Eclipsing Binary Star studies: Present and future

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Abstract

The importance of Eclipsing Binary (EB) star studies in better understanding stellar structure and evolution is underlined. The combined astrometric, photometric and spectroscopic data, obtained from ground-based and space observations, can be used to compute with high accuracy the physical parameters of the observed EBs. Moreover, the database of EB stars from ground-based surveys and the Gaia, COROT and Kepler space missions will provide light curves for many thousands new systems for which follow up ground-based observations can be carried out. In certain cases, light curves of superior quality will allow studies of fine effects of stellar activity and very accurate determination of stellar parameters. Moreover, many new discoveries of interesting systems are expected from those space missions, including low mass binaries and star-planet binary systems.

1. Introduction

Binary stars are pairs of stars, with the two components moving in bound orbits about their common center of mass. They are as common as single stars in the Universe. In the solar neighborhood more than 50% of stars are members of binary or multiple stars systems. Binary stars are the primary sources of our knowledge of the fundamental properties of stars. Their studies allow direct determination of stellar masses (star-star, star-planet cases), stellar radii and stellar luminosities.

The evolution of binary stars helps to explain a host of diverse and energetic phenomena such as: cataclysmic variables, novae, symbiotic stars, some types of supernovae and X-ray binaries. These binaries are classic examples of the fundamental contribution that stellar astrophysics makes to our general understanding of physical processes in the universe. Particularly, recent studies of Eclipsing Binaries (EBs) in other galaxies and clusters make it possible to explore stellar evolution and establish mass-luminosity laws for galaxies with vastly different evolutionary and chemical histories from our Galaxy (such as LMC and SMC).

Moreover, EBs are beginning to play an important role in cosmology as distant indicators to nearby galaxies. As more data are accumulated, the studies of these systems may lead to an improvement in the extragalactic distance scale. The types of binaries described by observational techniques are: visual, astrometric, spectroscopic, and eclipsing binary systems.

2. Categories of Close Binary Systems

Close binaries (also called Interacting binaries) are two stars that do not pass through all stages of their evolution independently of each other, but in fact each has its evolutionary path significantly altered by the presence of its companion. Processes of interaction include: gravitational effects, mutual irradiation, mass exchange and mass loss from the system. This is not the case for visual binaries (e.g. Sirius A and B) where the evolution of each component is independent of each other.

The zoo of Close Binaries contains

- Detached systems, Semi-detached systems, Contact systems
- High-Mass X-ray Binaries (HMXB); spectrum of primary O–BI-II, secondary: NS, BH
- Low-Mass X-ray Binaries (LMXB); spectrum of primary: A–MV, secondary: NS, BH
- Cataclysmic Variables; primary: WD, spectrum of secondary: K–MV
- RS CVn systems; spectrum of primary: GV, spectrum of secondary: KIV
- Pulsar Binaries; primary: NS, secondary: WD or NS
- Symbiotic stars; primary: red giant, secondary: MS, WD or SD
- (NS: neutron star; BH: black hole, WD: white dwarf; SD: subdwarf; MS: Main Sequence)

Table 1. *Categories of close eclipsing binary systems with non-degenerate components*

Type of system Mass ratio $=m_2/m_1$	Spectral range Orbital period	Photometric features	Spectral features
Two MS stars, not necessarily equal. Detached, $q \approx 0.1\text{-}1.0$	O–M Days to 100s of days	Normal eclipses of spherical stars, except some O–B	Normal absorption-line spectra
Algol systems Classical (e.g. Algol) O-B type Semi-detached Classical: $q\approx0.1\text{-}0.3$ O-B type: $q\approx0.3\text{-}0.7$	Pr/sec: B–AV/F–KIV O–B/B–A Days	Very different depths of eclipses; Reflection effect + distortion; often asymmetric light curves due to gas streaming	Emission lines of H, Ca II, in optical; C IV etc. in UV; accretion streams; occasional discs; mass loss
W UMa systems (e.g. W UMa) Contact systems $q \approx 0.08\text{-}0.9$	F – K ≤ 0.7 day	Continuous light variation due to ellipticity; some- times asymmetric due to starspots; soft X-ray sources	Rotationally broadened and blended absorption lines; emission lines in UV (chromo-spherically active

