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Close Binary Star Observables: Modeling Innovations 2003-06

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Abstract. Innovative work on close binary models in 2003-06 improved upon synthesized line spectra, line profiles, and polarimetry; developed new ways of parameter estimation; and increased solution effectiveness and efficiency. Recent applications demonstrate the analytic power of binary system line spectrum models that pre-date the triennium. X-ray binary line profiles and radial velocity curves were refined by solution of the radiative transfer problem with specific inclusion of X-irradiation. Model polarization curves were generated by Monte Carlo experiments with multiple Thomson scattering in thin and thick binary system disks. In the parameter estimation area, independent developments by two groups now allow measurement of ephemerides, apsidal motion, and third body parameters from whole light and velocity curves, to supplement the traditional way of eclipse timings. Although the new route to those parameters is not well known within the ephemeris community, there are accuracy advantages and the number of applications is increasing. Numerical solution experiments on photometric mass ratios have checked two views of their intuitive basis, and show that mass ratios are well determined where star radii and limiting lobe radii are both well determined, which is for semi-detached or over-contact binaries with total-annular eclipses. Solution efficiency and automatic operation is needed for processing of light curves from large surveys, and will also be valuable for preliminary solutions of individually observed binaries. Neural networks have mainly been used for classification, and now a neural network program reliably finds preliminary solutions for W UMa binaries. Archived model light curves and Fourier fitting also are being pursued for classification and for preliminary solutions. Light curves in physical units such as erg $\cdot$ sec$^{-1}\cdot$ cm^{-3} now allow direct distance estimation by combining the absolute accuracy of model stellar atmospheres with the astrophysical detail of a physical close binary model, by means of rigorous scaling between surface emission and observable flux. A Temperature-distance (T-d) theorem specifies conditions under which temperatures of both stars and distance can be found from light and velocity curves.

Keywords. radiative transfer, polarization, scattering, methods: analytical, stars: atmospheres, stars: distances, (stars:) binaries: eclipsing, (stars:) binaries (including multiple): close, (stars:) binaries: spectroscopic

1. Innovations in Overview

The three years following the Sydney General Assembly saw renewed progress in modeling of close binary star observables, partly spurred by large scale space and ground based observational programs. This review covers essential ideas for some of the more innovative work in the window 2003 to 2006, with mention of applications that demonstrate usefulness of earlier conceptual advances. The number of innovations precludes detailed examination of all areas, so one development, solution of light curves in standard physical units, is explained conceptually while others are described in terms of overall aims and motivations.

Disks are interesting in terms of their formation, structure and stability, and they occur in several binary star contexts as a challenge to modelers of light curves, line spectra, and time-dependent polarization. The variety of synthesized observables is increasing for stars as well as for disks, with notable attention to X-ray binaries. Examples of work on solutions include parameter estimation for third stars and for ephemerides, while numerical experiments have clarified the conceptual basis for photometric mass ratios. Solution efficiency and automatic operation are indispensible for surveys such as OGLE, ASAS, and Gaia, with neural networks and approximate fitting schemes now being adapted to several kinds of classification and to initial parameter estimates. Absolute flux solutions explore whether working in standard physical units might be advantageous, with the obvious connection being to distances.

2. Synthesized Observables

Models of 2003-06 demonstrated the power of earlier line spectrum syntheses, refined line profile and radial velocity (hereafter *RV*) curve computations, and produced signatures of disk polarization by Monte Carlo experiment.

2.1. *Line Spectra*

Whether for stars or disks, analysis of binary system line spectra is a difficult problem that stretches machine resources. However model line spectra can be powerful probes and, for non-eclipsing binaries, essentially the only probes of system astrophysics. The basic programming requirement is to attach model stellar atmosphere output to local star or disk surface elements, then integrate observable flux into the momentary line of sight throughout the spectrum, allowing for the same phenomena (eclipses, gravity effect, etc.) as for ordinary light curves. Computational and memory efficiencies and perhaps parallel processing will be needed to deal with the slowness of model atmosphere programs, with having another dimension (wavelength), with having sufficient resolution in that dimension, with smooth superposition of local Doppler shifts, and with having additional parameters. Chemical abundances can be a lure toward parameter proliferation, so hard decisions on parameterization must be made. A line spectrum generator based on Kurucz (1998) atmospheres is embedded within Prša & Zwitter's (2005a) user-friendly interface (called *PHOEBE*). Several applications (e.g., Hoard *et al.* 2004 and Linnell *et al.* 2005) on cataclysmic variable MV Lyrae; Hoard *et al.* (2005) on magnetic white dwarf YY Draconis; Linnell *et al.* (2006) on the non-eclipsing double-contact† binary V360 Lacertae) demonstrate effectiveness of the binary spectrum and light curve program by Linnell & Hubeny (1994, 1996) that is based on Hubeny (1990, 1991) atmospheres. Earlier spectral computations for disks and stars are cited by Linnell & Hubeny. Parameter extraction has so far been by trial and error. Trials on single stars and single star models can guide reasonable parameter choices in chemical abundances, damping, microturbulence, and perhaps even differential rotation.

