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THE ROTATION OF RR LYRAE STARS

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ABSTRACT

We report upper limits to rotation from the measurement of line breadths via cross-correlation analysis for 27 RR Lyrae variables. The eight best-observed stars of type RR*ab* show the same variation of breadth with phase: the breadth peaks sharply during the rise to maximum light, drops gradually, and reaches a broad minimum during the phase of maximum radius. During this phase the breadth is always narrow, consistent with instrumental resolution and turbulence alone. For the three well-observed RR*c* variables, the breadth is this narrow at all phases except for a slight increase during the rise to maximum light. The remaining stars also conform to these patterns, albeit with sparse phase coverage and lower signal-to-noise ratio. We interpret these results as indicating that lines are broadened in RR*ab* stars by shock-induced plumes or turbulence during the rise to maximum light, and perhaps by other causes as well, but not by rotation in RR Lyrae stars of either type. We estimate an upper limit of $v \sin i < 10$ km s^{-1} in all cases. This is in stark contrast to the rotation seen in field blue horizontal branch stars, where $v \sin i > 10$ km s^{-1} in three out of six well-studied field stars, and to the more rapid rotation, often exceeding 100 km s^{-1}, of the Population I δ Scuti variables which occupy adjacent regions of the instability strip.

Subject headings: stars: evolution — stars: horizontal-branch — stars: Population II — stars: variables (RR Lyrae) — stars: rotation — stars: variables: other

The behavior of rotation in late-type Population I main-sequence (MS) stars is now reasonably well understood, but that of Population II stars is not, being hard to detect. Among single Population I MS stars, the rotational velocity drops steadily with spectral type and with age (Kraft 1967; Skumanich 1972). The drop is attributed to the spindown of the surface of single MS stars (Soderblom et al. 1993). Given the old age of Population II stars and the resulting truncation of the MS at late F stars, it is then no surprise that Population II MS stars are generally extremely slow rotators. Rotation has been unambiguously detected only in tidally locked binaries (e.g., Peterson et al. 1980) or blue stragglers (Carney & Peterson 1981); for single MS turnoff stars, upper limits to $v \sin i$ of about 8 km s^{-1} have been estimated (see Carney & Peterson 1981). Rotation in red giants (RG) is expected to be even lower, given their larger envelopes.

Observations of angular momentum in normal Population II stars began with the discovery of rotation in evolved stars, the blue horizontal branch (BHB) stars, by Peterson, Tarbell, & Carney (1983, hereafter PTC). They concluded: "The most plausible explanation of HB rotation invokes internal core rotation in MS stars, which is hidden by surface spin-down in types later than F2 but reappears at the HB stage after RG evolution and mass loss." Peterson (1983, 1985a, 1985b) then demonstrated that BHB stars in globular clusters also showed rotation, some more than others, and that the degree of rotation corresponded to the blueness of the cluster HB. Most recently, Peterson, Rood, & Crocker (1995, hereafter PRC) have extended the $v \sin i$ measurements to two dozen BHB stars in three globulars, again finding significant rotation which differed from cluster to cluster, but which did not correlate directly with the blueness of the HB. No dependence of $v \sin i$ on color was found in any cluster, but the large spread in $v \sin i$ where it is large and the sizable uncertainties in $v \sin i$ where it is small precluded a strong statement.

Two additional aspects of BHB rotation strongly support its origin in MS rotation: the low cutoff in $v \sin i$ among BHB stars and the distribution of $v \sin i$ among BHB stars in clusters with rapid rotation. Among all the BHB $v \sin i$ values of PRC, none exceeded 40 km s^{-1}, while Population I stars of similar late A III spectral types typically have $v \sin i = 100$ km s^{-1} (Jaschek & Jaschek 1990). For the initial MS rotation of the two most rapid field BHB rotators, with $v \sin i = 17$ and 27 km s^{-1}, PTC estimated $v \sin i \sim 60$ km s^{-1}, assuming constant angular velocity (rigid rotation) within the RG convection zone (see also Pinsonneault, Deliyannis, & Demarque 1991). This estimate, coupled with the upper rotation limit of 200 km s^{-1} found by Soderblom et al. (1993) for solar-mass MS stars in young clusters, would imply a maximum $v \sin i$ of ~50–90 km s^{-1} for any BHB. Moreover, Soderblom et al. (1993) noted that the distribution of $v \sin i$ among MS stars in young clusters cannot be represented by a single rotational velocity, but rather implied a division into fast and slow rotators, with the former somewhat less than half the total. This same division was also found by PRC for BHB stars in the globular with the strongest rotation.

