Further Evidence for Activity-Related Radial Velocity Variations in Cool Stars

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Abstract. The discovery of planets around several solar-like stars by means of high precision radial velocity ($v_{\rm r}$) measurements makes it important to explore sources of $v_{\rm r}$ variations intrinsic to the stars themselves. Such studies guard against false planet detections, and can guide planet searches towards stars with low $v_{\rm r}$ "noise" levels. We explore $v_{\rm r}$ variations related to stellar activity – the rotation and temporal evolution of starspots and convective inhomogeneities – by studying the weighted RMS of $v_{\rm r}$ variations ($= \sigma_v$) for stars in the Lick planetary survey. After removing $v_{\rm r}$ effects of known planets and binaries, and correcting σ_v for the mean internal error (thus removing measurement RMS to first order), we study relationships between σ_v and spectral type, rotation, and activity. Excluding binaries and evolved stars in the sample, we find σ_v decreases with decreasing $T_{\rm eff}$, increases with activity level, and scales $\propto v \sin i$. For a G star with $v \sin i \approx 8 - 10$ km s^{-1} (age $\sim$ 0.3 Gyr), for example, $\sigma_v \sim 20 - 45$ m s^{-1}, roughly consistent with the predictions of Saar & Donahue (1997). Implications for planet searches are discussed.

1. Introduction

Nearly all extra-solar planets have been found in high-precision ($\sigma < 15$ m s^{-1}) radial velocity ($v_{\rm r}$) surveys. This kind of precision is crucial if Jupiter-like (or smaller) planets are to be found, yet at these tiny levels, $v_{\rm r}$ variations from a number of other physical effects could inhibit or confuse planet detection. In this poster we investigate $v_{\rm r}$ variability, and find evidence that much of the portion not due to planets or other companions can be explained by the rotation and evolution of starspots and of (possibly related) areas of altered convective flows. (The latter could arise, e.g., due to restricted convection in stellar active regions - see Brandt & Solanki 1990).

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2. Observations and Analysis

We have concentrated on the $v_{\rm r}$ data of highest precision (internal error $\sigma_i < 5$ m s^{-1}; Butler et al. 1995) taken after November 1994 as part of the Lick planetary survey (Marcy & Butler 1997). We calculated the σ_i weighted RMS of all $v_{\rm r}$ time series in Lick survey. This weighted RMS, σ_v reflects the combined influence of

1. photometric noise
2. systematic measurement effects (e.g., due to variations of σ_i with mean line strength and $v \sin i$),
3. binary and planetary companions
4. intrinsic stellar noise due to starspots and inhomgeneous convection (Saar & Donahue 1997 = SD97)
5. stellar pulsations (Hatzes 1996; Gray 1997).

We then subtract the mean internal error in quadrature to give a weighted *excess* $v_{\rm r}$ RMS, $\sigma'_v = \sqrt{\sigma_v^2 - \langle\sigma_i\rangle^2}$, thus removing, to first order, systematic and random instrumental noise. These σ'_v values were then correlated with stellar properties: $B-V$ color (i.e., $T_{\rm eff}$); $v \sin i$ (mostly from Soderblom 1983; Gray 1982, 84; Saar & Osten 1997; or Fekel 1997), $P_{\rm rot}$ (mostly from Donahue, Saar, & Baliunas 1996, or Baliunas, Sokoloff, & Soon 1996), and $R'_{\rm HK}$ (the normalized Ca HK flux with the photospheric component subtracted). $R'_{\rm HK}$ values were computed following the method of Noyes et al. (1984) from $\langle S\rangle$ values in Baliunas et al. (1995) or Rutten (1987). To focus on purely stellar σ'_v effects in solar-like stars, we have ignored all stars in known or suspected binaries, and all stars which are classed subgiants or giants. Stars with suspected planets are treated separately, and plotted both before and after removal of the proposed planet's orbital $v_{\rm r}$ variation.

3. Results and Discussion

The results of correlating σ'_v with various stelar properties is presented in Figures 1 to 4. We discuss each below.

