SEARCHING FOR PLANETS IN THE HYADES. V. LIMITS ON PLANET DETECTION IN THE PRESENCE OF STELLAR ACTIVITY

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ABSTRACT

We present the results of a radial velocity survey of a sample of Hyades stars and discuss the effects of stellar activity on radial velocity measurements. The level of radial velocity scatter due to rotational modulation of stellar surface features for the Hyades is in agreement with the 1997 predictions of Saar & Donahue—the maximum radial velocity rms of up to ~50 m s\(^{-1}\), with an average rms of ~16 m s\(^{-1}\). In this sample of 94 stars we find one new binary, two stars with linear trends indicative of binary companions, and no close-in giant planets. We discuss the limits on extrasolar planet detection in the Hyades and the constraints imposed on radial velocity surveys of young stars.

Key words: open clusters and associations --- (Hyades) --- planetary systems --- stars: activity --- techniques: radial velocities

On-line material: machine-readable table

1. INTRODUCTION

Radial velocity (\(v_r\)) surveys for extrasolar planets have been extremely successful (e.g., Butler et al. 1996). These surveys have, however, largely excluded young, active stars (Vogt et al. 2002; Cumming et al. 1999; Saar & Donahue 1997). The reason given was that the activity levels of young stars is significant enough to cause large variations in the measured \(v_r\). Although it does not introduce a true \(v_r\) shift (e.g., Saar & Donahue 1997, hereafter SD97; Hatzes 2002), the apparent shift is caused by a change in the line shape of the absorption features. SD97 quantify the predicted amplitude of this phenomenon, and it has been observationally confirmed by several groups (e.g., Queloz et al. 2001; Henry et al. 2002; Paulson et al. 2004; Saar & Fischer 2000; Saar et al. 1998). While detection of extrasolar planets around young stars will be complicated by these spectral line profile variations, there is much to learn about the frequency of planets and their orbital characteristics at all stellar ages. Thus, it is necessary to learn the limitations of the techniques employed in planet detection and then proceed (if possible) with planet searches.

We present here the results of the radial velocity search for extrasolar planets in a sample of Hyades dwarfs. Primarily, we discuss the mean level of radial velocity noise caused by stellar magnetic activity and the possibilities of detecting planets in Hyades-aged stars.

2. OBSERVATIONS AND ANALYSIS

We have been studying a sample of Hyades dwarfs ranging from spectral classes F5 to M2 with the Keck I High-Resolution Echelle Spectrometer (Vogt et al. 1994). The observations and analysis of the \(v_r\) data are discussed in Cochran et al. (2002). While we made every attempt to include only stars that were not binaries, we discovered some stars that have too high \(v_r\) rms to be nonbinaries. These stars are discussed in § 3.

The measurement of \(v_r\) involves using an I\(_2\) gas absorption cell as a standard velocity reference (Valenti et al. 1995). A signal-to-noise ratio (S/N) of ~150–300 is achieved at 5000 Å with resolution \(R \approx 60,000\). In the case of high S/N (\(>200\)), we achieve an internal precision ~3–4 m s\(^{-1}\) for a given star (Cochran et al. 2002); while a spectrum with S/N ~100 yields precision of ~6 m s\(^{-1}\). In addition, the exposure times are maintained at \(\leq15\) minutes. We use standard IRAF packages to reduce the CCD images and extract the observed spectra. The \(v_r\) measurements are made using a program called RADIAL (developed at the University of Texas [UT] and McDonald Observatory) to measure precise radial velocities. This program was adapted for use with data from all of the planet search programs affiliated with UT. Discussions of RADIAL may be found in Cochran et al. (1997) and Hatzes et al. (2000). The \(v_r\) measurements of all data in this sample obtained with the Keck telescope are listed.
in Table 1. Measurements of vB 15, vB 18, and vB 153 taken with the HRS at the Hobby-Eberly Telescope (HET) are discussed and listed in Paulson et al. (2004, hereafter PSC04).

