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PROPERTIES OF SUN-LIKE STARS WITH PLANETS: 51 PEGASI, 47 URSAE MAJORIS, 70 VIRGINIS, AND HD 114762[1]

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ABSTRACT

Radial velocity variations have revealed planets orbiting 51 Peg, 47 UMa, and 70 Vir, and a low-mass companion orbiting HD 114762. We analyze parallel records of photometric measurements in Strömgren b and y and Johnson V, R, and I passbands and Ca II H and K fluxes in those stars. In the case of 51 Peg, the high precision of the differential photometric measurements made by the 0.75 m Automatic Photoelectric Telescope and the nonvariability of the star would allow the detection of a transit of a planet as small as Earth (corresponding to an amplitude of 0.0001 mag) if its orbit were nearly coplanar with our line of sight. No transits were observed.

For 51 Peg and 70 Vir, the upper limit of nondetection of photometric variability at their companion's orbital periods is $\Delta(b+y)/2 < 0.0002 \pm 0.0002$ mag. For HD 114762, it is $\Delta V < 0.0007 \pm 0.0004$ mag. Such small amplitudes of photometric variability seem to eliminate periodic velocity variations expected from p-mode oscillations.

All four stars are magnetically quiet; that is, they lack the typical Ca II and photometric variability due to rotation and activity cycles expected from surface magnetic activity in solar-type stars. Such quiescence produces an interesting observational bias that favors the detection of planets from low-amplitude radial velocity or photometric variations by minimizing the contribution from intrinsic stellar variability. We discuss the circumstances for which the probability of planet detections is improved by the reduced level of variability from surface magnetic activity in G and K stars. Stars with low variability in surface activity should be the best candidates for planet searches using radial velocity and photometric techniques. Searches for planets around younger, more active stars will be impeded by variations in velocity or brightness caused by time-varying surface features.

The Ca II H and K fluxes indicate that all four stars are older than 5 Gyr. Ages were estimated from the average levels of Ca II H and K fluxes and an existing relationship of the decrease of Ca II fluxes with age on the lower main sequence and were drawn from previous results based on theoretical isochrone fitting. Values of the projected rotational velocity, $v \sin i$, are determined for 70 Vir and 47 UMa from high-resolution spectra.

Subject headings: planetary systems — stars: activity — stars: fundamental parameters

1. INTRODUCTION

The observational description of extrasolar planetary systems has commenced at last with the discovery of planetary mass bodies around the solar-like stars 51 Pegasi, 47 Ursae Majoris, and 70 Virginis along with the earlier discovery of a somewhat more massive object around HD 114762. From precise radial velocity measurements at the Haute-Provence Observatory, Mayor & Queloz (1995) inferred the existence of a planet with a mass of at least 0.5 Jovian masses (M_J) in a circular orbit around 51 Peg. Its short orbital period of 4.2 days places it at a distance of only 0.05 AU from the star. From similarly precise radial velocity observations at Lick Observatory, Butler & Marcy (1996) detected an unseen companion with a minimum mass of $2.5 M_J$ in a 3.0 yr, roughly circular orbit around 47 UMa. Marcy & Butler (1996) found a body of $6.5 M_J$ in a 116.7 day orbit around 70 Vir with the surprisingly large orbital eccentricity of 0.38. Latham et al. (1989) found a low-mass companion of $> 11 M_J$ around the star HD 114762 with a period of 84 days and an eccentricity of 0.25. If the orbital inclination were low enough, this companion might be massive enough to be a brown dwarf. The unusual character of these new planetary systems (e.g., large masses, high e, short periods) poses challenges to present theories of planetary formation (e.g., Guillot et al. 1996).

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We provide information on the surface magnetic activity, photometric variability, rotation, and age of these four stars. We also consider the impact of surface magnetic activity on the signature of a planet in radial velocity and photometric observations. Such information is important for verifying the planetary interpretation of the radial velocity data as well as for formulating search strategies for extrasolar planets and studying the occurrence of planets among Sun-like stars.

2. OBSERVATIONS

The general properties of the stars are listed in Table 1. The Ca II H (3968 Å) and K (3934 Å) fluxes have been monitored for all four stars at Mount Wilson Observatory, and photometric variations at Fairborn Observatory, Mount Hopkins. In general, Ca II and photometric records can reveal the presence of surface inhomogeneities formed by magnetic fields, e.g., spots and active regions similar to the Sun. High-resolution spectra of 47 UMa and 70 Vir were taken at National Solar Observatory in order to estimate $v \sin i$.

2.1. *Photometric Observations*

Three of the four stars, 51 Peg, 47 UMa, and 70 Vir, have been monitored photometrically with the SAO/TSU 0.75 m Automatic Photoelectric Telescope (APT) as part of a long-term program that began in 1993 to measure small brightness changes in solar-type stars. This instrument makes nightly differential brightness measurements with a precision near 0.0010 mag in the Strömgren b and y passbands in a quartet sequence: A, B, C, D, A, B, C, D, A, B, C, D, where A, B, and C denote three comparison stars for each program star (D). Experience shows that the use of three comparison stars increases our chances of finding at least one comparison star that is constant to 0.001 mag or better yet leaves sufficient time for a large sample of variable stars to be observed. Differential magnitudes of the program stars with respect to each of the comparison stars are corrected for extinction and transformed to the Strömgren photometric system. Means are formed from the three repeated differential measurements within each group and are treated as single observations thereafter. We combine the b and y filter data into a single measurement, $(b + y)/2$, to improve the precision further, as done by Radick et al. (1995) in their manual photometry of solar-type stars. Further details of the automated data acquisition and reduction techniques can be found in Henry (1995, 1996).

