Part 2

Observations and Analysis of Exoplanets and Brown Dwarfs

From Interacting Binaries to Exoplanets: Essential Modeling Tools
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Challenges to Observations of Low Mass Binaries

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Abstract. Low mass stars in binaries are frequently used as unique tools to determine and establish fundamental stellar parameters. The need for their study and understanding has led to developing new instruments, new observational techniques and improved theoretical models. The relatively recent discovery of exoplanets and their study as the low-mass constituents around other stars is now opening new horizons in binary research. Here, I examine the most common observational challenges in studying low mass binaries across the electromagnetic spectrum.

Keywords. (stars:) binaries: general, stars: low-mass, brown dwarfs, methods: data analysis

1. Introduction

The launch and operation of space-based observatories revolutionized the field of binary star research and enriched our knowledge of our favorite systems, revealing a wealth of behaviors. With great discoveries, though, came great challenges in our study and understanding of stellar components - especially when it comes to low-mass stars. Also, during the last 10 years with the discovery of various planetary systems, low mass binaries with planet components are at the spotlight of research activity. The knowledge collected over decades from low-mass binary stars, are now applied and used in the discovery and study of exoplanets and their host stars. The unprecedented accuracy in the observed light curves, provided by space based observatories, revealed a suite of phenomena that could not be studied from the ground and require new tools for their study. In this review, I discuss some challenges arising for the study of low mass binaries. This is by no means a comprehensive inclusion of all aspects of low-mass binary star research; it is perhaps a reminder that binaries can be used as tools for understanding significant physical processes which stem from stellar interactions, and that they can provide a means to study nature under conditions hardly encountered on Earth-based laboratories. The star components discussed here have masses of $M \leqslant 0.7\ M_{sun}$ and luminosities less than 1/10 of that of our Sun. They represent the low-mass aspect of all phases of the HR diagram, including stellar remnants such as white dwarfs. The challenges presented here, are relevant to all low-mass stars in binaries - from interacting binaries to exoplanets.

2. Challenges in studying low-mass binaries

Low-mass stars are some of the favorites in the field, since they comprise more than 70% of the galactic stellar population and they spend a substantial time at all stages of their life allowing for a generous insight on stellar evolution. Their presence in eclipsing binary systems, provides an opportunity for the accurate determination of component masses, radii and temperatures. These are fundamental parameters enhancing our understanding of stellar structure in stars with mostly or fully convective interiors.

Binary stars are classified as detached, semi-detached or contact depending on the degree each of the two stellar components fills its respective Roche lobe: The main equation of the Roche geometry (Eggleton 1983) is $R_2/a = [0.49q^{2/3}] \, / \, [\, 0.6q^{2/3} + \ln(1{+}q^{1/3})]$ where the subscripts *1* and *2* refer to the "primary" and "secondary" mass components; the mass ratio of the two stars is $q{=}M_2/M_1$. Most commonly encountered, the *detached* binaries are those where none of the two stellar components fill their respective Roche lobes. When one of the binary components fills its Roche lobe, mass transfer is enabled through the inner Lagrangian point and the system is a *semi-detached* binary. In the rare case where both stellar components fill their respective Roche lobes, the system is known as a *contact* binary.

The main assumption in this present discussion is that the two stars are in Keplerian orbits, with orbital periods less than 3 days. A natural consequence of this is that one or both components are tidally locked to the orbit, forcing them to a very fast rotation. From an observational point of view, these systems require short exposure times (less than 10% of the orbital period) and larger telescope apertures for their study, which becomes observationally expensive. Nevertheless, if we surpass this obstacle, we are left with a very rich suite of phenomena to account for when it comes to studying those binaries and understanding their properties. For organizational purposes, I will discuss low-mass stars in detached and semi-detached binaries separately. I will treat the latter as a more complex version of the former, therefore all the relevant phenomena present in detached binaries are also present in semi-detached ones.

