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The Radii of Solar Neighborhood ZAMS Stars

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Abstract.
Constraints from optical data suggest that several members of a small but homogeneous sample of solar neighborhood, Pleiades-age, K dwarfs have radii that are 0.1-0.2 $R_\odot$ larger than the main sequence radius expected from their spectral types, implying that they may be slightly pre-main sequence. Alternatively, recent theoretical work indicates that strong magnetic fields may inhibit convection enough to distort measured V and $(B-V)$ values (and possibly spectral types); this, in turn, could skew certain radius calculations. Thus the stars might be slightly earlier (and more massive) than their spectral classes indicate, and already on the ZAMS.

1. Introduction

Several independent lines of evidence establish the 7 program stars in Table 1 as a homogeneous sample of solar neighborhood, Pleiades-age stars. All are between spectral types K0 V and K2 V, have near primordial lithium abundances, high activity levels, and space motions consistent with the Pleiades Moving Group. Therefore, within rather modest uncertainties, the stars are the same age, the same mass, and the same temperature. The only major difference among them is rotation rate ($0\overset{\mathrm{d}}{.}38 - 6\overset{\mathrm{d}}{.}9$).

All of the stars except one are confirmed single. HD 17925 is probably an unresolved SB2, on the basis of low amplitude radial velocity variations, but the companion appears too distant to affect its evolution.

2. Computed Radii: Methods and Data

The extent and quality of the observational data allow us to compute radii for each of the program stars by three different methods. The results indicate that most of the stars could be 5 - 20% larger than expected from their spectral types, or alternatively, a systematic effect exists that causes them to appear fainter, and with later spectral type, than they truly are.

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Table 1. Observed Properties of the Program Stars

Star	V_{max} (mag)	Sp. type	Hipp.[Tycho] π (mas)	$(B-V)_{max}$ (mag)	$v \sin i$ (km s^{-1})	P_{rot}(min) (d)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Speedy Mic	9.33[a]	K2-3 V[b]	22.52±1.64	0.93[a]	125 ±5[b]	0.380[a]
AB Dor	6.77[c]	K0-2 IV-V[d]	66.92±0.54	0.775[c]	88 ± 5[e]	0.5132[f]
HD 82558	7.78[g,h]	K2 V[i]	54.52±0.99	0.87[g,h]	27.9 ± 1 [b]	1.601[g,j]
HD 1405	8.715[k]	K2 V[b]	[45.70±10.20]	0.89[k]	23.4 ± 1[l]	1.745[m]
HD 220140	7.440[n]	K2 V[o]	50.65±0.64	0.843[n]	16.1 ± 1[l]	2.7137[p]
HD 82443	7.013[q]	K0 V[r]	56.35±0.89	0.775[q]	6.2 ± 1[l]	5.25[q]
HD 17925	6.00[s]	K2 V[r]	96.33±0.77	0.86[s]	4 ± 1 [b]	6.56[t]

[a] Cutispoto (1997); [b] this paper; [c]Pakull (1981); [d]Mewe *et al.* (1996); [e] mean of 85 km s^{-1} (Randich *et al.* 1993) and 91 km s^{-1} (Unruh *et al.* 1995); [f]V_{equ}: Donati & Collier-Cameron (1997); [g]Jetsu (1993); [h]Strassmeier *et al.* (1993); [i]Fekel *et al.* (1986); [j]Strassmeier *et al.* 1997; [k]Dulude *et al.* 2001; [l]Fekel (1997); [m]Houten & Hall (1990); [n]Mantegazza *et al.* (1991); [o]Bianchi, Jurcsik, & Fekel (1991); [p]Kahanpää *et al.* (1999); [q]Messina *et al.* 1999; [r] Henry *et al.* (1995b); [s]Blanco *et al.* (1979); [t]Donahue, Saar, & Baliunas (1996).

The three methods used to calculate radii are: 1) the Barnes-Evans relation (the observed flux-to-surface flux conversion factor, F/f, plus the distance, gives R_*), 2) the Stefan-Boltzmann law, and 3) R sin i. The $(B-V)$ Barnes-Evans relation is used because it appears to be slightly less sensitive to distortion of the color indices from stellar activity than the $(V-R)$ relation (Fekel, Moffett, & Henry 1986).

The Barnes-Evans and Stefan-Boltzmann methods both utilize V_{max} and $(B-V)_{max}$, and are therefore not independent. V_{max} is the brightest published (non-flare) V magnitude; it should reflect starspot minimum and be the truest measure of photospheric brightness. $(B-V)_{max}$ is the published $(B-V)$ value corresponding in time to V_{max}, i.e., not necessarily the bluest $(B-V)$ on record. T_{eff} was determined from $(B-V)_{max}$, the bolometric correction, and the $(B-V)$ - temperature correspondence of Flower (1996, Table 3).

Input data for the $R \sin i$ calculations are P_{rot}(min) and $V \sin i$. P_{rot}(min) is the minimum observed P_{rot}, minus 1-3% (depending on the extent of the data) to compensate for observational incompleteness and for differential rotation, which is indicated for several of the stars (Donahue et al. 1996; Jetsu 1993; Messina et al. 1999). $V \sin i$ values, except for AB Dor, were measured by co-author Fekel from KPNO coude feed spectra (Henry et al. 1995); Fekel 1997; this paper).

