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PROPERTIES OF SUN-LIKE STARS WITH PLANETS: ρ^1 CANCRI, τ BOOTIS, AND υ ANDROMEDAE[1]

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ABSTRACT

Planets have been reported orbiting the Sun-like stars ρ^1 Cnc, τ Boo, and υ And based on low-amplitude radial velocity variations. We have derived information on the first two stars from analysis of spectra, as well as parallel records of high-precision Strömgren *b* and *y* photometry and Ca II H + K fluxes. In the case of ρ^1 Cnc, the upper limit (peak to peak) of nondetection of photometric variability at the orbital period is $\Delta y \sim 0.0004$ mag. The possibility of a planetary transit cannot be ruled out completely from the photometric data. Variations of the Ca II fluxes suggest a rotational period of ~42 days, in agreement with the inferred $v \sin i \sim 2$ km s^{-1}. The age of ρ^1 Cnc is ~5 Gyr, based on its average Ca II flux and a relation between Ca II flux and age.

The star τ Boo, unlike the other reported solar-type stars with planets, is relatively young (~2 Gyr). Despite its young age, it is photometrically nonvariable at the orbital period with an amplitude of $\Delta(b + y)/2 \sim 0.0004$ mag (peak to peak); however, small-amplitude interseasonal variability is seen. No planetary transits were found in the photometry, which limits the inclination of the planet's orbital plane to Earth's line of sight to less than 83° (where 90° is coplanar). The Ca II record shows a weakly significant rotational period near 3.3 days, coincident with the orbital period of the companion. The Ca II record also shows a period of 116 days that has persisted for 30 years and is not seen in the photometric record. The persistence and timescale of this Ca II variation mean that it has no counterpart in Sun-like magnetic activity. The amplitude of the reflex velocity of the parent star (~450 m s^{-1}) is much larger than the radial velocity perturbations expected from the presence of either surface inhomogeneities or line-bisector variations. Thus the anticipated perturbations from those stellar effects do not refute the inference of reflex velocities.

We have few Ca II flux measurements for υ And. Its age and rotational period are estimated to be ~5 Gyr and 12 days, respectively. Our results for ρ^1 Cnc and τ Boo are consistent with the explanation of planets as the cause of the velocity variations.

Subject headings: planetary systems — stars: activity — stars: late-type — techniques: photometric — techniques: spectroscopic

1. INTRODUCTION

Butler et al. (1997) have reported planetary companions inferred from low-amplitude velocity variations for ρ^1 Cancri (G8 V), τ Bootis (F7 V), and υ Andromedae (F8 V). Analyses of photometric and magnetic-activity variability and estimates of rotation and age help to verify the planetary interpretation and improve search strategies for extrasolar planets. Henry et al. (1997) performed such analyses for the solar-like stars 51 Peg, 70 Vir, 47 UMa, and HD 114762.

2. OBSERVATIONS

Photometric observations of ρ^1 Cnc were made by the newly commissioned Tennessee State University (TSU)/Smithsonian Astrophysical Observatory (SAO) 0.8 m automatic photoelectric telescope (APT) and two-channel precision photometer on Mount Hopkins, Arizona. The observations of τ Boo were obtained with the SAO/TSU 0.75 m APT and single-channel photometer at the same site. Data acquisition and reduction procedures for the 0.8 m are identical to those described and referenced in Henry et al. (1997) for the 0.75 m telescope. Our APTs had made no observations of υ And.

The Ca II H + K fluxes, *S*, were made as part of the ongoing HK Project at Mount Wilson Observatory. The stars ρ^1 Cnc and τ Boo have numerous measurements going back many years; υ And has only a few observations. A more detailed description of such observations is given by Baliunas et al. (1995).

Spectra of ρ^1 Cnc and τ Boo were obtained with the KPNO 0.9 m coudé-feed telescope, coudé spectrograph, and a Texas Instruments CCD detector. The spectra have a central wavelength at 6430 Å, a range of 80 Å, and a resolution of 0.21 Å. Properties of the stars are listed in Table 1.