The upper envelope of σ'_v declines from F to mid-late K, then increases again in the M stars, with stars of higher $v \sin i$ generally having larger σ'_v at any given $T_{\rm eff}$ (Fig. 1). Three effects likely contribute to cause this behavior. First, the decrease in $\langle v \sin i\rangle$ from F to G to K stars results in a decreased ability of any surface inhomogeneities (spot or convective) to perturb $v_{\rm r}$ (SD97). Also, mean convective velocities are declining with $T_{\rm eff}$ (Gray 1984; Saar & Osten 1997), likely reducing the effect of inhomogeneous convection on $v_{\rm r}$. In contrast, relative spottedness *increases* towards lower $T_{\rm eff}$ (O'Dell et al. 1994); this, plus the effects of flares may be the cause of the rise of σ'_v in M stars. Due to their higher σ_i, low observation frequency, paucity of $v \sin i$ and $P_{\rm rot}$ measurements, and uncertainties about their $R'_{\rm HK}$ calibration and flare contributions, we neglect M stars in the following discussion.

Figure 2 shows $\sigma'_v \propto (v \sin i)^{0.9}$ for G and K stars (fit RMS = 0.23 dex)

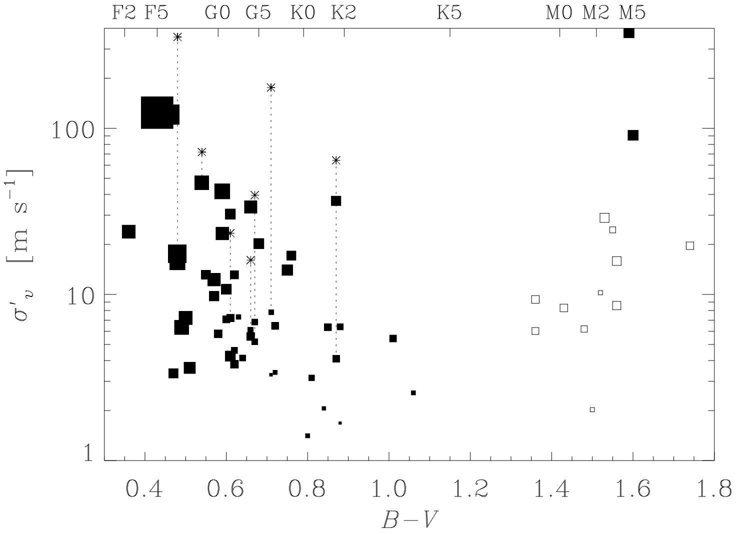

Figure 1. The weighted radial velocity RMS in excess of the measurement noise, σ'_v, from the Lick planet search $v_{\rm r}$ database, plotted against $B-V$ color (approximate spectral types given at top). The symbol area is $\propto v\sin i$, stars with $v\sin i$ upper limits are open symbols. Stars with planets are plotted twice, before ($*$) and after ($\Box$) removal of the planet orbit, and connected with a dashed line.

and $\sigma'_v \propto (v\sin i)^{1.4}$ for F stars (fit RMS = 0.34 dex). This is consistent with the models of SD97 if σ'_v(G & K) is dominated by spots, and in F stars by (predominantly) convective inhomogeneities. The dependence of σ'_v on $v\sin i$ is expected to be stronger than linear in the presence of non-uniform convection due to the extra velocity contribution of granular flows at the limb, especially when the $v\sin i$ is greater than the local line Doppler width (e.g., Smith et al. 1987). Since both convective velocities and $\langle v\sin i\rangle$ are larger in F stars, it is thus reasonable that they would show a non-linear trend between σ'_v and $v\sin i$.

The σ'_v values also increase with $R'_{\rm HK}$ (Figure 3), roughly as $\sigma'_v \propto {R'_{\rm HK}}^{1.2}$ in G and K stars (fit RMS = 0.26 dex), and more steeply (but with more scatter) for F stars. Stars with higher $v\sin i$ at a given $R'_{\rm HK}$ have larger σ'_v. These more vague trends are still consistent with an activity-related phenomenon (SD97): high activity ($R'_{\rm HK}$) is governed by rapid rotation (v) but a large σ'_v specifically requires a large $v\sin i$. A pole-on ($v\sin i \sim 0$) active star, for example, would show $\sigma'_v \sim 0$ from starspots, since there is no rotational velocity "push" to move their light deficits through the line profiles and generate an apparent $\Delta v_{\rm r}$. We thus expect a spread in σ'_v for a given $R'_{\rm HK}$, depending (in part) on $\sin i$. The weak trend of $\sigma'_v({\rm F}) > \sigma'_v({\rm G}) > \sigma'_v({\rm K})$ at fixed $R'_{\rm HK}$ may be due to some combination of decreasing convective velocities, and increasing $P_{\rm rot}$ (at fixed Rossby number).

