ROTATION AND MACROTURBULENCE IN METAL-POOR FIELD RED GIANT AND RED HORIZONTAL BRANCH STARS

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ABSTRACT

We report the results for rotational velocities, \( V_{\text{rot}} \sin i \), and macroturbulence dispersions, \( \zeta_{\text{RT}} \), for 12 metal-poor field red giant branch (RGB) stars and 7 metal-poor field red horizontal branch (RHB) stars. The results are based on Fourier transform analyses of absorption line profiles from high-resolution (\( R \approx 120,000 \)), high-S/N (\( \approx 215 \) per pixel; \( \approx 345 \) per resolution element) spectra obtained with the Geckospectrograph at the Canada–France–Hawaii Telescope (CFHT). The stars were selected from the authors’ previous studies of 20 RHB and 116 RGB stars, based primarily on larger-than-average line-broadening values. We find that \( \zeta_{\text{RT}} \) values for the metal-poor RGB stars are very similar to those for metal-rich disk giants studied earlier by Gray and his collaborators. Six of the RGB stars have small rotational values, less than 2.0 km s\(^{-1}\), while five show significant rotation/enhanced line broadening, over 3 km s\(^{-1}\). We confirm the rapid rotation rate for RHB star HD 195636, found earlier by Preston. This star’s rotation is comparable to that of the fastest known rotating blue horizontal branch (BHB) stars, when allowance is made for differences in radii and moments of inertia. The other six RHB stars have somewhat lower rotation but show a trend to higher values at higher temperatures (lower radii). Comparing our results with those for BHB stars from Kinman et al., we find that the fraction of rapidly rotating RHB stars is somewhat lower than expected from the observed rotation of the RGB stars. We devise two empirical methods to translate our earlier line-broadening results into \( V_{\text{rot}} \sin i \) for all the RGB and RHB stars they studied. Binning the RGB stars by luminosity, we find that most metal-poor field RGB stars show no detectable sign, on average, of rotation, which is not surprising given the stars’ large radii. However, the most luminous stars, with \( M_V \leq -1.5 \), do show net rotation, with mean values of 2–4 km s\(^{-1}\), depending on the algorithm employed, and also show signs of radial velocity jitter and mass loss. This “rotation” may in fact prove to be due to other line-broadening effects, such as shock waves or pulsation.

Key words: binaries: spectroscopic – Galaxy: halo – planetary systems – stars: kinematics – stars: Population II – stars: rotation

1. INTRODUCTION

In previous papers (Carney et al. 2003, 2008; hereafter C2003, C2008), we reported on radial velocities and line broadenings for 136 metal-poor field red giant branch (RGB) and red horizontal branch (RHB) stars, based on 2413 high-resolution, low-S/N spectra. One of the more intriguing results was that the more luminous red giants, as well as many of their evolutionary progeny, red horizontal branch stars, showed significant line broadening. Interpreting the enhanced line broadening as rotation, C2003 explored the possibility that it might have arisen from absorption of one (or more) Jovian-mass planets that were engulfed only as the red giants swelled to large enough radii.

C2003 suggested several follow-up studies. First, the sample size should be expanded, and C2008 presented the results for 45 stars to complement the original 91-star sample of C2003.

Second, high-precision radial velocity monitoring of metal-poor dwarfs and subgiants should be undertaken to explore the frequency of Jovian-mass planets with orbital periods of order one year, corresponding to aphelion distances comparable to the maximum radial size of metal-poor RGB stars. The initial results of such a study have been reported (Sozzetti et al. 2006), and it appears that such planetary companions are not sufficiently common to explain the modest frequency of significant line broadening among the most luminous metal-poor red giants.

This paper explores the separate contributions of rotation and macroturbulence, based on a selected subsample of stars studied by C2003 and C2008. For example, if macroturbulence is a strong function of luminosity, the enhanced line broadenings found by C2003 and C2008 among the field red giants might be explained. If macroturbulence is a strong function of temperature, perhaps the line broadening seen in some of the red horizontal branch stars could also be explained. But if rotation is the cause of the enhanced line broadening among the stars with the largest radii, some new explanations must be sought.

To test these hypotheses, we decided to exploit methods developed by Gray (1982), whereby line profiles measured using very high-resolution, high-S/N spectra could be analyzed via Fourier transform methods to distinguish the contributions of rotation and macroturbulence.
2. PROGRAM DESCRIPTION

The Fourier transform method requires very high-resolution and high-S/N spectra. The Gecko spectrograph on the Canada–France–Hawaii Telescope (CFHT) was deemed to be an ideal instrument for our work, but the wavelength coverage is quite limited. We therefore computed a grid of model atmospheres covering the stellar parameters appropriate to our field RHB and RGB stars, using ATLAS9. We then computed synthetic spectra using R. L. Kurucz’s code SYNTHE. We sought wavelength regions that had a significant number of uncrowded absorption lines. The lines must be reasonably strong, but not saturated since pressure-broadened line wings render the lines less useful. We determined that for the RHB stars, the optimal wavelength region should be centered at 5430 Å, while for the RGB stars, the central region should be 6150 Å. Figure 1 shows the spectra for one of the RGB and one of the RHB stars.

