*From Interacting Binaries to Exoplanets: Essential Modeling Tools*
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# Shaking the Pot of Modelling Tools: Some Open Problems in the Field

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**Abstract.** To inspire and provoke lively discussions, I argue that the accuracy of the basic physical properties of stars, based on analyses of well-observed detached binaries, might be worse than usually believed. I offer some ways how to deal with the situation. I end with a few comments on the studies of extra-solar planets.

**Keywords.** stars: fundamental parameters (classification, colors, luminosities, masses, radii, temperatures, etc.), (stars:) binaries: general, (stars:) binaries (including multiple): close, (stars:) binaries: eclipsing, stars: planetary systems, stars: evolution, stars: atmospheres

## 1. Introduction

Let me begin this talk in a somewhat personal tone. When many of us met at the IAU Symp. 240 *Binary Stars as Critical Tools and Tests in Contemporary Astrophysics* in 2006, we had the chance to welcome there Mirek J. Plavec, a Czech stellar astromomer who spent the last few decades of his life in the USA. Mirek was a teacher and friend of several of us, who are present in this audience. In one of his excellent review talks (Plavec 1983) he made a statement, which I believe will be very appreciated by the colleagues studying the wealth of data coming from the space observatories like MOST, CoRoT or Kepler:

*"I think it is fair to say that a theory or a model is always the closer to being worshipped the fewer are the observational data."*

My intention, as an astronomer who tries to analyze observations in an effort to learn something new about stars, is to inspire lively discussions during this meeting. I shall touch on some problems worth considering and ask various questions, to which I hope to hear answers and/or comments from the experts, who met here.

## 2. How accurately do we know the masses, radii and other basic physical properties of stars?

Andersen (1991) claimed the errors in stellar masses and radii smaller than 2% and Torres *et al.* (2010) relaxed this accuracy to better than 3% in their excellent review of the properties of 95 well detached binary systems. I am afraid, however, that this estimate is still too optimistic as detailed below. Besides, we should keep in mind the current strong selection effect, namely that we have most observations for the systems seen roughly equator-on. It will be very interesting to study also spectroscopic binaries seen under lower inclination when the interferometry will become a widely used technique to see whether our theoretical models of the gravity and limb darkening are sufficiently sophisticated or not.

### 2.1. *Radial-velocity curves and stellar masses*

In spite of great progress in the spectral resolution and $S/N$ ratios, there still must be a difference in accuracy between the radial velocities (RVs hereafter) from the photographic and electronic spectra. Torres *et al.* (2010) discuss carefully various techniques of RV determination and orbital solutions and the potential sources of systematic errors. They recalculated the orbital and light-curve solutions for all of their systems, but they did not mention which programs they had used. Furthermore, there was no warning that the accuracy of RV and mass determination inevitably decreases with the increasing projected rotational velocity of the stars and can be affected by different spectral resolutions of different spectrographs. Take the example of hot stars: Different authors use different effective laboratory wavelengths for He I triplet lines and there is always the problem of line blending, especially for stars with non-negligible rotational velocities. Most authors publish only mean RV, which is usually based on different numbers of spectral lines for different spectra, depending on the quality of each spectrogram. If the RV of each spectral line has its own '$\gamma$ velocity,' then averaging RVs not always for the same set of lines will inevitably decrease the RV amplitude of the mean RV curve. One should investigate the RV solutions line by line to see if there are such systematic differences or not. Such an approach is possible with the technique of spectral disentangling (Simon & Sturm 1994, Hadrava 1995, 1997, 2004), where one can derive separate solutions in the neighbourhood of all stronger spectral lines. It is not possible, however, for the RV determinations based on the principles of the cross-correlation technique, where the orbital velocity shifts of all available spectra are mutually compared (see, e.g., Simkin 1974, Hill 1993, Zucker & Mazeh 1994). There is, therefore, some danger that the effects such as inaccuracies in the wavelength scale or different sensitivities of different spectral lines to unrecognized slight physical variability of the line profiles can affect the resulting amplitude of the RV curves, and therefore also the estimates of stellar masses. The fact that one can only derive $M_j \sin^3 i$ $(j = 1, 2)$ from the orbital solutions implies that the accuracy of stellar masses depends critically also on the accuracy of the determination of the orbital inclination $i$ from the light-curve or accurate interferometric solution. I admit that there are some very-high accuracy mass determinations for sharp-lined late-type stars (for instance Konacki *et al.* 2010) but the chances are hopelessly low that similar studies could be carried out for a representative sample of detached binaries with the needed spectral resolution.

