Exoplanets and the Rossiter-McLaughlin Effect

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**Abstract.**

A transiting planet eclipses part of the rotating stellar surface, thereby producing an anomalous Doppler shift of the stellar spectrum. Here I review how this “Rossiter-McLaughlin Effect” can be used to characterize exoplanetary systems. In particular, one can measure the angle on the sky between the orbital axis and the stellar rotation axis. This may help to discriminate among migration theories. Measurements have been made for 4 exoplanets, and in all cases the spin and orbital axes are fairly well-aligned. In the future, the Rossiter-McLaughlin effect may also be important as an alternative means of probing exoplanetary atmospheres, and for confirming the transits of objects identified by the satellite missions *Corot* and *Kepler*.

1. Introduction

For most of the participants in this workshop, the word “transit” brings to mind an image such as the left panel of Fig. 1. This is the beloved transit light curve, an inverted boxcar with its corners sanded down by limb darkening. For those of us who study the Rossiter-McLaughlin effect, the object of our affection is shown in the right panel of Fig. 1: an elegant antisymmetric blip with a gently sloping baseline.

![Figure 1](image_url)

Figure 1.: Simulation of a photometric transit (left) and the corresponding spectroscopic transit (right). The system parameters were chosen to be similar to those of TrES-1 (Alonso et al. 2004; Winn, Holman, & Roussanova 2006).
What is the meaning of this wiggly waveform? It is the variation in the apparent Doppler shift of the star throughout a transit, the most prominent spectroscopic effect of the planet’s passage. It arises because of stellar rotation. The emergent spectrum from a given point on the stellar disk is Doppler-shifted by an amount that depends on the local line-of-sight velocity. The spread in velocities across the disk broadens the spectral lines (along with thermal and turbulent broadening). When the planet hides a portion of the stellar surface, the corresponding velocity components are missing from the spectral lines. This distortion is usually manifested as an “anomalous” Doppler shift. When the planet is in front of the approaching (blueshifted) half of the stellar disk, the starlight appears slightly redshifted. The anomalous Doppler shift vanishes when the planet is in front of the stellar rotation axis, and then reverses sign as the planet moves to the receding (redshifted) half of the stellar disk.

This phenomenon is called the “Rossiter-McLaughlin effect,” in honor of the two gentlemen who described it in a back-to-back pair of papers in the Astrophysical Journal (Rossiter 1924; McLaughlin 1924), although in fact the effect had been observed years earlier (Forbes 1911; Schlesinger 1911). Of course, those observations involved eclipsing binary stars, rather than exoplanets.

The exoplanetary Rossiter-McLaughlin (RM) effect was first observed by Queloz et al. (2000) and Bundy & Marcy (2000) during transits of HD 209458b. It has since been observed in at least 3 other systems, and the motivation for additional measurements is strong. In this contribution, I explain the motivation, review the existing measurements and their implications, and discuss prospects for future observations. More details on the theory can be found in the works by Ohta, Taruya, & Suto (2005), Gimenez (2006), and Gaudi & Winn (2007).

2. Spin-Orbit Alignment

By observing the RM effect with a high signal-to-noise ratio, one can determine the trajectory of the planet relative to the (sky-projected) stellar rotation axis. Specifically, one can measure the angle $\lambda$ between the sky projections of the orbital axis and the stellar rotation axis. This is illustrated in Fig. 2. Pictured are three trajectories of a transiting planet, all of which have the same impact parameter (and hence produce exactly the same photometric signal), but which differ in $\lambda$ (and hence produce different RM waveforms).

Since the angular momentum of the star and of the orbits are derived from the same source—the protostellar disk—one would naturally expect the spin and orbit to be well-aligned and $\lambda$ to be small. Indeed, in the Solar system, the planetary orbital axes are aligned with the Solar rotation axis within $\sim 10^\circ$. Why, then, would one bother measuring $\lambda$ for exoplanets?

An answer that some readers may find satisfactory is “what one can measure, one should measure.” Exoplanets have rewarded observers with surprises in the past. Those readers requiring a theory-based motivation might ask whether or not the migration mechanism for hot Jupiters preserves spin-orbit alignment. Migration via tidal interactions with a disk would not be expected to perturb spin-orbit alignment, and may even drive the system toward closer alignment (see, e.g., Ward & Hahn 1994, 2003). In contrast, migration mechanisms involving disruptive events such as planet-planet interactions or planetesimal collisions
would act to enhance any initial misalignment. Another migration theory involves the Kozai mechanism, in which a companion star causes oscillations in the planetary orbit’s eccentricity and inclination. By the time tides circularize the orbit and halt “Kozai migration,” the orbital inclination can change substantially (Wu & Murray 2003; Eggenberger, Udry, & Mayor 2004; D. Fabrycky & S. Tremaine, priv. comm.). Thus, measuring spin-orbit alignment offers a possible means for discriminating among migration theories, or at least for identifying particular planets that migrated through disruptive mechanisms.

Results for $\lambda$ have been published for two systems. For HD 209458, the latest result is $\lambda = -4.4^\circ \pm 1.4^\circ$ (Winn et al. 2005). The small but nonzero angle is reminiscent of Solar system planets. For HD 189733, the result is also a very close alignment: $\lambda = -1.4^\circ \pm 1.1^\circ$ (see Fig. 3, from Winn et al. 2006). In addition, a paper in press by Wolf et al. (2007) states $\lambda = 11^\circ \pm 15^\circ$ for HD 149026. The lower accuracy in that case is mainly due to the smaller size of the planet relative to the star. Most recently, the TrES-1 system was found to be consistent with $\lambda = 0$ within about $30^\circ$ (N. Narita, this volume).