Because of the requirement for high-S/N, and limited available observing time, we had to choose our targets carefully. Of course, we selected a number of RHB and RGB stars with significant line broadening. We also elected to observe a few stars with smaller line broadening, partly as a test of the line broadening derived from the lower-resolution ($R \approx 32,000$) CfA spectra. Furthermore, if the line broadening is due to rotation, we assume that the less-broadened stellar spectra might reflect nearly pole-on inclinations, so that we could explore macroturbulence more carefully.

Our observations were obtained in two runs with the CFHT, and to check the consistency of our results, we observed HD 29574 during both. We also felt a need to compare our results with the extensive studies of disk stars completed earlier by Gray (1982, 1984), Gray & Toner (1986, 1987), and Gray & Pallavicini (1989). We therefore included η Ser (HR 6869) in our program, which had been studied previously by Gray & Pallavicini (1989).

3. OBSERVATIONS

We used the Gecko spectrograph at the CFHT on two observing runs, in 2004 December and 2006 October. We used the MIT2 detector, a thinned 2048 × 4096 chip with 15µ pixels. The read noise for this device is about 7.5 electrons, which was negligible given the strong exposures. The gain setting was 1.2 electrons per ADU. Gecko was fiber-fed by CAFE (Baudrand & Vitry 2000) from the Cassegrain focus of the telescope. Fiber modal noise was suppressed by agitating the fiber continuously (Baudrand & Walker 2001).

The RGB stars were observed using order 9 and the 1521 filter. The single order on the detector at 6150 Å spans only about 90 Å, and the dispersion is about 1.47 Å mm$^{-1}$ (0.022 Å pixel$^{-1}$). The RHB stars were observed using order 10 and the 1510 filter, which covered 86 Å at a dispersion of 1.40 Å mm$^{-1}$, or about 0.021 Å pixel$^{-1}$. We measured the resolution using Th–Ar comparison lines, finding a typical resolving power of 120,000. Figure 2 shows 8 Å coverage in spectra of two red giant branch stars. The line depths are comparable, and it is (marginally) apparent that HD 3008 is broader lined than HD 23798, as the analyses of both the CfA and the CFHT spectra revealed.
Figure 2. A “close-up” of the CFHT spectra of two of our program RGB stars. HD 3008 has slightly broader lines, as the analyses of the CfA and CFHT spectra indicated.

Table 1
Observational Data

| Star     | λ (Å) | HJD−2,450,000 | V | Exp (min) | S/N^a | S/Nrad | σ | Comments          |
|----------|-------|----------------|---|-----------|-------|--------|---|-------------------|
| HD 3008  | 6150  | 3366.7716      | 9.70 | 40 | 175 | −81.83 | 0.34 | RGB; CM Cet; jitter |
| BD−18 271| 6150  | 4015.8939      | 9.85 | 90 | 145 | −210.54 | 0.19 | RGB; jitter        |
| CD−36 1052| 5430  | 3366.8083      | 10.00 | 70 | 150 | +304.36 | 0.32 | RHB                |
| HD 23798 | 6150  | 3366.8681      | 8.32 | 25 | 210 | +88.83  | 0.54 | RGB                |
| HD 25532 | 5430  | 4016.9720      | 8.24 | 80 | 175 | −111.88 | 0.34 | RHB                |
| BD+6 648 | 6150  | 4015.1177      | 9.09 | 270 | 285 | −142.41 | 0.31 | RGB                |
| HD 29574 | 6150  | 3366.8934      | 8.38 | 60 | 155 | +17.86  | 0.37 | RGB; HP Eric; jitter |
| BD−18 271| 6150  | 4015.0694      | 35  | 250 |       | +17.67  | 0.48 |                   |
| HD 82590 | 5430  | 3366.9454      | 9.42 | 75 | 180 | +214.31 | 0.37 | RHB; NSV 4526      |
| BD+22 2411| 6150  | 3367.0135      | 9.95 | 90 | 160 | +35.05  | 0.26 | RGB; jitter        |
| HD 106373| 5430  | 3367.1146      | 8.91 | 75 | 190 | +83.68  | 0.21 | RHB                |
| HD 110281| 6150  | 3367.0801      | 9.39 | 45 | 170 | +139.90 | 0.51 | RGB; KR Vir; jitter |
| HD 165195| 5430  | 4011.7779      | 7.34 | 120 | 380 | +0.50   | 0.40 | RGB; V2564 Oph; jitter |
| HD 184266| 5430  | 4016.7436      | 7.57 | 50  | 250 | −349.20 | 0.39 | RHB                |
| HD 187111| 6150  | 4015.8079      | 7.75 | 40  | 395 | −186.16 | 0.15 | RGB                |
| HD 195636| 5430  | 4016.7877      | 9.57 | 140 | 130 | −258.34 | 1.62 | RHB                |
| HD 214925| 6150  | 4015.7595      | 9.30 | 50  | 215 | −327.26 | 0.60 | RGB; jitter        |
| HD 214362| 5430  | 4016.9199      | 9.10 | 60  | 105 | −92.48  | 0.14 | RHB                |
| HD 218732| 6150  | 4015.8478      | 8.47 | 40  | 270 | −294.24 | 0.25 | RGB; LS Aqr; SLSB; jitter |
| HD 221170| 6150  | 4009.8693      | 7.71 | 100 | 260 | −121.69 | 0.40 | RGB; NSV 14589    |
| η Ser    | 6150  | 3981.1383      | 3.26 | 20  | 300 | +12.24  | 0.15 | RGB; check; NSV 10675 |

Note. ^a S/N values are per pixel. A typical resolution element is 2.3 pixels.

