closer than 1 kpc will be discovered astrometrically. Systems with periods of up to 10 years will be recognized due to their non-linear proper motion and those with periods of over a century will be resolved (ESA SP-2000-4, Arenou 2003). Systems with orbital periods of less than a month will be mainly discovered by their photometric and spectroscopic variability.

GAIA is unique because it will re-observe the same region of the sky many times over. The number of transits for the spectroscopic focal plane will be around 100 with extremes a factor 2 higher or lower. The transits are not distributed evenly in time (see Fig. 1). This should pose no problems in analysis of binary stars if the satellite rotation and precession periods are kept incommensurable. The sampling permits a good phase coverage of all orbital periods that are shorter than the mission lifetime. Also the duration of individual focal plane passages is just 100 seconds, so orbital motion smearing is negligible.

Photometric variability does not need to be a consequence of the binarity of the source: pulsations, rotating and time-dependent stellar spots, as well as different types of semi-regular variables will be common among the G and K stars that will be the most frequent type of objects observed. The best way to recognize that the detected photometric variability is indeed due to binarity is by establishing its repeatability and light curve shape; so the orbital period needs to be determined. The same is true for spectroscopic observations. The exceptions are of course double-lined binaries where a quarter-phase spectrum with well separated lines immediately points to the binary nature of the source.

Potentials of photometry and spectroscopy for determination of orbital period are different, with spectroscopy being always preferable. As an example let us examine a detached system GK Dra (Fig. 2). It was discovered by the Hipparcos satellite. But a search for orbital period from the 124 Hipparcos observations proved unsuccessful. There are several possible periods with the most likely solution of 16.96-days (Fig. 2, top). This value, which is also quoted in the Hipparcos catalogue, is immediately shown to be wrong by only 35 spec-
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Figure 1. Accumulation of transits over the spectroscopic focal plane during the 5-year mission lifetime for four examples of binary stars. Dynamics of observations depends on the ecliptic latitude of the target ($\beta$). GK Dra is located close to ecliptic pole, so the transits are almost periodic. Coverage of stars at other ecliptic latitudes is more patchy.

Spectroscopic observations in the GAIA spectral window obtained by our GAIA-like ground-based observing campaign (Zwitter et al. 2003; Fig. 2, middle). The advantage of spectroscopic monitoring is in the fact that radial velocities are constantly changing with orbital phase. So every point contributes to the orbital period search. In the case of photometry the light curve out of eclipses is flat, so determination of orbital period is based only on a couple of points within the eclipses. An extensive photometry can of course resolve this problem, but note how a periodogram from over 1300 photometric observations (Fig. 2, bottom) is still more ambiguous than the one obtained from only 35 spectroscopic observations in the GAIA spectral window. The strength of spectroscopy for the orbital period determination can also be seen from the light curves in Figure 3.

Photometric information obtained by the GAIA satellite will be far superior to that of Hipparcos. GAIA will reach much fainter magnitudes and observe in many broad and narrow photometric bands. But the number of epoch observations will be similar to that of Hipparcos. The coverage of GK Dra to be obtained by GAIA is given in Figure 4. Note that only a single observation in broad band filters falls within eclipses. The eclipse coverage in intermediate passband filters is better. Broad- and narrow-band photometry can be used to measure orbital inclination as well as relative sizes and absolute temperatures of both stars. But the orbital period itself will be much easier to determine.
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Figure 2. Search for orbital period of GK Dra using a phase dispersion minimization method (Stellingwerf 1978) on three data sets. 
Top panel: 124 Hipparcos observations in the H_p-band. Middle panel: 35 spectroscopic measurements of radial velocity of the primary star. Bottom panel: 1323 ground-based V-band photometric observations (Dallaporta et al. 2002). Hipparcos data favour the 16.96-day period, while spectroscopy and dedicated photometry identify the correct value of 9.97-days.
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Figure 3. Orbital phase plots of GK Dra for orbital period of 16.96 days (left panels) and 9.9742 days (right panels). Top: Hipparcos observations in the H_P-band. Middle: spectroscopic measurements of radial velocity of the primary star. Bottom: ground-based V-band photometric observations.
from spectroscopy. A total of 81 spectra are well distributed over orbital cycle, so the orbital period, semi-major axis, and both masses will be unambiguously measured from spectroscopic radial velocity measurements.