2.1. *Detached binaries*

Spectral deconvolution

One of the main properties of stars in low-mass binaries is their low temperatures, allowing for the presence of molecules in their atmosphere - such as TiO and VO in M stars, and metal hybrid bands (FeH, but also CaH and CrH) and H_2O in cooler objects. Therefore, their spectral energy distribution peaks at (near-)infrared wavelengths. When it comes to binary stars, however, there is still a great lack of tools for disentangling individual stellar spectra. Spectral templates based on observations of individual stars are often used but they do not always reproduce the observations (e.g., Burgasser *et al.* 2010). A library of theoretical spectra is needed; this requires accurate knowledge of spectral atmospheres and molecular opacities in the near infrared in order to reproduce each spectrum and finally apply it to the data. The lack of such a library hinders understanding of low-mass stellar atmospheres and of variable phenomena (such as the presence of clouds in the lowest mass stars) and stellar evolution properties for the lowest mass systems.

Tidal distortions and rotation

The most obvious effect of gravity in low-mass binaries is the tidal distortion of stellar components because of their gravitational interaction. This results in a teardrop-like shape and tidal locking. The effect is primarily in action when the two stellar components are very close to each other and/or their mass ratio is large (for example, in binaries with a white dwarf): the gravitational potential of one of the two stars is distorting the shape of its companion. Tidal locking results in fast axial rotation of one (or both) of the components, also distorting the shape of stars to being more oblate towards the equator. The net observable effects on the light curves are ellipsoidal variations (e.g., Figure 1),

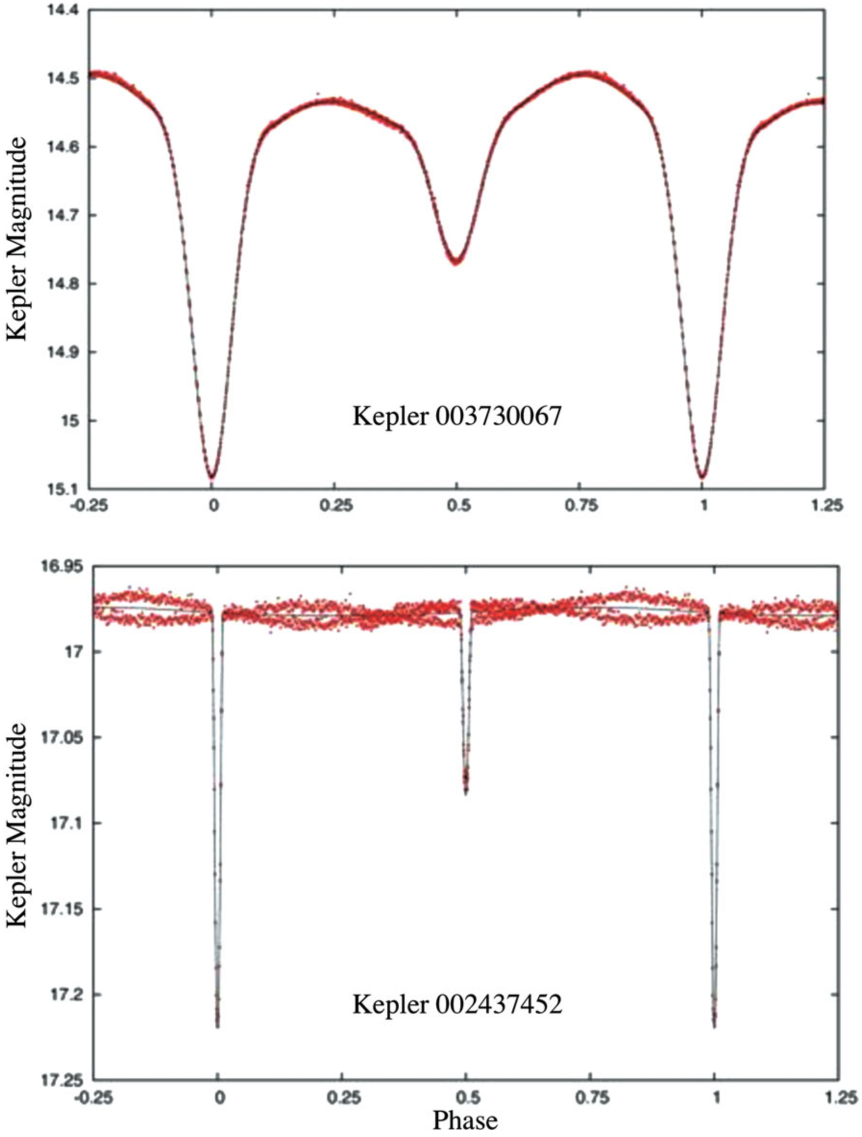

Figure 1. Kepler light curves from Coughlin *et al.* (2011), demonstrating the effect of out-of eclipse light curve distortion because of stellar activity (left) and tidal distortions (right) on the light curve of two different stars.

resulting from observing a larger surface stellar area of the star at quadratures than during conjunctions.