Table 1 provides a log of our observations, including the exposure time in minutes, the heliocentric Julian date of mid-exposure, and the estimated signal-to-noise obtained per pixel. Each spectral resolution element covered about 2.3 pixels, so the S/N per resolution element is that given in Table 1 multiplied by a factor of about 1.5.
4. DERIVATION OF ROTATIONAL AND MACROTURBULENT VELOCITIES FOR CFHT PROGRAM STARS

Since the Doppler broadening of rotation and macroturbulence are comparable in size, it is necessary to push toward high Fourier frequencies in order to distinguish the subtle differences in shape they impress upon the spectral lines. This is why the high resolving power of the Gecko spectrograph was needed. But high resolving power alone is not sufficient because the amplitudes at high Fourier frequencies are small and often below the noise level. For this reason high signal-to-noise ratios are also needed. Most of our observations are of sufficient quality to fulfill these requirements and allow us to distinguish rotation from macroturbulence.

Individual line profiles were extracted and corrected for small blends when necessary. The Fourier analysis then proceeds in the usual way (Gray 2005) by first dividing out the transform of a thermal profile computed from a model photosphere. Effective temperatures, surface gravities, and metallicities were taken from C2003 and C2008. Treatment of the thermal profile is not overly critical since its width is considerably smaller than the observed line widths. When this step is completed for all the usable lines, an average of these ratios is taken. The final manipulation of the data is to divide out the transform of the instrumental profile. We took the profile of a narrow emission line in a thorium–argon comparison lamp to be the instrumental profile. While we would have preferred using a narrower-line source, none was available. However, we expect no serious error to be introduced because the instrumental profile is many times narrower than the stellar lines. Since both the transforms of the thermal profile and the instrumental profile decline toward larger frequencies, division by them enhances the noise at the high frequencies. The transition to enhanced noise is fairly abrupt. Naturally, our analysis is restricted to Fourier frequencies below this transition.

The distribution of Doppler shifts from rotation and radial–tangential macroturbulence (Gray 2005) are computed by integrating over a model stellar disk on a sector-annulus format. A sector step of 0.5° is used and the annulus dimension is adjusted to be of comparable linear dimension. A limb darkening coefficient ($\varepsilon = 0.7$) is used. Fourier transforms of these Doppler-shift distributions are compared with the observations, and the broadening parameters, $V_{\text{rot}} \sin i$ and $\zeta_{\text{RT}}$, are adjusted until the best match is obtained. The ratio of rotational to macroturbulence broadening, $V_{\text{rot}} \sin i / \zeta_{\text{RT}}$, is determined from the curvature and any sidelobe structure. The absolute scale of the velocities comes from the translational match on the logarithmic abscissa. In those cases where $V_{\text{rot}} \sin i$ is considerably smaller than $\zeta_{\text{RT}}$, $V_{\text{rot}} \sin i$ will be poorly determined, and vice versa. We estimate the errors by altering the $V_{\text{rot}} \sin i$ and $\zeta_{\text{RT}}$ parameters by small amounts until obvious mismatch with the data occurs. Two examples of the final step are shown in Figure 3. HD 195636 is a rapid rotator, while HD 184266 has some rotation but larger macroturbulence. Table 2 summarizes the results of the Fourier analyses.

Our results appear to be consistent between the two observing runs, based on the very good agreement for the two sets of measurements of HD 29574. Furthermore, our results for $\eta$ Ser, $V_{\text{rot}} \sin i = 1.0 \pm 0.8 \text{ km s}^{-1}$ and $\zeta_{\text{RT}} = 4.1 \pm 0.5 \text{ km s}^{-1}$, agree very well with those obtained by Gray & Pallavicini (1989), 2.0 $\pm 0.5$ and 4.0 $\pm 0.5 \text{ km s}^{-1}$, respectively. 

\footnote{$\zeta_{\text{RT}}$ is the radial–tangential macroturbulence dispersion. It is not the Gaussian macroturbulent velocity, but is roughly 2.4 times larger (Gray 1978).}

Figure 3. The mean residual transforms (circles) are shown with the adopted models (line) for two of our program stars.
5. RESULTS

5.1. Radial Velocities

The radial velocities for each star reported in Table 1 were derived using rvsao (Kurtz & Mink 1998) running inside the IRAF8 environment. We compared our results with those reported in C2003 and C2008 (which therefore excludes η Ser). We did not include HD 218732 in the comparisons because it is a spectroscopic binary.

For the 11 stars not known to suffer velocity “jitter” (see C2003 and C2008 for a more complete discussion of this phenomenon), we find ⟨V_rad,CFHT − V_rad,CFA⟩ = +0.13 ± 0.14 km s−1, with σ = 0.46 km s−1. This agreement is very satisfactory. For the eight other stars known to be subject to “jitter,” the mean difference is −0.71 ± 0.44 km s−1, with σ = 1.24 km s−1. Considering the velocity variations in these stars, this agreement is good.

5.2. A First Look at Rotational and Macroturbulent Velocities

Figure 4 distinguishes the RGB (filled circles) from the RHB stars (open circles) in the V_rot sin i versus ζRT plane. Several points are apparent from the figure.