Because the 0.75 m APT collects data whenever it can find stars, it sometimes does so under nonphotometric conditions. We therefore use the standard deviation of the group mean magnitude, a measure of the internal precision of the observations, to discard any low-quality data. Since the precision during good nights usually ranges between 0.0010 and 0.0015 mag, we always discard all group observations with group mean standard deviations of 0.005 mag (roughly 3 times the usual standard deviation) or greater. Since we demand the highest possible precision in order to measure very small photometric changes, we analyze only data taken on demonstrably photometric nights (i.e., nights in which our standard star observations yield good solutions for all reduction parameters). The data selected for analysis, therefore, have not only survived a 0.005 mag "cloud filter" but have also been reduced with nightly extinction coefficients determined on good photometric nights.

The fourth star, HD 114762, has been observed every year since 1989 with the Fairborn-10 0.25 m APT, also at the Fairborn Observatory (Young et al. 1991; Henry 1995). The observations were made in the Johnson V, R, and I passbands with respect to comparison and check stars in the group sequence K, C, V, C, V, C, V, C, K, where K is the check star, C is the comparison, and V is HD 114762. All observations were corrected for differential extinction with seasonal mean extinction coefficients and transformed to the Johnson VRI photometric system. Standard deviations of group means on good nights usually range from 0.004 to 0.006 mag on this telescope; observations with standard deviations of the group mean exceeding 0.02 mag were discarded. For several reasons, the 0.25 m APT data are less precise than those from the 0.75 m APT (Henry 1995).

2.2. Ca II H *and* K *Observations*

These stars are also being monitored for long-term Ca II variations as part of Mount Wilson Observatory's HK Project (Wilson 1978; Baliunas et al. 1995). The Ca II H and K emission fluxes and their variations are proxies of surface magnetic activity, e.g., decade-long variations similar to the 11 yr solar cycle. The observed quantity, S, is the total flux measured in two 1 Å passbands centered on the Ca II H and K lines, normalized by two 20 Å sections of photospheric flux centered at 3901 Å and 4001 Å, and calibrated by a coefficient determined nightly from observations of a standard lamp and a set of standard stars (Baliunas et al. 1995). Since 1980, observations have been made several times per week of many of the survey stars as part of an ongoing effort to measure rotation (Vaughan et al. 1981; Baliunas et al. 1983) and surface differential rotation (Donahue 1993; Donahue, Saar, & Baliunas 1996).

2.3. *Rotational Velocity Observations*

High-resolution spectra of 47 UMa and 70 Vir were obtained with the McMath-Pierce stellar echelle spectrograph and a TI CCD (Smith & Giampapa 1987). We used the 180 mm transfer lens and the 10 slice image slicer to obtain resolution $\lambda/\Delta\lambda \approx 1.25 \times 10^5$ over $\approx$20 Å near 6170 Å. The data were bias subtracted, divided by a tungsten arc flat-field spectrum, optimally extracted, and wavelength-calibrated (using a Th-Ar lamp). The signal-to-noise ratio of the reduced spectra is about 275.

TABLE 1

SUN-LIKE STARS WITH PLANETARY SYSTEMS

HD Number	Name	$(B-V)$	Spectral Type	Photometric Comparison Stars
95128........	47 UMa	0.61	G1 V	HD 94669, HD 94177, HD 94425
114762......	...	0.54	F9 V	HD 114378, HD 114326
117176......	70 Vir	0.71	G4 V	HD 118660, HD 117304
217014......	51 Peg	0.67	G5 V	HD 218261, HD 218235, HD 217813

3. ANALYSIS

The photometric and Ca II H + K time series were examined for the presence of rotation periods in order to compare any periods with $v \sin i$ determinations. We inferred ages from the average level of magnetic activity according to Donahue (1993) using a technique initially developed by Soderblom, Duncan, & Johnson (1991). Table 2 lists information obtained from the analysis of Ca II records. The seasonal mean differential photometric magnitudes and their standard deviations for the four stars are given in Table 3. The smallest standard deviations of the mean are 0.0002 mag. We also searched for planetary transits in the 51 Peg, 70 Vir, and HD 114762 systems.

The high-resolution spectra were modeled with a simple velocity-broadening analysis (Saar, Nordström, & Andersen 1990; Saar & Osten 1996). Briefly, six moderately strong absorption lines per spectrum were calculated using a Milne-Eddington line model, where fundamental line properties (e.g., damping parameters) were determined from fits to solar lines in the Kurucz et al. (1984) flux atlas. The line profiles were calculated at 15 limb angles defined by an equal projected area grid (Bruning 1984) and integrated over the stellar disk using 60 azimuthal zones. A radial-tangential model was employed for the macroturbulence, v_{mac} (Gray 1988) that was assumed to be the same for all six lines. Values of the effective temperature were calculated from the approximate relation $\log T_{eff} = 3.908 - 0.234(B-V)$ (Noyes et al. 1984). Line blends were included, initially scaled by eye from the Sun, and then fitted to find optimal values. Comparison with previous results (Saar & Osten 1996) suggests that the simplicity of the line model does not adversely affect the derived velocities, in part because the lines studied are relatively weak ($W_\lambda \leq 100$ mÅ). The resulting $v \sin i$ and v_{mac} values are listed in Table 4 and are discussed below.