3. ANALYSIS

The photometric records of ρ^1 Cnc and τ Boo were searched for variability that might be due to spots, pulsations, or the transit of a planet across the stellar disk. We performed periodogram analyses (Horne & Baliunas 1986) of the Ca II records to search for variability attributable to rotation. Spectroscopic observations yielded spectral types and projected rotational velocities, $v \sin i$, which can be compared to the measured rotational period. Stellar ages were inferred from the mean level of Ca II fluxes and their relation to main-sequence age (Donahue 1993).

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TABLE 1

STARS WITH PLANETS

Name	HD Number	HR Number	$B - V$	Spectral Type	$\langle S \rangle$[a]	$v \sin i$ (km s^{-1})	$\langle P_{\rm rot} \rangle$ (days)	$P_{\rm calc}$[b] (days)	Age[c] (Gyr)
ρ^1 Cnc	75732	3522	0.86	G8 V–K0 IV[d]	0.190 ± 0.016	2.0 ± 1	41.7 ± 1.2	42.4	5
τ Boo	120136	5185	0.48	F7 V	0.190 ± 0.008	14.8 ± 0.3[e]	3.3[f]	5.1	2
υ And	9826	458	0.54	F8 V	0.154 ± 0.002	9.0 ± 0.4[g]	⋯	12	5

[a] Average value of S and its rms over the interval of the measurements.

[b] The estimated rotational period, $P_{\rm calc}$, is calculated from the mean Ca II flux and the period-activity relation of Noyes et al. 1984.

[c] Age is estimated from the decreasing function of average Ca II flux with age (Donahue 1993).

[d] See text, § 3.1.

[e] Gray 1982.

[f] None of the seasonal rotational period determinations are separately strong enough to be definitive. However, an excess of power at frequencies corresponding to 3.3 ± 0.5 days is seen in the periodogram of nearly all of the 14 observing seasons analyzed.

[g] Gray 1986.

3.1. *HD 75732 (ρ^1 Cnc)*

The 26 observations of ρ^1 Cnc on 21 photometric nights between 1996 April 17 and May 19 are plotted in Figure 1; the comparison star is ρ^2 Cnc (=HD 76219, G8 II–III, $V = 5.22$, $B - V = 1.00$). Orbital phases were computed from the ephemeris $T_{\rm conj} = 2{,}450{,}191.1707 + 14.648E$, where $T_{\rm conj}$ corresponds to a time of midtransit of the companion for an orbital inclination of 90° (computed from the orbital elements of Butler et al. 1997). The standard deviation of a single observation from the mean of the 26 observations is 0.0013 mag. The semiamplitude of a least-squares sine fit constrained by all the observations at the orbital period is 0.0002 ± 0.0003 mag. Therefore any light variations at that period cannot be much greater than 0.0004 mag (peak to peak).

The Ca II fluxes are shown in Figure 2. Rotational modulation is seen in all three observing seasons. The mean observed rotational period is 41.7 days, close to the period of 42.4 days predicted from the mean Ca II flux and the relationship of Noyes et al. (1984). The age inferred from the mean level of chromospheric activity is 5 Gyr.

The spectrum of ρ^1 Cnc is peculiar, and different results seem contradictory. Cowley, Hiltner, & Witt (1967) classified the spectrum as G8 V. However, Taylor (1970) identified it as a super–metal-rich K dwarf. A CN enhancement appears to be well established (see, e.g., Griffin & Redman 1960; Greenstein & Oinas 1968; Taylor 1970; Oinas 1974; Rose 1984), which suggests that the star may be a subgiant. Luminosity classes IV and V are difficult to distinguish spectroscopically in G8–K0 stars, but the CN bands are stronger in class IV stars (Griffin & Redman 1960; Wilson 1962).

Our spectrum of ρ^1 Cnc in the 6430 Å region was classified using the spectrum comparison technique of Strassmeier & Fekel (1990). The critical luminosity line ratios of ρ^1 Cnc are very different from those of G–K dwarfs such as ξ Boo A (G8 V; Wilson 1962) or HD 10780 (K0 V; Wilson 1962). In addition, the strong lines of ρ^1 Cnc are significantly stronger than those of such dwarfs, and numerous weak lines not seen in the dwarfs are present in the spectrum of ρ^1 Cnc. Thus, if ρ^1 Cnc is a dwarf, it is metal-rich relative to the Sun. Our spectrum of ρ^1 Cnc closely resembles that of the slightly metal-poor subgiant δ Eri (K0$^+$ IV; Keenan & McNeil 1989), which has [Fe/H] = −0.15 ± 0.05 (Taylor 1991).