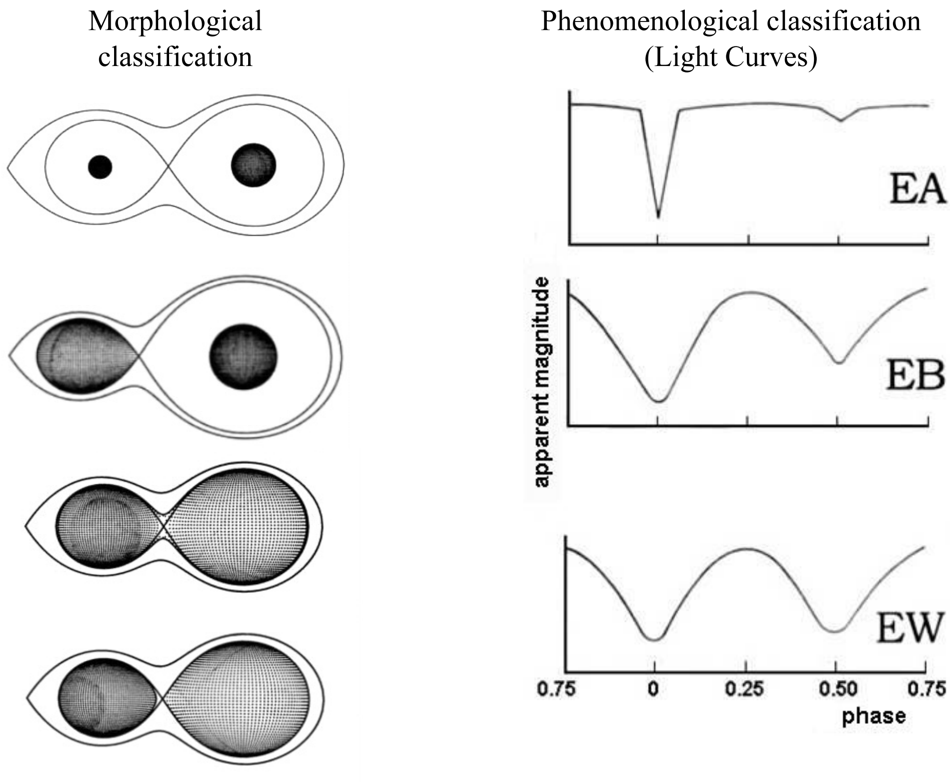

Figure 1. *Classification of Eclipsing Binaries*

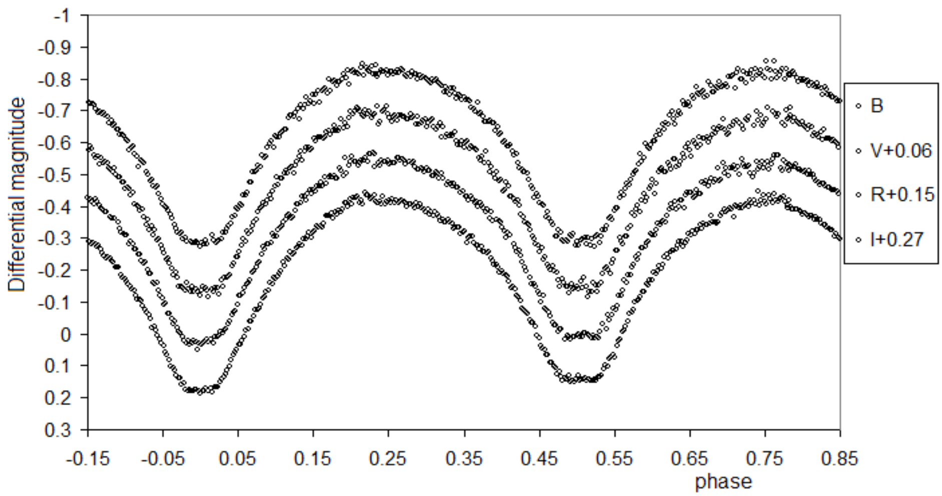

Figure 2. *The BVRI light curves of the contact system V839 Oph obtained at the Gerostathopoulion observatory of the University of Athens on August 6 & 7, 2008 (Courtecy A. Liakos)*

The classification of Eclipsing Binaries according to Roche model geometry and according to the shape of their light curves is given in Figure 1 and a typical light curve of a close binary system is shown in the Figure 2.

3. Derivation of physical parameters

The ultimate goal for observational astronomers who study the properties of binary stars is to make a direct determination of the astrophysical parameters: *masses, radii, shapes, temperatures and luminosities.*

The **absolute dimensions or physical parameters** are the parameters, derived from the analyses of light and radial velocity curves, which describe the component stars in SI units, regardless of the distances of the binaries from us. Much effort has been devoted so that the data derived from spectroscopy and photometry should be free from systematic errors and have the smallest possible random errors.

