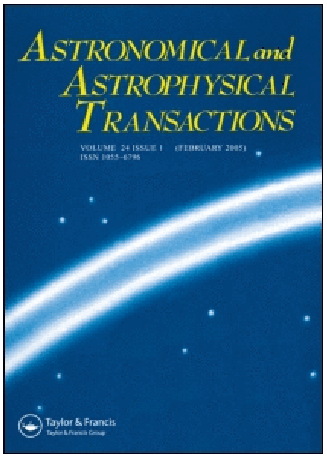

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Binary star systems: projects for the near future

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Binary star systems: projects for the near future

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Two computational models have now been extended to deal with the kinematics of triple systems via combined light–time and radial velocity variations of eclipsing binary mass centres. Applications to binaries known or suspected to be accompanied by third bodies can improve knowledge of multiple-system statistics. A neglected area is the measurement of polarization curves for Algol-type binaries, which pose instrumental and observational challenges. Algols should show polarization due to scattering in mass transfer streams and circumstellar discs, as well as Thomson scattering in the photospheres of their hot stars and Rayleigh scattering due to irradiation of their cooler stars. Polarization data need to be extended to sufficiently faint stars so as to observe these phenomena in a reasonable number of systems, which will require excellent polarimeters, large telescopes and good observing strategies. A third project is the measurement of distances, with standard errors, to many eclipsing binaries by direct distance estimation (DDE), for which the computer model will soon be made public. Accurate distances now can be found routinely by DDE. A fourth project is to establish photometric calibrations, by eclipsing binary observations, in standard physical units (say, erg s^{-1} cm^{-3} for a magnitude-zero star) in standard bands other than the modest number that have already been calibrated. Several of these projects will be made easier if journal regulations require that observation tables are always published and that times are given for all observations.

Keywords: Binary stars; Multiple systems; Distances; Flux calibration; Polarization

1. Introduction

Ways are suggested to improve knowledge and understanding in areas such as the statistics of stars and multiple systems, disc astrophysics and distances. Progress can follow if recent conceptual advances are widely applied, if polarimetric facililities are directed toward timewise variation and if photometric calibrations are extended. Some projects are observational while others can use published or archived data. Applications can increase substantially if we have conscientious publication of data.

2. Binary hierarchical statistics

The Tokovinin [1] catalogue summarizes the statistics of multiple stellar systems. As emphasized there, the fragmentary state of the multiple star field arises from the following:

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(i) the difficulty of discovery (with selection effects);
(ii) the numerous means of discovery;
(iii) the investigators' personal preferences.

The focus here is on eclipsing binaries (EBs) in multiple systems, and not so much on increasing the size of the database as on accuracy. Two present light curve models have the capability to extract ephemerides and third-body kinematics from solutions of whole light and radial velocity (RV) curves by combining RV information from the motion of an EB's mass centre with information from timewise excursions of its light curve waveform (preferably simultaneously). One of the programs is FOTEL [2, 3], for which a number of applications are cited in [4]. FOTEL's solutions are by the Simplex algorithm. The other facility is in the WD program [5–7], with the basics and abbreviated history on ephemerides covered in [8] and third-body logic covered in [9, 10]. WD's DC solutions utilize derivatives, whereas Simplex does not, with the analytical forms of those derivatives (of observable quantities with respect to parameters) given in [10]. The central ideas of mixed whole curve solutions for ephemerides are to fill gaps in coverage by having two kinds of data (RV shifts and light–time effect), and to access more kinematic information than eclipse timings contain. The project is to apply one or both of the third-body modelling programs to as many EBs as data permit so as to refine information on their companions. Although the programs streamline overall operation by analysing light and RV data together, the aims are still as follows:

(i) to find and assess multiple epochs of appropriate data that are reasonably well distributed over time, which may involve contacting researchers, unearthing old observations and dealing with various publishing practices;
(ii) to put the data into the machine;
(iii) to estimate starting numbers, partly via power spectral analysis;
(iv) to deal with aliasing of periods due to large gaps in coverage.

