PHYSICAL PARAMETERS FOR STARS IN CLOSE BINARY SYSTEMS

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Abstract

The importance of derivation of the physical parameters for stars in close binary systems is stressed and the basic observational approaches for their study are briefly presented. The new opportunities and challenges in the study of close binaries in the 21st century, mainly based on observations from space, are also discussed.

1. Introduction

Binary stars are important for several reasons: (i) 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 star systems; (ii) they are the primary source of our knowledge of the fundamental properties (stellar masses, radii and luminosities) of stars; (iii) they can be used as distant indicators for nearby galaxies; (iv) the evolution of binary stars helps us to explain a host of diverse and energetic phenomena such as cataclysmic variables, novae, symbiotic stars, some types of supernovae and X-ray binaries; (v) binaries in clusters are also very important since they provide the means for a detailed testing of stellar evolution theory.

Close binaries or 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.

2. Derivation of physical parameters

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, which describe the component stars in SI units, can be derived from the analyses of light and radial velocity curves, regardless of the distances of the binaries from us. The basic formulae used for the computation of the absolute elements are:

From double-lined binaries we get

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

where the masses are in solar masses, i is the inclination of the orbit, e is the eccentricity of the orbit, K_1, K_2 are the semi-amplitudes of the two radial velocity curves and P is the period in days.

The semi-major axes in solar radii are given by

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

For single-lined binaries the mass function can be determined by

$$\begin{aligned} f(m) &= (1.0361 \times 10^{-7})(1-e^2)^{3/2} K_1{}^3 P \\ &= m_2^3 \sin^3 i/(m_1 + m_2)^2 \\ &= m_1 q^3 \sin^3 i/(1+q) \end{aligned}$$

where $q = m_2 / m_1$ is the mass ratio.

From light curve solutions we obtain i, $r_{1,2}$,$T_{1,2}$ and the mass ratio q. Second-order parameters, such as *limb darkening*, *gravity darkening* and *bolometric albedos* are assigned theoretical values. The absolute radii or dimensions of the stars are given by $R_{1,2} = \alpha\ r_{1,2}$. 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 velocity semi-amplitudes.

One of the temperatures, usually T_1, can be adopted from other data, such as: (i) de-reddened colour indices at a total eclipse; (ii) using several values of de-reddened colour indices at different orbital phases; (iii) spectral types, or (iv) fitting of stellar-atmosphere models to tomographically separated spectra. The other temperature T_2 may be derived from the foregoing techniques and confirmed by the light-curve solutions or determined from the light-curve solutions directly.

The luminosities and absolute magnitudes of the two components are computed from the relations

$$L_{1,2} / L_{sun} = (R_{1,2} / R_{sun})^2 (T_{1,2} / T_{sun})^4$$

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

where

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

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.

3. Observational approaches of Close Binaries

3.1. Photometry

The photometric observations are made either by photoelectric photometers or by CCD cameras. Each detector has its own advantages and disadvantages, but photoelectric photometry is still the most precise and accurate means of obtaining flux measurements in optical astronomy. The CCDs have major advantages in doing photometric studies of multiple faint objects in crowded fields.

The modern synthetic light curve codes, based on Roche model, 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*** of the system, which is necessary for the calculation of the absolute dimensions for single line spectroscopic binaries. Mass-ratios determined by using photometric methods are ***model dependent*** and, in most cases, very poor because of the weak sensitivity of the light-curve shapes to changes of *q*. Only for W UMa contact binaries with total eclipses the mass-ratio can be determined with relatively high accuracy by synthetic light curve techniques.

3.2 Spectroscopy

Spectroscopic studies of Close Binaries aim 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 ~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 binary star modeling.

Contact Binary systems have been difficult to study with good precision because (i) the spectral lines are very broad (V_{rot} ~150 km s^{-1}) and blended ($\delta\lambda$~ 2 Å) and (ii) also because the systems are very faint for good spectral resolution (0.01 P ~5 min). These two problems have been overcome in the last 15 years by reducing the spectra in a digitized form using modern techniques, like ***Cross Correlation Technique*** [2], [3], [4] and ***Broadening Function Approach*** [5], [8], [11]**,** and by introduction of image intensifiers and high quantum efficiency CCD detectors.

3.3 Spectrophotometry

A combination of spectroscopy and photometry can provide a rich bounty for light curve analysis. A large number of narrow pass bands can greatly improve the radiative modeling of stars, since the wavelength-dependent parameters are adjustable for each pass-band, and together provide strong leverage for the determination of the temperatures and for any thermal perturbations projected onto the disk surfaces. In addition, the weight of the non-wavelength-dependent parameters is increased by virtue of the large number of light curves. Promising techniques to disentangle the separate spectral distributions of the component stars from the composite spectrum of an eclipsing binary system have been developed by [6] and [7].

3.4. Polarimetry

The sources of polarization in interacting binaries are: scattering of starlight by interstellar dust; light of one component scattered at the surface of the other; starlight scattered by a circumstellar disk, stream, or other locus of concentrated gas; thermal bremsstrahlung in the stellar environment, (electron scattering in gas flows or in coronae); nonthermal bremsstrahlung (from flares); electron scattering in high-temperature atmospheres, and magnetic surface fields. Although polarimetric observations are very important for the study of close binaries, there are several reasons for lack of adequate polarimetric studies. Hopefully, future investigators will pay this important field more attention and closer collaboration between model developers and observers of polarimetric data would also improve the situation.