2.2. *X-ray Binary Line Profiles and Radial Velocity Curves*

Problems of binary line profile distortions due to tides and irradiation and their effect on *RV*'s go back at least to Sterne (1941), with effects due to eclipses extending back to Schlesinger (1909, 1916) and Rossiter (1924), and with newer references in Wilson & Sofia (1976) and the Wilson (1994) review. The essential *RV* phenomena are included in several public *EB* observables models. Antokhina, Cherepashchuk & Shimanskii (2005) have now refined X-ray binary line profiles and *RV* shifts by solving the radiative transfer problem with specific treatment of X-radiation. Line distortions caused by stellar winds

† The double-contact morphological type is defined in Wilson (1979).

were modeled by Abubekerov, Antokhina & Cherepashchuk (2004), with applications to the High Mass X-ray Binaries LMC X4, Cen X3, SMC X1, Vela X1, and 4U 1538−52, particularly including consequences for mass estimates.

2.3. *Polarization*

By far the main present impediment to progress on time-dependent binary star polarization is lack of observations, as modelers are unlikely to work in an area devoid of data. Among the few observational papers over the years, a particularly illogical practice has been tabulation in terms of orbital phase† (with the whole cycles removed) instead of time. As some polarization phenomena are episodic rather than periodic, time records are essential – and require no more journal space than phases. A good start on the observational side was made with polarization curves of Algol by Kemp *et al.* (1983), but to date there have been no extensions of time-dependent polarization to fainter stars, either by refinement of polarimeters or by use of large telescopes. However Hoffman, Whitney & Nordsieck (2003) made exploratory radiative transfer computations of polarization due to multiple Thomson scattering in illuminated thin and thick circumstellar binary system disks. They give extensive tabular and graphical results of Monte Carlo simulations that follow radiative transfer in internal and external radiation fields. The disks are defined geometrically by a central opening angle and a radius. The parameter definition problem will need development when there are observations for applications.

3. Parameter Estimation

3.1. *Whole Light and Velocity Curve Ephemerides and Extension to Third Bodies*

The idea of finding *EB ephemerides from whole light and RV curves* is more than a decade old, yet remains nearly unknown in the "timing diagram" community, although good demonstrations of improvement over eclipse timing ephemerides (for comparable time spans) continue to appear. The same can be said for the extension to third bodies. Indeed, recent otherwise excellent accounts and reviews of *EB* ephemeris work (*e.g.* Kreiner *et al.* 2001; Rovithis-Livaniou 2005) do not mention the idea. Accordingly, inclusion within this review may foster awareness, whose present lack is likely due to the concept's rather quiet introduction in two independent developments – so quiet that the early conceptual work can be traced only through applications, with the two camps becoming aware of each others work only recently. Ephemeris parameters are a heliocentric reference time (HJD_0), the period at the reference time (P_0), the rate of period change (dP/dt), and the rate of advance ($d\omega/dt$) of the argument of periastron. The reference time may refer to periastron or to conjunction. For third bodies we have another example of the "Astronomy of the Invisible" that began with Neptune's discovery and continues through extra-solar planets, supermassive black holes in galactic centers, and Universal dark matter. Third body information is in Doppler shifts of the *EB* and in phase excursions of light curves and *RV* curves. Third body (subscript $3b$) parameters include $HJD_{0,3b}$, $P_{0,3b}$, e_{3b}, ω_{3b}, and orbital semi-major axis, a_{3b}. Essential to the procedure is to fit multiple curves in *time* rather than phase. Some applications are to light curves, some to *RV* curves, and others to light and *RV* curves combined. The main difficulty for a third body is identification of the correct orbit period among many aliases that follow from the typical large data gaps in astronomical data. Power spectral analyses

† Publication of phases in place of time also has become distressingly common for light curves. Although light variation is typically more nearly periodic than polarization, phased data cannot be used for ephemeris work and have greatly reduced value for investigation of cycle to cycle and epoch to epoch changes. Referees and editors should be aware of this problem.

of several kinds may find correct periods in reasonably favorable circumstances and the situation is helped by *simultaneous* solution of light and RV curves, as the combined data types partly fill gaps. The numerous successful applications demonstrate the power and adaptability of the overall process.