Magnetic activity

Perhaps the largest effect of fast rotation is the enhancement of magnetic activity in stars: there is a well known relationship of magnetic activity with rotation in the sense that all fast rotating stars are active (e.g., Browning *et al.* 2010). Magnetic activity is one of the most well-known but still puzzling challenges in studying low-mass binaries, mostly because of its variable (in time and nature) effects. The usual manifestations of magnetic activity (active regions, spots, flares and stellar coronal mass ejections) on one or both stars affect light curves and spectra in a manner that is not completely understood or modeled. Since magnetic activity is a manifestation of magnetic fields in action, there is a pressing need for a better understanding of stellar dynamos, their generation, evolution and their dependence on mass and internal stellar structure. The nature of the magnetic dynamo in single low-mass stars deviates significantly from the solar $\alpha-\Omega$ type. Rotation is of consequence: after a certain rotation rate ($vsini$~5 km/sec in M dwarfs; Reiners 2007), activity saturates with ultra-fast rotation in the sense that the x-ray flux of a star remains constant despite continuously increasing rotation. Furthermore, although there are expectations that magnetic activity in fully convective stars should change character, (consequence of different internal stellar structure) we fail to detect properties pointing to a specific dynamo mechanism in action, different to that of non-fully convective stars (e.g., Morin *et al.* 2011).

When studying low mass binaries, there are three main challenges attributed to stellar activity. The most pronounced effect on light curves is the presence of large starspots or spot groups, which appear as "dark" regions on the star†. Starspots represent cooler parts of the stellar photosphere in which magnetic pressure is suppressing gas pressure. Their effect on light curves is that the relevant area of the photosphere appears fainter, which is translated to depressions in light curve shapes (an example is also presented in Figure 1). At the same time, active regions ("bright" areas) result in increased stellar brightness and an increase in the stellar luminosity when the relevant area is in our line-of-sight. This leads to overall asymmetric light curve shapes, and the need for modeling of the spotted area in order to extract accurate stellar parameters.

A second considerable consequence of magnetic activity is that it can lead to erroneous estimates of stellar parameters. For example, Lopez-Morales & Ribas (2005) studied M dwarf stellar fundamental properties in eclipsing binaries such as GU Boo, and concluded that the observed stellar radii are larger by more than 10% - 15% than what is expected from low-mass models, independent of metallicity and age. The respective stellar effective temperatures also appear to be overestimated by 5% (the relevant measurements have accuracies of better than 3%). A possible (and the only proposed) interpretation is that the stars (which are tidally locked in synchronous orbit) are excessively active and covered with starspots, lowering their overall photospheric temperature. Each star responds by expanding its atmosphere and increasing its radius to conserve the total radiative flux. Ribas (2005) reviewed the effect, cautioning observers on the interpretation of their data and derivations of fundamental stellar properties in low mass components of binary stars.

The third effect is intra-binary emission due to magnetic field interactions between the two stars. This was first observed in the x-ray properties of the K0IVe+G5IV eclipsing binary AR Lac in which x-ray excess in the intra-stellar region attested to an excess of magnetic activity, likely due to magnetic interactions between the two stars (Siarkowski *et.al.* 1993). These effects are likely induced by the stellar component that has the stronger magnetic field, and they result from magnetospheric interactions between the components of the low-mass binary. Similar effects are now observed in the optical spectra of closed detached binaries and in exoplanets (e.g., Shkolnik *et al.* 2003), and are prominent on spectral lines such as the Hα emission and CaII H&K lines (e.g., Kafka 2011), which are common diagnostics of magnetic activity.

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† One could also consider the effect of active regions, which appear as "bright" features on the star.