3. RESULTS

While the target sample was selected in part on nonbinaarity, a handful of binaries did end up in our sample. The stars listed in Table 2 show either significant linear trends (most likely binaries) or a defined binary orbit (vB 88). The measured $v_r$ of binary stars and stars with significant linear trends are shown in Figure 1. Three binaries discovered by Patience et al. (1998) were not removed from the sample in the initial compilation of targets. These are noted in the column (3) of Table 2. Stars that only have a small slope (i.e., those with $\sigma_{v_r} \approx 40$ m s$^{-1}$) have not been included in this table. The object vB 88 appears to have almost completed one orbit. A tentative solution (shown in Fig. 1) gives an $m$ sin $i = 0.07$ $M_\odot$. Using the measured $v$ sin $i$ for vB 88 and an estimate of the true rotational velocity as derived by Paulson et al. (2003), we estimate the mass of the companion to be $\sim 0.86 \pm 0.31$ $M_\odot$, most likely a K dwarf, to the F8 V parent star. While 0.31 $M_\odot$ is the formal error, we note that if the mass were much larger than 0.86 $M_\odot$, we would see a double-lined spectrum, and we see no indication of this in the vB 88 spectra. Thus, 0.86 $M_\odot$ is likely an upper limit to the true mass. The orbital parameters for this binary companion are listed in Table 3.

With three exceptions discussed later in this section (those showing significant long-period trends) and one star with poor sampling but with velocity rms of 72 m s$^{-1}$, the remaining stars show no significant linear trends [with rms ($\sigma_{v_r}$) $\leq 40$ m s$^{-1}$]. Table 4 lists the program stars, the rms of the observations with internal errors removed ($\sigma_{v_r, m}$), and the average internal error of the observations for each star ($\sigma_{v_r, a}$). This is a summary of the observations presented in Table 1. Figure 2 shows a histogram of the $\sigma_{v_r}$ for the program stars excluding binaries and stars with linear trends. The internal $v_r$ errors have been removed. We note that the majority of stars have $\sim 5 \leq \sigma_{v_r} \leq 25$ m s$^{-1}$, which is what we expect from stars of this activity level and age (SD97; PSC04). In PSC04 we showed that some stars in the sample display $v_r$ variations of $\sim 40$ m s$^{-1}$ due to stellar active regions. Therefore, the stars with $\sigma_{v_r} \sim 50$ m s$^{-1}$ could also suffer from severe effects of activity. It is of interest that we do not find any stars in this sample with very large $\sigma_{v_r}$ ($\geq 100$ m s$^{-1}$) with suggestive short periods, thus no “hot Jupiters” with mass $\geq 1 M_\oplus$. To explore the spread in $\sigma_{v_r}$ in the sample, we compared the $\sigma_{v_r}$ of each star with the measured rotational velocity ($v$ sin $i$) from Paulson et al. (2003). Although a little less than half of the program stars have measured $v$ sin $i$, we are still able to see an obvious trend in the data (see Fig. 3: $\sigma_{v_r}$ vs. $v$ sin $i$, with binaries and stars with linear trends excluded and internal $v_r$ errors removed). While there is significant scatter in the figure, a trend is still present. The location of active regions, the fraction of the surface covered by activity, the rotational velocity, and the inclination of the stars all play significant roles in the measured $v_r$. The higher the $v$ sin $i$, the more broadened the spectral absorption features will be. The internal error becomes larger with increased $v$ sin $i$ (see Fig. 4), as determination of the line center becomes increasingly difficult. As the inclination of the star decreases (becomes pole-on), lower $\sigma_{v_r}$ is expected. This is because the most significant effects of active regions in this age of star (e.g., SD97) are short-period variations due to the rotational modulation of the features across the stellar surface. Take a simple case that assumes active regions are equatorial. When the star is pole-on (0$^\circ$), variations of this nature will diminish and similarly; when the star is face-on (90$^\circ$), the effect will be at a maximum. Certainly, the larger fraction of the stellar surface covered by active regions will cause larger amplitude variations, and the physical location of the features will cause variable effects on the line shape (and thus the measured $v_r$). It is not surprising, then, that there are a few stars with very large $\sigma_{v_r}$, as statistically a few stars should have very low inclinations. This effect of increased $\sigma_{v_r}$ with increased $v$ sin $i$ is also predicted by A. Hatzes (2003, private communication) and discussed in SD97. Additionally, scatter in $\sigma_{v_r}$ (in Fig. 3) at a given $v$ sin $i$ is caused by star-to-star variations in the overall activity level. Although the stars do not show cyclic behavior in chromospheric activity, the overall level of activity varies. As also shown in PSC04, some Hyades stars (vB 153, in particular) may show long-lived active regions or active longitudinal. Therefore, should we detect significant periods compatible with an expected or observed rotation rate, we could explore the nature of stars which display this type of activity. Therefore, for the remaining stars, we employed the same period-finding algorithm as used in PSC04 (that of Horne & Baliunas 1986). From this technique we are able to determine the most significant periods in a data set and the false-alarm probabilities (FAP) associated with each period. We also perform a bootstrap algorithm (e.g., Kürster et al. 1997) to determine a false-alarm probability based solely on the data. The bootstrap method does not assume a Gaussian noise distribution, as do the more traditional FAPs (such as Horne & Baliunas 1986). This method randomizes the data—keeping the observed times (in JD) the same but randomly assigning the $v_r$ observed to those JDs. The resultant “fake” data are run through the periodogram to determine the most significant period of this data. This randomization process is iterated 1000 times, and a FAP is the ratio of the number of