Together, these results rule out the (admittedly rather extreme) hypothesis of completely random alignment, with >99.9% confidence. Apparently, in these systems at least, the migration mechanism preserved spin-orbit alignment. (The observed alignment probably reflects the initial condition, because the timescale for tidal coplanarization is very long; see Winn et al. 2005.) Further measurements are needed to estimate the actual distribution of $\lambda$, and of course the discovery of even a single example of a grossly misaligned system would be of great interest. For planning purposes, Gaudi & Winn (2007) have provided formulas that can be used to estimate the accuracy with which $\lambda$ can be measured, given the geometry of the system and the characteristics of the data.
It is important to remember that $\lambda$ is the angle between the projected orbital and rotation axes. The inclinations of those two axes with respect to the sky plane must be determined using other means. The orbital inclination can be determined from the transit light curve, but in general the stellar inclination is unknown. For the special case of HD 189733, however, the rotation period has been measured; the star is chromospherically active and exhibits quasiperiodic flux variations, presumably due to star spots. The combination of a measured rotation period, stellar radius, and $v \sin i$ places a constraint on $i$. Hence this is the first case for which the true (3-d) angle between the orbital and rotational axes can be measured, and the result is an upper bound of 27° with 95% confidence (Winn et al. 2007).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{transit.png}
\caption{The photometric and spectroscopic transit of HD 189733, from Winn et al. (2006). Photometry was obtained with the 1.2 m telescope at the Fred L. Whipple Observatory, using Keplercam and a Sloan $z$ filter. Radial velocities were derived from spectra that were measured with the Keck I 10 m telescope and HIRES. The residuals (O−C) are displayed beneath each data set.}
\end{figure}

3. Transmission Spectroscopy

Snellen (2004) realized that the RM effect offers an alternative method of “transmission spectroscopy.” During a transit, a small portion of the received starlight is filtered through the planetary atmosphere, which may imprint detectable absorption (or emission) features. At the wavelength of a strong absorption line, the effective radius of the planet is larger. This can be detected through the wavelength-dependence of the photometric transit depth, a technique that was used by Charbonneau et al. (2002) to detect atomic sodium in the atmosphere of HD 209458. Since the RM anomaly also depends on the effective radius of the planet, the wavelength-dependence of the RM effect can be used for transmission spectroscopy. Rather than relying on accurate time-series photometry, the RM method relies on the comparison of the Doppler shifts of different lines within a single spectrum. In principle, this could lead to more accurate results (at least in comparison to ground-based photometry), although only upper limits have been achieved to date (Snellen 2004).
4. Transit Confirmation

It is interesting to compare the velocity amplitude $K_O$ of the star’s orbital motion with the velocity amplitude $K_R$ of the RM effect. For a small planet of mass $M$ on an edge-on circular orbit with period $P$, Gaudi & Winn (2007) showed that the order of magnitude of $K_R/K_O$ is

$$\frac{K_R}{K_O} \sim 0.3 \left( \frac{M}{M_{\text{Jup}}} \right)^{-1/3} \left( \frac{P}{3 \text{ days}} \right)^{1/3} \left( \frac{v \sin i}{5 \text{ km s}^{-1}} \right).$$

Thus, for hot Jupiters, the anomalous velocity is smaller than the orbital velocity. However, for smaller planets with longer periods, the amplitude of the RM effect will exceed the stellar orbital velocity. For an Earth-mass planet with a period of one year, $K_R/K_O \sim 3$ for $v \sin i = 5$ km s$^{-1}$.

This raises the appealing possibility of using the RM effect to confirm transits that will be detected by the forthcoming satellite missions Corot and Kepler. The most exciting discoveries by these satellites will be very small planets with transit depths of $\sim 10^{-4}$ or less. One would like to detect the spectroscopic orbit and thereby learn the planetary mass, but this will be challenging because $K_O$ is only $\sim 10$ cm s$^{-1}$ for an Earth-like planet in the habitable zone of a solar-type star. It would be useful to have a means of confirming the transits before chasing after the spectroscopic orbit. Photometric confirmation from the ground may prove very difficult. RM confirmation appears more feasible for at least some stars, not only because $K_R > K_O$ as mentioned above, but also because the RM velocity variation occurs over the time scale of the transit duration ($\sim 1$ day), which is much shorter than the time scale of the orbital velocity variation ($\sim 1$ yr). Both of these points are illustrated in Fig. 4.

![Figure 4. Simulated spectroscopic signal of a transiting terrestrial planet in the habitable zone of a solar-type star with $v \sin i = 5$ km s$^{-1}$, from Gaudi & Winn (2007). A circular, edge-on orbit is assumed. The sinusoid with a period of 1 yr is the spectroscopic orbit. The spike near time zero is the RM effect, which occurs over $\sim 1$ day.](image-url)
This idea is discussed at greater length in these proceedings by W. Welsh. A related idea by Ohta, Taruya, & Suto (2006) is to search for planetary rings using RM observations. Here too, the RM effect is used as an alternative means of measuring the transit depth, relying on the measurement of spectral features rather than photometric stability.

5. Summary

The RM effect is the anomalous Doppler shift of starlight that is observed during a planetary transit, due to stellar rotation. It provides another fundamental observable for exoplanetary systems: the degree of alignment between the planetary orbital axis and the stellar rotation axis (in projection on the sky). Observations of the RM effect are likely to grow in importance in the future, as an alternative means of confirming photometric transits and possibly also for transmission spectroscopy.

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