Requirements for the physical parameters

During the last two decades two distinct developments had a great impact in deriving the basic astrophysical quantities describing the Close Binary systems:
The first was the development of the **Roche model** for light curve analysis, and the second one was the invention of **new modern methods in deriving radial velocities** for Close Binary systems.

The Roche Geometry

Two forces need to be considered in the circular orbit and synchronous rotation case:

- the centrifugal force due to the rotation of the entire system
- gravitational attractions of two mass points (the two components) moving around the center of mass of the binary system.

The normalized potential Ω of all the forces acting on any point (x, y, z) around the two mass points is given by the equation

$$\Omega = \frac{2}{(1+q)r_1} + \frac{2q}{(1+q)r_2} + \left(x - \frac{q}{1+q}\right)^2 + y^2 \tag{3.4}$$

where $r_1 = \sqrt{x^2+y^2+z^2}$, $r_2 = \sqrt{(x-1)^2+y^2+z^2}$, $q = \frac{m_2}{m_1}$.

The surfaces produced by Ω = constant are called *equipotential surfaces*. Those passing through the inner Lagrangian point L_1 and through the external point L_2

are known as *critical Roche surfaces,* and particularly the first one is the **Roche limit** (see Figure 3).

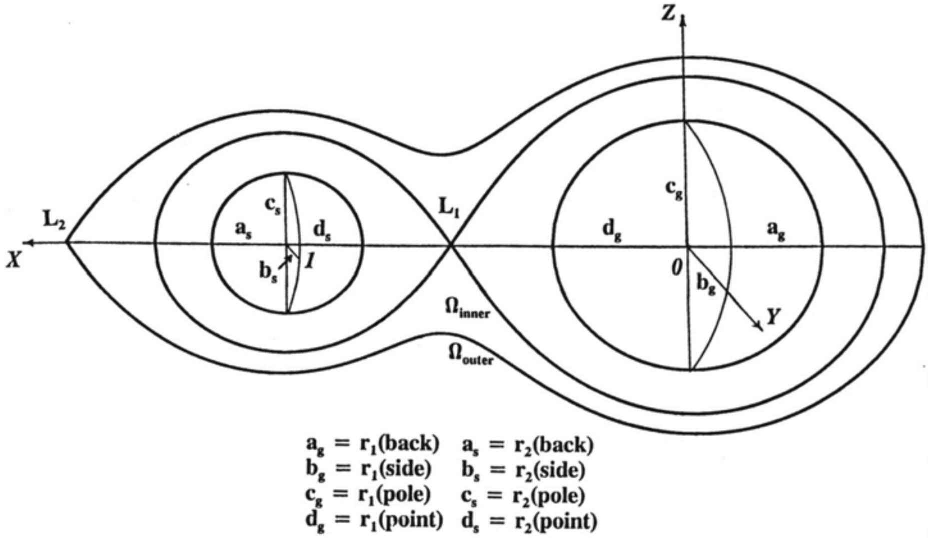

Figure 3. *The Roche geometry for a close binary system: the equipotential surfaces and the fractional radii of the two components are shown*

Photometry

Photoelectric photometry is still the most precise and accurate means of obtaining flux measurements in optical astronomy (single and two-star photoelectric photometers, etc). There are a number of reasons for this situation. In most of the cases, the best possible precision for a source of a given brightness is obtained when *shot noise* is the dominant source of uncertainty. Photoelectric photometers are capable of higher precision than present-day imaging devices and this can be obtained by using pulse counting technique with various filter systems (*UBVRI, uvby*, others).

CCD photometry has many advantages over conventional photomultiplier-based photometry. These include a broad spectral response (e.g., B, V, R, I) with a single detector, the precise differential photometry even through thin clouds (when the variable and comparison stars fall on a single CCD frame) and the ability to do photometric studies of multiple faint objects in crowded fields. The main disadvantages of CCD photometry are the loss of UV sensitivity, extensive image processing, and computer storage and standardization problems. The significance of cluster photometry should be also stressed. Variable and Binary stars in clusters can provide independent assessments of cluster distance and permit checks on luminosity calibrations. The expected precision can be 1–2%, if the photometric observations are carefully reduced and well transformed.

