From Interacting Binaries to Exoplanets: Essential Modeling Tools
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The Long History of the Rossiter-McLaughlin Effect and its Recent Applications

Simon Albrecht

Massachusetts Institute of Technology, Kavli Institute for Astrophysics and Space Research, Cambridge, MA 02139, USA

Abstract. In this talk I will review the Rossiter-McLaughlin (RM) effect; its history, how it manifests itself during stellar eclipses and planetary transits, and the increasingly important role its measurements play in guiding our understanding of the formation and evolution of close binary stars and exoplanet systems.

Keywords. techniques: spectroscopic, stars: rotation, planets and satellites: formation

1. Introduction

The Sun is the only star for which we can obtain detailed information on spacial scales much smaller than its diameter. For some nearby stars or giant stars, optical/infrared long baseline interferometry does give information on scales comparable to the stellar size (e.g. Baines *et al.* 2010). For most stars, however, we are not able to resolve their surfaces. These stars are essentially point sources, even for the biggest telescopes.

This is a pity as many questions in stellar astrophysics and astronomy would benefit from such knowledge. Astronomers have, therefore, developed a number of techniques to overcome this limitation. For example, Doppler imaging (Strassmeier 2002), polarimetry (see K. Bjorkman, these proceedings), or tomography (see M. Richards, these proceedings) let us gain under certain conditions information on small spatial features. Close binary star systems with orbits of only a few days or stars harbouring extrasolar planets (exoplanets) can provide us with an additional opportunity to obtain high spatial resolution, if the line of sight lies in the orbital plane. In such cases, eclipses or transits may be observed.

During eclipses or transits, telescopes integrate not over the complete stellar disk, as parts are hidden from view. Comparing the amount of light obtained at different phases of eclipses with the light received out of eclipse, system parameters like ratios of the radii of the two objects, orbital inclination, and possible inhomogeneities on the stellar surface of the background star, like star spots, can be determined (e.g., C. Maceroni, these proceedings).

What properties can be studied if we are not only to record the amount of light blocked from view, but also record the dimming as a function of the wavelength? In 1893, Holt realized that observing an eclipse with a spectrograph, which has a high enough spectral resolution to resolve stellar absorption lines, will lead to inside knowledge on stellar rotation (Holt 1893). Since stellar lines are broadened by Doppler shifts due to rotation, light emitted from approaching stellar surface areas is blue-shifted and light emitted from receding stellar surface areas is red-shifted. During the eclipse, parts of the rotating stellar surface is hidden, causing a weakening of the corresponding velocity component of the stellar absorption lines. Modeling of this spectral distortion reveals the projected stellar rotation speed ($v \sin i_\star$) and the angle between the stellar and orbital spins projected on the plane of the sky: the projected obliquity.†

A claim of the detection of the rotation anomaly was made by Schlesinger (1910), but more definitive measurements were achieved by Rossiter (1924) and McLaughlin (1924) for the β Lyrae and Algol systems, respectively. These researchers reported the change of the first moment of the absorption lines, sometimes called center of gravity, derived from the shape of the absorption line. Struve & Elvey (1931) reported the shape and its change during eclipse in the Algol system. The phenomenon is now known as the Rossiter-McLaughlin (RM) effect. Various aspects of the theory of the effect have been worked out by Hosokawa (1953), Kopal (1959), Sato (1974), Otha *et al.* (2005), Gimenez (2006), Hadrava (2009), Hirano *et al.* (2010) and Hirano *et al.* (2011a).

2. The RM effect and some quantities which can be measured with it

Holt (1893) realised that the rotation anomaly, occuring during eclipses, is an opportunity to measure $v \sin i_\star$ independently from a measurement of the width of absorption lines. Measuring $v \sin i_\star$ from line widths is challenging as these are influenced not only by rotation but also other processes, most notably by velocity fields on the stellar surface and pressure broadening. The strengths of these mechanisms are often not precisely known, introducing a substantial uncertainty in the $v \sin i_\star$ measurement even if the width of the line can be determined with high accuracy (e.g. Valenti & Fischer 2005). The amplitude of the RM effect is not as strongly influenced by these broadening mechanisms, making it an interesting tool for measuring $v \sin i_\star$ in particular cases (e.g. Twigg 1979, Worek *et al.* 1988, Rucinski *et al.* 2009). In addition, if differential rotation is present then it might be detected in fortunate cases via the RM effect (Hosokawa 1953, Hirano *et al.* 2011a). Currently, however, the RM effect is mainly seen as a tool to obtain the projection of stellar obliquity, an observable that is hard or impossible to measure otherwise.

However, not only stellar rotation can be studied. With the help of the differential RM effect, atmospheres of transiting planets may be studied (Snellen 2004, Dreizler *et al.* 2009). The RM effect might also aid in the search and confirmation of planet candidates (Gaudi & Winn 2007) or even exomoons (Simon *et al.* 2010). Also, accretion in an interacting binary might be studied via the RM effect (e.g. Lehmann & Mkrtichian 2004).