### Table 1: Radial Velocity Observations

| Star | JD − 2,400,000 | $v_r$ | $\sigma_{v_r}$ |
|------|----------------|------|---------------|
| BD+04810 | 50,792.118 | −15.06 | 5.55 |
| 51,076.998 | −45.51 | 2.82 |
| 51,441.129 | 5.76 | 4.27 |
| 51,549.832 | 10.87 | 4.48 |
| 51,880.897 | −5.16 | 4.05 |

**Note:** Table 1 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

### Table 2: Linear Trends and Binaries

| Star | Slope ($v_r$ sin$i$/JD) | Patience et al. |
|------|-------------------------|----------------|
| vA 486 | 1.7500 | No |
| vB 5 | −0.1364 | Yes |
| vB 17 | −0.0099 | Yes |
| vB 52 | −0.0333 | Yes |
| vB 88 | See Table 3 | No |
| vB 184 | 0.3818 | No |
times the power of the detected period in the fake data was equal to or larger than the power of the signal in the original data. If the data are pure noise, then the FAP should be very high ($C24$). The results of this analysis are listed in Table 5 for stars that had FAPs of less than 10% in each of the two methods (Horne & Baliunas and bootstrap). We explore the actual significance of these periods in §4.

It is not surprising that the periods we derive here are not consistent with the published values of rotation periods ($P_{rot}$), because active regions evolve. Table 6 lists the periods we derive versus those from literature (references included in the table notes) and predicted values from Duncan et al. (1984), where possible. In addition, the periods derived from the Keck data for the stars which we have derived $P_{rot}$ (from Paulson et al. 2004 for vB 15, vB 18, and vB 153) are inconsistent with each other (also see Table 6). Thus, significant phase variations have occurred in the span of observations of the data taken from Keck. Because we do not have sufficient temporal coverage, we are unable to perform detailed studies of the evolution of these active regions—the decay time or migration of the active regions.

4. LIMITS ON SUBSTELLAR COMPANIONS

Using the methods outlined in Nelson & Angel (1998, hereafter NA98) we compute analytical limits on the detectability of substellar mass companions based on the duration and accuracy of the data for each star. We then compare this with a periodogram-based analytical derivation to find significant peaks representing the significant signals in the data. At frequencies where peaks cross the analytical limits, the detection of periodic signals (either companions or periodic activity) is present at the 99% confidence level.

From equation (4) of NA98, the companion mass is $M_C \sin i = K \left[ PM^2/(2\pi G) \right]^{1/3}$, where $i$ is the inclination of the companion, $P$ is the period sampled, $K$ is the velocity amplitude, $M_*$ is the mass of the parent star, and $G$ is the gravitational constant. We derive $K$ and $P$ from the above periodogram analysis and $M_*$ is estimated from $B-V$ measurements (Allende Prieto & Lambert 1999) and Gray (1992). We will refer to the resultant $M_C \sin i$ as the “companion mass power spectrum” (solid curve, Fig. 5).