From the solution of the light curves (which can be made by codes based on the Roche model of EBs) we obtain the orbital inclination i, the fractional radii $r_{1,2}$ (the radii expressed in terms of the separation of the two components taken as unit), the component temperatures $T_{1,2}$ and the mass ratio q $(=m_1/m_2)$. Second-order parameters, such as limb darkening coefficients (u_1, u_2), gravity darkening coefficients (g_1, g_2) and bolometric albedos (A_1, A_2) are assigned theoretical values. The observed flux L can be expressed as a function of several fundamental parameters of the two components through the equation

$$L = f\,(r_1, r_2, i, T_1, T_2, q, u_1, u_2, g_1, g_2, A_1, A_2, \lambda) \tag{3.1}$$

where λ is the wavelength of observations. The absolute radii R_1 and R_2 are given by $R_{1,2} = \alpha r_{1,2}$, where α is the separation of the two components (distance between the centers of the two components). This is the case that masses and radii are the most accurately determined fundamental parameters for stars in binaries. The relative radii determined from solutions of good light curves are accurate to ±1% or better, and the major source of uncertainty about masses and radii arises from the accuracies of the radial velocity semi-amplitudes.

The luminosities of the two components are computed from $L_{1,2} = 4\pi R_{1,2}^2 \sigma T_{1,2}^4$ or, more usually, from $L_{1,2} / L_{sun} = (R_{1,2} / R_{sun})^2 (T_{1,2} / T_{sun})^4$, where the subscript *sun* refers to the respective parameters of the Sun. The uncertainties of the adopted/derived temperatures obviously have a strong influence on the accuracy of the determination of luminosity, because enter at the forth power. Then, the absolute magnitudes can be derived from

$$M_{bol\,1,2} = C - 5\log_{10}(R_{1,2} / R_{sun}) - 10\log_{10} T_{1,2} \tag{3.2}$$

where $C = M_{bol\,sun} + 10\log_{10} T_{sun} = 42.369$ for $M_{bol\,sun} = +4.75$ and $T_{sun} = 5780K$.

Spectroscopy

The second development with a great impact on deriving the stellar parameters is the invention and use of modern methods in deriving radial velocity curves for close binary systems. It has been difficult to study contact binary systems spectroscopically with good precision because

- the spectral lines are very broad (V_{rot} ~ 150 km s^{-1}) and blended ($\delta\lambda$ ~ 2 Å) and
- also because the systems are very faint for good spectral resolution (0.01 P ~ 5 min).

The above problems have been overcome in the last 20 years by reducing the spectra in a digitized form using modern techniques (**Cross-Correlation Technique, Broadening Function Approach, Spectral Disentangling**), and by introduction of image intensifiers and high quantum efficiency CCD detectors.

For spectroscopy the resolution ($R = \lambda/\Delta\lambda$) is usually $R > 1000$ and $R \sim 10^5$ or higher for extra-solar planet research. The kinds of studies include: spectral classification, line profile analysis and radial velocity determinations. The low resolution is for spectral classification, while higher resolutions are desirable for precise RV work for binary star modelling. Particularly, highest resolution is needed for the analysis of spectral line profiles. Radial velocity surveys can provide: the mass ratio, the separation of components in physical units (if the inclination i is known), the orbital dimensions (if i known) and the period P (also from light curve). Typical radial velocity uncertainties are ~ 1 km/s.

From *double-lined* binaries we compute the masses $m_{1,2}$ of the two components (in solar masses) from

$$m_{1,2} \sin^3 i = (1.0361 \times 10^{-7})(1 - e^2)^{3/2} (K_1 + K_2)^2 K_{2,1} P \tag{3.3}$$

and the semi-major axes $\alpha_{1,2}$ of the orbits (in solar radii) from

$$a_{1,2} \sin i = (1.9758 \times 10^{-2})(1 - e^2)^{1/2} K_{1,2} P \tag{3.4}$$

where i is the inclination of the orbital plane, e the eccentricity of the orbits, P the orbital period and $K_{1,2}$ the semi-amplitudes of the two radial velocities (see Fig. 4).

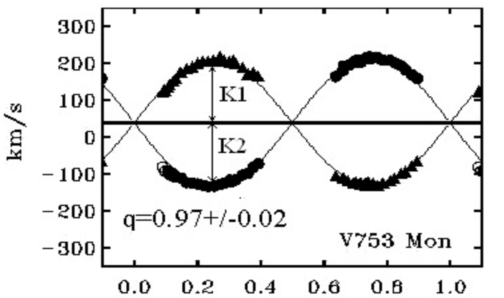

***Figure 4**. The radial velocities of the contact system V753 Mon (Rucinski et al. 2000)*

A combination of the photometric and spectroscopic observations yields the fundamental source of information about sizes, masses, luminosities and distances or parallaxes of stars. If adequate model and modelling code is used (provided that no intrinsic variation exists and second order effects are properly modelled), the geometric elements (i, r_1, r_2), the masses and luminosities of the components can be determined to below the 1% level.