### 2.2. *Two different connotations of the effective temperature*

The situation regarding the accuracy of the determination is even worse for the radiative properties of the stars: luminosity and effective temperature. The principal definition of the effective temperature, which is also adopted in stellar evolutionary models is that it is a parameter characterizing the total bolometric luminosity of a star via

$$L = S\sigma T^4_{\mathrm{eff.}},\ (S = 4\pi R^2 \text{ for spherical stars}),$$

where $S$, $R$, and $\sigma$ are the stellar surface area, stellar radius and the Stefan-Boltzmann constant. The problem is that the observer on the Earth can only record the flux $\mathcal{F}_{\mathrm{E}}$ coming from the star in the direction of the observer. At present, the stellar bolometric luminosity and $T_{\mathrm{eff.}}$ are the quantities that *cannot be directly measured* and are only *deduced.* Denoting $\mathcal{F}_{\mathrm{S}}$ the bolometric flux from the unit area of the stellar surface, $d$ the distance to the star and $\theta$ the stellar angular *diameter* and assuming the simplest case of a spherical star with a uniform brightess distribution, one has $L = 4\pi R^2 \mathcal{F}_{\mathrm{S}}$ and $F_{\mathrm{S}} = \frac{d^2}{R^2}\mathcal{F}_{\mathrm{E}}$ or $\sigma T^4_{\mathrm{eff.}} = \frac{4\mathcal{F}_{\mathrm{E}}}{\theta^2}$. However, already for rotating stars, $\mathcal{F}_{\mathrm{S}}$ becomes a function of the stellar latitude. A proper estimate of $T_{\mathrm{eff.}}$ from the observed $\mathcal{F}_{\mathrm{E}}$ requires the knowledge of the

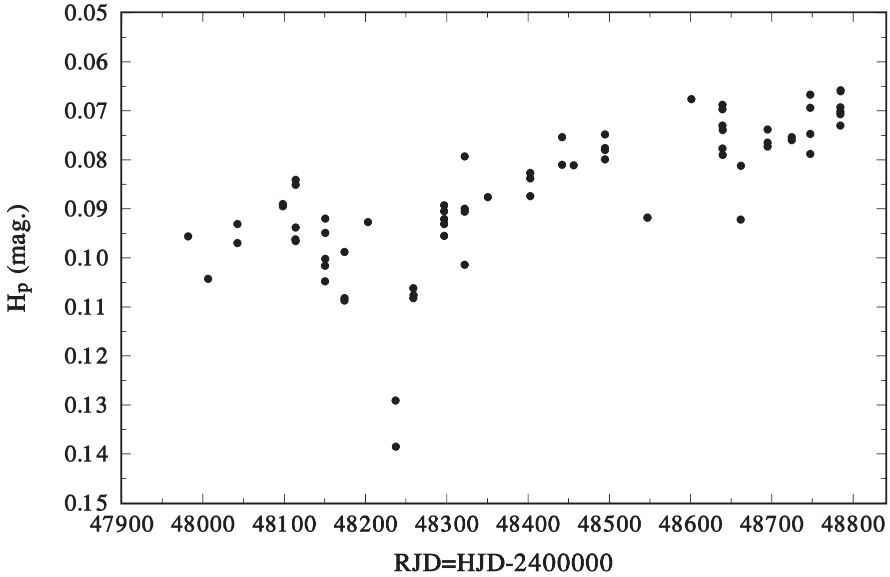


**Figure 1.** A plot of the Hipparcos $H_{\rm p}$ photometry (Perryman & ESA 1997) of $\alpha$ Lyr vs. reduced heliocentric Julian days. Only the observations with error flags 0 and 1 were used and the largest rms error of individual data points is 0.005 mag. Clear secular light variations are observed.