3. Accuracy of fundamental parameters

As mentioned in the Introduction we are observing 18 Hipparcos binaries in the GAIA-like mode. This means we are trying determine their orbital solution and fundamental parameters using only Hipparcos \((H_p, B_T, V_T)\) photometry and ground based spectroscopy in the GAIA spectral range. Spectroscopic data are extracted from a single Echelle order observation with the 1.8-m telescope of the Asiago observatory. It turns out that such an approach is realistic as the accuracy of the solution is limited by a rather small \((\sim 100)\) number of Hipparcos photometric measurements resulting in a poor coverage of eclipses. This will be also the case with GAIA. The results we obtain should present a lower limit to the expected GAIA accuracy, as we are using only rather noisy Hipparcos photometry, while GAIA photometry will have excellent precision and a much larger number of photometric bands. Figure 5 presents the light curve shapes of the overcontact binary V781 Tau obtained in different narrow and broad passbands. Note that the photometric accuracy for objects brighter than \(V \sim 18\) will be better than 0.01 mag, so even rather subtle differences in the
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Figure 5. Simulated light curves of an overcontact binary V781 Tau for different narrow- (top) and broad-band (bottom) GAIA filters as defined in Munari (1999). Each curve will be sampled with \( \sim 100 \) points with errorbars not exceeding 0.01 mag at V=18.

light curve shape and magnitude level for this binary with \( T_1 - T_2 = 170 \) K will be easily discernible.

Table 1. Accuracy of fundamental parameters obtained from observations in the GAIA-like mode. Quoted errors are formal mean standard errors to the solution.

| object type | V570 Per detached F5 | OO Peg detached A2 | V505 Per detached F5 | V781 Tau overcontact G0 | UV Leo detached G0 | GK Dra detached G0 |
|-------------|----------------------|---------------------|----------------------|------------------------|-------------------|-------------------|
| sp. type    |                      |                     |                      |                        |                   |                   |
| a           | 0.7%                 | 0.5%                | 0.5%                 | 0.2%                   | 1.2%              | 0.5%              |
| mass_1      | 2.3%                 | 1.7%                | 1.5%                 | 1.8%                   | 7%                | 3.5%              |
| mass_2      | 2.5%                 | 1.8%                | 1.6%                 | 1.8%                   | 6%                | 3.3%              |
| T_1         | 150 K                | 150 K               | 40 K                 | 50 K                   | 100 K             | 100 K             |
| T_2         | 180 K                | 180 K               | 60 K                 | 30 K                   | 100 K             | 100 K             |
| R_1         | 10%                  | 4%                  | 1.4%                 | 0.4%                   | 2%                | 1.5%              |
| R_2         | 25%                  | 4%                  | 3%                   | 0.3%                   | 2%                | 1.7%              |
| distance    | 6%                   | 6%                  | 7%                   | 1.5%                   | 20%               | 10%               |

In Table 1 we quote accuracies of fundamental parameters for 6 systems published so far (M2001, Zwitter et al. 2003). We note that relative errors in most parameters are 2% or lower. The exceptions are individual radii which are not well determined due to a scarce photometric coverage of eclipses. Solutions of UV Leo and GK Dra also have large uncertainties. This is due to their intrinsic variability (see below). V781 Tau is a binary which fills its Roche lobe up to the L2 point. Temperatures and sizes of such binaries can be accurately determined. So the distance can also be calculated with a remarkable accuracy.
4. Intrinsic variability

Many stars of G and K spectral types are intrinsic variables. This is true also for binary members. With this goal in mind the observations in that GAIA-like mode that use only Hipparcos photometry with \( \sim 100 \) observations of each star were supplemented by devoted ground-based photometric campaigns (Dallaporta et al. 2000, 2002, 2002a, Mikuz et al. 2002, Frigo et al. 2002).