As suggested by Figure 2, a plot of σ'_v vs. $P_{\rm rot}$ shows a tight, nearly linear relation: $\sigma'_v \propto P_{\rm rot}^{-1.1}$ with fit RMS = 0.29 dex in G and K stars (Fig. 4). The relation is less distinct in F stars, but these stars lack many measured $P_{\rm rot}$ values.

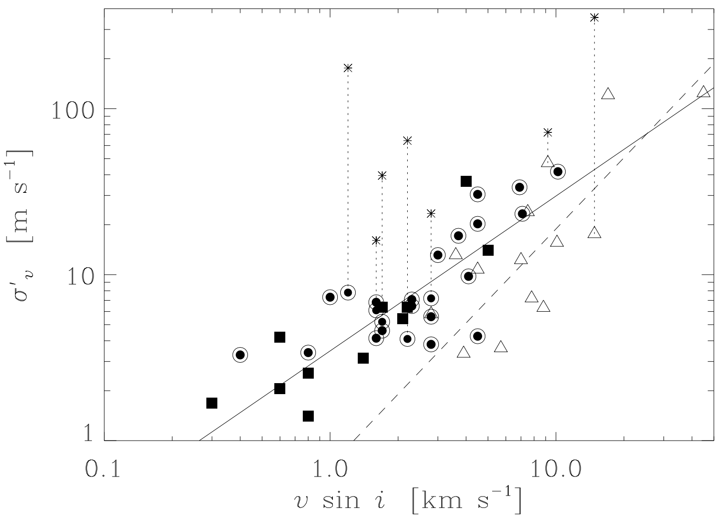

Figure 2. σ'_v vs. $v \sin i$, for F ($\triangle$) G ($\odot$) and K ($\Box$) stars; stars with planets are plotted twice and connected, as in Fig. 1. Power law fits with $\sigma'_v \propto (v \sin i)^{0.9}$ in G and K stars (solid, RMS = 0.23 dex) and $\sigma'_v \propto (v \sin i)^{1.4}$ in F stars (dashed, RMS = 0.34 dex) are also shown.

These figures demonstrate that $v_{\rm r}$ *"noise" due to magnetic activity in young stars may make planet detection difficult* in many cases. For 8 km $\mathrm{s}^{-1} \leq v \sin i \leq$ 10 km s^{-1} (similar to UMa stream stars with age $\sim$ 0.3 Gyr), $\sigma'_v \sim 20 - 45$ m s^{-1} in G stars. In F stars with the same $v \sin i$, $\sigma'_v \sim 7 - 30$ m s^{-1}. Conversely, old, slowly rotating stars ($v \sin i \leq 2$ km s^{-1}, $P_{\rm rot} \geq 16$ days) have the lowest activity-related $v_{\rm r}$ noise, and are the best targets for easier detection of Jupiter-like planets by $v_{\rm r}$ methods.

The trends with $T_{\rm eff}$, rotation and activity are consistent with those found in the Walker et al. (1995) data (SD97), but the actual σ'_v values are somewhat smaller, partly because SD97 did not remove σ_i. Trends are also considerably clearer, due to the smaller $\langle\sigma_i\rangle$ and larger sample size of the Lick data.

It is also apparent that prior to correction for planetary companions, *all of the stars with suggested planets show enhanced* σ'_v *(over the mean relationships for their spectral types) in at least one of these diagrams* (Figs. 1-4). Once the planetary orbital $v_{\rm r}$ are identified and removed, their parent stars are almost always consistent with the observed σ'_v relationships (the exception has a longterm $v_{\rm r}$ trend of uncertain origin; Butler et al. 1997). Thus, *searching for stars with* σ'_v *values enhanced relative to typical trends with* $P_{\rm rot}$, $v \sin i$, *and* $R'_{\rm HK}$ *can be an useful tool to identify stars with likely planets.*