inclination of the rotational axis of the star and also proper modelling (which includes the limb and gravity darkening and also reflection in the case of binaries). Regrettably, a parameter, which is also called $T_{\rm eff.}$ is used as one of the basic parameters characterizing a specific model of a stellar atmosphere, the most often a plane-parallel one. A frequent 'logical short-circuit' then is that the $T_{\rm eff.}$ characterizing the stellar atmosphere model providing the best fit of the observed stellar line spectrum, is interpreted as the true stellar $T_{\rm eff.}$. Alternatively, in the cases when one has some idea about the geometry of a non-spherical star, one can find statements like that the $T_{\rm eff.}$ varies from the equator to the pole of the star in question. I maintain that this is a misuse of the term 'effective temperature,' which may complicate the comparison of the observations with the stellar evolutionary models.

There are various calibrations between indices of standard photometric systems and the stellar effective temperature. One, which has been often used in recent years is Flower's (1996) calibration between $B-V$, $T_{\rm eff.}$, and the bolometric correction. Flower undoubtedly did a great job but it is necessary to realize that he only critically collected the published data for 335 stars with published $T_{\rm eff.}$ between 2900 and 52500 K. There is no guarantee the these determinations are mutually consistent. What is in the background are observations and model atmospheres of various degrees of accuracy and sophistication as they developed over several decades. In many cases, the spectral energy distribution of particular stars near its maximum was only approximated by a model atmosphere. Flower tabulates the bolometric corrections to three valid digits but I am afraid that their accuracy might be less than two digits in fact, especially at the hot end of the $T_{\rm eff.}$ range.

Many published studies rely on several published absolute flux calibrations of Vega ($\alpha$ Lyr). Figure 1 shows the good Hipparcos broadband $H_{\rm p}$ observations of Vega,

**Table 1.** Various determinations of the distance of the Pleiades cluster

| Distance (pc) | Method | Source |
|---|---|---|
| 129–134 | PHOT | Pinsonneault *et al.* (1998) |
| 113–120 | HIP | Pinsonneault *et al.* (1998) |
| 135.56± 0.72 | DYN | Li & Junliang (1999) |
| 115–122 | HIP | van Leeuwen (1999) |
| 131± 11 | HIP | Narayanan & Gould (1999) |
| 121–134 | PHOT | Robichon *et al.* (1999) |
| 115–121 | HIP | Robichon *et al.* (1999) |
| 126–134 | HIP | Makarov (2002) |
| 132± 2 | V1229 Tau | Munari *et al.* (2004) |
| 133–137 | 27 Tau | Pan *et al.* (2004) |
| 132± 4 | 27 Tau | Zwahlen *et al.* (2004) |
| 139.1± 3.5 | V1229 Tau | Southworth *et al.* (2005) |
| 134.6± 3.1 | Hubble FES | Soderblom *et al.* (2005) |
| 138.0± 1.5 | V1229 Tau | Groenewegen *et al.* (2007) |

*Column "Method":* PHOT... estimates from calibrated photometric observations; DYN... estimate from the proper motion and radial velocities of a number of individual cluster members; HIP... distance derived from analyses of Hipparcos satellite astrometric observations; V1229 Tau... distance estimated from combined orbital and light-curve solutions for this eclipsing-binary member of the cluster; 27 Tau... distance estimated from the comparison of the angular size of the semi-major axis of this visual and double-lined spectroscopic binary with the semimajor axis in km derived from the orbital solution; Hubble FES... distance derived from the astrometric observations with the Hubble Space Telescope's Fine Guidance Sensor used as a white-light interferometer.

indicating that Vega is a variable star! This finding must be verified by systematic observations and may have serious consequences for existing calibrations.