TABLE 2

PROPERTIES INFERRED FROM ANALYSIS OF Ca II H AND K FLUXES

HD Number	Name	$\langle S \rangle$	$\sigma_S/\langle S \rangle$ (percent)	P_{obs} (days)	P_{calc}[a] (days)	Age[b] (Gyr)
Sun	...	0.179	6.5	26.1[c]	23.7	4[d]
95128	47 UMa	0.148	1.8	...	21.5	7
114762	...	0.156	3.2	...	12.0	5
117176	70 Vir	0.142	2.3	...	36.3[e]	9[e]
217014	51 Peg	0.149	3.0	37.1	29.6	10

[a] The expected period, P_{calc}, is estimated using the mean Ca II activity-rotation of Noyes et al. 1984.

[b] Age is calculated from a decreasing function of average activity with age (Donahue 1993). Variations in activity cause inaccuracy in estimating age.

[c] Donahue, Saar, & Baliunas 1996. The rotation period depends on the latitude of predominant activity. The range of observed periods of P_{obs} from the chromospheric time series analyzed is 24.5–28.5 days; the average is listed above.

[d] The age of the Sun has been inferred from the last three cycles, a similar length of observations to the stars. The average activity over the last three solar cycles has been high; hence, the implied age is younger than actual.

[e] Value is valid only if the star is on or near the main sequence. See text.

3.1. *HD 217014* (*51 Pegasi*)

Photometric observations of 51 Peg taken during the 1993 and 1994 observing seasons and surviving the filtering process described above are plotted against the orbital phase of the companion in Figure 1. Two of our comparison stars (A and C) were found to be slightly variable, so we plot differential magnitudes determined with respect to comparison star B (HR 8788 = HD 218235, F6 V). The arrow in Figure 1 marks the phase of inferior conjunction (and pos-

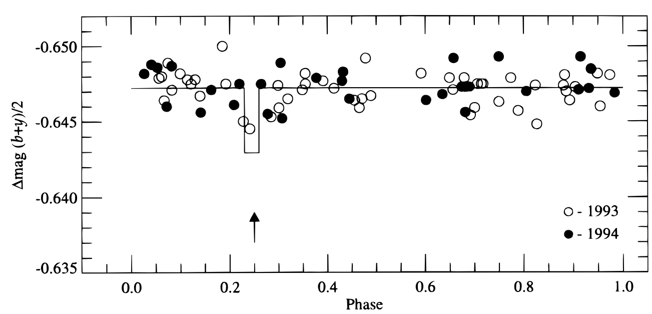

FIG. 1.—Differential magnitudes, $(b + y)/2$, of 51 Peg plotted against orbital phase. The open and filled circles are from the 1993 and 1994 observing seasons, respectively. The arrow at phase = 0.25 represents the time of conjunction with the planet between Earth and the star computed from the ephemeris of Mayor & Queloz (1995). The line describes the drop in light caused by a hypothetical transit of a planet about $0.8R_J$ against a 1.3 $R_\odot$ star, lasting 4 hr. The semiamplitude of any sinusoidal light variation on the 4.2 day planetary period is less than 0.0002 mag.

TABLE 3

SEASONAL PHOTOMETRIC MAGNITUDES

Star Name	Date Range (JD −2,400,000)	N_{obs}	Seasonal Mean (mag)[a]	Standard Deviation of Mean (mag)
51 Peg	49145–49362	51	−0.6471	0.0002
	49512–49666	30	−0.6474	0.0002
47 UMa	50052–50123	38	−2.2621	0.0002
70 Vir	49094–49164	44	−0.7852	0.0002
	49339–49546	53	−0.7856	0.0002
	49718–49908	67	−0.7864	0.0002
HD 114762......	47632–47701	74	2.9735	0.0011
	47871–48067	131	2.9717	0.0009
	48269–48441	160	2.9732	0.0008
	48605–48813	159	2.9729	0.0010
	48968–49168	176	2.9744	0.0009
	49335–49546	190	2.9734	0.0007
	49802–49908	70	2.9738	0.0012
	50044–50078	30	2.9749	0.0022

[a] Differential magnitudes are computed from $(b + y)/2$ for 51 Peg, 47 UMa, and 70 Vir, and from Johnson V for HD 114762.

TABLE 4

ROTATIONAL AND TURBULENT VELOCITIES

HD Number	Name	$v \sin i$ (km s^{-1})	v_{mac} (km s^{-1})
95128........	47 UMa	1.9 ± 0.6	3.5 ± 0.6
114762	...	<1.0[a]	4.7[a]
117176	70 Vir	0.9 ± 0.4	3.3 ± 0.5
217014	51 Peg	2.2 ± 1[b]	...
		1.7 ± 0.8[c]	3.0[c]
		3.0[d]	2.1[d]

[a] Cochran, Hatzes, & Hancock 1991.
[b] Mayor & Queloz 1995.
[c] Soderblom 1983; the value for v_{mac} is assumed, not fitted.
[d] Valenti 1994; v_{mac} is adjusted to a common scale. See Saar & Osten 1996.

sible transit) of the companion determined from the ephemeris of the orbit of Mayor & Queloz (1995).

Periodogram analysis of the photometry in Figure 1 reveals no significant periodicities. Fourier analysis of the photometric data at the orbital period (4.2293 ± 0.0011 days) gives an upper limit of the semiamplitude in the $(b + y)/2$ passband of 0.0002 ± 0.0002 mag, thereby improving on previous upper limits of variability by Guinan (1995; <0.0018 mag) and Burki, Burnet, & Kuenzli (1995; <0.0020 mag). Kjeldsen & Bedding (1995) proposed an empirical relation between the luminosity change and velocity amplitude caused by *p*-mode oscillations. An upper limit of 0.0002 mag indicates a velocity amplitude of $\lesssim 9$ m s^{-1}, which is significantly smaller than the observed amplitude of 59 m s^{-1} (Mayor & Queloz 1995). This negligibly small upper limit to the amplitude appears to rule out *p*-mode oscillations as the cause of the radial velocity variations and so is consistent with the planetary hypothesis of Mayor & Queloz (1995).