The problem would be far easier if we could have continuous coverage. All this is more work than it would seem to be and also requires independent checks, but of course it is needed to explore the formation and evolution of multiple-star systems. The DC third-body modelling facility is now under test and will soon be included within the public WD program, probably in about 1 year. Its details will be published in [10].

Naturally the general scheme is well suited to the discovery of exoplanets and the evaluation of their properties, as it combines the extra information in the timing ticks of eclipses with ordinary RV analysis, while the EB type is not restricted to well-detached stars but can have the full possibilities of the FOTEL or WD model.

3. Polarization in Algols

The idea of this project is to observe timewise polarization in Algols, which are semidetached binaries that are understood to be in their first episode of mass transfer and have the following features, whether so far detected or not:

(i) stream polarization, with the stream due to intermittent lobe overflow onto a star or existing optically thin disc;
(ii) disc polarization (usually optically thin);
(iii) photospheric Thomson scattering polarization in the hot primaries, often called 'Chandrasekhar polarization';

(iv) photospheric Rayleigh scattering polarization due to irradiation of the cool secondaries (reflection effect).

The project is observational but may also require instrument development, as suitable polarimeters are not common, and those that exist are mainly dedicated to surveys rather than to polarization curves of variable objects. At some level, Algols should show polarization due to all four phenomena. A minority of Algols have achieved notoriety for active streams and discs, with RW Tauri and U Cephei being notable examples, but nearly all Algols may be polarimetrically active at potentially observable levels. Is there a suitable EB polarization model with simulations? Yes, for discs, one is given in [11]. Is there an analysis scheme that finds polarization parameters? Yes, there is in [12]. Are there useful polarization curves? Signal-to-noise ratios have so far limited successful targets to one – Algol itself [13]. Progress will require fainter limiting magnitudes.

The main issue is to have data; otherwise there is no point in model development. What would polarimetric curves of Algols achieve for astrophysics? The answers are as follows.

(i) They would test stellar atmosphere models (*i.e.* would measure the wavelength dependence of scattering for direct radiation and re-radiation).
(ii) Inclinations over the range from 0° to 180° and nodal position angles could be measured (*i.e.* the complete orbit orientation and the sense of motion could be given).
(iii) The geometry and physics of streams and discs could be probed.
(iv) They would allow simultaneous [light, velocity, polarization] solutions by the least-squares criterion.

High accuracy will be crucial for success. A new polarimeter called Planetpol [14] is expected to reach signal errors of a few parts per million for a star with a V magnitude of 5 in 1 h with a 4–8 m telescope. An hour is too long to avoid serious time and phase smearing for most Algols, but 10 min observations should typically give adequate time resolution at a loss of a factor of 2.5 in signal-to-noise ratio. Adequate signals will require an efficient polarimeter, a large telescope and bright, polarimetrically active Algols. Emission lines and variable periods are signposts of likely stream and disc polarization and should help in target selection. Photospheric Thomson scattering signals (in eclipses) increase strongly towards the ultraviolet; so reasonably accurate measurement of that effect will require above-atmosphere polarimetry, although ground-based data in the U or u bands may be worthwhile if observing programs and polarimeter design are highly optimized.

4. Distances of eclipsing binaries via direct distance estimation

The aims of direct distance estimation (DDE) [4, 8, 15–17] are to improve accuracy and statistical uniformity while reducing human work, thereby increasing both quality and production. The project is to compute distances in great numbers (not tens of EBs but hundreds or thousands of EBs), starting from WD solutions of published data and newly observed data. Why is WD specifically utilized? DDE solutions are obtained via the WD model because WD operates with physically consistent units among bandpass luminosity, bandpass flux and bandpass intensity and has always done so. The plan is to make use of the recently developed DDE algorithms:

(i) that work directly in standard (cgs) flux units;
(ii) include all ordinary EB phenomena;

(iii) allow for aspect (observer location) in temperature estimation;
(iv) that directly produce distance, with a standard error.