3. The RM effect and obliquities in extrasolar planetary systems

The properties of exoplanets discovered over the last few years have been very surprising. Many exoplanets orbit their hosts stars on eccentric orbits and giant planets have been found on orbits with periods of only a few days ('Hot Jupiters'). These findings present challenges for planet formation theories as it is thought that giant planets can only form at distances of several AU from their host stars, where the radiation is less harsh and small particles can survive long enough to build a rocky core which attracts the gaseous envelope from the disk.

Different classes of migration processes have been proposed which might transport giant planets from their presumed birthplaces inward to a fraction of an astronomical unit where we find them. Some of these processes are expected to change the relative orientation between the stellar and orbital spin (e.g. Nagasawa *et al.* 2008, Fabrycky & Tremaine 2007), while others will conserve the relative orientation (Lin *et al.* 1996), or

† This angle is denoted either β after Hosokawa (1953) or λ after Ohta *et al.* (2005), $\lambda = -\beta$.

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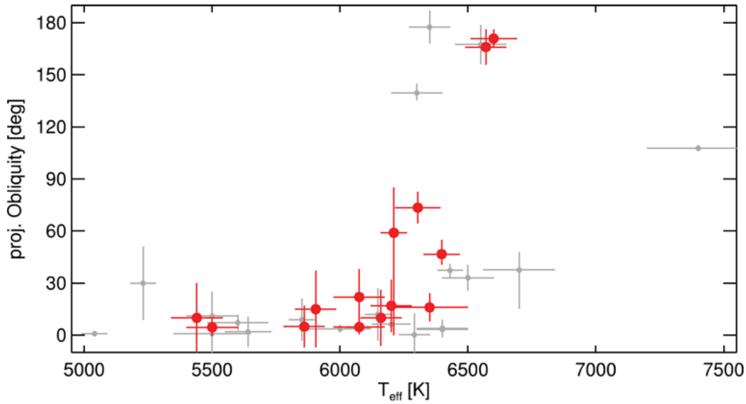

Figure 1. Hotter stars have oblique rotation. The projected obliquity of Hot Jupiter ($M_{planet} > 0.2$ M_{Jupiter}; Period < 6 days) systems is plotted as function of the effective temperature of the host star. Using the measurements available 2010 (Winn *et al.* 2010a) noticed that systems with cool stars are aligned, while the obliquities of hot stars tends to be higher (gray small circles). Since then 16 new RM measurements have been reported (red large circles). The systems Kepler-8, CoRoT-1/11, have been omitted (see section 3.2) and the values for WASP-1/2 have been taken from Albrecht *et al.* (2011)

even reduce a possible misalignment (Cresswell *et al.* 2007). Therefore, measuring the obliquity of these systems will lead to inside knowledge of the formation and evolution of these systems.

3.1. *Results of RM measurements*

The first measurement of a projected obliquity in an extrasolar system was made by Queloz *et al.* (2000). They found that HD 209458 has an aligned spin. Over the following years, the angle between the stellar and orbital spins have been measured in about 30 systems. It was found that for some of these systems, the orbits are inclined or even retrograde with respect to the rotational spins of their host stars (see e.g. Hébrard *et al.* 2008, Winn *et al.* 2009, Triaud *et al.* 2010, Simpson *et al.* 2011). Winn *et al.* (2010a) found that close-in giant planets tend to have orbits aligned with the stellar spin if the effective temperature (T_{eff}) of their host star is $\lesssim$ 6250 K and misaligned otherwise. Schlaufman (2010) obtained similar results measuring the inclination of spin axes along the line of sight. Winn *et al.* (2010a) further speculated that this might indicate that *all* giant planets are transported inward by processes which randomize the stellar spin. In this picture, tidal waves raised on the star by the close-in planet realign the two angular momentum vectors. The realignment time scale would be short for planets around stars with convective envelopes ($T_{\mathrm{eff}} \lesssim 6250$ K), but long, compared to the lifetime of the system, if the star does not have a convective envelope ($T_{\mathrm{eff}} \gtrsim 6250$ K). Over the last year, the RM effect was measured in another 16 systems, and the predictions made by Winn *et al.* (2010a) were confirmed for these systems (see Fig. 1)†.

3.2. *Challenges*

When analysing RM measurements, there are challenges which need to be overcome before a robust estimation of the stellar spin can be derived. Stellar rotation is not the only mechanism that affects the meaured stellar absorption lines. They are also broadened by stellar rotation fields and the point spread function of the spectrograph.

† Rene Heller maintains a webpage with updated information of obliquity measurements: `http://www.aip.de/People/rheller/content/main_spinorbit.html`

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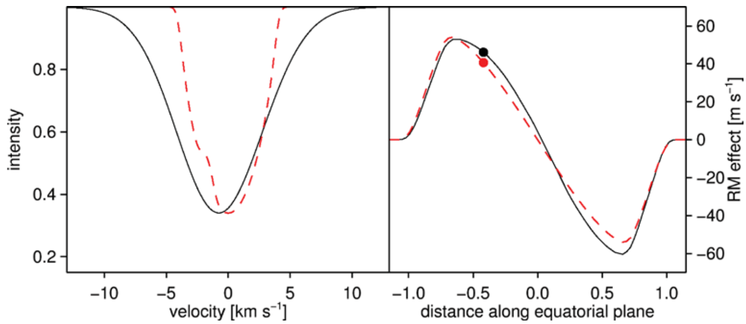

Figure 2. Line broadening mechanisms and their effect on the RM effect. The left panel shows a model of a absorption line broadened by solid body rotation only (red) dashed line and a model of a line taking also macro turbulence, convective blue shift and solar like differential rotation in account. The right panel shows the RM effect for both models. The circles indicate the transit phase when the snapshot of the absorption lines on the left side have been taken. On can see how the lines as well as the expected RM effect differ.