Whether RR Lyrae stars share this rotation is the subject of this Letter. These stars, reviewed by Preston (1964) and Smith (1995), occupy the redward extension of the BHB into the instability strip engendered by helium ionization. Theoretical

HB treatments (e.g., Rood 1973) show that, despite the unexplained presence of gaps and bimodal distributions, globular cluster HBs represent a continuous sequence of stars along which the primary change is in the ratio of envelope mass to core mass. Thus rotation might be present in RR Lyraes as well.

Pulsation could conceivably damp or otherwise alter such rotation, but both theoretical arguments and observational facts suggest otherwise. Theoretically, the period of RR Lyrae pulsation (0.2–0.8 days) is ten times smaller than the minimum rotation period (6 days; PTC), and the fractional change in stellar radius is small (less than 20%), so pulsation should not damp rotation. Observationally, the Population I variables which fall closest in the HR diagram to RR Lyraes rotate rapidly. These are the δ Scuti stars (Breger 1979), with spectral types A–F III and periods 0.3 days or less, and frequently with multiple modes, low amplitudes, and $v \sin i > 100$ km s^{-1} (Russell 1995).

The position a star takes up on the HB might be influenced by rotation. This is difficult to judge, given the known sensitivity to factors such as mass loss the origin of which is not yet understood. As described by Lee, Demarque, & Zinn (1994), investigators must assume a mean mass loss of 0.2–0.3 $M_\odot$ per star, and a star-to-star spread one-tenth as large, and examine the effects of other variables on top of this. Upon doing so, Lee et al. estimated that the net effect of rotation is to produce bluer HBs. This might mean less rotation in RR Lyrae stars, though as yet no strong $v \sin i$ dependence on color is seen among stable BHB stars (PRC).

If rotation does bring about a bluer HB, it might be found preferentially among the metal-rich field RR Lyraes. These stars, with $\Delta S < 2$ and [Fe/H] > -0.6, are common in the field, but rare in globular clusters (Preston 1959; Kraft 1972). Suntzeff, Kinman, & Kraft (1991) and Lee (1992) noted that this inconsistency is reduced by the tendency at a given metallicity towards bluer cluster HBs at small galactocentric radial distance, and Lee (1992) also argued for an older age for the bulge. This may not be consistent with the ΔS results of Walker & Terndrup (1994): few if any bulge RR Lyraes have metallicities as high as the highest of the local field RR Lyraes. If the bulge population includes very metal-rich K giants, and if it is old, many metal-rich RR Lyraes should have been produced. Clearly more information is desirable on the factors involved.

We thus set out to measure rotational velocities in RR Lyrae stars. We used the existing observational database obtained with echelle spectrographs at Center for Astrophysics (CfA) telescopes by Carney, Latham, and collaborators. Much of this work combined photometry with radial velocities to derive Baade-Wesselink distances and magnitudes for nine field RR Lyrae stars, eight from CfA spectra (see Jones, Carney, & Latham 1988; Jones et al. 1992). Additional data are available and analyses underway for three more field stars, TV Leo, AP Ser, and AU Vir. Storm, Carney, & Latham (1994) have analyzed members of the globular clusters M5 and M92 using the velocities of Storm et al. (1992). For each of these stars, dozens of CfA radial-velocity measurements well-distributed in phase were obtained. In addition, a fainter group of field stars was observed sporadically at lower S/N. Velocities for the field stars were obtained with an echelle spectrograph and Reticon detector on both the 1.5 m Tillinghast reflector at the Whipple Observatory on Mount Hopkins near Tucson, Arizona, and on the 1.55 m Wyeth telescope at the Oak Ridge Observatory in Harvard, Massachusetts. Both systems yield a resolution of 8.3 km s^{-1} and a spectral coverage of ~50 Å centered at 5190 Å, with typical exposure times of 10 minutes giving S/N ~ 20 per resolution element for $V = 10$. The M5 and M92 spectra were obtained at similar resolution with the echelle/Reticon on the Multiple Mirror Telescope (MMT) at Mount Hopkins.

All stars with at least six CfA spectra are listed in Table 1 except one, XZ Dra, which was observed only at unsuitable phases. For each star we give the pulsation period in days, the blue amplitude in magnitudes and its source, the ΔS index and its source, and three metallicity indices [Fe/H]. The first was converted from ΔS using the calibration of Lambert et al. (1996), the second is from Layden (1994), and the third is from the spectroscopic sources listed. Observational information includes the telescope(s) of observation, a typical exposure time or range, and the number of CfA spectra. The last column notes Blazhko and RR*c* variables.