First, much of the line broadening found by C2003 and C2008 for the most luminous red giants, with V_broad9 values approaching 12 km s−1, is due more to macroturbulence than to rotation, whose maximal value among the 12 RHB stars we have studied is only 5.5 km s−1. The 12 RGB stars have ⟨V_broad,CFA⟩ = 8.1 ± 0.6 km s−1 (σ = 2.2 km s−1), but ⟨V_rot sin i⟩ = 2.3 ± 0.6 km s−1 (σ = 1.9 km s−1), and ⟨ζRT⟩ = 6.8 ± 0.2 km s−1 (σ = 0.7 km s−1).

Second, the macroturbulence levels are generally higher in the observed RHB stars than in the RGB stars, with ⟨ζRT⟩ = 9.1 ± 0.7 (σ = 1.8 km s−1). The RHB stars have higher gravities than the RGB stars, so we would be tempted to assume that macroturbulence increases at higher gravities, smaller radii, or lower luminosities, but the discussion in Section 6.2.2 reveals the opposite to be the case. This also conflicts with the findings of Gray (1982) and Gray & Pallavicini (1989), who found that lower-gravity disk giants have higher values of ζRT. Therefore, temperature must play a significant role as well, as had been demonstrated earlier by Gray (1982) and by Gray & Toner (1986).

Third, rotation and macroturbulence play comparable roles in the line broadening of the observed RHB stars. Including the rapid rotator HD 195636, ⟨V_rot sin i⟩ = 9.5 ± 2.2 km s−1 (σ = 6.0 km s−1). Excluding that star, ⟨V_rot sin i⟩ = 7.4 ± 0.9 km s−1 (σ = 2.3 km s−1). These values are comparable to ⟨ζRT⟩ for the observed RHB stars.

Table 2

| Star          | M_V | T_eff | log g | [Fe/H] | V_broad | V_rot sin i | ζRT  | Comments       |
|---------------|-----|-------|-------|--------|---------|-------------|------|----------------|
| HD 3008       | −1.5| 4140  | 1.00  | −1.43  | 9.2     | 4.4 ± 0.8   | 6.9 ± 0.6 | RGB            |
| BD−18 271     | −2.1| 4150  | 0.70  | −1.98  | 7.3     | 0.0 ± 1.5   | 7.2 ± 1.0 | RGB            |
| CD−36 1052    | +0.62| 5890  | 2.50  | −2.00  | 14.4    | 8.8 ± 0.8   | 8.9 ± 0.8 | RHB            |
| HD 23798      | −1.8| 4310  | 1.00  | −1.90  | 5.0     | 0.0 ± 1.0   | 6.7 ± 0.6 | RGB            |
| HD 25532      | +0.79| 5320  | 2.54  | −1.33  | 8.5     | 4.8 ± 1.0   | 7.6 ± 0.7 | RHB            |
| BD+6 648      | −1.79| 4160  | 0.87  | −1.82  | 6.1     | 1.2 ± 1.5   | 6.6 ± 1.0 | RGB            |
| HD 29574      | −2.11| 3960  | 0.57  | −2.11  | 10.2    | 3.7 ± 1.0   | 7.4 ± 0.6 | RGB            |
| HD 82590      | +0.7| 5960  | 2.70  | −1.85  | 13.0    | 7.7 ± 0.6   | 11.0 ± 0.5 | RHB            |
| BD+22 2441    | −1.7| 4320  | 1.00  | −1.95  | 7.3     | 0.0 ± 2.0   | 7.5 ± 0.7 | RGB            |
| HD 106373     | +0.57| 6160  | 2.70  | −2.48  | 13.5    | 10.8 ± 0.7  | 6.5 ± 1.5 | RGB            |
| HD 110281     | −2.6| 3850  | 0.20  | −1.75  | 11.5    | 5.5 ± 1.0   | 6.2 ± 1.0 | RHB            |
| HD 165195     | −2.14| 4200  | 0.76  | −2.16  | 7.6     | 1.8 ± 0.7   | 6.4 ± 0.5 | RGB            |
| HD 184266     | +0.7| 5490  | 2.60  | −1.87  | 11.7    | 5.0 ± 0.5   | 11.5 ± 0.3 | RHB            |
| HD 187111     | −1.54| 4260  | 1.04  | −1.65  | 5.2     | 2.4 ± 0.5   | 5.5 ± 0.7 | RGB            |
| HD 195636     | +0.5| 5370  | 2.40  | −2.40  | 21.5    | 22.2 ± 1.0  | 10.0 ± 1.5 | RGB            |
| HD 214925     | −2.5| 3890  | 0.30  | −2.14  | 9.7     | 4.5 ± 0.7   | 8.4 ± 0.4 | RGB            |
| HD 214362     | +0.6| 5700  | 2.60  | −2.20  | 11.1    | 7.5 ± 1.0   | 8.5 ± 0.7 | RGB            |
| HD 218732     | −2.8| 3900  | 0.20  | −2.00  | 11.1    | 3.1 ± 0.5   | 6.4 ± 0.7 | RGB            |
| HD 221170     | −1.7| 4410  | 1.10  | −1.56  | 7.4     | 1.0 ± 1.0   | 6.4 ± 0.5 | RGB            |
| η Ser         | +1.87| 4890  | 3.21  | −0.42  | 4.0     | 1.0 ± 0.8   | 4.1 ± 0.5 | Disk RGB       |