That distance estimation can now be *direct* means that *every solution* based on standardized data (see below) can routinely produce a distance and contribute to a rapid increase in the numbers of published distances. Contrary to widespread opinion, distances for over-contact (OC) and semidetached (SD) binaries typically are *not* less accurate than those for detached binaries (DBs) and in reality are usually somewhat more accurate for the reasons given in [17]; so, if preference is assigned according to morphological type, the priority order should be OC binaries first, SD binaries second and DBs third.

4.1 *Eclipsing binaries as distance indicators*

Many recent papers (see, for example, [18–21]) have found EB distances within the Local Group of galaxies, with examples as far as M31 and also in our own Galaxy. EBs have a major advantage over standard candles such as Cepheids in that nearby examples with known distances are not needed; the essential requirements are only that good light curves, RV curves and temperature estimates are readily accessible. So EBs are important as distance indicators; yet, because their luminosities need not be known in advance but are individually measurable, they are *not* standard candles. Interstellar extinction also must be estimated, but that is also true for standard candles; so, apart from an extinction study, only the EB distance target is involved; there is no need for similar and recognizable calibration objects with known distances. Of course, interstellar extinction uncertainties affect only the EB targets, not targets *and* calibration stars, as with standard candles. Naturally the extinction problem disappears for sufficiently nearby objects. The essential EB distance idea goes back at least to remarks in [22], and a history of the subject has been given in [23]. Distances to 96 components of EBs were estimated by Lacy [24]. (The catalogues in [25, 26] each contain more than 1000 EB distances but invoke a mass–luminosity relation so that the distances are not fundamental measurements.) If one asks how the advantage of independence from nearby examples is brought about, the essential answer is as follows:

Step 1. Light curves set relative dimensions (R_1/a, R_2/a), etc. (a picture with an unknown scale). Here a is the orbital semimajor axis length.
Step 2. RV curves set the absolute scale.
Step 3. Spectra fix radiative behaviour (*i.e.* at least one temperature, and thereby the emission per unit surface area). A model stellar atmosphere program quantifies emission.
Step 4. Light curves further provide a $T_2 = f(T_1)$ relation, thus leading to the second temperature and emission per unit area for both stars.
Step 5. Steps 1, 2, 3 and 4 together give the bandpass luminosities $L_{1,2}$ (*i.e.* area × emission/area), and the observable flux at a given distance (thus directly the physical luminosities and fluxes).
Step 6. Comparison with the actually observed flux (after allowance for interstellar extinction) gives the distance. Variations on the idea are mainly in step 3, the means by which temperatures (or, alternatively, surface brightnesses) are estimated, which can be decided in individual cases.

4.2 *Direct distance estimation – the essential idea*

That EB distances can be accurate is shown by published results for EBs in the Large and Small Magellanic Clouds (see, for example, [27–30]) that not only are mutually consistent but even trace the Clouds' three-dimensional structure. However, EB publication history overwhelmingly consists of papers without distance estimates – a situation that now can change via routine DDE applications.

The accuracy advantage of DDE over conventional EB distance work mainly lies in its tapping of the absolute information in the model stellar atmosphere output and in avoidance of approximations based on assumed spherical stars in the flux–distance scaling step. Furthermore, DDE does not need bolometric corrections, as it works entirely within the directly observed standard photometric bands, avoiding uncertainties of conversion to bolometric luminosities. Specifically,

(1) modern stellar atmosphere models provide absolute emission with percentage uncertainties (integrated over photometric bands) that are negligible compared with those of most astrophysical distance estimates and,
(2) an EB light curve model accurately converts surface emission to observable flux without spherical symmetry approximations. Effective temperature $T_{\rm eff}$ estimates typically set accuracy limits and are less troublesome than standard candle calibrations. Once $T_{\rm eff}$ has been set for a reference surface point, the EB model can compute it for an arbitrary point and pass $T_{\rm eff}$ and $\log g$ to a routine for stellar atmosphere emission. The error propagation problem has been treated in [31].