Line breadths as a function of phase were determined by cross-correlating each spectrum against a synthetic template matched in abundance [Fe/H], temperature $T_{\rm eff}$, and gravity (Nordstrom et al. 1994). For the stars with published Baade-Wesselink analyses, each spectrum was cross-correlated against several templates to verify that the choice of template did not affect the deduced breadth.

Figure 1 shows the breadth measured for each individual spectrum plotted against phase for three of the well-observed field RR Lyraes of type *ab* and one of type *c*. In each RR*ab*, the breadth increases most rapidly around phase 0.9, during the approach to maximum light at phase 1.0. It then drops, first quickly and then gradually, reaching a broad minimum plateau between phases 0.2–0.5 where the radius reaches a maximum. Where it is low, the breadth does not depend on the choice of template, as long as the metallicity of the template agrees with that of the star and its $T_{\rm eff}$ is within ~500 K of that of the star. The maximum breadth varies significantly from star to star, and also from cycle to cycle for the star X Ari, but the minimum remains around 10 km s^{-1} in each case. The five other well-observed RR*ab* stars also exhibit sizable breadth variations around phase 0.9, but there is no obvious trend of maximum breadth with metallicity. Preston, Smak, & Paczynski (1965) also noted an increase in line broadening during the rise to maximum light in some, but not all, of their spectra of RR Lyrae.

The three RR*c* variables show less variation, with the breadth constant just below 10 km s^{-1} except for perhaps a small increase at phase 0.9. The remaining RR*ab* stars also show breadth changes, while the remaining RR*c* stars also show little change of breadth with phase. The minimum is always $\leq$12 km s^{-1} for every star.

If rotation were detected and angular momentum conserved through a cycle, then $v \sin i$ should vary as the inverse of the radius. However, the radial variation of a typical RR*ab* star, plotted in Figure 4.12 of Smith (1995) (from Gillet, Burki, & Crowe 1989), shows a nearly sinusoidal behavior over the cycle. Thus, rotation itself is an unlikely cause of the breadth variation. While it might be suspected of contributing to the low-frequency, low-amplitude breadth variation, the rather consistent amplitude of that variation from star to star suggests otherwise.

Smearing due to the change in velocity during an exposure is generally small, since integration times were short. The data most susceptible are long exposures of stars with large velocity

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TABLE 1

RR Lyrae Stars with Line-Breadth Measurements

Star	Period (day)	A_B[a]	ΔS[a]	[Fe/H] (ΔS)	[Fe/H] (K)	[Fe/H][a] (Spectra)	Telescope[b] (minutes)	Number	Notes
				RR Lyraes Included in Baade-Wesselink Programs					
SW And.....	0.442	1.27/5	−0.4/1	−0.07	−0.38	−0.18/7,8,10	T/5–10	87	⋯
X Ari........	0.651	1.26/5	10.9/1	−2.22	−2.40	−2.52/7,10	T,W/15	114	⋯
RS Boo......	0.377	1.65/5	1.6/1	−0.45	−0.32	−0.36/7,10	W/5–10	188	Blazhko
SW Dra	0.570	1.22/5	3.5/1	−0.82	−1.24	−1.28/8	T/10	92	⋯
TW Her	0.400	1.69/5	2.2/1	−0.57	−0.67	⋯	T,W/10	76	⋯
TV Leo......	0.673	1.35/2,12	10.3/1	−2.11	−1.97	⋯	T/15	72	⋯
DH Peg	0.256	0.64/5	3.5/3	−0.82	⋯	−1.23/10	W,T/5–8	49	RR*c*
VY Ser......	0.714	0.88/5	8.9/1	−1.84	−1.82	−1.79/4,7,8,10	T/10	158	⋯
AP Ser	0.254	0.57/2	6.9/9,14	−1.46	⋯	⋯	T,M/7–10	65	RR*c*
UU Vir......	0.475	1.50/5	2.3/1	−0.59	−0.82	−0.80/8	T,W/5–15	120	⋯
AU Vir......	0.343	0.58/2	10.1/9	−2.07	⋯	⋯	T/10–17	58	RR*c*
M5-V8.......	0.546	1.32/16	5.5/3,8,13	−1.20	⋯	−1.17/15	M/20–25	58	⋯
M5-V28	0.544	1.30/16	5.5/3,8,13	−1.20	⋯	−1.17/15	M/20	45	⋯
M92-V1	0.703	1.06/6	12.2/3	−2.47	⋯	−2.24/14	M/20	50	⋯
M92-V3	0.637	1.34/6	12.2/3	−2.47	⋯	−2.24/14	M/20	68	⋯
				Other RR Lyrae variables:					
XX And.....	0.723	1.22/2	9.3/1	−1.92	−2.01	⋯	T/10	17	⋯
AT And	0.617	0.64/1,2	4.3/1	−0.97	⋯	⋯	T/10	7	⋯
RW Ari	0.354	0.59/2,10	5.2/18	−1.14	⋯	⋯	M/15	5	RR*c*
TV Boo	0.313	0.71/2	12.1/10	−2.45	⋯	⋯	T/10	15	RR*c*
RW Cnc.....	0.547	1.24/1,2	8.7/1	−1.80	−1.52	⋯	T/15	10	Blazhko
SS Cnc	0.367	1.66/2	1.8/1	−0.49	−0.07:	⋯	T/15	17	⋯
XZ Cyg......	0.467	1.24/1	6.2/1,3,17	−1.33	−1.52	−1.46/11	T/10	17	Blazhko
RY Com	0.469	1.52/2	3.5/1	−0.82	−1.65	⋯	T/15	7	⋯
RR Lyr......	0.567	1.23/1	6.1/1	−1.31	−1.37	−1.44/7,11	T/10	26	Blazhko
RZ Lyr......	0.511	1.35/1	9.7/3,17	−1.99	−2.13	⋯	T/10	8	Blazhko
RU Psc......	0.390	0.55/10,12	8.9/10	−1.84	⋯	⋯	T/10–30	16	RR*c*
RU Scl	0.493	1.63/2	5.1/1	−1.12	−1.25	⋯	T/10	8	⋯