The data from the first two observing seasons intermingle well on the phase plot; the mean $(b + y)/2$ magnitudes from the 1993 and 1994 observing seasons are -0.6471 ± 0.0002 and -0.6474 ± 0.0002 mag, respectively. Therefore, no measurable change in mean magnitude over 2 years is seen, consistent with the great age of 51 Peg inferred from its slow rotation and low average level of surface magnetic activity.

The long-term Ca II record of 51 Peg from 1977 onward is plotted in Figure 2. While some season-to-season jitter is present, the signal has been essentially constant ($\sigma_S/\langle S \rangle = 3.0\%$), with an rms variation that is among the quietest of our solar-type stars (Baliunas et al. 1995). Periodogram

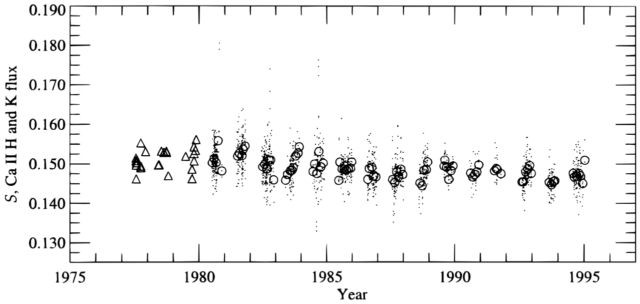

FIG. 2.—Ca II H and K relative fluxes, a proxy of surface magnetic activity, in 51 Peg. Triangles are nightly measurements from Vaughn, Preston, & Wilson (1978); after 1980, large circles are 30 day means of individual measurements (*small dots*; Baliunas et al. 1995). The record shows essentially no long-term variation in surface activity.

analysis reveals no significant power at the planetary orbital period. In 1987 and 1989, weak rotation modulation was detected with periods of 37.2 ± 0.4 and 36.9 ± 0.7 days, respectively. Reported values of $v \sin i$ are 3.0 km s^{-1} (Valenti 1994), 1.7 ± 0.8 km s^{-1} (Soderblom 1983), and 2.2 ± 1 km s^{-1} (Mayor & Queloz 1995). Of these measurements, Soderblom's is the most consistent with the P_{rot} measurements. Assuming 51 Peg is on the main sequence, the predicted rotation period (Noyes et al. 1984) is shorter, only 29.6 days (Table 2). This means that in the activity-rotation relationship, 51 Peg appears to be more active (observed $\langle S \rangle = 0.149$) than its observed rotation period would suggest. If the observed, slow rotation period is correct, then 51 Peg should have a lower value of S (~ 0.125, based on the activity-rotation relation of Noyes et al. 1984), and an age of 14 Gyr, based on the activity-age relation of Donahue (1993). On the other hand, using the observed values of $\langle S \rangle$ and $(B-V)$ in the age-activity relation, and ignoring the rotation period, we find an age of only 10 Gyr. Based on isochrone fitting, Edvardsson et al. (1993) estimate the age to be 8.5 Gyr. The discrepancy between the observed and calculated rotation periods and ages could be resolved by considering evidence ($\log g = 4.13$, Xu 1991; $\log g = 4.18$, Edvardsson et al. 1993) that the star has begun to evolve off the main sequence.

It may be coincidental that two of the three lowest points (including the lowest point) on the light curve in Figure 1 lie very near the time of conjunction when a planetary transit would occur if the orbital inclination to our line of sight were near 90°. The orbital elements of the planet imply a distance of approximately 7.6×10^6 km, assuming a mass of 1 $M_\odot$ for the star. If 51 Peg has a radius of 1.3 $R_\odot$ (Mayor & Queloz 1995), then the duration of a central planetary transit would be at most 4 hr or 0.04 phase units. A transit of this duration would just fit between the two points flanking the two low points near phase 0.25. For a planet half as massive as Jupiter but with similar density, $R \approx 0.8 R_J$. If transiting a 1.3 $R_\odot$ star, such a planet would dim the star's light by as much as 0.0043 mag during a transit, again consistent with the slightly dim points in Figure 1.

Consequently, we monitored 51 Peg during the 1995 observing season, with the 0.75 m APT in excellent photometric conditions for over 4 hr between JD 2,450,018.5888 and JD 2,450,018.7705, until it moved out of our observing window. This time interval corresponds to orbital phases, ϕ, 0.211–0.254 (Fig. 3). No trace of a transit was found; the standard deviation of the individual observations from the mean for the night was only 0.0005 mag. However, the uncertainties in the radial velocity ephemeris translate into an uncertainty in the time of transit of 1.5 hr at $\pm 1\ \sigma$ at the epoch of our observations. Therefore, the phase of mid-transit (at $\pm 1\ \sigma$) could lie anywhere in the range $0.227 \lesssim \phi \lesssim 0.273$. Our observations of 1995 October 28 rule out the possibility of an early transit; however, our phase coverage is insufficient to have monitored a transit had it occurred later than expected because of uncertainties in the orbital elements. Additional high-precision monitoring observations during the 1996–1997 observing season along with improved orbital elements are required to completely rule out a transit.