Applications on one side include Mayer *et al.* (1991) [HJD_0, P_0, and $d\omega/dt$ from RV's and light curves of the EB V1765 Cygni]; Harmanec & Scholz (1993) [HJD_0, P, and dP/dt from a century of RV's for β Lyrae†]; Tarasov *et al.* (1995) [HJD_0 and P from RV's of the non-eclipsing triple system ϵ Persei]; Harmanec *et al.* (2004) [P and dP/dt for ER Vulpeculae, a solar-type EB]; Janik *et al.* (2003) [$d\omega/dt$ for the well-detached EB V436 Persei]; and Horn *et al.* (1996) [$HJD_0, dP/dt, d\omega/dt, HJD_{0,3b}$,and P_{3b} from RV's of the non-eclipsing triple system 55 Ursae Majoris]. The Horn *et al.* third body results for 55 UMa agree accurately with speckle (*i.e.* visual binary) parameters by McAlister, Hartkopf & Franz (1990). All of the above-mentioned applications are by means of the combination light-RV program by P. Hadrava, with the basic idea having been briefly mentioned in Hadrava (1990), and are by the Simplex algorithm, as formulated by Kallrath & Linnell (1987). A guide to specifics is in Hadrava (2004).

Ephemeris solutions for the parallel development are by the Differential Corrections (DC) algorithm, with the basic logic and mathematics and many references on applications (starting with Elias *et al.* 1997) in Wilson (2005). The extension to third bodies is in Van Hamme & Wilson (2005, 2007). Basic to the DC version is that ephemeris parameters are found along with all other parameters in a general solution, and with standard errors, rather than separately in an initial step. The [HJD_0, P, dP/dt, $d\omega/dt$] solution facility has been in the public *W-D* program since 2003.

3.2. *Photometric Mass Ratios*

Incorrect published remarks about photometric mass ratios (q_{ptm}) probably outnumber correct ones. A common misconception is that q_{ptm}'s mainly derive from ellipsoidal (*i.e.* tidal) variation, whereas they mainly derive from relative radii ($r_{1,2} = R_{1,2}/a$) in relation to limiting lobe radii. The origins of photometric mass ratios are recounted in Wilson (1994) for the logically distinct cases of semi-detached (SD) and over-contact (OC) binaries. For SD's, q_{ptm} follows from the condition of the contact star's mean radius matching its mean lobe radius, which is a definite function of q. A solution constraint that one star accurately fills its limiting lobe is required to exploit the SD condition properly. The situation is slightly more complicated for OC's, where *two* radii are involved. There the essential q_{ptm}-related quantity is R_2/R_1, the ratio of mean star radii, which depends strongly on q and relatively weakly on over-contact level (f), with the relation being inverted to find $q(R_2/R_1, f)$. Since R_2/R_1 and f are measurable from light curves, q_{ptm} naturally follows. Many OC's are only slightly over-contact so their q relation approximately reduces to $q(R_2/R_1)$. With radii the links to q_{ptm} and total-annular eclipses the link to strong measures of radii, *completely eclipsing* OC 's and SD's should have the strongest q_{ptm}'s. Indeed, experiments (Terrell & Wilson 2005) find correct and fast-converging q's within standard error expectations for OC's and SD's from solutions of noisy synthetic light curves with total-annular eclipses (*viz.* Fig. 1).

The q_{ptm} concept basically does not apply to detached binaries (DB), except that a weak q estimate can sometimes be found by graphing variance against q.

† Harmanec & Scholz conclude that β Lyr's ephemeris can be derived more accurately by whole curve RV fitting than by times of eclipse minima.