[a] Number following the slash indicates reference(s).

[b] Telescopes: T = Tillinghast, W = Wyeth, M = MMT; number(s) following the slash indicate(s) typical exposure time(s).

References.—(1) Blanco 1992; (2) Bookmeyer et al. 1977; (3) Butler 1975; (4) Carney & Jones 1983; (5) Carney, Storm, & Jones 1992; (6) Carney et al. 1992; (7) Clementini et al. 1995; (8) Costar & Smith 1988; (9) Fernley & Barnes 1996; (10) Kemper 1982; (11) Lambert et al. 1996; (12) Simon & Teays 1982; (13) Smith & Perkins 1982; (14) Sneden et al. 1991; (15) Sneden et al. 1992; (16) Storm, Carney, & Beck 1991; (17) Suntzeff, Kinman, & Kraft 1991; (18) Walker & Terndrup 1991.

amplitudes during phases 0.9–1.0, the period of rapid velocity change. We cannot entirely rule out smearing during this phase, but argue that it is not responsible for most of the increase in the peak breadth, as this begins while the velocity is constant and ends while the velocity change is still large.

We also consider the variation of velocity with atmospheric height to be an unlikely cause of line broadening. If this effect were large enough to smear lines, it would displace weak lines (formed at shallow layers) with respect to strong lines (formed deeper). This is seen in X Ari only for the Balmer lines (Oke 1966); Jones et al. (1987) saw no differences greater than 2 km s^{-1} between weak and strong metal lines.

Instead, we suggest shock-induced plumes or turbulence as a more likely cause of the rise in breadths near phase 0.9 in