The $v \sin i$ was determined from the full width at half-maximum of several lines in a transformation based on 50 stars (Gray 1982, 1989). Because the broadening is so small, the $v \sin i$ is critically dependent on the assumed macroturbulence. An assumed macroturbulence of 2.5 km s^{-1} leads to a $v \sin i$ of 1.9 ± 1 km s^{-1}.

Our $v \sin i$ and the measured rotational period from the Ca II record yield a minimum radius 1.6 ± 0.8 $R_\odot$. Broadband photometry implies that the angular diameter is ∼0.79 mas (Barnes, Evans, & Moffett 1978). Since the parallax is $\pi = 0''.0768 \pm 0''.0024$ (van Altena, Lee, & Hoffleit 1995), the radius is ∼1.0–1.2 $R_\odot$. Depending on its luminosity class, the mass lies between 0.8 and 1.2 $M_\odot$. If the star is 1 $M_\odot$, the planet would orbit it at a distance of 0.117 AU. Assuming $R = 1.1\ R_\odot$ and $i \sim 90°$, we estimate the observed transit duration to be ±0.007 units from the phase of midtransit. With a planetary radius of ∼1 $R_{\rm J}$, the transit depth would be nearly 1%. Only one of our observations falls within the transit window (Fig. 1) and does not show the expected dimming. However, the uncertainty in the time of conjunction computed from the elements of Butler et al. (1997) is several times the estimated duration of the transit. Thus our photometric observations do not yet rule out the possibility of planetary transits.

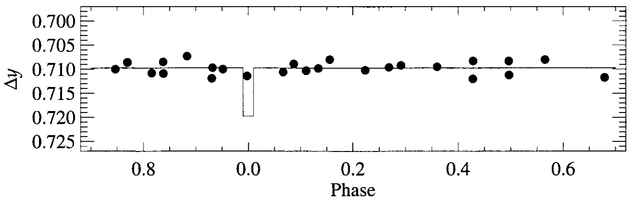

FIG. 1.—Strömgren differential y magnitudes of ρ^1 Cnc plotted modulo the 14.648 day planetary orbital period (Butler et al. 1997). A least-squares sine fit at the orbital period yields a semiamplitude of 0.0002 ± 0.0003 mag. Phase 0.0 corresponds to a time of conjunction with the planet closest to Earth. The solid line shows the predicted light curve from the transit of a 1 $R_{\rm J}$ planet across the star with 1.1 $R_\odot$. Because of the uncertainty in the time of conjunction, we cannot rule out a possible planetary transit.

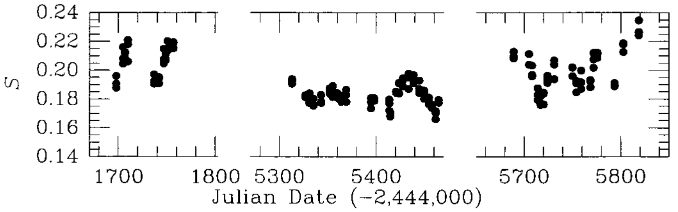

FIG. 2.—Ca II H + K data during three observing seasons for ρ^1 Cnc. Rotational modulation is visible in each observing season, with a mean period of ∼41.7 days, and varying amplitude, presumably due to the growth and decay of active regions.

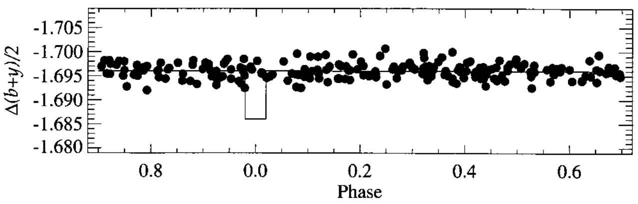

FIG. 3.—Four seasons of Strömgren $(b + y)/2$ differential magnitudes of τ Boo plotted modulo the 3.3128 day orbital period of the companion (Butler et al. 1997). Phase 0.0 corresponds to the time of conjunction when the companion would transit the star, also as computed by Butler et al. (1997). A least-squares sine fit at the orbital period yields a semiamplitude of 0.0002 ± 0.0001 mag. The solid line shows the predicted light curve from the transit of a 1 R_J planet across the star. However, our photometric measurements rule out the possibility of such a planetary transit.