### 2.3. *Stellar radii, luminosities and distances*

It is true that there are several advanced programs for the light-curve solutions or even combined solutions for several different observables, such as the WD program (Wilson & Devinney 1971). Although the flux and temperature distribution are properly modelled in such programs, one still has to assume $T_{\rm eff.}$ of the primary, again depending on the existing calibrations. It is true that Wilson (2008) pushed forward eclipsing-binary solutions in physical units, which should in principle lead to direct distance estimates. It seems, however, that the calibrations of photometric systems and theoretical spectral energy distributions vs. $T_{\rm eff.}$ will need further improvement before it will be possible to derive individual $T_{\rm eff.}$ for both components in binaries from the combined light-curve and RV-curve solutions. Note also the alarming case of the W UMa binary AW UMa, which seems to be a detached system with equatorial disks mimicking the contact configuration (Pribulla & Rucinski 2008), a situation which could not be properly analysed for the stellar radii with the WD program.

The situation is even worse for the stellar luminosities and the distances deduced from them. An incomplete knowledge of the true interstellar reddening forces us to use statistical mean relations, for instance the well-known expression for the reddening of the Johnson $V$ magnitude as a function of the $B-V$ index $A_{\rm V} = \alpha\,{\rm E}(B-V)$. A search in the literature shows that various authors are using $\alpha$ values from 2.9 to 3.2, with certainly not quite negligible effect on the deduced distance moduli. Our current uncertainties can be well illustrated on several determinations of the distance to the Pleiades cluster, especially those based on analyses of V1229 Tau, a double-lined spectroscopic and eclipsing binary, and of 27 Tau, which is a double-lined spectroscopic and interferometrically resolved binary – see Table 1.

## 3. What could be done to improve the situation?

### 3.1. *Improving calibrations*

I believe that if we really want to improve our knowledge of basic properties of stars, the whole community must begin to oppose the current attitude of time-allocating committees to allocate observing time at the best ground-based and space observatories only to such science projects, the results of which look great in the prime-time TV news. In particular, we need to select a representative subset of well detached double-lined spectroscopic and eclipsing binaries with low $v \sin i$ values and to launch their systematic observations over virtually the entire electromagnetic spectrum and with a good distribution over orbital phases. Their spectral energy distribution combined with a detailed comparison of disentangled component spectra with the best present-day model atmospheres should allow us to define an accurate and universally adopted scale of $T_{\mathrm{eff.}}$ and bolometric corrections. In another part of such a project, these would be calibrated vs. all frequently used standard photometric systems. Then, at least for basically spherical stars, we could really critically compare the results of observations with the prediction of stellar evolutionary models.

The much more complicated problem of the proper modelling of rapid rotators might become solvable later, when optical interferometry becomes a standard tool like spectroscopy and photometry are today.

### 3.2. *Obligatory constants and units*

As suggested by Harmanec & Prša (2011) and by Prša & Harmanec (this proc.), one thing can be done immediately. We should start using obligatory *nominal* values of the solar radius and luminosity, which would serve as exact, error free conversion factors to express the stellar radii and luminosities from solar to SI units. It would not be wise to do the same at present with the solar mass since the gravitational constant is known with an accuracy, which is full five orders of magnitude worse than that of the product $GM_\odot$. Fortunately, Kepler's 3$^{\mathrm{rd}}$ Law and the formulas to derive stellar masses, expressed in the units of the solar mass from the RV-curve solutions, both depend on the $GM_\odot$ product. One can therefore express the stellar masses in the units of solar mass very accurately while an accurate conversion to SI can be carried out later when a truly exact value of $G$ will be known. See the above-quoted papers for more details but our prescription is