4. Prospects and expectations

Ground-based and space observations

Thousands of new candidates of Eclipsing Binaries have been discovered through surveys looking for micro-lensing events, like the MACHO project, EROS, OGLE and others in very crowded fields. In different areas, devoted all-sky surveys have recently started searching for variability patterns using robotic telescopes. The number of observed light curves will continue to exceed the number analyzed (use of CCDs etc.).

According to Andersen (2002), for less than 100 separate stars of binary systems the fundamental parameters are determined to 2% or better. Harries et al. (2003) and Hilditch et al. (2005) have determined the fundamental parameters of 50 EBs of spectral types O and B in SMC. (Typical uncertainties: ± 10% on masses, $\pm 4\%$ on radii, and $\pm 0.07\%$ on $\log L$ – remarkably good values considering the limited spectral resolution and data quality available).

In the frame of the W UMa program (Canada – Poland – Greece) accurate physical parameters of > 100 W UMa systems will be determined from high-quality spectroscopic and photometric observations (see Kreiner et al. 2003).

Space experiments in operation or under development (like COROT, Kepler, and Gaia) will discover huge numbers of eclipsing binaries. The numbers are orders of magnitude larger than everything collected in the last century from ground (Niarchos 2006). It is expected that about 1×10^6 EBs (with $\mathrm{V} \leq 16$ mag) will be discovered and some 10^5 of these will be characterized as double-lined in Gaia spectral observations. Moreover, most of the Gaia binaries will be of spectral type G or K (Zwitter & Henden 2003) for which accurate solutions exists for only a small number of systems. Even if for only 1% of the observed EBs reliable parameters are derived, this will be a giant leap in comparison with what has been obtained so far from ground-based observations.

Future developments

The quality of light curve analyses can also be expected to improve. New techniques of analyzing data should be invented. Such programs will treat phenomena of extended atmospheres, semi-transparent atmospheric clouds, variable thickness disks, and gas streams. Targets of modelling work: besides the determination of orbits, stellar sizes and masses, it seems likely that the detailed physics of stellar surfaces, including those arising from activity cycles, will be included.

Large data set (hundred-thousands or even millions of systems) requires an automation of all stages of reduction and interpretation. The interpretation and classification has to be completely automatic (with only the most unusual cases to be marked for human inspection). Semi-automatic procedures exist, e.g. for classification of EBs in the OGLE database (Wyithe & Wilson 2002). The development of reliable classification and analysis procedures is one of the major tasks facing the scientific community before the launch of the astrometric satellite Gaia (Pace 2003).

Important observations of Close Eclipsing Binaries

Observers of Close Eclipsing Binaries should consider the following cases:

- Mid-range to long-period binaries ($P > 5^d$, but especially $P > 50^d$) need observations of all kinds. The longer period binaries are nearly unexplored territory.
- Infrared light curves are especially needed for binaries with large temperature differences between the two components. Simultaneous observations in the optical and infrared are critically important.
- Individual observations should be published or archived with easy access to them. Binaries with active mass flow need to be followed continuously over at least several orbits. They are suitable targets for automatic photoelectric telescopes (APTs).
- Polarimetric observations are equally important. Although light curves are nearly periodic, polarization curves mainly show transient events
- Spectrophotometry provides an even greater potential bounty, and, in principle, thousands of light curves, if proper star spectra are taken (not easy and seldom done).

5. Concluding Remarks

There are many theoretical and observational areas in the field of Binary Stars that remain practically unexplored. We expect to make great advances on the observational front with (1) optical interferometers and (2) large-scale photometric surveys. With the optical interferometers now operating or nearing completion, we will be able to resolve many more interacting binaries and complement our current photometric and spectroscopic data, allowing us to answer questions that currently remain out of reach. Driven by the interest in detecting transits of extra-solar planets, large-scale photometric surveys (from ground and space) will monitor huge numbers of stars for photometric variability, revealing thousands of new EBs. Space missions with the required photometric precision are currently under development in Europe and USA. The proposed techniques will allow that shallow or even marginal stellar eclipses will be very easy to detect.

The observational determination of fundamental parameters of binaries (e.g. masses, radii, luminosities) carries a deep satisfaction of its own: Provided the work is properly done and the errors kept to $\sim 1\%$, the results preserve their value and form the basis for front-line research even today (Terrell 2001). Prospects are that they will remain useful for another few decades.

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