### TABLE 3

**Orbital Parameters for vB 88**

| Parameter       | Value        |
|-----------------|--------------|
| $m \sin i$ ($M_*$) | 0.069        |
| Period (days)   | 2809.2 ± 80.7 |
| $V_0$ (m s$^{-1}$) | -485.3 ± 5.8 |
| $T_0$ (JD)      | 2452100.01 ± 18.9 |
| $e$             | 0.5166 ± 0.0123 |
| $\omega$ (deg)  | 136.45 ± 3.12 |
| $K_1$ (m s$^{-1}$) | 1152.2 ± 15.0 |

**Fig. 1.**—Known binaries and stars with linear trends (suspected binaries). The orbital fit to the $v_\tau$ data for vB 88 is shown along with its $v_\tau$ data. Internal error bars are shown.
To define the limits on companion masses detected (or significant periodicity from intrinsic sources), we must calculate the limit on the detectable velocity. $\tilde{K}$ (eq. [15] in NA98) is the velocity amplitude exceeded by any of the $N$ fits to randomized data in a given period range with probability $1\%$; where $X$ is the product of probabilities of each fit at each period sampled ($X = P^n$), and $n$ is the number of sampled periods. Thus, $\tilde{K} = 2\sigma \sqrt{(n-1) \ln \left[ 2\pi P_0 f_1 f_2 (1-X)^{-1} \right]}^{1/2}$, where $P_0$ is the duration of the original data ($JD_{\text{fin}} - JD_{\text{beg}}$), and $f_1$ and $f_2$ are the lower and upper limits, respectively, of the period intervals (in our case, four bins per dex). $X$ is determined from the bootstrap FAP described in § 3. Using $\tilde{K}$ now in place of $K$ in equation (4) (NA98), we obtain the 99% confidence level of the mass limits of companions. Shown in Figure 5 are representative cases of these calculations. We show both the Keck and HET data with two different error assumptions, described below, for three stars. The Keck data for all stars show the same behavior as the three stars shown in Figure 5. Thus, we only show here these three because we also have data from the HET for each. The histogram plot limits have been suppressed at 1 and 11 yr for HET and Keck data, respectively.

The dashed histogram lines in Figure 5 assume that the only error in the observations are internal effects ($\sim 4-7$ m s$^{-1}$). In

