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MAGNETIC ACTIVITY–RELATED RADIAL VELOCITY VARIATIONS IN COOL STARS: FIRST RESULTS FROM THE LICK EXTRASOLAR PLANET SURVEY

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ABSTRACT

The discovery of the radial velocity (v_r) signatures of planets around several solar-like stars highlights the importance of exploring the sources of v_r variations intrinsic to the stars themselves. We study the stars in the Lick planetary survey for v_r variations related to stellar activity: the rotation of starspots and convective inhomogeneities and their temporal evolution. We study the relationships between the weighted v_r dispersion, σ'_v (which has first been corrected for the orbital contribution from known planets and the mean internal error), and spectral type, rotation, and activity (as measured by Ca II H and K). We find that the largest σ'_v values occur among both the coolest (dMe) and the warmest (active F) stars. Values of σ'_v increase with H and K emission and scale proportional to $v \sin i$ in G and K stars and proportional to $(v \sin i)^{1.3}$ in F stars. For a G star with $v \sin i \approx$ 8–10 km s^{-1} (age ~0.3 Gyr), for example, 20 m s$^{-1} \lesssim \sigma'_v \lesssim$ 45 m s^{-1}, roughly consistent with the predicted σ'_v levels due to magnetic activity (Saar & Donahue). All the stars with proposed planetary companions show σ'_v values typical for their spectral type, activity, and/or rotation. However, before the planetary v_r perturbations are removed, these stars show significantly enhanced σ'_v values. We develop a simple model that can predict the σ'_v expected for a given star (within ≈40%) as a function of $v \sin i$, spectral type, photometric variability, and macroturbulent velocity. The implications for extrasolar planet searches are discussed.

Subject headings: convection — stars: activity — stars: late-type — stars: planetary systems — stars: spots — techniques: radial velocities

1. INTRODUCTION

Nearly all of the candidate extrasolar planets have been discovered through periodic signals in high-precision ($\sigma < 15$ m s^{-1}) radial velocity (v_r) surveys (e.g., Mayor & Queloz 1995; Butler & Marcy 1996; Cochran et al. 1997; Noyes et al. 1997). This level of precision is required for the discovery of extrasolar Jupiter-like planets (which induces a solar v_r perturbation with a semiamplitude of ≈12.5 m s^{-1}). At these small amplitudes, however, one must be concerned about other astrophysical effects, such as magnetic activity (e.g., Walker et al. 1995) or convective nonuniformities (e.g., Dravins 1985), which could produce v_r variations and possibly inhibit or confuse planet detection. In this Letter, we investigate v_r variability in cool dwarfs using the Lick v_r survey data (Marcy & Butler 1998). We find evidence that much of the v_r variation not attributable to planets or binary companions can be explained by the rotation and evolution of starspots and areas with altered convective flows (the latter perhaps the result of magnetic inhibition of convection in active regions; see, e.g., Brandt & Solanki 1990).

2. OBSERVATIONS AND ANALYSIS

The Lick extrasolar planet search has been operating for about 10 years (Marcy & Butler 1998). Early data achieved a Doppler precision of ≈10 m s^{-1}, but after 1994 November, improvements in the instrumentation and analysis permitted data with internal errors $\sigma_i < 5$ m s^{-1}, approaching 3 m s^{-1} in the best cases (Butler et al. 1996). In this Letter, we study only this most recent, highest precision v_r data, specifically, those taken between 1994 November and 1997 April. Details of the v_r analysis can be found in Butler et al. (1996), and a complete list of the targets is available from the authors.[5]