The star 51 Peg has favorable circumstances for observing a transit: its companion is relatively large (e.g., roughly Jupiter-sized) and therefore would produce a significant amplitude of photometric darkening during a transit. The

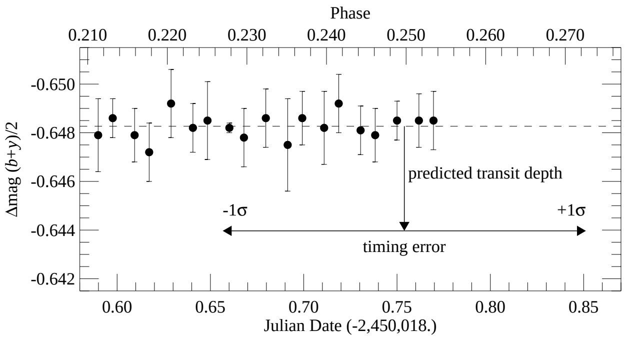

FIG. 3.—Differential magnitudes of 51 Peg and its mean (*dashed line*) covering 4 hr on JD 2,450,018. Each point represents the mean of a group observation, while errors mark the internal standard deviation of each group mean. The standard deviation of a single observation from the mean for the night is 0.0005 mag. The vertical arrow shows the time of conjunction from Mayor & Queloz (1995). The horizontal arrows show the accumulated uncertainty ($\pm 1\ \sigma$) of the time of conjunction as a result of the uncertainties in the orbital elements. The horizontal arrow is placed at the approximate depth of the expected transit for a planet roughly $0.8 R_J$ against a 1.3 $R_\odot$ star. These observations rule out a transit with amplitude $\gtrsim$0.0005 mag that is early or on time, but not a late one.

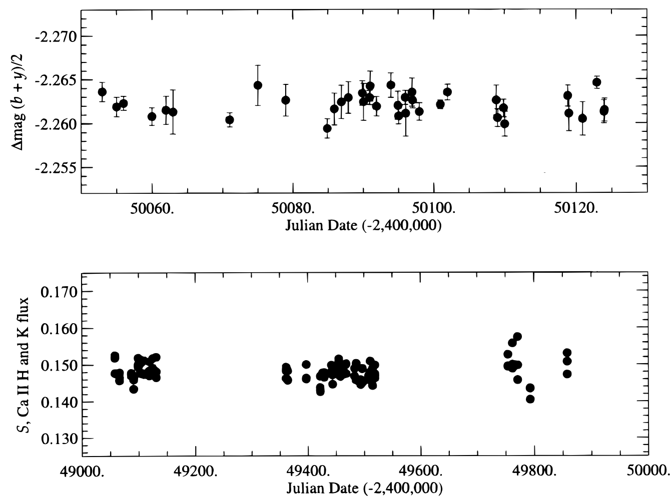

FIG. 4.—*Top:* Differential magnitudes, $(b + y)/2$, of 47 UMa from the beginning of the 1995–1996 observing season. The standard deviation of a single observation from the mean of these observations is 0.0013 mag. *Bottom:* Individual Ca II H and K relative fluxes are plotted for the last three observing seasons. Little variability either in brightness or in S is found.

companion of 51 Peg is also near its parent star, which increases the allowable inclinations to our line of sight for a transit to occur. One disadvantage of the 51 Peg system is that transits would have short durations; on the other hand, such transits would be frequent. The first two and last conditions tend to increase the chance of viewing a transit, *yet a transit has not been observed*. This suggests an orbital inclination less than 85°, assuming the transit time was within the time of observations.

The nondetection of a transit for 51 Peg in this favorable case underscores the important fact that the probability of alignment for a transit to occur is very low (Rosenblatt 1971). The low probability of alignment suggests that a radial velocity search will be far more efficient for *detecting* roughly Jupiter-sized planets, in part because it is not as limited in inclination as is a transit search. This seems so despite the fact that the amplitude of brightness change during a transit would be as large as 0.01 mag and therefore readily detected. Furthermore, detecting a planet by means of a transit may require continuous observations since a transit may only occupy a minute fraction of the star's orbital period. For example, in the case of Jupiter, the transit duration would be only 30 hr (Rosenblatt 1971), or 0.03%, of its 11.88 yr orbital period. A strategy of detecting planets by transit searches seems inefficient but would be useful for obtaining follow-up information after planetary systems with favorable alignments are identified from radial velocity observations. To this end, the ground-based photometric data presented here are sufficiently precise to detect a favorably placed planet as small as 1 $R_\oplus$; although the standard deviation of a *single* observation in Figure 3 is 0.0005 mag, a *systematic* dimming of 0.0001 mag as a result of the transit of an Earth-sized planet would be detectable if most or all of an event were monitored under ideal conditions.

3.2. *HD 95128* (*47 Ursae Majoris*)

Photometric observations of 47 UMa were begun in 1995 December. Differential magnitudes with respect to the comparison star HD 94177 (K0 V) for the first 70 days of the 1995–1996 observing season are plotted against Julian Date in Figure 4 (*top panel*). Periodogram analysis reveals no evidence of significant brightness changes over this limited time interval. The standard deviation of a single observation from the 70 day mean is only 0.0013 mag. We have insufficient data to test for any light variation on the 1088 day planetary orbital period.

Long-term Ca II monitoring of 47 UMa at Mount Wilson began in 1990. The time series is plotted in the bottom panel of Figure 4. The star is similar to other inactive stars (Baliunas et al. 1995) in that the long-term activity record is flat. The mean level of activity, $\langle S \rangle = 0.148$, implies an age of 7 Gyr from the activity-age relationship of Donahue (1993), in excellent agreement with the estimate of 6.9 Gyr by Edvardsson et al. (1993) from isochrone fitting. Rotation was not detected from analysis of the available time series.