### Table 4

| Star         | $\sigma_{v_{\text{int}}}$ (m s$^{-1}$) | $\sigma_{v_{\text{int}}}$ (m s$^{-1}$) |
|--------------|--------------------------------------|--------------------------------------|
| BD +04°810...| 10.12                                | 3.92                                 |
| BD +07°499...| 15.15                                | 4.52                                 |
| BD +08°642...| 12.94                                | 4.73                                 |
| BD +17°455...| 11.07                                | 4.01                                 |
| BD +17°719c...| 737.05                              | 4.32                                 |
| BD +19°650...| 17.56                                | 3.47                                 |
| HD 18632     | 10.46                                | 3.42                                 |
| HD 19902     | 5.76                                 | 3.31                                 |
| HD 23453     | 6.82                                 | 4.42                                 |
| HD 26257     | 7.72                                 | 5.71                                 |
| HD 35768     | 6.16                                 | 4.97                                 |
| HD 240648    | 11.85                                | 4.38                                 |
| HD 242780    | 8.26                                 | 4.13                                 |
| HD 283869    | 5.56                                 | 3.65                                 |
| HD 284552    | 25.63                                | 4.60                                 |
| HD 284653    | 14.27                                | 3.62                                 |
| HD 284930    | 14.86                                | 4.36                                 |
| HD 285367    | 27.47                                | 3.80                                 |
| HD 285482    | 13.13                                | 3.73                                 |
| HD 285590    | 6.03                                 | 3.98                                 |
| HD 285625    | 72.92                                | 4.91                                 |
| HD 285837    | 16.11                                | 5.92                                 |
| HD 285849    | 20.22                                | 6.54                                 |
| HD 286363    | 15.98                                | 4.38                                 |
| HD 286554    | 13.82                                | 5.18                                 |
| HD 286734    | 6.87                                 | 3.37                                 |
| HD 286789    | 7.45                                 | 3.83                                 |
| HD 286929    | 6.14                                 | 3.99                                 |
| HIP 15720    | 5.04                                 | 4.66                                 |
| HIP 16548    | 17.31                                | 7.11                                 |
| HIP 17766    | 9.66                                 | 3.71                                 |
| HIP 19082    | 22.57                                | 4.98                                 |
| HIP 22177    | 9.66                                 | 5.71                                 |
| J303         | 3.10                                 | 4.79                                 |
| J332         | 12.08                                | 4.75                                 |
| J348         | 7.40                                 | 4.54                                 |
| VA 115       | 22.81                                | 7.39                                 |
| VA 146       | 10.45                                | 5.40                                 |
| VA 383       | 3.31                                 | 4.64                                 |
| VA 486       | 231.93                               | 39.20                                |
| VA 502       | 10.73                                | 7.19                                 |
| VA 529       | 5.91                                 | 9.47                                 |
| VA 637       | 22.14                                | 6.96                                 |
| VA 638       | 8.98                                 | 5.84                                 |
| VA 731       | 2.63                                 | 4.99                                 |
| VB 1         | 29.87                                | 4.55                                 |
| VB 2         | 19.03                                | 4.69                                 |
| VB 4         | 13.47                                | 3.45                                 |
| VB 5*a       | 25.26                                | 3.85                                 |
| VB 7         | 16.02                                | 3.60                                 |
| VB 10        | 23.62                                | 4.83                                 |
| VB 12        | 20.84                                | 4.02                                 |
| VB 15        | 40.39                                | 5.12                                 |
| VB 17*a      | 21.44                                | 4.99                                 |
| VB 18        | 31.36                                | 4.78                                 |
| VB 19        | 17.11                                | 11.49                                |
| VB 21        | 6.79                                 | 3.62                                 |
| VB 25        | 8.49                                 | 4.36                                 |
| VB 26        | 10.33                                | 4.15                                 |
| VB 27        | 15.99                                | 3.89                                 |
| VB 31        | 27.46                                | 6.54                                 |
| VB 42        | 12.45                                | 4.34                                 |
| VB 46        | 4.88                                 | 5.28                                 |
| VB 48        | 21.76                                | 8.92                                 |
| VB 49        | 14.15                                | 5.20                                 |
| VB 52*a      | 15.99                                | 5.81                                 |
| VB 65        | 19.91                                | 7.01                                 |
| VB 66        | 32.23                                | 6.54                                 |
| VB 73        | 21.05                                | 6.51                                 |
| VB 76        | 10.14                                | 4.69                                 |
| VB 79        | 14.87                                | 4.73                                 |
| VB 87        | 15.10                                | 5.18                                 |
| VB 88*a      | 18.44                                | 9.67                                 |
| VB 92        | 9.66                                 | 4.39                                 |
| VB 93        | 53.15                                | 6.09                                 |
| VB 97        | 21.05                                | 6.09                                 |
| VB 99        | 11.46                                | 4.17                                 |
| VB 105       | 15.28                                | 4.96                                 |
| VB 109       | 17.09                                | 3.79                                 |
| VB 118       | 16.67                                | 5.42                                 |
| VB 127       | 12.18                                | 3.98                                 |
| VB 143       | 13.92                                | 7.76                                 |
| VB 153       | 22.96                                | 4.01                                 |
| VB 170       | 17.24                                | 4.09                                 |
| VB 173       | 23.99                                | 3.85                                 |
| VB 174       | 12.02                                | 3.75                                 |
| VB 178       | 12.37                                | 4.14                                 |
| VB 179       | 12.31                                | 4.41                                 |
| VB 180       | 11.36                                | 3.96                                 |
| VB 183       | 8.81                                 | 5.65                                 |
| VB 184*a     | 40.52                                | 6.16                                 |
| VB 187       | 17.09                                | 3.93                                 |
| VB 191       | 2.91                                 | 3.93                                 |

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* The values of $\sigma_{v_{\text{int}}}$ and $\sigma_{v_{\text{int}}}$ listed are residuals of the stellar data with linear trends (slopes given in Table 2) removed.