We calculated the weighted standard deviation, σ_v, of each time series of high-precision Lick v_r data. No time averaging of the v_r data was performed prior to determining σ_v. We weighted σ_v by the internal error σ_i, the standard deviation of the mean of v_r for a single stellar echelle observation; σ_i measures the scatter of the radial velocities derived from each of ~700 spectral segments and averaged to compute v_r for each observation (see Butler et al. 1996 for details). Note that σ_i reflects the combined effects of the signal-to-noise ratio (S/N) of the spectrum and changes in v_r precision due to the strength, width, and number of the absorption lines in the star (e.g., broader and shallower lines yield higher σ_i). The σ_v value also reflects the contributions of several effects, including (1) random noise and systematic measurement effects (through σ_i), (2) possible stellar and planetary companions, and intrinsic stellar sources of v_r variation, including (3) pulsations (Hatzes 1996; Gray 1997) and (4) the rotation and evolution of starspots and inhomogeneous convection (Saar & Donahue 1997, hereafter SD97). To remove the effects of noise as much as possible, we adopt the mean $\langle\sigma_i\rangle$ as the representative internal error for a given star and compute a weighted *excess* v_r dispersion, $\sigma'_v = \left(\sigma_v^2 - \langle\sigma_i\rangle^2\right)^{1/2}$. (In a few cases where $\sigma_v < \langle\sigma_i\rangle$, we have set $\sigma'_v \le \langle\sigma_i\rangle$.) This procedure is justified because absorption lines are roughly Gaussian in shape, implying that Gaussian random noise will also produce Gaussian errors in the line widths and depths—all included in $\langle\sigma_i\rangle$. We will show that after correction for $\langle\sigma_i\rangle$ and planets (effects 1 and 2), the v_r dispersion

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[5] See http://www.physics.sfsu.edu/~gmarcy/planetsearch/planetsearch.html, by G. Marcy & R. P. Butler.

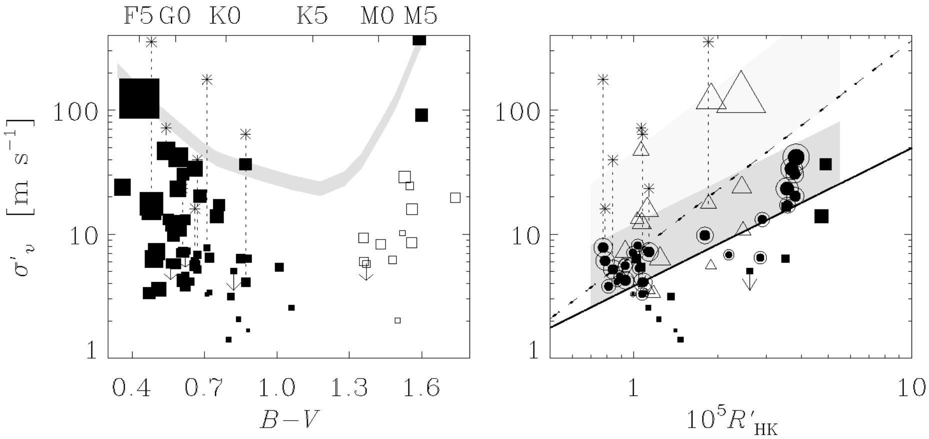

FIG. 1.—*Left*: the weighted radial velocity dispersion in excess of the measurement noise, σ'_v, from the Lick planet search v_r database, plotted against $B-V$ color (approximate spectral types given at top). The symbol area is proportional to $v \sin i$; stars with $v \sin i$ upper limits are open symbols. Stars with planets are plotted twice, before (*asterisks*) and after the removal of the planet orbit, and connected with a dashed line. The shaded area gives the approximate upper envelope of observed (planet-corrected) σ'_v values. *Right*: σ'_v vs. $R'_{\rm HK}$ for F (*open triangles*), G (*circled dots*), and K (*filled squares*) stars; stars with planets are indicated twice and connected. Here the symbol area is proportional to $v \sin i$. Power-law fits for the G and K stars (*solid line*: $\sigma'_v \propto R'^{1.1}_{\rm HK}$, $\sigma_{\rm fit} = 0.25$ dex) and the F stars (*dashed line*: $\sigma'_v \propto R'^{1.7}_{\rm HK}$, $\sigma_{\rm fit} = 0.41$ dex) are shown, together with the regions $\leq 2\sigma_{\rm fit}$ above each fit (*shaded dark gray and light gray, respectively*). All stars with planets lie $\geq 2\sigma_{\rm fit}$ above the fit for their respective spectral types prior to adjustment for the planet's orbital Δv_r.

(as measured by σ'_v) is dominated by magnetic-related activity (effect 4) in cool stars.