Values for V_{max}, $(B-V)_{max}$, $V \sin i$, and P_{rot}(min) for each star are given in Table 1.

3. Radius Results: Are The Stars Actually Above the ZAMS?

Table 2 compares radii as calculated by each of the three methods above. The range comes from incorporating observational uncertainties in order to give minimum and maximum values of $R_*/R_\odot$. We find that, for those stars where the inclination, i, is relatively high ($\gtrsim 60°$), the $R \sin i$ method sets the most reliable constraints on R_*.

Table 2. Stellar Radii: Comparison of Methods & Adopted Values

Star (1)	$R_*/R_\odot$ (Stef.-Boltz.)[a] (2)	$R_*/R_\odot$ (Barnes-Evans)[b] (3)	Min. $R \sin i$[c] (4)	$R_*/R_\odot$ (R sin i)[d] (5)	Adopted $R_*/R_\odot$ (6)	d (pc) (7)	$\frac{d^2}{R^2}$ (8)
Speedy Mic	0.72-0.91	0.82-0.95	0.88	0.88-0.98	0.93±0.05	44.41	4.48(18)
AB Dor	0.69-0.76	0.75-0.77	0.84	0.84-0.95	1.0±0.06	14.94	4.39(17)
HD 82558	0.60-0.67	0.67-0.69	0.83	0.83-0.95	0.95±0.04	18.34	7.33(17)
HD 1405	0.40-0.68	0.44-0.70	0.75	0.75-0.84	0.85±0.05	21.88	1.30(18)
HD 220140	0.73-0.81	0.81-0.83	0.80	0.80-0.93	0.85±0.06	19.74	9.90(17)
HD 82443	0.73-0.81	0.80-0.82	0.53	0.53-0.78	0.81±0.05	17.75	9.44(17)
HD 17925	0.78-0.86	0.85-0.87	0.39	0.39-0.67	0.85±0.05	10.38	2.92(17)

[a] Range reflects uncertainties in parallax and in temperature.
[b] $R^2 = d^2/(\mathcal{F}/f)$. Range reflects the uncertainties in parallax; the precision of $V_{max} \sim 1\%$.
[c] For comparison, $R_*/R_\odot = 0.81 - 0.75$ for K0 V - K2 V stars, respectively (Gray 1992).
[d] Range reflects uncertainties in $v \sin i$ and P_{rot}.

For two of the stars, Speedy Mic and HD 220140, the radius ranges for all three methods overlap and are physically reasonable, although slightly larger than main sequence values. For K0 V - K2 V stars, the expected $R_*/R_\odot = 0.81$ - 0.75 (Gray 1992); the ZAMS radius would be slightly smaller. The adopted radii for both stars (Table 2, col. 6) was taken to be the midpoint in the $R \sin i$ range: for Speedy Mic, this is certainly reasonable, as the star's extreme $v \sin i$ implies $i \sim 90°$.

For two more stars, HD 82443 and HD 17925, $R \sin i$ sets no constraints at all, presumably because i is low. Fortunately, the Barnes-Evans and Stefan-Boltzmann radii overlap and are physically reasonable; the final adopted radii were taken from this overlap region.

However, for the remaining three stars, HD 82558, HD 1405, and AB Dor, the Barnes-Evans and Stefan-Boltzmann methods give radii significantly smaller than $R \sin i$; this is clearly unphysical (Table 2). Uncertainties in the input observations are too small to make up the difference. It seems likely that the problem lies with the two variables that are common to both the Barnes-Evans and Stefan-Boltzmann methods: V_{max} and $(B-V)_{max}$. It is known that the presence of plage can affect $(B-V)$ readings, making them bluer by as much as 5%, while starspots can redden $(B-V)$ by a similar amount (Jetsu 1993). Still, to raise either the Barnes-Evans or Stefan-Boltzmann radii up to $R \sin i(\min)$ (Table 2, col. 4), V_{max} would have to be 0.5-1.0 mag brighter. Even for a star like HD 82558, where Doppler imaging studies find extensive spot coverage (e.g., Rice & Strassmeier 1998), this is improbable. The final adopted radii for these three stars are the midpoints of the respective $R \sin i$ ranges.

It has recently been shown that strong magnetic fields, undoubtedly present in these very young, very active stars, can alter the physical conditions underlying the onset of convection, causing stars to appear slightly cooler and less luminous than in the non-magnetic case (Mullan, these proceedings).

Since the derived $R \sin i$ values (Table 2, col. 5) are independent of V and $(B-V)$, and thus of uncertainty in photospheric brightnesses, they should be reliable lower limits to R_*. For five of the stars in Table 2, $R \sin i$ values exceed the main sequence radius of a K0 V star (0.81 $R_\odot$). There are now two ways to interpret this: 1) the spectral classes are accurate, V_{max} reflects a minimally spotted photosphere, and the stars are slightly above the main sequence, or 2) strong magnetic fields cause a slight distortion in both the spectral classes and V_{max}, the stars are actually slightly earlier (and more massive) stars disguised as K dwarfs, and they are actually on the ZAMS.

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