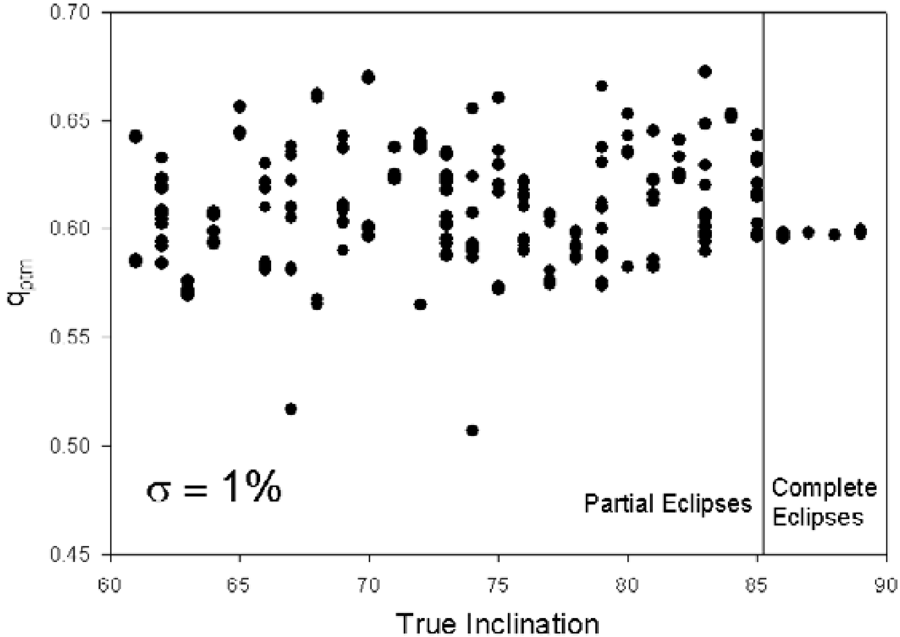

Figure 1. Dramatic q_{ptm} accuracy improvement in passing from partial to total-annular eclipses as the orbital inclination is stepped in 1° increments (Terrell & Wilson 2005). Results are from *DC* solutions of noisy synthetic *OC* light curves for a true mass ratio of 0.60. The standard deviation of the Gaussian noise is 1%.

4. Solution Efficiency and Automatic Operation

Although schemes for automatic light curve classification and for starting parameter generation have been stimulated by existing and anticipated large databases, applications to individually observed binaries also can profit from artificial intelligence and other automation, thereby saving computational as well as human time and eliminating incorrect solutions before publication. Competition should identify the leading programs for preliminary solutions and for classification, and also suggest ways to extract their best features for building later generations of programs.

4.1. *Neural Networks*

Neural networks have been utilized for automatic classification by Sarro, Sanchez-Fernandez & Gimenez (2006), and for starting parameters in the *Eclipsing Binary Artificial Intelligence* (*EBAI*) project by Devinney *et al.* (2006). Sarro *et al.* briefly summarize previous neural network usage in astronomy. Aims of their program are to separate pulsating stars from *EB*'s and to classify *EB*'s into four categories according to characteristics such as eclipse depths and widths. Sarro *et al.* then statistically relate their four categories to the morphological types of *DB*, *SD*, and *OC* via numerical experiments on 81 systems from the literature. *EBAI* has so far been tried on synthetic W UMa light curves, with added noise, and seems impressively reliable.

4.2. *Archived Model Light Curves*

The idea of Archived Model Light Curves (*AMLC*) for starting parameter generation is to store large numbers of theoretical light curves over parameter ranges for comparison with observed curves. The central point is that even with millions of archived synthetic light curves, computation of variance on modern computers is simple and goes very fast. Of course, the theoretical and observational data are definite numbers and require no model computations, once an archive has been generated. *AMLC* goes back at least to Wyithe & Wilson (2001, 2002), where it was tried on the full dataset of *OGLE EB*'s in the Small Magellanic Cloud with good results, based on some thousands of archived curves. Now Kallrath & Wilson (2007) are developing archives with millions of curves. Efficient data packing algorithms and substantial computing times in the generation step are needed for such large archives.