We studied correlations between σ'_v and various stellar properties: $B-V$ color (i.e., $T_{\rm eff}$), rotational period $P_{\rm rot}$, $v \sin i$, and $R'_{\rm HK}$ (the fractional Ca II H and K flux, corrected for the photospheric flux). The values of $P_{\rm rot}$ were taken from (in order of preference) Donahue, Saar, & Baliunas (1996), Donahue, Dobson, & Baliunas (1997), or Baliunas, Sokoloff, & Soon (1996), and $v \sin i$ came from Saar & Osten (1997), Gray (1982a, 1984, 1986), Soderblom (1983), or Fekel (1997). The values of $R'_{\rm HK}$ were computed using the calibration 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 ignored stars in known or suspected binaries and all stars that are classified as subgiants or giants. Stars with suspected planets were treated separately and considered both before and after the removal of the planet's apparent orbital v_r variation. After all these adjustments, the σ'_v values should reflect only intrinsic stellar sources of Δv_r, or possible planets. As a working hypothesis, we assumed that stellar pulsations were negligible and that all remaining excess v_r "noise" (σ'_v) was due to activity-related phenomena. The relationships between σ'_v and various stellar properties for the 72 remaining stars (14 F, 24 G, 16 K, and 18 M type) are presented in Figures 1 and 2. We discuss each figure below. Preliminary results given elsewhere (Saar, Butler, & Marcy 1998) are improved on here with updated stellar parameters and a more complete treatment of M dwarfs and σ'_v upper limits.

The upper envelope of σ'_v declines with $B-V$ from F to mid-late K, appears to reach a (poorly defined) minimum around $1.0 \lesssim B-V \lesssim 1.3$, and increases again in the M stars (Fig. 1, *left panel*). Stars with higher $v \sin i$ generally have

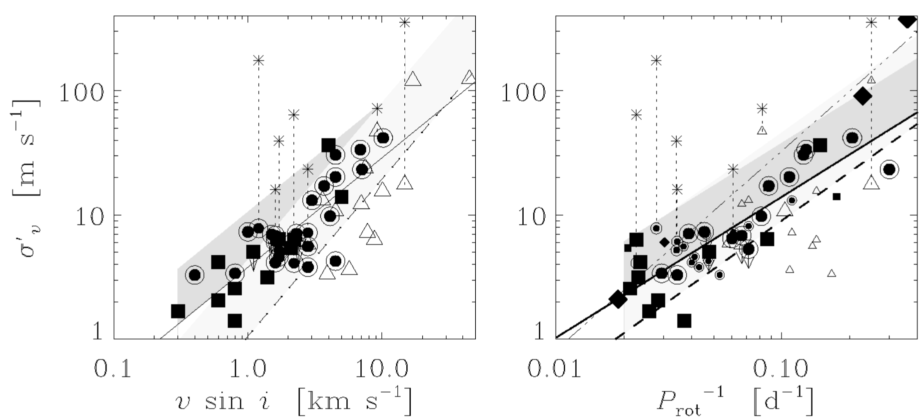

FIG. 2.—*Left*: σ'_v vs. $v \sin i$, for F (*open triangles*), G (*circled dots*), and K (*filled squares*) stars; stars with planets are plotted twice and connected, as in Fig. 1. Power-law fits with $\sigma'_v \propto (v \sin i)^{0.9}$ in G and K stars (*solid line*, $\sigma_{\rm fit} = 0.22$ dex) and $\sigma'_v \propto (v \sin i)^{1.3}$ in F stars (*dashed line*, $\sigma_{\rm fit} = 0.31$ dex) are also shown, and regions $\leq 2\sigma_{\rm fit}$ above each fit are shaded (*dark gray and light gray, respectively*). With one exception, all stars with planets lie $\geq 2\sigma_{\rm fit}$ above the fit for their spectral type. *Right*: σ'_v vs. $P_{\rm rot}$, with M stars (*filled diamonds*) now included, and stars with $P_{\rm rot}$ estimated from $R'_{\rm HK}$ are plotted at half-size. Power-law fits with $\sigma'_v \propto P_{\rm rot}^{-1.1}$ in G and K stars (*solid line*, $\sigma_{\rm fit} = 0.22$ dex) and $\sigma'_v \propto P_{\rm rot}^{-1.3}$ in F stars (*dashed line*, $\sigma_{\rm fit} = 0.35$ dex) and M stars (*dash-dotted line*, $\sigma'_v \propto P_{\rm rot}^{-1.6}$) are shown, together with the regions $\leq 2\sigma_{\rm fit}$ above each fit (*dark gray and light gray, respectively*). All stars with planets lie $\geq 2\sigma_{\rm fit}$ above the fit for their respective spectral types.