A combination of the above observations yields the fundamental source of information about *sizes, masses, luminosities and distances or parallaxes* of stars. This information provides the means to test stellar structure and stellar evolution theories, to improve our understanding of such exotic objects as X-ray binaries, novae and Wolf-Rayet stars, to get a great wealth of knowledge from binaries in globular clusters and to solve astrophysical problems (Algol paradox, convection in stars, mass transfer and mass loss, gas streams and discs around stars, physical processes in stars, etc.).

4. Observations from Space. The GAIA mission

The GAIA mission is one of the next two "cornerstones" of ESA's science program [13]. The objectives of the GAIA mission are to build a catalogue of ~10^9 stars with accurate positions, parallaxes, proper motions, magnitudes and radial velocities. The catalogue will be complete up to V = 20 mag. The overall mission contain three parts: (1) extremely precise astrometry, (in the micro-arcsec regime) with the measurement of stellar position, parallax and proper motion; (2) photometry, with measurements in different spectral bands; (3) radial velocity measurements up to V = 17 mag.

4.1. GAIA's contribution to the study of Close Eclipsing Binaries

The GAIA large-scale photometric survey will have significant intrinsic scientific value for the study of variable stars of nearly all types, including detached eclipsing binaries, near contact or contact binaries and pulsating stars. The strength of the GAIA mission is in the numbers. GAIA will observe ~ 4×10^5 eclipsing binaries brighter than V =15 and ~ 10^5 of these will be double-lined systems. The observing fashion is quite similar to Hipparcos operational mode. Even if the stellar parameters will be determined at 1% accuracy for only 1% of them, this is still 25-times more than what has been obtained from all ground-based observations in the past [1].

4.2. Measurement Performances

• Catalogue: ~1 billion stars; 0.34×10^6 to V=10 mag; 26×10^6 to V=15 mag; 250×10^6 to V=18 mag; 1000×10^6 to V=20 mag

• Median parallax errors: 4 μas at 10 mag; 11 μas at 15 mag; 160 μas at 20 mag
• Distance accuracies: 2 million better than 1%; 50 million better than 2%; 110 million better than 5%; 220 million better than 10%
• Tangential velocity accuracies: 40 million better than 0.5 km s^{-1}; 80 million better than 1 km s^{-1}; 200 million better than 3 km s^{-1}; 300 million better than 5 km s^{-1}; 400 million better than 10 km s^{-1}
• Radial velocity accuracies: 1-10 km s^{-1} to V=16 - 17 mag.
• Photometry : to V=20 mag in 4 broad and 11 medium bands

4.3. Accuracy of fundamental parameters

GAIA will provide light curves for millions of faint eclipsing binaries and also the absolute luminosities and temperatures (from parallaxes and colours). These data, combined with the radial velocity measurements obtained from spectroscopic observations, will allow us to determine the fundamental parameters *(radii, masses, luminosities, temperatures)* of hundred thousands eclipsing systems. Although the expected accuracy will be moderate, the large amount of data will allow us to look for large deviations from the "normal" mass-radius-luminosity relations.

As mentioned above the number of Close Eclipsing Binaries discovered by GAIA will reach hundred thousands. Combined astrometric, photometric and spectroscopic observations of these systems will be reduced and analyzed by suitable codes in order reliable orbital and physical parameters are determined. There are two crucial questions regarding the reliability of the derived stellar parameters from GAIA observations:

(1) How these observations can be compared with the state-of-the-art ground-based observations?
(2) What is the accuracy to which Close Eclipsing Binaries can be investigated using GAIA data alone?

From an analysis of spectroscopic and photometric observations for a small sample of eclipsing systems, obtained by GAIA-like ground-based observing campaign (for spectroscopy) and by GAIA-like Hipparcos photometry, it was shown [10], [12], [14], [15], [16] that the orbital elements and the fundamental parameters of these systems can be determined at ~ 2% accuracy level. By no means this will have an immense impact on theories of stellar structure and evolution.

5. Prospects and expectations

- Thousands of new candidates CBs have been discovered through surveys looking for micro-lensing events, like the MACHO project, EROS, OGLE and others in very crowded fields.
- The number of observed light curves will continue to exceed the number analyzed (use of CCDs etc.) and their quality is expected to improve
- GAIA mission will observe about 1 million different EBs.
- For the future, new approaches will also be possible with highly efficient photometric searches looking for very shallow eclipses, such as those produced by Earth-like extra-solar planets.
- Space missions with the required photometric precision are currently under development in Europe and USA. The eclipses are expected to be 10^{-4} or less in depth, so that normal or even marginal stellar eclipses will be very easy to detect.
- New techniques of analyzing data should be invented and new programs to treat phenomena of extended atmospheres, semi-transparent atmospheric clouds, variable thickness disks, and gas streams should be developed.

Close binary analysis is a formidable astrophysical task. The field includes radiation physics and sometimes hydrodynamics. Physical models are required for radiation transport in the component's atmospheres and for the dynamic forces controlling the stellar mass distribution. Close binary research might initiate projects involving complicated physics and requiring sophisticated mathematics and numerical methods [9].

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