From Interacting Binaries to Exoplanets: Essential Modeling Tools
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Ground-Based and Space Observations of Interacting Binaries

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Abstract. Multi-wavelength observational data, obtained from ground-based and space observations are used to compute the physical parameters of the observed Interacting Binaries (IBs) and study the interactions and physical processes in these systems. In addition, the database of IBs from ground-based surveys and space missions will provide light curves for many thousands of new binary systems for which extensive 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 ground-based all-sky surveys and space missions, including low mass binaries and star-planet binary systems. The most important current and future programs of observations of IBs from ground and space are presented.

Keywords. Surveys, stars: fundamental parameters, (stars:) binaries (including multiple): close-binaries: (stars:) binaries: eclipsing

1. Introduction

Interacting Binaries (IBs) or Close Binaries (CBs) 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. The study of CBs provides insights into nearly all areas of astrophysics, including stellar interiors and atmospheres, stellar evolution, nucleosynthesis, plasma physics, magnetic dynamos (in cool stars), and relativistic physics to name a partial list. Recently, the study of Eclipsing Binaries (EBs) in other galaxies and clusters makes 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.

2. Observational approaches of Interacting Binaries

The ultimate goal for observational astronomers who study the properties of binary stars is to make direct determination of the astrophysical parameters: *masses, radii, shapes, temperatures and luminosities.* These parameters, also called *absolute dimensions*, can be derived from the analysis of light and radial velocity curves, regardless of the distances of the binaries from us. During the last three 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.

2.1. *Photometry*

The photometric observations made by modern detectors (CCDs) are expected to have 1-2% precision if they are carefully reduced and well transformed. The photometric light curves are analysed with modern synthetic light curve codes (Prša & Zwitter 2005), based on Roche model, and enable us to derive much more realistic and accurate physical parameters of close binary systems. These codes allow also a simultaneous solution of photometric and radial velocity curves. Among those parameters the one of main interest is the mass ratio (q) of the system, which is necessary for the calculation of the absolute dimensions for single line spectroscopic binaries.

2.2. *Spectroscopy*

Spectroscopic studies of CBs lead to spectral classification, line profile analysis and radial velocity determinations. Low resolution, usually R>1000, is used for spectral classification, higher resolutions are desirable for precision radial velocity work, and highest resolution $R \geqslant 10^5$ is needed for the analysis of spectral line profiles and extra-solar planet research. In any case high level of precision and accuracy in radial velocities is needed for close binary star modeling. The present day precision is better than 1m/s (e.g. HARPS spectrograph at ESO). During the last three decades it has been possible to overcome difficulties in studying spectra of close binaries by reducing the spectra in a digitized form using modern techniques, like *Cross Correlation Technique* (Mazeh & Zucker 1994), *Broadening Function Approach* (Rucinski 2002) and *Spectral Disentangling* (Hadrava 2006). A combination of photometric and spectroscopic observations yields the fundamental source of information about *sizes, masses, luminosities and distances or parallaxes* of stars.

2.3. *Polarimetry*

Almost every class of binary stars can produce observable polarimetry. In these systems, polarimetry can help to: determine the geometry of the circumstellar or circumbinary matter distribution, yield information on asymmetries and anisotropies, identify obscured sources, map star-spots, detect magnetic fields, and establish orbital parameters, particularly the orbital inclination i which is an important parameter for deriving the stellar masses. (See the paper by K. Bjorkman, this symposium).

2.4. *Interferometry*

Interacting binaries typically have separations in the milliarcsecond regime. Recent advances in optical interferometry have improved our ability to discern the components in these systems and have now enabled the direct determination of physical parameters. Application of interferometric observations in the study of binary stars yield individual stellar masses, distances to the systems and provide reliable data for the empirical mass-luminosity relation in a region which is intermediate between visual and purely spectroscopic data. In addition, speckle interferometry is applicable to the determination of the angular diameters of objects, and the development of long baseline techniques allows the achievement of angular resolutions sufficiently high for the determination of the diameters of the individual components of close binaries (e.g. Zavala *et al.* 2010). The mas, or sub-mas separation can be reached only with VLB radio interferometry, or the recent, most powerful optical, near-IR long-baseline interferometric equipment, e.g. CHARA array, Palomar Testbed Interferometer and others. Only the brightest close binaries can be reached by such methods (Coughlin *et al.* 2010; see also the paper by Ph. Stee, this symposium).

3. Why multi-wavelength observations?

Modern astrophysics requires studying an object across the whole EM spectrum, since different physical processes can be studied at different wavelengths. In the optical range, information from the massive companion can be collected. For systems with degenerate components, the compact object is responsible for the emission of high energy photons (X-rays and γ -rays), while IR and UV observations give us information about the interstellar environment and the mass transfer from one component to the other. In some systems, e.g. those containing a BH, radio emission can be expected.