larger σ'_v at fixed $T_{\rm eff}$. Three effects likely contribute to this behavior. First, the decrease in $\langle v \sin i\rangle$ from F to K stars reduces the ability of any surface inhomogeneities (spot or convective) to perturb v_r (SD97). Also, mean convective velocities ($v_{\rm conv}$) decline with decreasing $T_{\rm eff}$ (Gray 1984; Saar & Osten 1997), reducing the effect of inhomogeneous convection on v_r. In contrast, the relative spottedness *increases* toward lower $T_{\rm eff}$ (Krishnamurthi et al. 1998) and is sharply enhanced above a critical rotation rate (Bopp & Fekel 1976; Hall 1991; O'Dell et al. 1995). This, plus possible v_r effects of flares (e.g., perturbing the cores of strong lines), may cause the rise of σ'_v in dMe stars. Because of possible flare contamination, plus higher σ_i, a paucity of $v \sin i$ and $P_{\rm rot}$ data, and the reduced importance of Ca II H and K for total chromospheric losses (see Rutten et al. 1989), we neglect M stars in the much of following.

The σ'_v values also increase with $R'_{\rm HK}$ (Fig. 1, *right panel*), scaling like $\sigma'_v \propto R'^{1.1}_{\rm HK}$ in G and K stars (the standard deviation of the fit $\sigma_{\rm fit} = 0.25$ dex for 35 stars) and like $\sigma'_v \propto R'^{1.7}_{\rm HK}$ in the F stars ($\sigma_{\rm fit} = 0.41$ dex, 13 stars). For fixed $R'_{\rm HK}$, stars with higher $v \sin i$ usually have larger σ'_v. These trends are consistent with a phenomenon at least partly related to magnetic activity (SD97). The relationship is not simple though—high activity ($R'_{\rm HK}$) is governed by rapid rotation (v), but a large σ'_v requires a large $v \sin i$. A pole-on ($v \sin i \sim 0$) active star, for example, would have $\sigma'_v \sim 0$ from starspots, since their light deficits would show no rotational Δv_r. We thus expect (and observe) a spread in σ'_v for a given $R'_{\rm HK}$, depending (in part) on $\sin i$. The larger scatter in F stars is consistent with the idea that mass-dependent properties ($v_{\rm conv}$) *independent* of activity are also important (although the *extent* of convective inhomogeneities is likely to be activity related). The weak trend of $\sigma'_v({\rm F}) > \sigma'_v({\rm G}) > \sigma'_v({\rm K})$ at fixed $R'_{\rm HK}$ is likely due to some combination of decreasing $v_{\rm conv}$ and increasing $P_{\rm rot}$ (and thus decreasing Δv_r) with cooler $T_{\rm eff}$ at a fixed inverse Rossby number (proportional to $R'_{\rm HK}$; e.g., Noyes et al. 1984).

Models and analysis of line bisector data suggest $\sigma'_v \propto (v \sin i)^n$, where $n \approx 1$ if spots dominate Δv_r (SD97) and $1 < n \lesssim 2$ if convective inhomogeneities dominate (Smith, Huang, & Livingston 1987; Gray 1988; SD97). The presence of nonuniform convection induces $n > 1$ because of the extra velocity contribution of granular flows near the limb, especially when the $v \sin i$ is greater than the local line Doppler width (Smith et al. 1987). Figure 2 (*left panel*) shows $\sigma'_v \propto (v \sin i)^{0.9}$ for G and K stars ($\sigma_{\rm fit} = 0.22$ dex, 30 stars) and $\sigma'_v \propto (v \sin i)^{1.3}$ for F stars ($\sigma_{\rm fit} = 0.34$ dex, 12 stars). This is consistent with the estimates of SD97 if σ'_v is dominated by spots in G and K stars, and by (predominantly) convective inhomogeneities in F stars, where both $v_{\rm conv}$ and $\langle v \sin i\rangle$ are larger.