($a$) Fix the nominal solar radius and luminosity and use the accurately known product $GM_\odot^{2010} = 1.32712442099(10) \times 10^{20}\mathrm{m}^3\mathrm{s}^{-2}$:

$$1\ M_\odot^{2010} = 1.988416 \times 10^{30}\ \mathrm{kg}, \tag{3.1}$$

$$1\ \mathcal{R}_\odot^{\mathrm{N}} = 6.95508 \times 10^{8}\ \mathrm{m},\ \text{and} \tag{3.2}$$

$$1\ \mathcal{L}_\odot^{\mathrm{N}} = 3.846 \times 10^{26}\ \mathrm{W}. \tag{3.3}$$

($b$) Use IAU (CODATA) constants like $G$ or $\sigma$ and always quote their source (or values) explicitely in your publications.

Note that all of the most frequently used formulas become either error free or depend on the accuracy of *only one* physical constant if our suggestion is applied. For example the stellar equatorial rotational velocity in km s$^{-1}$ becomes error free:

$$V[\mathrm{km\,s}^{-1}] = 50.57877 \frac{R[\mathcal{R}_\odot^{\mathrm{N}}]}{P_{\mathrm{rot}}[\mathrm{days}]}. \tag{3.4}$$

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We suggest that exactly the same should be also done with the basic properties of Jupiter and Earth, which are used by the students of brown dwarfs and extrasolar planets.

## 4. A few comments on the technique of spectral disentangling from the user's point of view

The spectral disentangling invented by Simon & Sturm (1994) and Hadrava (1995), Hadrava (1997) is the most advanced method for the determination of orbital elements and reconstruction of individual line spectra of the components of a binary or even multiple system of stars. According to my experience, the technique performs best for binaries with components of widely different spectral types and not so extreme luminosity ratios. The situation gets more complicated in cases when the secondary is some 3 or more magnitudes fainter than the primary. The sum of squares of the residuals, which is usually used as the minimizer, is dominated by the primary and the noise of the observed spectra in such cases. This decreases the sensitivity of the method to the spectrum of the secondary and a relatively large range of mass ratios might lead to a similar sum of squares of residuals. I hope the experts present here might have some suggestions for a better criterion for the optimal solution in such situations. Also disentangling of the spectra of binaries composed from two fast rotating components of similar spectral types is complicated and need not lead to a unique solution simply because the resulting line widths and semi-amplitudes of the orbital motion are strongly correlated.

One of the widely used programs for spectral disentangling, KOREL by Dr. P. Hadrava (see, e.g., Hadrava 2004) provides an excellent possibility to remove also telluric lines from the spectra via modelling them as a distant component moving with a period of the Earth's orbit around the Sun and allowing for their varying strength from one spectrum to another. The users should be aware, however, that the relative line strength is treated as a single value for each spectrum. Since the strength of the water vapour lines varies much more than that of the atmospheric oxygen, it is not advisable to disentangle the spectral regions containing both types of telluric lines in one program run.

As demonstrated in detail in the contribution by Chadima *et al.* (in these proceedings), it is always advisable to verify the result of disentangling in some independent way. While preparing a recent detailed study of a large number of electronic spectra of $\varepsilon$ Aur by Chadima *et al.* (2011), we made an attempt to disentangle the spectra of both binary components, keeping the orbital period of 9890.62 d and other orbital elements fixed from the solution derived by Chadima *et al.* (2010). Solutions with two independent computer programs, KOREL (Hadrava 1995, 2004) and FDBINARY (Ilijić *et al.* 2001) were obtained and led to very similar disentangled spectra. To our surprise, both programs returned also a clear spectrum of the secondary for all spectral lines also seen in the spectrum of the primary. However, the secondary is hidden in a cool and opaque disk and a very detailed attempt by Bennett *et al.* (this proc.) to detect any trace of the secondary spectrum failed. Chadima *et al.* (this proc.) also tried to disentangle the same set of observed spectra of $\varepsilon$ Aur for the dominant period of observed physical variations, 66.21 d and for an arbitrarily chosen, non-existent period of several hundreds of days. The secondary spectrum was disentangled in both of these attempts, too. The probable explanation lies in the fact that the semi-amplitude of real RV changes (about 15 km s$^{-1}$) is so low that the lines of both putative spectra remain completely blended in all orbital phases. The disentangling programs then try to interpret the varying line asymmetries, caused by real physical changes, in terms of the spectrum of the secondary, which is inevitably similar to that of the primary.