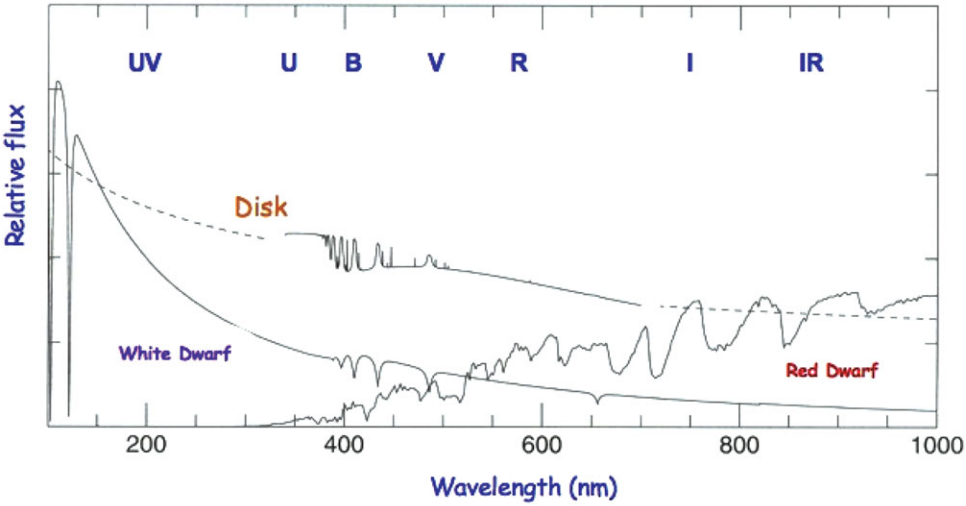

Figure 2. Spectral energy distribution of the various components of a cataclysmic variable from the UV to the near IR demonstrating that accretion-related emission is the main challenge to studying the two stellar components (modified from Hellier 2001).

2.2. *Semi-detached binaries*

Low-mass semi-detached binaries are generally known as cataclysmic variables (CVs), in which a white dwarf (WD) is accreting material from its Roche-lobe filling, low-mass companion (a WD or a low mass, lower main sequence star)†. CVs are widely used for the study and understanding of phenomena connected to a disk or magnetically controlled accretion. At the same time, the presence of accretion is also the main challenge for the study of the two stars in the binary. A pictorial summary of the effect of accretion-generated light, is presented in Figure 2 (Hellier 2001): the spectral energy distribution of the three main components of a cataclysmic variable system (white dwarf and M-dwarf semi-detached binary), are overplotted on a relative intensity scale, from the UV to near-infrared wavelengths. The spectrum of the white dwarf peaks in the UV (as WDs are hot sources) and the K/M dwarf donor star emerges in the near-infrared. In the absence of accretion-generated light, it would be easy to study each of the two stellar components at the wavelength region of their peak emission (UV for the white dwarf and near-infrared for its companion). However, the superimposed spectrum of the accretion disk (or that of the accreting magnetic column in the case of magnetic CVs) onto the composite spectrum of the two stars is dominant at all wavelengths. Therefore, accretion-generated light is overwhelming the light from the binary at all wavelengths and is the main challenge we face while studying semi-detached systems. Related phenomena are reflected on their light curves and spectra, and include outbursts, high and low states, mass transfer variations, magnetic activity, irradiation, accretion disk phenomena (spiral arms, disk rim flaring and accretion hotspot), magnetically-controlled accretion (threading region, atmospheric shocks), outflows and nova explosions.

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† Some Algols behave like CVs, therefore they present similar phenomena and challenges in their study.

3. Final remarks

It would be possible to spend a whole symposium on only of the challenges faced when we study low mass stars in binaries - the aforementioned phenomena are just the tip of the iceberg. Among others, I left out the contribution of limb darkening, the Rossiter-McLaughlin effect, Doppler beaming, gravitational beaming and irradiation, but these will be covered extensively in other parts of this symposium volume.

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Discussion

A. Burrows: I will remind people that there is not one theoretical radius-mass relation for late M-dwarfs and brown dwarfs, but a range of such models for a given mass and age that depends upon metallicity, and for brown dwarfs upon the (unknown) character of atmospheric cloud opacities. This range in radii for a given mass and age could be ∼ 10-15%.