As implied by the correlation with $v \sin i$ (Fig. 2, *left panel*), a plot of σ'_v versus $P_{\rm rot}$ shows a tight, nearly linear relation in G and K stars: $\sigma'_v \propto P_{\rm rot}^{-1.1}$ with $\sigma_{\rm fit} = 0.22$ dex for 36 stars (Fig. 2, *right panel*). (Stars with $P_{\rm rot}$ values estimated from $R'_{\rm HK}$—denoted by the smaller symbols—were given half-weight in the fit.) The σ'_v-$P_{\rm rot}$ relationship is steeper in F stars ($\sigma'_v \propto P_{\rm rot}^{-1.3}$ with $\sigma_{\rm fit} = 0.35$ dex for 13 stars), again probably due to a significant Δv_r from nonuniform convection, but it is less distinct, since most of the $P_{\rm rot}$ values are estimates. The few M dwarfs with $P_{\rm rot}$ data trace out a steeper relationship ($\sigma'_v \propto P_{\rm rot}^{-1.6}$), but this result (for only four stars) is quite uncertain. Since $v \sin i$ is more physically significant than $P_{\rm rot}$ for determining Δv_r, we would expect $\sigma_{\rm fit}$ for the $P_{\rm rot}$ fits to be larger by a factor of $\sim\langle \sin i\rangle^{-1}$ (e.g., $\sigma_{\rm fit} \sim 0.36$ for the G and K stars). The smaller $\sigma_{\rm fit}$ actually observed ($\sigma_{\rm fit} = 0.22$ dex) probably reflects the fact that fractional measurement errors for $v \sin i \lesssim 2$ km s^{-1} are much larger than in the corresponding $P_{\rm rot}$.

3. COMPARISON WITH A SIMPLE MODEL

We now construct a very simple model to demonstrate that σ'_v can be explained plausibly by starspots and nonuniform convection. The maximum semiamplitude of v_r variation due to completely black, equatorial spots, A_S (in units of m s^{-1}), can be estimated as $A_S \approx 6.5 f_S^{0.9}(v \sin i)$, where f_S (in percent) is the effective starspot filling factor (i.e., that portion responsible for the photometric variability; see SD97). Assuming that the rotational dependence of Δv_r is roughly sinusoidal, the associated v_r "noise" due to spots for an average line-of-sight angle $\langle\theta\rangle$ is $\sigma_S \approx A_S \cos\langle\theta\rangle/\sqrt{2}$.

In SD97, observations of variable line bisector velocity spans ($v_{\rm span}$) were used as a proxy for convective v_r variation. Unfortunately, $v_{\rm span}$ data are sparse, and the relationship between $\Delta v_{\rm span}$ and Δv_r is uncertain (SD97). Hence, in this Letter, we try to model the effect directly.

The velocity "noise" due to altered convection should scale with ($\langle v_{\rm conv}\rangle + v \sin i$), since the local fractional alteration of $v_{\rm conv}$ produces a local Δv_r, even if $v \sin i = 0$, and $v \sin i$ adds to this to produce the total perturbation. Convective σ_v should also scale with the area of the regions, although the scaling will clearly not be linear: $\sigma_v = 0$ for both 0% and 100% area coverage. Since granulation in the Sun is reduced in both plages and spots, the area of altered $v_{\rm conv}$ is likely dominated by the (much larger) plage area, rather than f_S. Thus, to the first order, we expect convective v_r perturbations to scale like $\Delta v_r \propto A(f_P)(v_{\rm conv} + v \sin i)$, where $A(f_P)$ is some nonlinear function of the plage area f_P.