Figure 4. A comparison of our derived macroturbulence dispersion values, ζRT, and rotational velocities, V_rot sin i.
Fourth, the RHB stars show higher rotational velocities than the RGB stars, especially in the case of HD 195636, a star whose rapid rotation was noted first by Preston (1997). Since RHB stars represent some of the descendents of RGB stars, and since RHB stars have smaller radii, more rapid rotation is expected. But there is a discrepancy when the results are examined more closely. Taking simple means, we find that the 12 RGB stars have $\langle R \rangle = 68 R_\odot$, while the seven RHB stars have $\langle R \rangle = 7.5 R_\odot$ (7.2 $R_\odot$ if we exclude HD 195636). We have been unable to find published moments of inertia of RGB and RHB stars, so we make the assumption that since the core masses and total masses of both classes of star are similar, then if the envelope density distributions are similar, the total moment of inertia will scale as the stellar radii. In this case, we expect the RHB stars to be rotating about nine times faster than the mean RGB rotation rate. The ratio is, in fact, 4.1, if we include HD 195636, and is 3.2 if we exclude it. While our RGB and RHB samples were selected with a bias in favor of larger line broadening, this does not alter our conclusion. In subsection 7.2.2 (see Table 5), we found that the mean $V_{\text{broad}}$ value for the 20 most luminous red giants is $7.7 \text{ km s}^{-1}$, very similar to 8.1 $\text{ km s}^{-1}$ for the RGB stars observed at CFHT. So the bias does not strongly affect the mean rotational value of the luminous red giants. The same is not true for the RHB stars, however. The seven RHB stars in Table 2 have $\langle V_{\text{broad}} \rangle = 13.4 \text{ km s}^{-1}$ (12.0 $\text{ km s}^{-1}$ if we exclude HD 195636), while the 13 RHB stars not observed at CFHT have $\langle V_{\text{broad}} \rangle = 6.4 \text{ km s}^{-1}$. Correcting for the bias for the RHB sample will only lower their mean rotational velocities, increasing the magnitude of the discrepancy between the expected ratio of rotational velocities. What might cause the discrepancy? One possibility is the loss of angular momentum, perhaps by a vigorous stellar wind or pulsation at the most luminous final stages of RGB evolution. RHB stars have larger envelopes than blue horizontal branch (BHB) stars, so, presumably, RHB stars lost less mass during the RGB stage. But as we discuss in Section 7.1.3, it is not clear that the two classes of HB stars have significantly different net amounts of angular momentum. Finally, and this bears on discussions below, the rotation we have measured in the most luminous red giants may reflect a combination of rotation and some other effect, such as pulsation, that may also result in line broadening.

5.3. The Case of HD 195636

The rotation of HD 195636 is much higher than the other RHB stars. It is, however, not out of line with the maximal rotation seen in blue horizontal branch stars. We consider the BHB stars studied by Kinman et al. (2000), excluding BD+32 2188 because the radius derived from its log g value, 11.8 $R_\odot$, suggests it is not a BHB star. Of the remaining 29 stars, two have $V_{\text{rot}} \sin i \approx 40 \text{ km s}^{-1}$, and estimated radii of about 3.3 $R_\odot$. At the estimated radius of HD 195636, $\approx 9.1 R_\odot$, this would correspond to a rotational velocity of about 15 $\text{ km s}^{-1}$, somewhat smaller than our derived value of 22 $\text{ km s}^{-1}$. If these largest rotational velocities simply reflect stars with the most favorable viewing angles ($\sin i \approx 1$), this small sample suggests that there is no great difference between the maximum values of rotation in BHB and RHB stars.

In drawing attention to this star, Preston (1997) explored whether a close binary companion could have interacted tidally, producing such a high rotational velocity. Preston’s observations had limited time coverage, but displayed no sign of radial velocity variability. C2003 reported 43 radial velocities covering 5086 days (13.9 years), and did not detect any radial velocity variability. Our additional radial velocity measure (Table 1) extends the time coverage to 8460 days (23.2 years), and the star has maintained the same radial velocity. We conclude that tidal locking in a binary system is not the source of the rapid rotation. Indeed, of the 20 RHB stars studied by C2003 and C2008, only one has proven to be a spectroscopic binary (HD 108317), and it has one of the smallest line-broadening measures (C2003), with $V_{\text{broad,CfA}} = 5.1 \text{ km s}^{-1}$. Tidal locking does not explain the relatively high rotational velocities seen in some of our RHB stars.

6. ESTIMATION OF ROTATIONAL VELOCITIES

MACROTURBULENT DISPERSIONS FOR A LARGER SAMPLE OF STARS

We have obtained rotational velocities and macroturbulent dispersions for 7 of the 20 RHB stars studied by C2003 and C2008, and 12 of the 116 RGB stars. Furthermore, those 12 RGB stars are all near the tip of the red giant branch. We believe we can extract rotational velocity estimates of the other 13 RHB and 104 RGB stars, at least in a statistical sense.

We use two basic approaches. In one case, we seek to identify a means whereby we can reliably estimate $\xi_{\text{RT}}$ as a function of some parameter, such as absolute magnitude, gravity, or temperature, and then employ some algorithm to remove that contribution to the total line broadening determined using the CfA spectra. In the second case, we simply compare the $V_{\text{broad}}$ values determined from the CfA spectra with the rotational velocities obtained from the CFHT data. This essentially assumes that macroturbulence is either constant among our program stars or small in comparison with rotation.