Preferably, RV and light curves are entered into the machine together and solved simultaneously. DDE works in cgs flux units (erg s^{-1} cm^{-3}) rather than in comparison star units, with the input being standard magnitudes such as U, B, V, etc. (not magnitude differences). Conversion of observations to cgs flux requires a calibration constant (so many erg s^{-1} cm^{-3} for a magnitude-zero star), for which the Johnson [32] and Bessell [33] calibrations can serve. The Johnson and Bessell calibrations differ by only 4% in U, B and V (see [16] for a full comparison), which corresponds to only a 2% disagreement in distance. A discussion of calibration fine points has been given in [17]. The advantages of DDE include the following.

(i) Distance becomes an ordinary solution parameter, to be found together with the other parameters and with a standard error.
(ii) Solutions are coherent and in one step (although iterative, as in any EB solution), thus saving astronomers' time.
(iii) There is no loss of distance accuracy for SD and OC binaries because there is no assumption of spherical symmetry at any stage of the process.
(iv) Temperatures of *both* stars can be found objectively from light curves in two or more bands (namely the $T - d$ theorem, below) as a consequence of the fact that the light curves are standardized (U, B, V, etc.).

The radiative computations of DDE are currently performed via Legendre polynomials that reproduce integrations of Kurucz [34] model stellar atmosphere emission over standard bands [35]. Numerous small problems are handled in ways that are transparent to the user. For example, stars in close binaries are likely to have a variable temperature over their surfaces and some have (often small) regions that are above or below the temperature limits of Kurucz atmospheres. As a discontinuous jump to black-body emission would lead to several problems, strategic transitions between atmosphere and black-body radiation [35] ensure smooth overall operation. Note that most EB distance estimation work has been for well-detached binaries, partly to have only one temperature for each star rather than a distribution, thereby avoiding any difference between the spectroscopically observed temperature and the mean surface temperature. The DDE model eliminates the problem by converting between the observed and the mean surface temperature according to a rigorous derivation [17], thus improving applications to SD, OC and near-contact binaries. A preliminary result for the W UMa-type OC binary AW UMa finds a DDE distance, based on the Bessell calibration, of 67.86 ± 0.45 pc, which agrees well with the star's HIP distance (Hipparcos catalogue) of 66.1 ± 3.7 pc. The Johnson calibration would give a distance about 1.3 pc smaller. Further solutions are planned for AW UMa and other binaries and will be reported in a forthcoming paper [17].

4.3 *$T - d$ theorem*

The canonical EB analysis problem is carried out with RV curves of both stars and light curves in some number of photometric bands. A temperature–distance ($T - d$) theorem [16] specifies the requirements for finding the temperatures of both stars and the distance, under the assumption that all such curves are sufficiently accurate and well covered. Arbitrarily scaled light curves (say, in units of comparison star light) provide star dimensions relative to the orbit dimension and a relation between temperatures, $T_2 = f(T_1)$, from relative eclipse depths. The timewise integration of the RVs (length/time units) gives the absolute scale (*i.e.* the orbit size), with both RV curves needed to complete the calculation. (The RVs of one star may be sufficient if the mass ratio is known from a morphological condition such as the SD or OC condition, *i.e.* if a photometric mass ratio is known.) Light curves in standard physical units contain further length information that can provide distance and, ideally, even both temperatures by comparison with model stellar atmospheres. The two-temperature part of these ideas was first published by Prsa and Zwitter [36], and the temperature–distance connection by Wilson [16]. Standardized light curves (*e.g.* U, B, V, R, I, etc.) can be converted to physical units by application of a suitable calibration such as that by Johnson or by Bessell. Of course actual magnitudes, and not differential magnitudes, are required. The $T - d$ theorem can be stated as follows:

$T - d$ theorem: *Eclipsing binary light curves can yield the temperatures of both stars and distance if and only if the light curves are standardized, two or more substantially different photometric bands are fitted, and radial velocities determine the absolute length scale.*

The rationale is analogous to the fundamental theorem of algebra, namely that the number of unknowns should match the number of simultaneous equations to have a unique solution; *i.e.* we need a match between the number (three) of essential light curve observables (the relative eclipse depths and two absolute scalings) and the number (three) of parameters ($[T_1, T_2, d/a]$). RV curves add parameter a, thereby producing distance via $d = a \times d/a$. Further discussion has been given in [16, 17]. Why is the $T - d$ theorem important?