4.3. *Fourier Fitting*

The long history of Fourier series applications to light curves has continued in the recognition of *EB*'s among other variables in work by Groenewegen (2004, 2005) and in morphological *EB* classification (*DB, SD, OC*) by Pojmanski (2002), who applied ideas on cosine series fitting by Rucinski (1993). Although slightly before the 2003-2006 triennium, Pojmanski's work is incorporated in analysis of *ASAS*, the All Sky Automated Survey (Paczynski *et al.* 2006) that has observed light curves of more than 10,000 *EB*'s, many being discoveries. Although the scheme's true uncertainties remain to be established, its potential for efficient impersonal classification appears promising.

4.4. *Words of Caution*

All procedures for starting parameter estimation and for classification should be tested on *noisy synthetic data*, as that is the only way to know true values and morphological types for comparison with procedure results. Most schemes have not been so tested and can give false impressions of reliability (*EBAI* is an exception, as it has been so tested). Tests on real binaries have considerably reduced value as their characteristics are known only approximately, with some published solutions even being in local minima of parameter space and therefore wrong. The common practice of testing against real data can likely be traced to recognition that models can and do have shortcomings. However one must remember that a model is involved either way, whether the test data are real or synthetic, as adopted parameters for real binaries are based on a model.

4.5. *A User-friendly Interface*

Among several programs constructed over recent decades to serve as user-friendly interfaces to *EB* light curve and solution programs, that by Prša & Zwitter (2005a) is especially well designed and multi-faceted. It offers a variety of solution algorithms (*DC*, Simplex, others), generates line spectra with broadened profiles, and conveniently makes pictures and graphs. It also introduces a conceptual innovation (*viz.* Prša & Zwitter 2005a) by utilizing the color index information in *standardized* light curves to allow solution for a second component temperature. Of course, tradition is to set the temperature of one star from spectra or other evidence and solve light curves for the other. Another innovation is to compensate the effect of interstellar extinction on light curves (a problem of finite bandwidth) so as to reduce or eliminate corresponding solution errors (Prša & Zwitter 2005b).

5. Absolute Light Curves and Distance

That light curves need not be in standard physical flux units to yield much of their astrophysical information has been recognized from the earliest work on *EB* analysis, but the question arises: might there be advantages in working with "absolute" light curves? A recently suggested answer (Wilson 2006, 2007) invokes the following 3-part idea:

1: The absolute emission accuracy of modern model stellar atmospheres can now be combined with the structural detail of *EB* models.

2: Conventional synthetic light curves can be made absolute by simple but rigorous scaling (*not* global scaling for spherical stars).

3: Parts 1 and 2 together allow distance to be an ordinary solution parameter by *DC* or another algorithm (Direct Distance Estimation = *DDE*), and with a standard error. A side benefit is that bandpass luminosities can directly be produced in standard physical units or in solar luminosities. Potential benefits are uniform and accurate distance statistics, and improved thruput (reduced human work). Experience shows that the procedure works as least as well (actually better) for *SD*'s and *OC*'s as for *DB*'s, so there no longer is any reason to limit *EB* distance targets to *DB*'s.

Model stellar atmospheres accurately give absolute emission, so they allow computation of *EB* light curves for comparison with observed light curves, which can be made absolute via the Johnson (1965) or Bessell (1979) calibrations. These calibrations differ by only 4% in *U, B,* and *V*, with the Johnson/Bessell ratio essentially the same in the three bands, so corresponding derived distances (*i.e.* Johnson *vs.* Bessell) differ by only 2%. Neither active model atmosphere computation nor storage of theoretical spectra nor integration over photometric bands is needed because those steps have already been taken via the Van Hamme & Wilson (2003) Legendre polynomial representation of model atmosphere emission. Observable flux over bandwidth in cm can be in $\mathrm{erg \cdot sec^{-1} \cdot cm^{-3}}$. The bolometric luminosity parameter, L_{bol}, of traditional distance scaling is in $\mathrm{erg \cdot sec^{-1}}$, but L_{bol} – being emission over all directions and all wavelengths – is not observable in practice. An impediment to accuracy in traditional L_{bol}-distance scaling is that author-dependent bolometric corrections are needed. The *DDE* idea is to work from the observational side with the directly observable quantity $F(t)$ (time dependent flux in a given band), and from the model side with local intensity I in $\mathrm{erg \cdot sec^{-1} \cdot sr^{-1} \cdot cm^{-3}}$ that becomes integrated into theoretical $F(t)$. Thus Part 1 (above) can be realized, but let us ask whether *local* introduction of *cgs* units – an annoying programming problem – is really necessary. Part 2 says that it is not, provided that one starts from a model such as *W-D* that is fully consistent in regard to radiative units. Even the oldest *W-D* versions produce observable fluxes (output) and local intensities (internal quantities) that correspond rigorously, unit-wise, to bandpass luminosity (input). So the user's choice of luminosity unit fixes the flux unit, the program operates in user-defined flux units, and a readily computable scaling factor converts *W-D* flux from user-defined to *cgs* units. Computation of that factor might be done in several ways, with a straightforward way being to scale from normal emergent intensity at a surface reference point (Wilson 2003, 2005). A convenient reference point is one of the poles. The scaling relation naturally involves the star-observer distance, d, and is