## 5. A common language

In passing, I am going to ask a few questions related to the field of exoplanet studies, in which I am not working actively. So I only hope to learn the answers while listening to the talks during this meeting.

As the so far most fruitful techniques of the exoplanet detection, accurate RV measurements and photometric eclipses of host stars by passing planetary bodies, are methodologically very similar to binary studies, one would expect that the same terms will be used. This has not been quite so. While the binary community talks about *eclipsing binaries*, the students of exoplanets prefer the term *transiting exoplanets*. The binary community distinguishes 'transits' and 'occultations,' depending on the actual geometry of the eclipse and it is true that the eclipses of host stars by planets are indeed 'transits.' Still, I would tend to talk about the time of mid-eclipse, not mid-transit, even in the case of exoplanets.

I also hope to learn how well the very-small amplitudes of the RV curves of cool stars hosting the planets are actually known. Possible small inhomogeneities of the brightness distribution over the stellar surfaces can be reflected differently in individual spectral lines and any cross-correlation technique must invevitably mask such effects, returning some averaged RV curve. Finally, talking about the limits of accuracy of precise RV measurements, I hope to hear how accurately the barycentric RV corrections can be obtained. Should one use the geographic coordinates of the slit of the spectrograph or which particular point inside the dome?

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## Discussion

I. Hubeny: I do not quite agree with the suggestion that there should be a single effective temperature defined for the whole star. Such a quantity would only be a proxy for the total stellar luminosity and its surface extent. The term effective temperature has a well-defined, and widely used, meaning in the stellar atmosphere theory, namely that it represents total energy flux coming from the stellar interior on the lower boundary of the atmosphere. Since the stellar atmosphere is a passive region where no additional energy is generated or destroyed, this effective temperature also represents a total, frequency integrated outgoing radiation at the upper boundary of the atmosphere. It is perfectly legitimate to assign different values of so defined effective temperature to different positions on the stellar surface for a non-spherical star, or for regions where the total incoming energy is modified by intervening external forces, as for instance for sunspots driven by magnetic field.

R. Wilson: My point is similar to Ivan's. Effective temperature is a fundamental quantity in stellar atmosphere theory and in reality. Teff is a single number that serves as a basic stellar atmospheric parameter and a natural parameter for eclipsing binary analyses, given proper modeling. There is no need to use other temperature-related parameters such as color temperature, etc.

P. Harmanec: I understand that Teff is one of the parameters characterizing model atmospheres. But you compare the model atmosphere with *the flux* coming in the direction towards the observer; and for non-spherical or any more complicated object the model-atmosphere Teff giving the best fit between the observed and model spectrum will not describe the bolometric luminosity properly. For instance the Be stars have time-variable pseudophotospheres, which can mimic, say, a B6 star at one epoch, and B8 star at another. So I do believe the term Teff should be reserved for a parameter characterizing the bolometric luminosity of a star (to be compared with evolutionary models).

R. Wilson: To define and utilize a consistent effective temperature for EB solutions is straightforward, as has always been the situation in the WD model. The solution parameter is a flux-weighted mean effective temperature over the surface. Starting from that parameter, one can recover the full Teff distribution over the surface, including all modeled physical effects, if the distribution is needed.