The plage area should be related to the magnetic filling factor measured from the broadening of Zeeman-sensitive lines, f_M. We take $f_P \sim f_M \approx 8(\tau_C/P_{\rm rot})^{1.8} \lesssim 65\%$ (Saar 1996), where τ_C is the convective turnover time (Noyes et al. 1984). The functional form of $A(f_P)$ is then suggested by noting that identical regions at the same projected distance from the disk center, but placed at phases $\phi = \pm\Delta\phi$ from the central meridian, will cancel each other's Δv_r. Thus, even with optimal placement (all regions in one half-disk), σ_v will decrease for $f_P > 50\%$. Simple geometric arguments then suggest that $A(f_P) \propto \sin(\pi f_P/100)$, since the tangential component of $v_{\rm conv}$ toward the limb should produce the largest Δv_r effect (Smith et al. 1987). For a (more realistic) random plage placement, the effect of the cancellation will make steps in f_P like a random walk, so that in effect $A(f_P) \rightarrow A(\sqrt{f_P})$, peaking at smaller f_P. As a very crude approximation then, we assume that $A(f_P) \propto \sin(\pi\sqrt{f_P}/100)$. We take the macroturbulent velocity, $v_{\rm mac}$, as a proxy for $v_{\rm conv}$, based on the observed relationship between $v_{\rm mac}$ and $v_{\rm span}$ (Gray 1982b, 1988). Combining spot and convective components (assuming no correlation between them), the total predicted v_r dispersion may be estimated as

$$\sigma'_v \approx \sqrt{[4.6 f_S^{0.9}(v \sin i)\cos\langle\theta\rangle]^2 + [\alpha A(f_P)(v_{\rm mac} + v \sin i)]^2}$$

(in units of m s^{-1}), where α is an adjustable constant. We take $f_S \sim 0.4\Delta(b+y)$ (see SD97) and $\langle\theta\rangle = 45^\circ$.

We can now estimate σ'_v for a star, given its $P_{\rm rot}$, $v \sin i$, $v_{\rm mac}$, and photometric variability. A total of 13 G and K stars in our sample have $\Delta(b+y)$ data (Lockwood, Skiff, & Radick

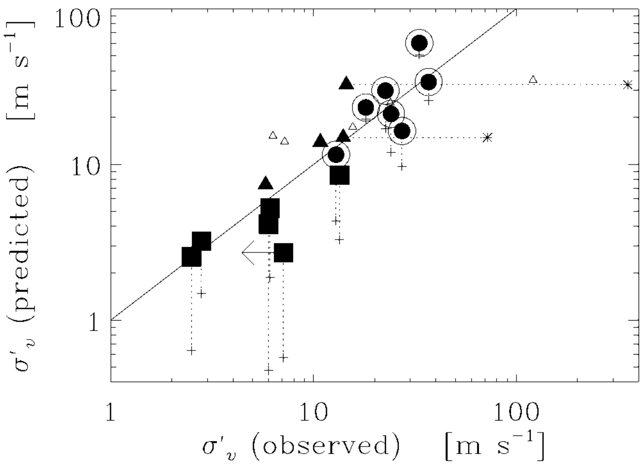

FIG. 3.—The σ_v'(observed) vs. σ_v'(predicted) for F (*open triangles*), G (*circled dots*), and K (*filled squares*) stars ($\alpha = 9$); the smaller symbols indicate estimated $P_{\rm rot}$. Two F stars with planets are shown before (*asterisks*) and after planet orbit removal and connected. G and K stars are also plotted a second time, indicating σ_v'(predicted) with and without (*plus signs*) the model's approximate convective inhomogeneity term. We assume $f_S \equiv 0$ for the F stars. The scatter about the line of equality (*solid line*) is $\sigma = 0.14$ dex (or ≈40%) for the G and K stars and $\sigma = 0.16$ dex for all stars with measured $P_{\rm rot}$.

1997). To these, we added 10 F stars with published $v_{\rm mac}$ data and assumed $f_S = 0$ for them, since the photometric variability, even in active F stars, is typically very small (Lockwood et al. 1997). We took $v_{\rm mac}$ values from Saar & Osten (1997), Gray (1982a, 1984, 1986), or Valenti (1994; modified by $\sqrt{2}$; see Saar & Osten 1997). Figure 3 compares the predicted and observed σ_v' values for $\alpha = 9$ (the best-fit value). The agreement is remarkably good considering the simplicity of the model: the scatter about σ_v'(observed) = σ_v'(predicted) is $\sigma = 0.14$ dex (or ∼40%) for the G and K stars. Despite the lack of a starspot term, even the F stars agree reasonably well ($\sigma \approx 0.16$ dex for all stars with measured $P_{\rm rot}$). The results suggest that the convective term dominates σ_v' in most F stars and in inactive G and K stars, while spots are important in active G and K stars.