In the first case, following Massarotti et al. (2008), C2008 found that

$$V_{\text{broad}} = \left( V_{\text{rot}} \sin i + 0.95 \xi_{\text{RT}}^2 \right)^{1/2}.$$  

Figure 5 compares the results from this equation using our CFHT data with those derived at CfA. It is important to recall that this is a purely empirical fit. It is not based on any
Figure 6. A comparison of the rotational velocity, \( V_{\text{rot}} \sin i \), derived from the CfA spectra, \( V_{\text{broad}} \) (CfA), using Equation (2), with that measured using the CFHT spectra, \( V_{\text{rot}} \sin i \) (CFHT). Filled circles are RGB stars; open circles are RHB stars.

Figure 7. A comparison of our derived macroturbulence dispersion values, \( \zeta_{\text{RT}} \), as a function of temperature and gravity. We employ different sizes for the data points to illustrate the different magnitudes of \( \zeta_{\text{RT}} \).

A comparison of our derived macroturbulence dispersion values, \( \zeta_{\text{RT}} \), as a function of temperature and gravity. We employ different sizes for the data points to illustrate the different magnitudes of \( \zeta_{\text{RT}} \).

between \( T_{\text{eff}} \) and \( \zeta_{\text{RT}} \). A weighted least-squares fit results in

\[
\zeta_{\text{RT}} = -0.00158 T_{\text{eff}} + 18.17, \tag{3}
\]

with a correlation coefficient of only \(-0.28\). The scatter about this relation is \(1.7 \text{ km s}^{-1}\), which is negligibly better than taking the mean value for all seven stars, which, as noted above, results in \( \langle \zeta_{\text{RT}} \rangle = 9.1 \pm 0.7 \text{ km s}^{-1} \), with \( \sigma = 1.8 \text{ km s}^{-1} \). In Section 7.1, we return to this topic, finding an additional reason to doubt that a simple description of the behavior of \( \zeta_{\text{RT}} \) can be applied to RHB stars. On the other hand, the RGB stars appear to be well behaved, as we discuss below.

6.2. Expanding the Sample of Calibrating Red Giants

As we have pointed out, the red giant stars studied in this program tend to lie near the tip of the RGB, as may be seen in Figure 7. But the other 104 RGB stars in C2003 and C2008 have a much wider range of luminosities, temperatures, and gravities, and hence we require additional data. Since our results appear to be in good agreement with those obtained for the disk population giant \( \eta \) Ser, we explore now how the results for our metal-poor field red giants compare with results obtained earlier for metal-rich disk population field red giants.

6.2.1. Selection of Disk Stars

The behavior of macroturbulence and rotation of very old and very metal-poor halo stars merits comparisons with the values of younger and more metal-rich disk stars. We have assembled a sample of disk stars from the work of Gray (1982, 1984, 1989), Gray & Toner (1986, 1987), and Gray & Pallavicini (1989), who employed the same tools to determine \( V_{\text{rot}} \sin i \) and \( \zeta_{\text{RT}} \) from very high-resolution, very high S/N spectra, as employed here. Stars retained in the final comparisons with the halo giants had to satisfy several criteria.

First, we chose to exclude stars with spectral types earlier than G8. Nothing is lost thereby since our halo stars have temperatures cooler than this. The additional benefit is that the stars we employ are cooler than the transition in rotational
velocities seen in giant stars with G spectral types (Gray 1989). Stars cooler than G0 to G3 III stars have significantly lower rotational velocities than warmer stars, presumably due to a rotational dynamo-generated magnetic brake.

We elected to retain only those stars with a consistently-applied photometric or high-resolution spectroscopic approach to determinations of stellar parameters. We are fortunate that McWilliam (1990) undertook an extensive spectroscopic survey of metallicities of disk giants, and employed consistent photometric estimations of temperatures and gravities. Fortunately, many of the stars in the studies by Gray and his colleagues were also studied by McWilliam. We have adopted his photometric estimates of effective temperature and gravity, and his spectroscopic determinations of [Fe/H]. However, to avoid extending the comparisons of disk giants and halo giants to temperatures far beyond those of our available halo sample giant stars, we have retained only those stars in McWilliam (1990) with \( T_{\text{eff}} \leq 5000 \) K, in order to be consistent with the use of stars with spectral types of G8 and later.

Gray (1982) noted that the macroturbulence dispersions, \( \xi_{\text{RT}} \), are double-valued for spectral classes G8–K2, with weaker lines indicating larger values than stronger lines in the same star. We have adopted a straight average of the two sets of results because we are going to apply the \( \xi_{\text{RT}} \) results to the line broadenings, \( V_{\text{broad}} \), determined from the CfA spectra (C2003; C2008). Those velocities, in turn, were determined from a match involving all lines, weak and strong, in a narrow wavelength region. Finally, we replaced the \( \xi_{\text{RT}} \) values from Gray (1982) with the newer values presented by Gray (1989).