For 47 UMa, we find $v \sin i = 1.9 \pm 0.6$ km s^{-1} and $v_{\rm mac} = 3.5 \pm 0.6$ km s^{-1}, consistent with the star's color (Saar & Osten 1996). Nissen (1981) determines [Fe/H] = $-$0.08, while Taylor (1994) gives $T_{\rm eff} = 5875$ K. Fits to the high-Landé $g_{\rm eff}$ Fe I line at 6173 Å and their residuals are shown in Figure 5. If $R_* = 1.1\ R_\odot$, then the rotation period is $P_{\rm rot} \approx 23$ days assuming $\sin i = \langle \sin i \rangle = \pi/4$, roughly consistent with $P_{\rm calc} = 21.5$ days, predicted from $\langle S \rangle$.

3.3. *HD 117176* (*70 Virginis*)

The differential photometric observations of 70 Vir from the 1993, 1994, and 1995 observing seasons are plotted versus Julian Date in Figure 6; differential magnitudes are measured with respect to the comparison star 71 Vir (HR 5081 = HD 117304; K0 III). The seasonal mean magnitudes for these three seasons are -0.7852, -0.7856, and -0.7864, respectively, implying that 70 Vir has brightened by 0.0012 mag over the three seasons. This object is one of two program stars in its quartet group sequence, so only two comparison stars are available. Measurements of 70 Vir with respect to the second comparison star (HR 5129, HD 118660, A9 Vs) also reveal a gradual brightening of 70 Vir over the three observing seasons but with a lower amplitude of 0.0005 mag. The mean of these two results suggests a brightening of 0.0008 mag over three years.

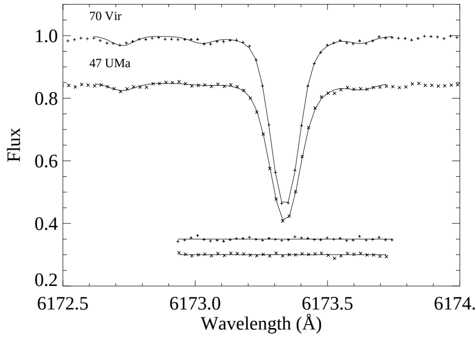

FIG. 5.—High-resolution ($\lambda/\Delta\lambda \approx 1.25 \times 10^5$) echelle spectra of 70 Vir (*plus signs*) and 47 UMa (*crosses*; displaced by −0.15) in the vicinity of the high Landé $g_{\rm eff}$ Fe I 6173 Å line. The symbol sizes correspond to the rms of the observations (S/N ≈275). Radiative transfer models for the 6173 Å feature and nearby blends are shown (*solid lines*) together with fit residuals (shown displaced below). We derive $v \sin i = 0.9 \pm 0.4$ km s^{-1} and $v_{\rm mac} = 3.3 \pm 0.5$ km s^{-1} for 70 Vir, and $v \sin i = 1.9 \pm 0.6$ km s^{-1} and $v_{\rm mac} = 3.5 \pm 0.6$ km s^{-1} for 47 UMa.

Periodogram analysis of the 70 Vir photometry fails to yield any significant period that could be interpreted as the stellar rotation period. Fourier analysis of the data at the 116.7 day orbital period gives a semiamplitude of 0.0001 ± 0.0002 mag for both the second and third observing seasons. The partial, first observing season is too short to allow searching for the 116.7 day period. Similar to discussion for 51 Peg in § 3.1, the expected *p*-mode oscillations on the order of 9 m s^{-1} cannot explain the observed radial velocity amplitude of 311 m s^{-1} (Butler & Marcy 1996). Like 51 Peg, the extreme constancy in the brightness of 70 Vir over the period rules out pulsations and spots as the cause of the observed radial velocity variations. The three seasons of photometry plotted versus phase reveal no evidence for a planetary transit.

The record of Ca II H and K fluxes for 70 Vir (Fig. 5) is similar to that of 47 UMa in that it has low average activity ($\langle S \rangle = 0.156$), which suggests an age of ∼9 Gyr (Donahue 1993), and little Ca II variability. However, the Ca II H and K flux has decreased slightly from 1991 to 1995. Over the past 3 years, the star has *increased* in photometric brightness and *decreased* in Ca II H and K flux, which is contrary to the sign of the correlation between photometric and chromospheric variability in stars close to mass and age to the Sun (Radick, Lockwood, & Baliunas 1990).

Hearnshaw (1974) found log $g = 3.75$ for 70 Vir, which implies it is somewhat evolved off the main sequence. This value is consistent with the star's mean parallax (0".041; Jenkins 1952) and its apparent angular diameter (0.971 mas; Blackwell & Lynas-Gray 1994), the weak wings seen in the high-resolution spectra, and the old age derived from $\langle S \rangle$. Using the above log g value, we find $v \sin i = 0.9 \pm 0.4$ km s^{-1} and $v_{\rm mac} = 3.3 \pm 0.5$ km s^{-1} for 70 Vir (Fig. 5). Taylor (1994) gives $T_{\rm eff} = 5590$ K. Its line strengths are very similar to those of HD 101501 (G8 V, $B-V = 0.72$, $T_{\rm eff} = 5580$ K; Taylor 1994), which suggests a similar, near-solar metal abundance ([Fe/H] = −0.035; Hearnshaw 1974). The $v_{\rm mac}$ value is somewhat higher than the average for dwarfs of the star's color ($\langle v_{\rm mac} \rangle \approx 2.7$ km s^{-1}; Saar & Osten 1996), consistent with the star's somewhat evolved status. The parallax and angular diameter imply that $R_* \approx 2.5\ R_\odot$, in which case the upper limit for the rotation period is ∼140 days. This value is considerably larger than that implied by the star's $\langle S \rangle$ value (which suggests $P_{\rm rot} \approx 35$ days) and would require that the star be seen nearly pole-on and that the mass of the companion be much larger. Marcy & Butler (1996) determine the mass of the companion to be $\gtrsim 6.5 M_{\rm J}$.