$$F_d^{\mathrm{abs}} = 10^{-0.4\mathrm{A}} \left[F_{\mathrm{a},1}^{\mathrm{prog}} \left(\frac{I_1^{\mathrm{abs}}}{I_1^{\mathrm{prog}}} \right) + F_{a,2}^{\mathrm{prog}} \left(\frac{I_2^{\mathrm{abs}}}{I_2^{\mathrm{prog}}} \right) \right] \left[\frac{a}{d} \right]^2 , \tag{5.1}$$

where F_d is flux at the observer's location, F_a is flux at distance a (the orbital semimajor axis length), I is polar normal emergent intensity, and A is bandpass interstellar extinction in stellar magnitudes. Of course the units of a and d need only be the same. Superscripts *abs* and *prog* mean "absolute" and "program" and subscripts $1, 2$ denote the binary components. The computation is thereby easy, yet brings the sophistication of stellar atmosphere and *EB* models (tides, irradiation, gravity effect, etc.) to bear on the problem.

5.1. *A Temperature-distance Theorem*

In traditional *EB* solutions, where the flux unit is comparison star flux, the idea is to set one temperature from "external" information (*e.g.* spectra) and find the other from light curves (essentially from relative eclipse depths). Distance can be estimated separately from a standard magnitude measured outside eclipse, corrected for interstellar extinction. The *DDE* way is to make full use of the absolute flux and color information in *standardized* light curves to find distance (d) and the second temperature, and with standard errors.† A Temperature-distance (*T-d)* theorem (Wilson 2006) specifies conditions under which various combinations of $[T_1, T_2, d]$ can be measured: *Temperatures of both stars and distance can be found objectively from standard light curves in 2 or more bands* (*e.g. U, B, V*, etc., not differential). A solution of only one standard light curve must sacrifice one of the three parameters, thus finding $[T_1, T_2]$, $[T_1, d]$, or $[T_2, d]$ while assuming the third parameter. A solution of three or more curves will be over-determined in $[T_1, T_2, d]$, with consequent biases that may or may not be significant, depending on calibration consistencies in particular bands, on assumed chemical composition, and on accuracy of the adopted model stellar atmospheres. The logical basis is explained in Wilson (2006) and numerical experiments that agree with the theorem's predictions will be described later.

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† In §4.5 we have already seen the Prša & Zwitter idea for finding two temperatures from standardized light curves.

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Discussion

PETR HARMANEC: Bob, I find it appropriate to mention that many things you were describing in your talk with reference to studies dated 2005–2007, such as including time derivatives, including apsidal motion into solutions, modeling triple star motion or dereddening, were successfully realized in Petr Hadrava's program FOTEL already early in the nineties (Hadrava 1990, 2004).

WILSON: Thanks for the information. Foundations of the ephemeris work that I described go back to 1997, but I was not aware that Petr Hadrava's program had those capabilities since 1990. I will reference his work in the review's printed version. It seems that we have two independent developments.

EDGARD SOULIE: In order to calculate third order corrections, did you resort to the technique branded <<Automatic differentiation of algorithms>>, which is implemented efficiently? Proceedings of conferences were published notably by Corliss & Griewank (1991) and Faure, Griewank, & Hascoet (2000).

WILSON: Do you mean "third *body* corrections"? Anyway, the derivations were found by hand, just differentiating the functions.

CARLSON CHAMBLISS: $O - C$ data on eclipsing binary minima were often used to "discover" 3^{rd} components. Some of these are spurious. Can new procedures be used to determine which are real and which are spurious?

WILSON: Yes, and our work (Van Hamme & Wilson 2007) finds that in one "classical" triple system (very well known), the third body doesn't seem to be there.