It is also significant to note that $\sigma'_v < 8$ m s^{-1} for 10 G stars with $P_{\rm rot} \geq 20$ days (Fig. 4). This makes it difficult to argue that the 4 G stars with proposed planets and $P_{\rm rot} > 20$ days are actually undergoing some exotic non-radial pulsation (NRP; Hatzes 1996; Gray 1997). If they are pulsating, why are other G stars of similar $T_{\rm eff}$ and $P_{\rm rot}$ not doing so as well? It is possible that these stars could have different internal structures which might promote the NRP (e.g., due to different metallicity, mass, and/or age from the other G stars). But the stars

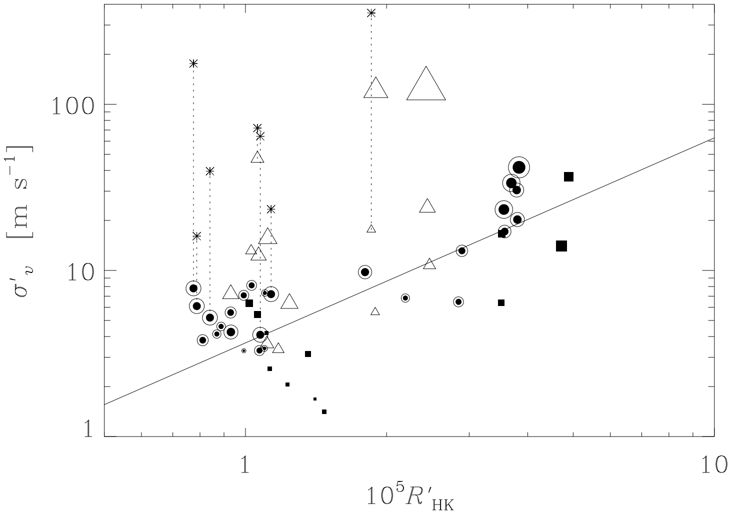

Figure 3. σ'_v vs. $R'_{\rm HK}$ for F (△) G (⊙) and K (□) stars; stars with planets indicated twice and connected. Here, symbol area is $\propto v \sin i$. A power law fit for G and K stars, $\sigma'_v \propto {R'_{\rm HK}}^{1.2}$, is shown (solid, RMS = 0.26 dex).

with anomalously high σ'_v are also neither consistently metal poor or rich, nor of anomalous gravity (see also Marcy & Butler 1997). Thus, since the G stars with possible planets are not uniformly distinct from other G stars of similar $P_{\rm rot}$ in any obvious physical property other than enhanced σ'_v, *our results here make NRPs less likely as a general explanation of the apparently planetary* $v_{\rm r}$ *signatures.*

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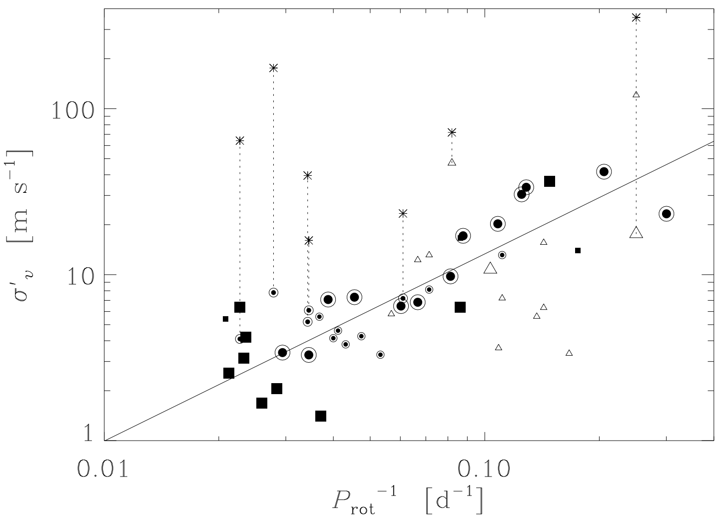

Figure 4. σ'_v vs. $P_{\rm rot}$, for F (△) G (⊙) and K (□) stars. Stars with planets are indicated twice and connected, and stars with estimated $P_{\rm rot}$ are plotted at half size. A power law fit with $\sigma'_v \propto P_{\rm rot}^{-1.1}$ in G and K stars (solid, RMS = 0.21 dex) is shown.

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