3.2. *HD 120136 (τ Boo)*

Nightly differential magnitudes from the 1993–1996 observing seasons are plotted in Figure 3. The standard deviation of a single nightly observation from its seasonal mean ranged from 0.0012 to 0.0015 mag in the four observing seasons. The comparison star is HD 121560 (=HR 5243, F6 V, $V = 6.16$, $B - V = 0.5$). Orbital phases were computed from the ephemeris $T_{\rm conj} = 2{,}450{,}216.4089 + 3.3128E$ (Butler et al. 1997). Periodogram analysis yields no significant frequencies; the semiamplitude of a least-squares sine fit to all the observations at the planetary orbital period is 0.0002 ± 0.0001 mag, suggesting an upper limit of ~0.0004 mag of light variability (peak to peak) at that period. While τ Boo exhibits no detectable light variation within any observing season, our photometry does suggest a season-to-season variation of approximately 0.001 mag. Mean differential Strömgren $(b + y)/2$ magnitudes for the four observing seasons are -1.6957, -1.6954, -1.6970, and -1.6960 mag, respectively, where each seasonal mean has a standard deviation of 0.0002 mag. Virtually identical variations are seen when another comparison star (HD 120601, F0) is used.

Our spectrum of τ Boo in the 6430 Å region was compared with rotationally broadened spectra of F4–F9 dwarfs. The best fit is with HR 5694 (F8 IV–V; Johnson & Morgan 1953), which has nearly solar abundances. If τ Boo were slightly metal-rich, its spectral type would be a bit earlier and consistent with previous classifications. Assuming a macroturbulence of 4 km s^{-1}, we infer $v \sin i = 15 \pm 1$ km s^{-1}, essentially identical to that of Gray (1982; $v \sin i = 14.8 \pm 0.3$ km s^{-1}) but smaller than Soderblom's (1982) measurement of 17.0 ± 1.0 km s^{-1}.

Our value of $v \sin i$, combined with the suggested rotational period of 3.3 ± 0.5 days from our Ca II H + K observations (see below), yields a minimum radius between 0.8 and 1.2 $R_\odot$, which suggests a high inclination. Conversely, the parallax of $0\farcs0545 \pm 0\farcs0048$ (van Altena et al. 1995) and its broadband photometric colors suggest a radius of 1.7 ± 0.2 $R_\odot$ (Barnes et al. 1978). This radius implies an equatorial rotational velocity of ~26 km s^{-1}, which in turn would require a low inclination ($\lesssim 40°$) to match the observed $v \sin i$.

A high inclination, combined with the companion's nearness to the star, implies that transits may be observable. If we assume τ Boo has a mass of 1.2 $M_\odot$, then the semimajor axis of the orbit of the companion is 0.046 AU. Likewise, if τ Boo were 1.1 $R_\odot$ and the orbital inclination were 90°, the duration of the planet's transit would be nearly ±0.02 phase units. For a planet with radius 1 R_J, a central transit would dim the light of τ Boo by almost 0.01 mag. Such transits are clearly ruled out by our observations (Fig. 3), implying an orbital inclination $\lesssim 83°$.

The mean Ca II flux and the activity-rotation relation of Noyes et al. (1984) predict a rotational period of 5.1 days. Analysis of 14 observing seasons in the Ca II record with sufficient data to search for variability at this timescale yields no strong period in any season. However, near the orbital period there is a weakly detected period of 3.3 ± 0.5 days in almost every observing season. We assume that these periods are attributable to rotation.

Because the orbital and rotational periods are close, we consider velocity perturbations caused by axial rotation of a spotted surface. Since our photometric data show no semiamplitude of variation above 0.0002 ± 0.0001 mag at 3.3 days, the differential filling factor for starspots is certainly $\lesssim 0.1\%$. Using the approximation of Saar & Donahue (1996), we find that the amplitude of radial velocity perturbations from starspots is less than 10 m s^{-1}, although the estimate is based on results for stars whose $T_{\rm eff}$ are more similar to the Sun's.