3.4. *HD 114762*

The photometric observations of HD 114762 taken with the 0.25 m APT span eight observing seasons and are plotted against Julian Date in Figure 7 (*top panel*). Differential magnitudes in *V*, *R*, and *I* are measured with respect to the comparison star 42 α Com (HR 4968/9 = HD 114378/9), a close visual binary with the spectral classification F5 V and a separation of 0".2. Seasonal mean *V* magnitudes, along with the standard deviation of the mean magnitudes, are listed in Table 3. The brightness of HD 114762 is constant to 0.001 mag over the 8 year interval of the observations. The standard deviation of the seasonal mean *V* magnitudes is 0.0010 mag. Periodogram analysis also finds no significant periodicities over the period range of 1–100 days. The Ca II relative fluxes are plotted in Figure 7

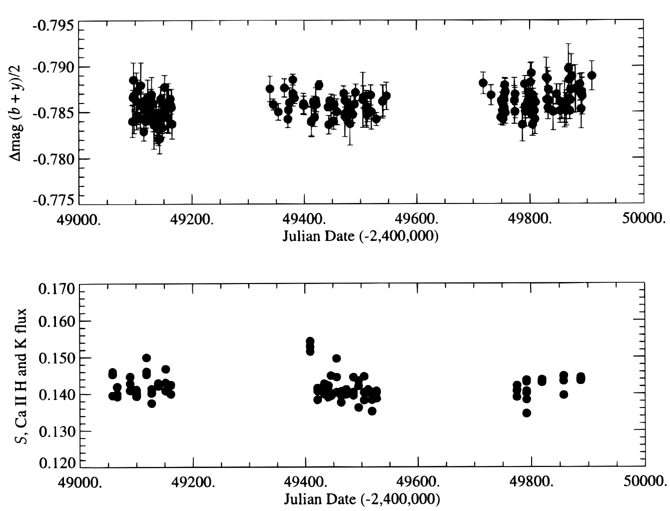

FIG. 6.—*Top*: Differential magnitudes, $(b + y)/2$ (*upper panel*) of 70 Vir from 1993 through 1995. *Bottom*: Ca II H and K flux for the last three observing seasons. Little variability is detected in either record, but a very small trend over the three seasons may be present.

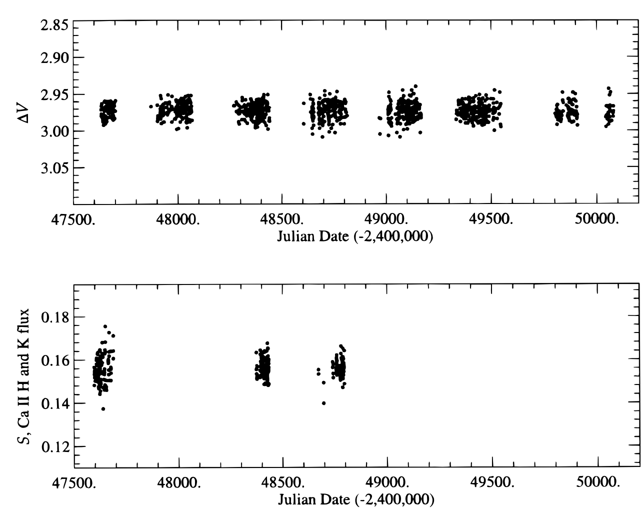

FIG. 7.—*Top*: Differential *V*-band photometry (*upper panel*) of HD 114762 covering eight observing seasons. Seasonal mean magnitudes are constant to within 0.0010 mag. *Bottom*: Ca II H and K fluxes (*lower panel*) beginning in 1989. Little variability is detected.

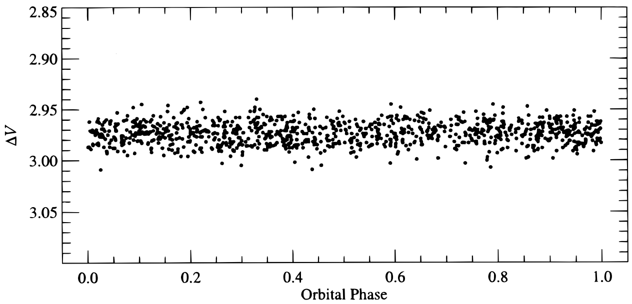

FIG. 8.—Eight seasons of differential V-band photometry of HD 114762 (Fig. 7) folded against the orbital phase of the companion (Latham et al. 1989). Phase = 0.0 corresponds to the predicted time of transit of the companion, but none is seen.

(*bottom*). The record of the star is essentially constant on all time scales observed.

The photometric observations in Figure 7 are replotted against the orbital phase of the companion in Figure 8. The orbital period of 84.05 days is given by Latham et al. (1989). Zero phase corresponds to the epoch of conjunction with the companion nearest Earth as computed by Robinson et al. (1990). We confirm the result of Robinson et al. (1990), although with far more numerous observations, that no eclipse of the primary by the companion is visible. Fourier analysis of the photometry on the 84.05 day period gives the negligibly small semiamplitude of 0.0007 ± 0.0004 mag. This upper limit of photometric variability is larger than those of 51 Peg and 70 Vir, but the radial velocity variation in HD 114762 is relatively large (570 m s^{-1}). Thus, the photometric variability seems to exclude p-mode oscillations as the cause of the velocity variations.