* The values of $\sigma_{v_{\text{int}}}$ and $\sigma_{v_{\text{int}}}$ listed are for residuals of the data with the orbital parameters listed in Table 3 removed.
the HET data (*left column*), we discover significant peaks crossing the 99% threshold. This tells us that there are significant periods at these crossings. However, these significant periods do not correspond to companions but to the rotational period of the star and aliases thereof. For the Keck data (*right column*), there are several crossings. This is expected, as the sampling is extremely poor. There are \(~15\text{–}20\) observations of these stars over the course of 6 yr, and many “significant” periods can be derived with this quality of sampling.

NA98 suggest that all sources of error be included. Thus, a far superior assumption, and that recommended by NA98, is that the error in the observations is not only due to internal errors but also to the rotational modulation of active regions. For this, we assume an error equal to the mean \(v_r\) rms for the sample (~16 \(\text{m s}^{-1}\), ignoring stars with linear trends and binary stars). Thus, any period spikes that cross the 99% threshold should come from external sources (stellar and substellar companions). The calculation using this assumption is depicted by the solid histogram lines in Figure 5. We note that for all nonbinary stars, there are absolutely no companion mass power spectrum crossings of the 99% threshold for stars in these Keck data. The binary stars have insufficient phase coverage. The threshold crossings are therefore beyond the reasonable limits of the calculations described above.

Thus, we can use this method for determining the value of “significant” periods derived from a periodogram analysis quite apart from a calculated FAP.

In general, we can provide constraints on the characteristics of systems that are detectable around young stars via the radial velocity technique, also employing the methods in NA98. Figure 6 presents an analysis for stars of Hyades age with

**TABLE 5**

| Star | \(P\) (days) | FAP\(_{\text{H&B}}\) | FAP\(_{\text{bootstrap}}\) |
|------|-------------|----------------|-------------------|
| vB 7 | 9.61        | 0.088          | 0.045             |
| vB 12| 4.04        | 0.097          | 0.001             |
| vB 18| 17.36       | 0.040          | 0.089             |
| vB 19| 6.02        | 0.056          | 0.006             |
| vB 49| 4.91        | 0.089          | 0.017             |
| vB 87| 7.60        | 0.069          | 0.088             |
| vB 118| 6.15      | 0.068          | 0.037             |
| vB 153| 4.62       | 0.010          | 0.011             |
| vB 170| 26.24      | 0.053          | 0.014             |
different sampling. Both panels show the $K$ velocity semi-amplitude versus orbital period. The histograms are the limits for a 99% confidence detection. The solid histogram ($a$) represents sampling similar to that which we observed from Keck, while the dotted histogram ($b$) is similar to the sampling we obtained from HET. The dotted histogram has been suppressed beyond 1 yr. The two curves shown are for reference—the solid curve ($c$) is a $1M_J$ companion and the dotted curve ($d$) is a $3M_J$ companion. These curves are the $K$ velocities of companions given that they are in orbits with zero eccentricity and are