3.1. *UV observations of Interacting Binaries*

The UV is of outmost importance in the study of IBs, as a large part of their luminosity is radiated away in this wavelength range, and the UV hosts a multitude of low and high excitation lines of a large variety of chemical species. UV spectroscopy of IBs obtained with IUE, HST and FUSE have dramatically improved our understanding of IBs and of the physical processes that characterize their emission. UV imaging has made it possible to isolate binaries and the products of binary evolution in old stellar populations and thereby test directly models of binary evolution in dense stellar systems (Gansicke *et al.*, 2008). With the future World Space Observatory-Ultraviolet (WSO-UV) (http://wso.inasan.ru/), powered stellar flares, developed from the complex processes of interaction between the accretion disk and the central star, and other energetic processes accompanied by strong UV radiation will be studied. Monitoring with WSO-UV of extrasolar planet transits will provide important information on the planetary atmosphere and its interaction with the parent star.

3.2. *X-Ray Variability*

X-ray Binaries (XRBs) are variable on many timescales in different ways: (a) X-ray pulsations: are periodic with spin period, due to magnetically funnelled accretion onto the poles, (b) flickering: quasi-periodic oscillations caused by instabilities in the disc (noise), (c) transient accretion events: alternation between phases of high and low accretion rates due to thermal transitions in the accretion disc (in particular for BHs accreting at low rates; also CVs), and (d) thermonuclear explosions, once enough H/He fuel has been accreted. The active X-ray observatory satellites are ESA XMM-Newton (0.1-15 keV), INTEGRAL (15-60 keV), and the NASA Rossi X-ray Timing Explorer (RXTE), Swift and Chandra.

3.3. *Infrared observations of IBs*

IR observations may yield substantial information on the location, size, density and temperature of dust and gas components. Close companions in systems with high mass loss rates may modify the rate of mass loss, flow velocity or grain formation and these effects will change the infrared emission characteristics, a study of which allows a deeper understanding of the underlying mechanisms of the mass loss itself. IR observations from space provide the means to study the mid-IR properties of systems with compact objects. The goals are to establish the mid-IR SED, search for signatures of jets, circumbinary disks, low mass or planetary companions and debris disks, and study the local environment of these sources (Adame *et al.* 2011).

3.4. *Radio observations of IBs*

Radio observations with Interferometric Arrays provide a key tool for a unified understanding of XRBs in the context of accretion powered sources in the Universe. We can learn about the anatomy of X-ray and possibly γ-ray sources. The very sensitive arrays under construction will allow us to address new astrophysical issues about the interaction of relativistic jets with the galactic ISM. They will also resolve and study the ejecta of XRBs. Using these observations we can develop the first semi-quantitative models to interpret how jet production, or suppression, is related to the X-ray spectral states of the accretion disk and corona in the system (Miller-Jones 2008).

4. Ground-based observations

New catalogues of various categories of IBs have been compiled from ground-based and space observations. A catalogue of CVs, LMXBs, and Related Objects (ROs), containing 98 LMXBs, 114 HMXBs, 880 CVs, 312 ROs (7th Edition, rev. 7.15, March 2011) is given by Ritter & Kolb (2003), and a catalogue of symbiotic stars with 188 + 28 (suspected) was presented by Belczyński *et al.* (2000). An updated catalogue, based on the GCVS, of 6330 EBs was presented by Malkov *et al.* (2006). That number will increase tremendously over the next couple of decades, as large and smaller-scale surveys are undertaken. Thousands (over 10^4 of 13-14 mag) of new candidates EBs have been discovered through surveys looking for micro-lensing events, like EROS, OGLE, MOA and MACHO, the DIRECT project and others in very crowded fields.

4.1. *Microlensing Surveys*

The main objective was the search and study of dark stellar bodies, so-called "brown dwarfs" or "MACHOs" in our Galaxy. This is made possible by their gravitational microlensing effects on stars in the Magellanic Clouds. The surveys are:

• *EROS*: EROS-1 (1990-1995) and EROS-2 (1996-2003). EROS has localized about (75+176) eclipsing binaries in LMC.

• *MACHO*: (1993-2001). A catalogue with 4500 binaries in LMC and 1500 in SMC is underway. About 3000 are genuine EBs.

• *SuperMACHO project* (CTIO Blanco 4 m tel.) has surveyed the MCs down to VR 23 mag (some W UMa).

• *OGLE* (since 1992). Two catalogues exist with 1459 EBs detected in SMC and 2580 EBs detected in LMC. A catalogue of 10862 EBs (detected in the galactic bulge fields) was presented in OGLE II (Devor, 2005).

• *MOA* (1996-2004): A catalogue of 167 EBs in SMC was presented by Bayne at al. (2002).

• Two other microlensing surveys toward M31: *Wendelstein Calar Alto Pixellensing Project, WeCAPP*, (2000-2003) (Fliri *et al.* 2006) discovered 31 EBs in M31; *POINT-AGAPE Survey* (1999-2001, INT+WFC) (An *et al.* 2004) has released a catalogue with 35000 variables (systematic search for EBs, 20 CNe).