The estimated rotation period is 12 days from $\langle S \rangle = 0.156$, and the estimated age from this chromospheric activity is 5 Gyr. This disagrees with the estimate of 13.8 Gyr obtained from analysis of isochrones by Edvardsson et al. (1993). However, $\log g = 4.24$ (Edvardsson et al. 1993), which suggests the star is slightly evolved and that P_{rot} may therefore be longer. The star's low metallicity ([Fe/H] $= -0.63$; Taylor 1994) also suggests considerable age.

4. DISCUSSION

As stated earlier, Ca II and photometric records of surface magnetic activity of the four stars discussed here are all relatively constant, showing little evidence for activity cycles observed in other solar-type stars. The records also show very little variability within a season, which explains why rotation periods were generally undetected. One explanation for the relatively constant photometric and Ca II H and K records is that the stars may be in a temporary phase of inactivity similar to the Sun's Maunder Minimum of the 17th century, where the level of surface activity declines and the variability associated with spots also diminishes. Maunder minimum episodes may last several decades and occur every few centuries (Eddy 1976).

Whatever the explanation for inactivity, the fact is that low-mass companions have been detected around four stars with little variability in surface magnetic activity. This fact suggests that variations in surface magnetic activity set thresholds for planetary detection. While planets with short orbital periods or that produce large velocity amplitudes will be the most easily detected, and the companions detected thus far were discovered partly because of this fundamental selection effect, this does not preclude the existence of other secondary effects that may become more important when searching for low-amplitude radial velocity modulation. The growth and decay of active regions, rotation, and activity cycles could add radial velocity perturbations on various time scales as surface features appear at different stellar longitudes, i.e., different radial velocities. Substantial variability of surface magnetic activity, especially on timescales similar to the orbital period, could conceal a companion's orbital velocities. Similarly, significant photometric noise from surface magnetic activity could mask transit events, despite a transit's geometric and repeated signature in photometric variation. Therefore, selecting stars with little variability in surface magnetic activity offers minimal stellar perturbations in both photometric and radial velocity measurements. That choice increases the chances for planetary detection, especially for a planet with small radius or small reflex motions of the parent star. On the other hand, monitoring of stellar activity, e.g., Ca II or photometric fluxes, could allow unambiguous detection of planets around more active stars.

We comment on two causes of velocity perturbations. First is the effect from the presence of temperature inhomogeneities such as starspots on a rotating star. Spots only occupy an average area, $f \lesssim 0.1\%$ of the Sun's surface (Noyes, Guinan, & Baliunas 1991). A star with $f < 1\%$ and $v \sin i = 2$ km s^{-1} would introduce a semiamplitude of velocity perturbation, $A_{\Delta v}$, less than 10 m s^{-1} as the star's rotation moves the spot across the visible hemisphere (Saar & Donahue 1996). This is below the orbital velocity amplitudes of the reported companions to the stars studied in this paper. However, more active stars can have considerably larger spot coverage (e.g., for κ Ceti, $f < 2\%$ and $f \sim 6\%$ for HD 129333; Dorren & Guinan 1994), resulting in larger velocity perturbations of 100 m s^{-1} or larger, in which case planets with low velocities (on the order of several tens of m s^{-1}) will be more difficult to detect.

Another significant perturbation to velocity measurements is line-bisector variations due to the presence of velocity inhomogeneities on the stellar surface. One example is the rotational modulation of areas of suppressed convection associated with magnetic regions (Livingston 1982). Analysis of limited data available on the time variability of bisector spans (Saar & Donahue 1996) shows that inactive G and early K stars with activity similar to the Sun's typically have $A_{\Delta v} \leq 20$ m s^{-1}. On the other hand, early G or active stars show larger values of $A_{\Delta v}$ because the bisector velocity spans increase under three conditions: (1) with increasing T_{eff} (Gray 1982; Saar & Osten 1996), (2) when many active regions are present (e.g., Toner & LaBonte 1990), and (3) when $v \sin i$ is high (see, e.g., Gray 1986). An example is the rapidly rotating, active G0 V star χ^1 Ori. Its bisector data (Bruning & Saar 1990) suggest that $A_{\Delta v}$ is on the order of 100 m s^{-1} (Saar & Donahue 1996). In this case, the velocity perturbations from bisector spans are significantly larger than the orbital velocity variations of 51 Peg B and 47 UMa B. Therefore, the velocity amplitude of planetary companions reported here would be seen against the typical background velocity perturbations similar to those of the Sun. However, the amplitudes of the companions for 47 UMa (45 m s^{-1}) and 51 Peg (59 m s^{-1}) would be difficult to see against the activity of χ^1 Ori or a star with similar activity.

Similarly, a strategy using photometric transit searches for a star as active as χ^1 Ori would also be hindered by its activity because of significant irradiance variations by spots: rotation (with mean rotation amplitude, $\langle \Delta V \rangle \sim 0.030$ mag; Dorren & Guinan 1994), growth and decay, and long-term activity are all present.

Surface features and line-bisector variations make active (i.e., young and rapidly rotating) stars of early G type difficult targets for planet detection by means of reflex velocities or transits. The effect of significant, intrinsic stellar velocity or photometric perturbations will be lessened if the orbital period of a planet differs distinctly from the timescales of rotation and surface activity. However, it will be important to monitor stellar activity variations to identify them in the velocity or photometric records used in the search for extrasolar planets. An observational bias raises the chance of planet detection in lower main-sequence stars that are inactive, have low projected rotational velocity, or are cooler than early G type.

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The data for Figures 1 and 3 are available at URL http://www.mtwilson.edu/Services/Professional/ on the World Wide Web.

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