The Effects of Plage on Precision Radial Velocities

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Abstract. I present the first results of semi-empirical modeling of the effects of magnetic plage on measured radial velocities in G stars. I use solar line bisectors observed in quiet and active regions at a range of disk positions as proxies for stellar bisectors. These are then used to “warp” model line profiles and construct model stars with various $v \sin i$ and plage areas. The models predict the sun should show a maximum of $\Delta v_r \sim 10 \text{ m s}^{-1}$ short-term $v_r$ fluctuations atop $\sim 3 \text{ m s}^{-1}$ long-term (cyclic) modulation, while a Hyades age G dwarf with $v \sin i = 6 \text{ km s}^{-1}$ exhibits $\Delta v_r \sim 90 \text{ m s}^{-1}$ (short-term) atop $\sim 14 \text{ m s}^{-1}$ (long-term).

1. Introduction

Current radial velocity ($v_r$) searches for extrasolar planets can achieve precisions of $3 \text{ m s}^{-1}$ in chromospherically inactive stars (e.g., Butler et al. 1996), and there are hopes for future improvements to $\sim 1 \text{ m s}^{-1}$ (Queloz et al. 2001a). At this level of $v_r$ precision, intrinsic stellar sources of $v_r$ fluctuations such as magnetic spots and plage (Saar et al. 1998) may be important even in inactive stars. If so, it is likely these sources of $v_r$ “jitter” will need to be understood and corrected for to achieve the desired $v_r$ precision. The effects of starspots on $v_r$ have been explored (Saar & Donahue 1997; Hatzes 1999) and mainly involve decreased brightness (reduced signal) at a given rotational Doppler position on the stellar disk. The effects of plage are more complex: although both spots and plage alter local convection, only plage regions are bright enough for this effect to be observable in integrated light. This paper is a first exploration of the $v_r$ effects of plage in G stars.

2. Modeling and Analysis

Methods for modeling line formation in plage typically involve tradeoffs. One route, computing lines from full 3-D MHD models, is physically consistent but very time consuming; simpler multi-stream models on the other hand (e.g., Dravins 1990), are faster to compute but are less physical and have ill-constrained parameters. I took a third, semi-empirical approach, and constructed stellar line models using observed solar line bisectors (Cavallini et al. 1985; Figure 1). The solar bisectors, taken from quiet and active regions at a variety of limb angles, were used to “warp” LTE model intensity profiles, which could then be disk-integrated to produce stellar integrated flux line profiles for any desired $v \sin i$ and plage geometry. The model profile’s $v_r$ was determined by its intensity-weighted centroid. Other methods of determining $v_r$ can yield shifts differing
by almost a factor of two, but these \( v_r \) generally scale with each other (see Saar et al. 2003), leaving the trends described here - if not the absolute numbers - unchanged. Both spatially uniform plage (with a filling factor \( f_p \)) and isolated circular plages were studied. In general, we have assumed the plage brightness \( I_p \) equal to the quiet star.

The regions have a 20\(^\circ\) radius at latitude \( \theta = 0 \), for stars with \( v \sin i = 10 \) and 2 km s\(^{-1}\) (heavier lines). A linearly scaled 2 km s\(^{-1}\) plage \( \Delta v_r \) curve (dotted) is almost indistinguishable from the 10 km s\(^{-1}\) curve.

### 3. Results and Discussion

The main results of the modeling are:

- Compared to spots of the same size, the \( \Delta v_r \) induced by a circular plage shows an altered rotational dependence (with larger \( \Delta v_r \) values more concentrated around rotation angle \( \phi = 0 \)), only a slightly lower amplitude, and a non-zero mean \( \Delta v_r \) offset (Figure 2). The plage \( \Delta v_r \) rotation curves scale linearly with \( v \sin i \) and plage filling factor \( f_p \). The \( \Delta v_r \) amplitude is given by \( A_p \approx 19.1(v \sin i/4 \text{ km s}^{-1})(f_p/1\%) \text{ m s}^{-1} \).

- A uniform distribution of plage essentially yields the average of the \( \Delta v_r \) curves in Figure 2. Compared to an inactive hemisphere, the resulting \( \Delta v_r \) is only mildly dependent on \( v \sin i \), and almost independent of the mean macroturbulent velocity (Figure 3).

- \( \Delta v_r \) increases linearly with plage brightness \( I_p \), but the effect decreases \( f_p \rightarrow 1 \) and the contrast is reduced (Figure 4).
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Figure 3. (Left) The maximum $\Delta v_r$ amplitude for a spatially even, $f_p = 1$ plage relative to an inactive ($f_p = 0$) hemisphere, as a function of $v \sin i$, for various values of the mean macroturbulent velocity (2, 3, and 4 km s$^{-1}$ are dotted, solid, and dashed, respectively).