Absolute visual magnitudes were determined for all the disk stars using parallaxes from Hipparcos. Following McWilliam (1990), we assumed that most stars had zero interstellar absorption. For the stars for which McWilliam estimated \( V_{\lambda} \) values (his Table 7), we adopted those values. We had to exclude \( \gamma^{2} \) Leo because it does not have a measured \( V \) magnitude.

We adopted uncertainties for the determinations of \( V_{\text{rot}} \sin i \) and \( \xi_{\text{RT}} \) given by Gray & Toner (1986, 1987), and by Gray (1989). Gray (1982) did not provide such estimates, so we conservatively adopted \( \sigma(V_{\text{rot}}) = \sigma(\xi_{\text{RT}}) = 1.0 \) km s\(^{-1}\). For the stars from the work of Gray & Pallavicini (1989), we used only the ESO spectra and the lines in the \( \lambda \) 6250 domain, for which the errors were estimated to be \( \pm 0.5 \) km s\(^{-1}\). Table 3 summarizes the results for the 32 disk giants that satisfied the above criteria, although as discussed below, we chose not to use all of them in the final analyses.

6.2.2. Halo Giants Versus Disk Giants

In Figures 8–10, we compare the macroturbulent dispersions, \( \xi_{\text{RT}} \), we have derived for the halo giants and results for disk giants discussed above. Open triangles are disk stars with luminosity classes Ib or II, open squares are disk stars with luminosity class II–III, and open circles are disk giants of luminosity class III. The filled circles represent the halo giants observed at CFHT. Two significant results are apparent.

First, the Ib and II stars do not show a consistent trend. This should be expected, since these stars are generally descendants of massive stars, which do not undergo as much rotational braking while on the main sequence, nor even during their very brief spans as red supergiants or bright giants.

Second, with the exceptions of \( \beta \) Sge and \( \lambda \) Peg, the rest of the disk stars appear to follow the same trends as the older halo giants. If we discard the luminosity class Ib and II stars, as well as \( \beta \) Sge and \( \lambda \) Peg, and employ weighted least-squares fits, we find

\[
\xi_{\text{RT}} = -0.62 M_{V} + 5.307, \tag{4}
\]

with a scatter of only 0.7 km s\(^{-1}\), and a correlation coefficient of \(-0.78\). If we consider the gravity, we find

\[
\xi_{\text{RT}} = -0.80 \log g + 7.33. \tag{5}
\]

In this case the scatter is only slightly greater, 0.8 km s\(^{-1}\), and the correlation coefficient, \( R = -0.72 \), is likewise slightly inferior. Using effective temperature as the independent variable, we find

\[
\xi_{\text{RT}} = 10.85 T_{\text{eff}} - 6.54. \tag{6}
\]

The scatter, 1.0 km s\(^{-1}\), and the correlation coefficient, \(-0.59\), are a little worse than in the above two cases. While it is true that for a fixed age and metallicity, red giants obey monotonic relations between the three independent variables, \( M_{V} \), \( \log g \), and \( T_{\text{eff}} \), when we mix in stars of different metallicities and ages, such correlations fail. Consider, for example, a metal-rich disk giant with \( [\text{Fe/H}] = -0.27 \), \( [\alpha/\text{Fe}] = 0.0 \), an age of 5 Gyr, and \( T_{\text{eff}} = 4000 \) K. According to the “Yale–Yonsei” isochrones (Yi et al. 2003; Demarque et al. 2004), such a star has \( \log g = +1.29 \) and \( M_{V} = -0.77 \). A typical halo giant with the same temperature, but with \( [\text{Fe/H}] = -1.50 \), \( [\alpha/\text{Fe}] = +0.3 \), and an age of 10 Gyr has \( \log g = +0.50 \) and \( M_{V} = -2.40 \). Figures 8–10 indicate that whether one considers \( M_{V} \), \( \log g \), or \( T_{\text{eff}} \) as the independent variable, metallicity differences do not seem to have significant effects on the derived macroturbulence relations.

7. REVISED ROTATIONAL VELOCITIES FOR THE FULL CfA SAMPLE

7.1. Red Horizontal Branch Stars

7.1.1. Macroturbulence

Equation (1) offers us an opportunity to estimate stellar rotational velocities for the stars observed at CfA but not at the CFHT, if we have some knowledge of \( \xi_{\text{RT}} \). In the case of the RGB stars, this turns out to be a vexing problem.

C2008 observed that macroturbulence might explain the monotonic rise in line broadening with increasing effective temperature seen in their sample of 20 field RHB stars. The suggestion relied primarily on the finding by Gray & Toner (1986) that \( \xi_{\text{RT}} \) is a significant function of spectral type (i.e., temperature) within individual luminosity classes. Figure 11 shows a modified version of Figure 12 from C2008. Filled circles represent the line broadenings reported by C2003 and C2008, with the red ones representing stars for which we have derived rotational and macroturbulent velocities (Table 2). Open squares depict \( V_{\text{rot}} \sin i \), and open triangles show \( \xi_{\text{RT}} \). If we focus on the stars in red (from Table 2), we note the near-constancy of the macroturbulent dispersion, \( \xi_{\text{RT}} \), from \( T_{\text{eff}} \approx 5300–6200 \) K. The value appears to be constant, unlike that predicted by Gray & Toner (1986), although the temperature spread is not large, and the sample size is small.