(i) The theorem leads to reliable recognition of light and velocity curve information and ensures its full utilization.
(ii) It provides guidance for making observations best suited to temperature and distance determinations.
(iii) It warns of attempts to achieve the impossible (extract information that is not there) and points out unrealistic claims.
(iv) Obvious extensions of the theorem predict requirements for finding two temperatures (but not distance) or the distance and one temperature.

The $T - d$ theorem has been thoroughly checked by numerical simulations with synthetic data. Fast convergence to results that are correct within standard errors is the norm where $T - d$ predicts success, while poor or no convergence to wrong results obtains where it predicts lack of success. Solutions converge in a few iterations to plausible $[T_1, T_2, d]$ for real binaries RZ Cnc and AW UMa, where the theorem is satisfied [17].

5. Photometric calibrations for standard bands

Photometric calibrations from one colour index to another, from colour index to temperature, from spectral type and luminosity class to temperature, and from temperature to bolometric correction have been published by many researchers, but only two papers calibrate in terms of standard physical units (e.g. flux in erg s^{-1} cm^{-3} for a star with magnitudes of $V = 0.00$, $B = 0.00$, etc.). Calibrations of that kind are needed for DDE applications but exist only in the Johnson and the Bessell papers. Johnson calibrated U, B, V, R, I, J, K, L, M and N while Bessell calibrated U, B, V, R_C, I_C and K, where the subscript C denotes the Cousins [37–40] systems. Johnson's calibrations are based on previously published solar spectrometry and a mean of six published $V_\odot$ estimates. Bessell's calibrations are based on the spectral energy distributions of eight spectrophotometric standard stars and the Hayes–Latham [41] absolute flux calibration for Vega. They are converted to erg s^{-1} cm^{-3} and compared in [16, 17]. Although Johnson versus Bessell agreement is within a few per cent in U, B, V and K (the only bands in common), the fact remains that we have only two publications on the subject. A way to extend the existing calibrations to other bands by observation of EBs is outlined in section 5.1.

Do we need highly accurate calibrations? Johnson versus Bessell fluxes F differ by a consistent 4% in U, B and V; so, since the distance $d \propto 1/F^{1/2}$, corresponding distance estimates might seemingly differ by only an unimportant 2%. That would be the case if d were the only parameter affected by the calibration. However, there will be parameter trade-offs among T_1, T_2 and d, with the $T_2 = f(T_1)$ relation being sensitive to absolute flux measures because the solution process must find a $[T_1, T_2, d]$ combination *that reproduces the absolute scales in two bands and the relative eclipse depths*, as predicted by the $T - d$ theorem. Furthermore the good Johnson versus Bessell agreement could possibly be fortuitous; so new independent work is needed. Motivation comes from the prospect of measuring $[T_1, T_2, d]$ from EB light and RV curves alone.