Figure 4. (Right) Change in $\Delta v_r$ amplitude due to a plage as a function of plage filling factor $f_p$ and plage brightness $I_p$ for $I_p = 2$, 4, and 6% above the quiet surface (dotted, dashed, and solid, respectively).

The uniform plage models mimic the mean $\Delta v_r$ changes due to long-term variations in the average activity (e.g., magnetic cycles), while the circular plage models explore short-term (rotational) changes. To investigate how $\Delta v_r$ varies with rotation rate, one needs a more realistic estimate of the relevant plage area (instead of $f_p = 1$ in Figure 3). Note that it is the change in $f_p$ ($\Delta f_p$) and not $f_p$ itself which is most important. On both short and long time scales, rms Ca ii HK emission variation scales approximately with the normalized HK emission flux: $\sigma_{\text{HK}} \propto R'_{\text{HK}}$ (Radick et al. 1998). I assume $\Delta f_p \propto \sigma_{\text{HK}}$ and so $\Delta f_p \propto R'_{\text{HK}}$, which is strongly correlated with rotation period $P_{\text{rot}}$ (Noyes et al. 1984). If one further normalizes to a short-term $\Delta f_p(\odot) = 1\%$ and long-term $\Delta f_p(\odot) = 4\%$, the maximum $\Delta v_r$ as a function of $P_{\text{rot}}$ can be estimated (Figure 5).

Short-term rotational contributions to $\Delta v_r$ appear to dominate, especially in more active stars (Figure 5). This could explain why $v_r$ corrections using correlations with activity are mostly only successful in less active stars (Saar & Fischer 2000); in the more active stars, the rotational $\Delta v_r$ (which the correlations do not remove) is relatively stronger. For the sun, the model predicts maximum short-term fluctuations of $\Delta v_r \sim 10$ m s$^{-1}$ atop a $\Delta v_r \sim 3$ m s$^{-1}$ cyclic variation. In a Hyades G dwarf with $v \sin i = 6$ km s$^{-1}$ ($P_{\text{rot}} \approx 8.5$ d), these values rise to $\Delta v_r \sim 90$ m s$^{-1}$ (short-term) atop a $\Delta v_r \sim 14$ m s$^{-1}$ (long-term) base.

Clearly, plage is at least as important as spots for generating $\Delta v_r$ in G dwarfs (Figure 2); indeed, to the extent that $\Delta f_p > \Delta f_s$ (the equivalent spot inhomogeneous area), plage-induced $\Delta v_r$ will dominate. For low-to-moderate activity stars, $f_p \gg f_s$, and thus $\Delta f_p > \Delta f_s$, and plage $\Delta v_r$ will dominate. However, the spot-to-plage area ratio increases rapidly with activity, and so at some point, $\Delta f_s$ and spot-induced $\Delta v_r$ will take over. The importance of plage
Figure 5. Predicted maximum $\Delta v_r$ amplitude due to the rotational of a single plage (solid) and due to cyclic variation in the mean activity (dotted), as a function of rotation period $P_{\text{rot}}$ (see text for details).

$\Delta v_r$ is likely higher in F stars, and lower in K stars, following the trends in bisector spans, convective and macroturbulent velocities (Gray 1988).

Several caveats must be noted. Use of solar bisectors as input restricts the applicability of the models to stars with convective properties similar to the sun (i.e., stars with temperatures $T_{\text{eff}} \sim T_{\text{eff}}(\odot)$ and gravities $g \sim g_{\odot}$, or $\approx$ G0V – G5V). The models are based on the behavior of a single Fe I line (6301.5 Å) with an excitation $\chi_L = 3.65$ eV. Similar lines of different depth can be modeled with segments of the input bisectors, but lines of significantly different wavelength or $\chi_L$ will show altered behavior (e.g., Asplund et al. 2000). The maximum $\Delta v_r$ in Figure 5 scales linearly with the assumed long- and short-term $\Delta f_p(\odot)$; improved estimates for these will alter the curves accordingly.

The next step in this work is to examine the bisectors of the model lines in detail. The aim is to develop methods to correct $v_r$ for the presence of plage by using correlations seen in the models between bisector shape and displacement and the inferred $\Delta v_r$. Use of the bisector of the mean cross-correlation function (e.g., Queloz et al. 2001b) may not be optimal for this purpose, since that method implicitly assumes all lines have the same bisector shape.

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References
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Discussions at the Poster Session