Another source of stellar radial velocity variability comes from convection and is seen in line bisectors. The amplitude of such velocity perturbations increases with $v \sin i$ and with decreasing $B - V$ (Saar & Donahue 1996) and is potentially important in τ Boo because of its small $B - V$ and rapid rotation. In fact, Butler et al. (1997) find the rms of the residual radial velocity noise, after subtracting a Keplerian fit to the reflex velocity, is $\lesssim 80$ m s^{-1}, which is consistent with the expectation of perturbations from line bisectors.

Since τ Boo exhibits very little activity variation and its observed reflex velocity (450 m s^{-1}) is much greater than the expected velocity perturbations from starspots and convection combined (i.e., $\lesssim 100$ m s^{-1} for stars even more massive than τ Boo; Saar & Donahue 1996), we conclude that the 3.3 day reflex velocity is not an artifact of the 3.3 day rotational period.

The Ca II record contains additional information on τ Boo. The mean Ca II flux suggests an age of 2 Gyr (Donahue 1993). Baliunas et al. (1995) reported a low-amplitude, 11.6 yr activity cycle. A 116 day variation is also present over the 30 yr length of the record (Maulik et al. 1996). Too long to be rotation and too persistent to be the growth and decay of active regions, the period has no counterpart in solar activity. If a secondary activity cycle, it is much shorter than any primary or secondary cycle previously detected.

3.3. *HD 9826 (υ And)*

We did not observe this star photometrically. The Ca II observations are few—four independent epochs over 9 years. The age is estimated (Donahue 1993) to be 5 Gyr, and the rotational period is expected to be 12 days (Noyes et al. 1984).

Blackwell et al. (1990) inferred the angular diameter to be 1.10 mas, which is nearly identical to the diameter obtained by using the Barnes-Evans relationship (Barnes et al. 1978) and $V - R = 0.461$ from Moffett & Barnes (1979). This, combined with the parallax of $0\farcs0568 \pm 0\farcs0041$ (van Altena et al. 1995), yields a radius of 2.1 $R_\odot$, slightly above the main sequence. If the estimated rotational period of 12 days is correct, then the equatorial velocity (~9 km s^{-1}) suggests a high inclination, which agrees with estimates by Soderblom (1982; 9.2 ± 0.7 km s^{-1}) and Gray (1986; 9.0 ± 0.4 km s^{-1}). Although the star is listed as a spectroscopic binary in several catalogs, Morbey & Griffin (1987) have indicated that this is not the case.

Without photometric measurements, it is not possible to assess radial velocity perturbations expected from starspots. In contrast, velocity perturbations arising from convection may be substantial since υ And is bluer than the Sun and is more rapidly rotating, like τ Boo.

4. DISCUSSION

The results for ρ^1 Cnc and τ Boo are consistent with the explanation of planets as the cause of the observed radial velocity variations. The stars ρ^1 Cnc and υ And are similar to the stars previously reported to have planets (51 Peg, 70 Vir, 47 UMa), in that they are relatively old ($\gtrsim$5 Gyr) and have little Ca II or photometric variability and, hence, little surface magnetic activity. In contrast, τ Boo is the youngest Sun-like star with a detected planet. The star has substantial radial velocity noise that may be caused by line-bisector variations. Furthermore, it has an unexplained 116 day variation in Ca II flux that persists throughout the entire 30 year record and is dissimilar to Ca II variations on other Sun-like stars. It is also unusual in that the stellar rotational period and orbital period of the companion are similar.

The stars τ Boo and υ And have high 0.1–2.4 keV X-ray fluxes ($\log F_X = 5.91$ and 4.98 ergs cm^{-2} s^{-1}, respectively; Hempelmann, Schmitt, & Stepien 1996; Piters et al. 1996) compared to the Sun ($4.46 \lesssim \log F_X \lesssim 4.99$ ergs cm^{-2} s^{-1} for the Sun's range of activity over the 11 yr cycle). Higher X-ray flux is consistent with their more rapid rotation. In contrast, 51 Peg, 47 UMa, and 70 Vir have only upper limits of nondetection ($\log F_X \lesssim 5.2, 5.7, 5.3$ ergs cm^{-2} s^{-1}, respectively).

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