5.1 *Eclipsing-binary-based bandpass calibrations and checks on calibrations*

Calibrations of the type done by Johnson and by Bessell type are difficult to establish accurately, as they are based on spectrometry of a modest number of bright stars and absolute bandpass photometry of *one* star (Bessell), or on troublesome observations of the Sun (Johnson). The project is not for fully new calibrations, but for conversion of a calibration in one band to calibrations in other bands. The plan follows from the $T - d$ theorem, whose message is that two standard EB light curves, together with RVs, yield three parameters (two temperatures and a distance). However, given a *known* distance, one of the three parameters (distance) can be exchanged for a calibration constant; *i.e.* we use a natural object (the binary) and a model stellar atmosphere to gauge the calibration constant in one band, given that in another. It is not necessary to have full phase coverage in both bands, as the second band only serves to establish the ratio of the two calibrations. To eliminate complications, identify a nearby EB with an accurate HIP parallax, negligible interstellar extinction and no hint of a third body. Ideally, [Fe/H] also should be well known. However, the binary need not be detached; so a W UMa or Algol-type binary can be a good target. AW UMa, at about 66 pc, should be excellent, although it probably has a companion roughly 1% as bright as the EB. AW UMa's companion problem translates into only 0.5% distance error which, although systematic, is very small compared with the HIP standard error of 6%. Apart from the above-mentioned selection criteria, the main criteria are just those that lead to reliable solutions, namely total-annular eclipses and absence of peculiarities (*i.e.* good adherence to the EB and atmosphere models). Now apply the DDE program simultaneously in two standard bands with distance fixed by HIP and solve for T_1, T_2 and one of the two calibration constants, given the other constant, thereby essentially finding the ratio of the two constants. Adopt, for example, the Bessell B value as correct and solve for the Bessell V value as a consistency check or find a new calibration for a non-Johnson non-Bessell band. The procedure will be especially useful for standard bands for which there are no Johnson or Bessell calibrations. Only a few trigonometrically measured EB distances are now accurate enough for good applications, but the much improved GAIA distances will extend the project to many binaries. For now, demonstrations (real binaries) and simulations (synthetic binaries) can stimulate applications when GAIA distances become available. Suitable light and RV curves exist for AW UMa, 44 Boo, Algol, U Cep and several other close binaries.

6. Remarks on publishing traditions

Some of the projects can be partly or entirely carried out with observations that have already been made, a possibility that leads to a broad question: should it be possible to check and attempt improvements upon published analytical results? Surely all would agree that the answer is 'yes'. However, many astronomical papers are based on new data that are unpublished or old data that have never been published, and accordingly their results cannot be checked or improved upon. Later observations may lead to progress but cannot substitute for lost data as a record of earlier observational epochs. A published analysis of unretrievable data can better be described as a testimonial than as a scientific paper, although it may be quite well suited to the *Journal of Irreproducible Results* (http://www.jir.com/). Not only do published observations allow checking of results and conclusions, but they also provide incentives for development, generalization and refinement of theoretical models, as theorists tend to invest effort where real observations exist. Observing programs are stimulated by existence of models and so we have *no computational models–no observations* and *no observations–no computational models*. The overall result of non-publication of data can be stagnation of a field and a waste of large amounts of expensive telescope time. A related problem is that many papers fail to state observation times, sometimes publishing phases (with the whole cycles omitted) for supposedly periodic but not necessarily periodic phenomena, and even for phenomena that are unlikely to be periodic such as polarization in binaries.

It is not only huge tables that often are unpublished, but perhaps merely hundreds of numbers or even fewer. Ironically, we *have* Tycho Brahe's very useful light curve of SN 1572 that shows the supernova to be type Ia, while modern journals lose many data with every issue. It is not that archiving was better 400 years ago, but we should be well past data loss problems by now. What did Tycho Brahe have? Even notebooks were primitive by today's standards and there was no local copy shop. We now have electronic databases and should use them. Statements are made by authors, to editors or in print, that data will be provided upon request but, with passage of time, old observations are often discarded, unreadable or lost, and authors retire or become incapacitated. In summary, we should guard against data loss for the following reasons:

(i) Observations usually are the most valuable part of a paper, as a better model will be developed.
(ii) Observations are a permanent record of the state of an object.
(iii) Multiple epochs processed together may allow direct solution for timewise variation of parameters.

What should be done? To begin, editors and referees need to be aware of the data loss problem and be vigilant. Journal policy should be that data on which a paper is based should be in print or electronically archived, and observation *times* should be published for all kinds of data, whether a phenomenon is believed to be periodic or not, and whether it is one observation or many. Of course the policy should be stated clearly to authors and referees. Phases for periodic data are not needed, as they can be trivially computed from an ephemeris. Mirror sites guard against hardware failure.

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