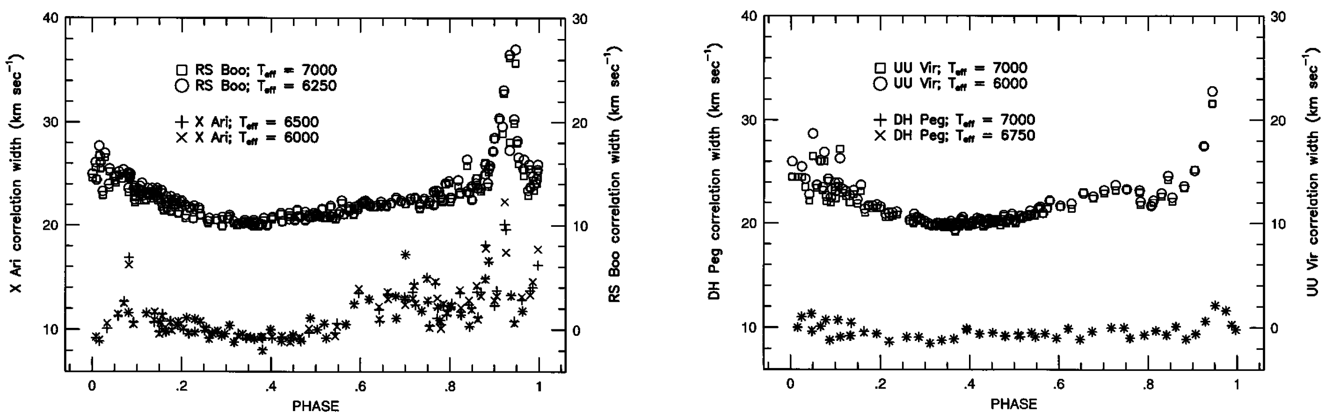

Fig. 1.—Plots are shown of the cross-correlation line breadth vs. phase for three RR Lyrae *ab*-type stars, X Ari, RS Boo, and UU Vir, and one *c*-type star, DH Peg. In each panel, the ordinate is the breadth of the cross-correlation peak in km s^{-1}, and the phase is indicated with respect to maximum light at 0.0. Cross-correlations against templates of different temperature are indicated by different symbols as shown.

RR*ab* stars. Line breadths of Cepheids show a similar behavior (Bersier & Burki 1996). Shocks are often seen in RR*ab* stars (notably X Ari), but are weak or absent in RR*c* stars; they are strongest at phase 0.9 and may vary in strength from cycle to cycle and from star to star (cf. Smith 1995).

The minimum breadth is always reached during the most quiescent phase of the star, when its radius is a maximum. The RR*ab* stars show a persistent change in breadth around both sides of this minimum, which is not due to velocity smearing or shifts. Turbulence seems a most likely cause.

The level of the minimum can be attributed to instrumental resolution plus minimum turbulence alone. This was evaluated explicitly by convolving templates broadened by known amounts of rotation against the standard, nonrotating templates. For $[Fe/H] \geq -0.5$, the minimum breadth increases with increasing abundance and decreasing T_{eff} (as expected from the increasing wings of the Mg *b* lines). For pairs $\{[Fe/H], T_{eff}\}$ of $\{\leq -1.0$, 6000–7000 K$\}$, $\{-0.5$, 6500 K$\}$, $\{-0.5$, 6000 K$\}$, and $\{0.0$, 6000 K$\}$, the breadth ranges from 10.3 ± 0.1 to 10.5 to 10.8 to 11.4 km s^{-1} for nonrotating templates, and 11.0, 11.1, 11.5, and 12.2 km s^{-1} for templates with $v \sin i = 10$ km s^{-1}. We thus estimate an upper limit to $v \sin i$ of 10 ± 3 km s^{-1} for the well-observed cases and 10 ± 5 km s^{-1} for the others.

This low level of rotation is supported by a comparison of the cross-correlation functions of the 1.5 m spectrum of VY Ser at phase 0.407, plotted in Figure 1 of Carney & Latham (1984), with the MMT spectrum of the marginally rotating ($v \sin i = 9 \pm 3$ km s^{-1}) BHB star HD 86986, plotted in Figure 1 of Peterson (1983). Measured FWHM values of the peak breadth are 21.4 and 20.0 km s^{-1}, respectively, the same to within the measurement uncertainties. The templates used were those of actual stars: the Am star 68 Tau for VY Ser and the metal-poor MS turnoff star HD 84937 for HD 86986, which are both sharp-lined.

We have briefly examined the possibility that the RR Lyrae variables showing the Blazhko effect might be rotating. These stars, whose pulsation amplitude varies somewhat irregularly over a cycle of several tens of days, were generally excluded from the sample used for Baade-Wesselink analysis. The shortest known Blazhko period is that of AH Cam, 10.9 days (Smith et al. 1994). This is the same (to within a factor of 2) as the period of the most rapidly rotating BHB stars, noted above. Moreover, roughly 20% of all RR*ab* variables may show the Blazhko effect (Smith 1995); a similar fraction of BHB stars shows strong rotation.

This encouraged us to look specifically for the line broadening of Blazhko variables. Those with the shortest Blazhko periods were targeted during a run in 1995 June with the 4 m echelle at Kitt Peak National Observatory. Three stars, WY Dra, AR Her, and Z CVn, were observed for ≤ 15 minutes during phases 0.2–0.5. None showed detectable rotation, with $v \sin i < 10$ km s^{-1}.

Thus, we have no ready explanation for the lack of detectable rotation in the RR Lyrae variables. While a larger sample of RR*c*, metal-rich RR*ab*, and Blazhko stars is needed before rotation can be completely ruled out among them, so far we have no encouragement for finding rotation in any of these groups. Why rotation greater than 10 km s^{-1} should occur frequently among BHB stars and be absent from RR Lyraes, and why metal-rich field RR Lyrae stars are common, remain a mystery.

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