UV Leo is a detached system with surface spots which cause a variation of system brightness by \( \sim 0.04 \) mag (Mikuz et al. 2002). The system also showed a sudden change in the orbital period in Feb. 1981, possibly due to a passage of a low-mass third body. Devoted photometry of GK Dra (Fig. 3, bottom right) shows unusually large scatter. It turns out that the differences between the binary solution and observations are not due to noise but point to an intrinsic variability of \( \delta \)-Sct type (Figure 6).

A limited number of photometric and spectroscopic observations obtained by GAIA will make it difficult to study intrinsic variability of the binary components. Still a large number of photometric bands will easily point to temperature changes that do not repeat with orbital cycle and are so due to intrinsic variability of the binary components. Interesting cases could be picked for detailed follow-up observations. These include new interacting binaries (Cropper 2003).

5. Non-eclipsing and non-spectroscopic binaries

So far we discussed eclipsing double-lined spectroscopic binaries. In majority of cases we will be less fortunate. The systems could be too faint to obtain any useful spectroscopy, non-eclipsing or single-lined. We discuss these in turn.

For systems fainter than \( V = 15 \) spectroscopic radial velocities will be difficult to measure even in double-lined cases. These faint objects will far outnumber the bright spectroscopic binaries. Binarity will have to be established from eclipses or a reflection effect, both measured with a large number of photometric passbands but in a limited number of epochs. Some problems with the determination of orbital period of such systems have been discussed in Section 2. Here we only note that the binarity of these sources could be in general easily established due to a large photometric accuracy. In many cases the orbital ephemeris could also be derived, therefore permitting ground-based spectroscopic follow-up observations at quarter phases establishing absolute masses and dimensions of the binary components. The easiest to recognize will be systems close to contact, where much of the system information could be recovered from photometry alone.

Eclipses will be rather uncommon, especially in the wide detached cases. But for a double-lined non-eclipsing spectroscopic binary the mass ratio can still be easily calculated. And in not too wide binaries the reflection effect can be measured from accurate photometry. This constrains the temperatures and inclination of the system. The inferred spectral classification can be finally checked against the properties of the spectra obtained close to quadratures where the spectral lines are well separated.

Most binaries with the mass ratio below 0.3 will be single-lined, permitting to derive only a spectroscopic mass function.
Figure 6. The difference between the observed $B$ magnitudes of GK Dra (Dallaporta et al. 2002) and the ones generated from the binary system solution, folded on an intrinsic stellar variation period of $\sim 170$ minutes. Differences pertaining to different orbital phase bins ($P_{\text{orb}} = 9.97$ days) are marked by different symbols and vertically offset for clarity. Note that a sinusoidal variation with a peak-to-peak amplitude of $\sim 0.05$ mag is present throughout the orbital cycle and is maintaining its phase. Intrinsic variability of binary components will be common among GAIA binaries.
6. Some remarks on reduction and interpretation procedures

GAIA will discover huge numbers of spectroscopic and eclipsing binaries. The numbers are orders of magnitude larger than everything collected in the last century from the ground. In many cases the observations obtained by GAIA will be good enough to determine system parameters at 1-2% accuracy level. They will have an immense impact on theories of stellar structure and evolution.

Such a large data set requires an automation of all stages of reduction and interpretation. No-one could recognize photometric eclipses or winging radial velocity curves in hundred-thousands or even millions of systems by eye. But even interpretation and classification has to be completely automatic with only the most unusual cases to be marked for human inspection. Wythe & Wilson (2001, 2002) successfully classified some photometric eclipsing binaries from the OGLE database with semi-automatic procedures. Prsa (2003) obtained some encouraging results for double-lined eclipsing binaries. Clearly development of reliable classification and analysis procedures is one of the major tasks facing the scientific community before the launch of GAIA.

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