Lines are also not strictly symmetric due to the convective blue shift (Shporer & Brown 2011). See Fig. 2 for an illustration of this effect. In addition, it is not the line center that is measured (the quantity most often used by descriptions of the RM effect), but a cross correlation between a template and the spectrum recorded during transit (Hirano *et al.* 2011a). For the measurement process additional complications can arise.

• Similar to transit photometry, observations before and after transit are important. The RM effect needs to be isolated from other sources of RV variations (orbital movements, star spots, unknown companions, etc.). We, therefore, expect the uncertainty in the Kepler-8 system to be greater then reported by Jenkins *et al.* (2010).

• Analyzing low SNR RV data can lead to results which are systematically biased. This was the case for WASP-2 for which a retrograde orbit was reported by Triaud *et al.* (2010), but it was later found that from the currently available data no information on the obliquity can be derived. See Albrecht *et al.* (2011b) for details.

• For systems nearly edge on (i.e. low impact systems), there exists a strong degeneracy between $v \sin i_\star$ and the projected obliquity and care has to be taken when applying photometric and spectroscopic priors. This is the case for WASP-1 (Simpson *et al.* 2011, Albrecht *et al.* 2011b).

4. Eclipsing binaries

Although it has been more than 80 years since the first RM measurements in binaries, there are relatively few quantitative analyses of the RM effect in these systems. In the past, observing the RM effect was generally either avoided (as a hindrance to measuring accurate spectroscopic orbits) or used to estimate stellar rotation speeds. Almost all authors explicitly or implicitly assumed that the orbital and stellar spins were aligned. This lack of measurements is a pity as the knowledge of obliquity might guide our understanding of binary formation, in particular the formation of close binaries (e.g. Fabrycky & Tremaine 2007, Albrecht *et al.* 2011a).

There is a complication in the RM measurement relative to the low mass companion or exoplanet case, if one wants to measure the RM effect in double-lined binaries. Also, the foreground object emits light and contributes to the observed spectrum. Measuring the center of gravity of absorption lines would lead to erroneous results. Albrecht *et al.* (2007), therefore, developed a method to model the stellar absorption lines during occultations. A similar method was also employed in exoplanet systems (Collier Cameron *et al.* 2010).

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The BANANA project (see Albrecht *et al.*, these proceedings) aims to measure the projected obliquities in a number of eclipsing binaries to understand what sets systems with spin-orbit alignment apart from systems where the spins are not aligned. They find that alignment is not a simple function of orbital separation or eccentricity.

Anther project led by Amaury Triaud aims to measure obliquities in binaries with F-star primaries and late-type secondaries (A. Triaud, these proceedings).

5. Outlook

The future for RM-measurements looks bright. Not only will the number of known eclipsing binaries and transiting exoplanets increase thanks to missions like *Kepler*, but these missions will also discover long-period systems and systems with multiple transiting planets. Also, the obliquities in systems with smaller planets, likely to have a different formation history, can be probed (Winn *et al.* 2010b, Hirano *et al.* 2011b). With an improved understanding of the RM effect, we might also be able to measure in a few systems some second order effects, as described above.

Stellar obliquities will also be measured by other techniques, like the method employed by Schlaufman (2010), which is not as accurate as RM measurements, but has the virtue that it does not require transit observations. For slowly rotating stars, the crossing of star-spots can be used as a tracer of stellar obliquity (e.g. Sanchis-Ojeda & Winn 2011). For fast rotating stars, which exhibit gravity darkening, the projected obliquity can be estimated from high-quality photometry (Szabo *et al.* 2011). Having very precise photometry further opens the possibility to measure obliquities via the photometric RM effect (Groot 2012, Shporer *et al.* 2012). Finally, optical interferometry is now able to measure the projected obliquity for some nearby systems (Le Bouquin *et al.* 2009). Therefore, there is the chance that our understanding of stellar obliquity, so far an elusive quantity, will be greatly improved over the coming years.

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Discussion

P. Bonifacio: Since you translated effective temperatures to masses in your Teff-Obliquity relation, I assume all your stars are dwarfs. If the physical parameter determining the trend is really mass, you should be able to find some cool massive giants with a high-obliquity planet.

S. Albrecht: That is correct. We only have R-M (Rossiter-McLaughlin) measurements for dwarf stars. Unfortunately, it is very difficult to detect transiting planets around giants as the radius ratio is so big. Also the R-M measurements would be very difficult.