4. DISCUSSION AND CONCLUSIONS

Figures 1 and 2 further emphasize that v_r "noise" due to magnetic activity in young stars may make planet detection difficult (SD97). Measures of rotation ($v \sin i$ or $P_{\rm rot}$) are somewhat better at predicting σ_v' than activity (e.g., $R'_{\rm HK}$), probably because rotation is more closely connected with the physical mechanism producing σ_v'. For G stars in our sample with $8\ {\rm km\ s^{-1}} \leq v \sin i \leq 10\ {\rm km\ s^{-1}}$ (similar to UMa stream stars with ages ∼0.3 Gyr), $20\ {\rm m\ s^{-1}} \lesssim \sigma_v' \lesssim 45\ {\rm m\ s^{-1}}$; $7\ {\rm m\ s^{-1}} \lesssim \sigma_v' \lesssim 30\ {\rm m\ s^{-1}}$ in F stars with the same $v \sin i$ range. Conversely, old, slowly rotating stars ($v \sin i \leq 2\ {\rm km\ s^{-1}}$, $P_{\rm rot} \geq 15$ days) have the lowest activity-related v_r noise ($\langle\sigma_v'\rangle = 4.6 \pm 1.8\ {\rm m\ s^{-1}}$) and are therefore the best targets for detection of Jupiter-like planets by v_r methods.

The trends with $T_{\rm eff}$, rotation, and activity that we find are generally consistent with those found by SD97 in their study of the Walker et al. (1995) data. The actual σ_v' values are somewhat smaller though, since SD97 did not remove σ_i in their study. The correlations found here are also considerably clearer, due to the Lick data's smaller $\langle\sigma_i\rangle$ (≈5.3 m s^{-1} in the G and K stars here vs. $\langle\sigma_i\rangle \approx 12$ m s^{-1} in the Walker et al. sample) and larger sample size (72, vs. 17 in SD97).

It is also clear that prior to correction for the planetary orbital v_r, all of the stars with proposed planets show σ_v' values $\gtrsim 2\ \sigma$ larger than the mean relationships for their spectral types in at least two of the correlations presented here (Figs. 1 and 2, *asterisks*). Furthermore, after the planetary orbital v_r is removed, the corrected σ_v' is almost always consistent with the observed σ_v' relationships for stars without identified companions (the exception, HR 3522, has an additional long-term v_r trend of uncertain origin; Butler et al. 1997). Thus, *searching for stars with σ_v' values that are enhanced relative to typical trends with $P_{\rm rot}$, $v \sin i$, and $R'_{\rm HK}$ can be a useful tool for identifying stars with large Δv_r caused by planets*. Since one can estimate σ_v' in far fewer observations than are needed to determine a companion orbit, searches for stars with enhanced σ_v' should be an effective way of rapidly focusing on the best candidates for having giant planets in relatively close orbits.

Our results also make it difficult for nonradial pulsations (NRPs; Hatzes 1996; Gray 1997) to be a *general* explanation for the v_r signatures uncovered to date. Out of 14 G stars with $P_{\rm rot} \geq 20$ days, the 10 without proposed planets show $\sigma_v' < 8$ m s^{-1} (Fig. 2, *right panel*). Since all 14 G stars are physically similar (old and of similar $T_{\rm eff}$), it seems unlikely that only four are undergoing some exotic, large-amplitude NRP mode, especially since these four with unusually high σ_v' are not otherwise peculiar, either in metallicity or in gravity (Marcy & Butler 1998). We also note that new observations of 51 Peg (Brown et al. 1998; Gray 1998; Hatzes, Cochran, & Bakker 1998) have not shown the levels of $\Delta v_{\rm span}$ (suggesting NRPs) reported previously.

Our simple model of the v_r variation due to surface magnetic and convective activity successfully predicts (to within about 30% or 7 m s^{-1}) the σ_v' seen in F, G, and K stars. The model results tend to confirm earlier suggestions (SD97) that convective inhomogeneities are more important in F stars while spots contribute significantly in G and K stars. The nonlinear rotational dependence of σ_v' in the sparse M dwarf data (Fig. 2, *right panel*), suggesting a nonspot contribution, may point to another source of Δv_r in these stars (v_r shifts due to flares?).

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