4.2. *Other large-scale surveys*

• *The Robotic Optical Transient Search Experiment (ROTSE-I, -III)* (1998) was designed to look for the optical counterparts to gamma ray bursts. In the process it has discovered over 1000 EBs in a survey covering about 5% of the sky area that it monitors (Gettel *et al.* 2006).

• *ASAS (All Sky Automated Survey)*. The ASAS-3 Catalog of Variable Stars contains over 11,099 EBs binaries found among 17,000,000 stars on the sky south of dec. +28 (Paczynski *et al.* 2006).

• *SuperWASP photometric survey* (Pollacco *et al.* 2006; Norton, A.J. *et al.* 2011): 48 EBs (40 W UMa with P<0.23 d and 1 with P<0.20 d)

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• *The Sloan Digital Sky Survey (SDSS)*: The result is a catalogue of more than 1200 spectroscopically selected close binary systems observed (Silvestri *et al.*, 2007).

• *The Panoramic Survey Telescope & Rapid Response System (Pan-STARRS)* (2006). Goal: discover and characterize Earth-approaching objects (asteroids & comets).

• The Large Synoptic Survey Telescope (LSST) (See the paper by L. Eyer, this symposium).

4.3. *Specialized Projects*

• The *DIRECT project* (1996-1999). The aim was to determine the distances to nearby galaxies M31, M33 by monitoring for Cepheids and Detached EBs (Stanek *et al.* 1998). Results: 89 EBs were found in 6 fields surveyed in M31, 237 EBs in M33, and 437 EBs in M31 (by INT 2.5 m tel.) (Vilardell *et al.* 2006).

• The *W UMa project*. The aim is the determination of very accurate physical parameters of stars in contact binaries of W UMa-type by using high quality homogeneous photometric and spectroscopic observations. The program is a novel approach and the systems to be studied are > 100 (Kreiner *et al.* 2006).

5. Observations from Space

5.1. *Past missions*

Hipparcos (1989-1993, ESA). In the catalogue released in June 1997, there are 120,000 stars with 1 milliarcsec level astrometry. From these 1034 are EBs with 117 unsolved cases. 35% of these EBs were not previously known.

5.2. *Current space missions*

• The *COROT* Mission (CNES, ESA, Brazil; launched December 2006). The objectives are: (i) a search for extrasolar planets of large terrestrial size, and (ii) perform asteroseismology in solar-like stars. Selected binary systems will be observed in the Additional Program frame as targets of long and continuous pointed observations (see the paper by C. Maceroni, this symposium).

• *Kepler* Mission. Launched in March 2009. The aim is to detect one-Earth radius planets in the habitable zone of solar-like stars. The total number of identified EBs systems in the Kepler FOV has increased to > 2200, 1.4% of the 156,000 Kepler target stars (see the paper by C. Maceroni, this symposium).

• MOST (Microvariability and Oscillations of STars telescope). A Canadian Space Agency mission, in operation since 2003. 16 new EBs have been detected (Pribulla *et al.* 2010).

• STEREO (Solar TErrestrial RElations Observatory) mission (since 2006). Researchers have discovered 122 (!) new EBs and observed hundreds more variable stars in an innovative survey (NASA, Press Release: 19 April, 2011).

5.3. *Future space missions*

The *Gaia* mission. (See the paper by L. Eyer, this symposium). Launch date 2013. Objectives: to build a catalogue of $\sim 10^9$ stars with accurate positions, parallaxes, proper motions, magnitudes and radial velocities. The catalogue will be complete up to V = 20 mag with no input catalogue and therefore no associated bias. The strength of the Gaia mission is in the numbers. Gaia will observe $\sim 4 \times 10^5$ EBs brighter than $V \leqslant 15$ and $\sim 10^5$ of these will be double-lined (SB2) systems. For $V \leqslant 13$ the number of SB2 will be about 16 000 for which Gaia should provide orbital solutions formally accurate to $\sim 2\%$ (Niarchos *et al.* 2006). This is a fantastic number compared to <100 systems studied at similar accuracy by ground-based observations so far (Andersen 1991).

6. Concluding Remarks

There are many theoretical and observational areas in the field of Binary Stars that remain practically unexplored, and the mysteries are challenging and important. Great advances on the observational front are expected with large-scale photometric and spectroscopic surveys (from ground and space) and radio-optical interferometers. The new advanced techniques will allow shallow or marginal stellar eclipses to be detected easily, and complex physical processes to be observed. Binaries of all types can now be studied across the entire EM spectrum. New technologies and instruments used in large-scale surveys will lead to a renaissance and a "Brave New World" of binary star studies.

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Discussion

J. Southworth: The SuperWASP survey has discovered thousands of eclipsing binaries in the course of its search for transiting extrasolar planets. We reckon that there are maybe 100,000 in our archive, which is now publicly available. If someone has the time then this is an excellent research project.

P. Niarchos: I agree, but we must keep in mind that photometric data alone are not enough to derive the physical parameters of the system's components (with the exception of W UMa systems with complete eclipses). Radial Velocities (RVs) of the components are needed to be used with the photometric data. Even with no RVs available, valuable information about EBs can be extracted from such a large amount of data.

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