**TABLE 6**

| Star | $P_{\text{ours, Keck}}$ (days) | $P_{\text{HET}}$ (days) | $P_{\text{lit}}$ (days) | Reference | $P_{\text{pred}}$ (days) | Notes |
|------|-------------------------------|------------------------|----------------------|-----------|------------------------|-------|
| vB 21 | 5.49                          | ...                    | 9                    | 1         | ...                    | ...   |
| vB 25 | 4.91                          | ...                    | 12.6                 | 1         | ...                    | ...   |
| vB 26 | 4.6                           | ...                    | 9.3, 9.4, 9.1        | 2, 1, 1   | 11.22                 | Alias?|
| vB 31 | 4.72                          | ...                    | 5.4                  | 1         | 4.6                    | ...   |
| vB 52 | 5.64                          | ...                    | 7.9, 8.0             | 2, 3      | 5.04                   | ...   |
| vB 65 | 4.65                          | ...                    | 5.9                  | 1         | 5.51                   | ...   |
| vB 73 | 12.92                         | ...                    | 7.4                  | 2, 3      | 5.24                   | ...   |
| vB 79 | 6.13                          | ...                    | 11.4, 9.7            | 2, 3      | 12.56                  | Alias?|
| vB 92 | 22.53                         | ...                    | 9                    | 1         | 9.9                    | ...   |
| vB 97 | 6.45                          | ...                    | 8.5                  | 2, 3      | 7.46                   | ...   |
| vB 173 | 20.82                        | ...                    | 14.1                 | 1         | ...                    | ...   |
| vB 174 | 10.12                        | ...                    | 11.9                 | 1         | ...                    | ...   |
| vB 18 | 7.43                          | 8.18                   | ...                  | ...       | 6.22                   | Alias?|
| vB 153 | 17.36                        | 8.65                   | ...                  | ...       | ...                    | Alias?|
| vB 15 | 4.63                          | 9.42                   | ...                  | ...       | ...                    | ...   |

References.—(1) Radick et al. 1987; (2) Lockwood et al. 1984; (3) Radick et al. 1995.

Fig. 5.—Limits of our data on the detection of companions. The solid curve represents a power spectrum of the data translated to $M \sin i$ units. The dashed histogram plot, as discussed in the text, is a 99% confidence level for the detection of significant peaks in the data (where a data peak crossing this line would have a 99% confidence of being a true companion). This assumes that the only error for each data point is the internal error of the observations (ranging from about 5–7 m s$^{-1}$). The solid histogram plot represents a 99% confidence level considering an average error as determined from the rms of $v_r$, caused by stellar activity.
companions to a 1 $M_\odot$ star with 90° inclination. The velocity-period space lying above the histograms are detectable with 99% confidence. So, for example, the top panel representing data with errors (radial velocity jitter from activity + internal errors) of $\sigma = 16$ m s$^{-1}$ shows that a 1$M_\odot$ companion is only detectable if it has periods less than $\sim 100$ days with only a few observations a year for 5 yr and is detectable if with longer orbital periods only if the sampling is quite good (several observations a month). On the other hand, the bottom panel shows a more realistic case, as the true noise from activity will be higher than 16 m s$^{-1}$ if the system is edge-on (corresponding to the $K$ curves $c$ and $d$, which are for edge on orbits). For data with errors of $\sigma = 40$ m s$^{-1}$, the detectability of planets with $\leq 1M_\odot$ becomes impossible for poor sampling. For young stars with such high levels of activity related radial velocity noise, it is only feasible either to look for very high mass companions or for the data to be taken with extremely good sampling (several observations a month for $\leq 3$ months).

5. DISCUSSION

We can determine significant period in data by various techniques, including those discussed in this paper. But it is most useful to understand when significant periods are real or simply artifacts of sampling. The analysis of the periodogram produces periods with FAPs $\sim 10\%$ for several stars. Phasing the data to these periods produces periodic curves (by-eye inspection). This is inadequate. Therefore, we have employed the method of Nelson & Angel (1998) to explore the significance of detections. All short periods detected turn out to be artifacts of the sampling and of the quality of the data.

The detection of planets around young stars is complicated by the rotational modulation of stellar active regions. The activity not only causes high levels of $v_r$ noise but can also yield periodic variations in the measured $v_r$, causing false detections. The procedure we adopted (Nelson & Angel 1998) picks out all significant signals given the quantity and quality of data, so we must be careful in the identification of the source of variability. In our data we find no evidence for short-period massive planets or brown dwarfs. Finally, of the 94 stars in this sample, six are either suspected or identified binaries and one has a velocity rms that is somewhat large, but further observations are required to say anything more concrete—it is still within possible “jitter” from high activity levels.

Future detection of extrasolar planets around young stars via the radial velocity method will be limited to high-mass planets and, in particular, to those with short orbital periods. Constraints on telescope time needed for these surveys becomes clear. To increase the odds of planet detection, as current planet searches have determined that only $\sim 1\%$ of stars do have “hot Jupiters,” data must be sampled several times a month, which requires a great deal of allocated telescope time.

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