There is a more fundamental concern. The mean value of \( \xi_{\text{RT}} \) for the seven RHB stars observed at CFHT is 9.1 ± 0.7 km s\(^{-1}\). If Equation (1) is correct, then none of the other 13 RHB stars observed only at CfA should have \( V_{\text{broad}} \) values smaller than that, but Table 4 contains several values near 4 km s\(^{-1}\). Figure 11 shows that the seven stars observed at the CFHT are a bit hotter than the thirteen stars observed only at CfA. If \( \xi_{\text{RT}} \) depends on \( T_{\text{eff}} \), as expected, could that explain the disagreement? We answer that question by considering only
the stars in the narrow temperature range of 5200–5600 K.
The three stars observed at the CFHT have \( \xi \text{ eff} \) values of 9.7 ± 1.1 km s\(^{-1}\) (\( \sigma = 2.0 \) km s\(^{-1}\)). The 12 stars observed only at CfA have \( \xi \text{ eff} \) values of 6.1 ± 0.5 km s\(^{-1}\), significantly lower than Equation (1) would predict.

Are the CfA results reliable at such low \( \xi \text{ eff} \) values? Recall that the CfA instrumental resolution is about 8.5 km s\(^{-1}\). Six of the twenty RHB stars studied by C2003 and C2008 were also studied by Behr (2003), using higher resolution and higher S/N spectra, and the mean difference in derived line broadenings for those six stars is only +0.8 ± 0.4 km s\(^{-1}\), \( \sigma = 1.0 \) km s\(^{-1}\). For the two stars common to both sets of studies and with the lowest line broadening, Behr (2003) reports values of 6.6 and 5.4 km s\(^{-1}\) for BD+11 2998 and BD+9 3223, while C2003 found 6.8 and 4.8 km s\(^{-1}\), respectively. The CfA \( \xi \text{ eff} \) values appear to be reliable.

The observational bias of our program may be partly to blame. Most of the stars we observed were selected for study because of their larger-than-average \( \xi \text{ eff} \) values. If that also means that we have selected stars with larger-than-average \( \xi \text{ eff} \) values,
then we might understand the discrepancy between the CFHT results for $\zeta_{RT}$ compared to the smaller values of $V_{\text{broad}}$ for the remaining RHB stars. But if that is the explanation, then the validity of Equation (1) must be questioned because in that case $\zeta_{RT}$ would itself be highly variable even within a narrow range of temperature.

In the absence of a simple explanation, we are forced to conclude that whereas the macroturbulence of red giants appears well behaved (see Figures 8–10), that is not the case for RHB stars. This might be due to short-term variability of the phenomenon, for example. It might also be due to differences in evolutionary state that we cannot readily discern in field stars. For example, some of the field stars may have begun core helium burning with a surface temperature cooler than the instability strip; what we would call zero-age red horizontal branch stars. Other stars may have begun core helium burning within the instability strip (as RR Lyrae variables) or even hotter (BHB stars). There is a trend among globular clusters’ horizontal branches such that the more metal-poor clusters tend to have horizontal branches populated mostly by BHB stars while the more metal-rich clusters favor RHB stars. Most BHB stars eventually evolve back across the $H$–$R$ diagram en route to the asymptotic giant branch, so more highly evolved stars now in the RHB domain might be distinguishable statistically by lower metallicities. Let us consider the 13 stars observed at the CfA for which we do not have CFHT spectra. The seven stars with $V_{\text{broad}} \leq 6$ km s$^{-1}$ have $\langle [\text{Fe/H}] \rangle = -1.99 \pm 0.23$ ($\sigma = 0.62$), while the six other stars, with $6.8 \leq V_{\text{broad}} \leq 9.7$ km s$^{-1}$, have $\langle [\text{Fe/H}] \rangle = -1.61 \pm 0.19$ ($\sigma = 0.47$). There is marginal evidence for the stars with smaller broadening values being more metal-poor (and more likely to have evolved away from the BHB and now be more luminous and slightly larger in
radius than zero-age RHB stars). The argument fails, however, when we consider the seven RHB stars in Table 2 with large rotational velocities and large \( \zeta_{\text{eff}} \), since \( ([\text{Fe/H}]) = -2.02 \pm 0.15 \) (\( \sigma = 0.39 \)). We believe that the simplest interpretation at this point is to admit that the RHB stars do not share a well-defined relationship between macroturbulent dispersion and effective temperature.

7.1.2. Rotational Velocities

While we are not confident in our ability to “remove” the contribution of macroturbulence to the values of \( V_{\text{rot,CIA}} \) using Equation (1), we may still estimate rotational velocities for the other 13 RHB stars using Equation (2). The basic stellar parameters for these stars, taken from C2003 and C2008, are given in Table 4, which includes the results from the application of Equation (2). Figure 12 shows the results, with filled circles representing \( V_{\text{rot}} \) values from Table 2 and open circles representing values deriving employing Equation (2). As expected, the stars observed at the CFHT have larger rotational velocities, due to our bias toward stars with larger line broadening. Excluding the anomalous star HD 195636, the average rotational velocity for the remaining nineteen RHB stars is \( 3.3 \pm 0.8 \) km s\(^{-1}\) (\( \sigma = 0.8 \) km s\(^{-1}\)).

There is an apparent trend in the upper limits of \( V_{\text{rot}} \) as a function of \( T_{\text{eff}} \), with lower values at cooler temperatures (again, we neglect HD 195636). We do expect some sort of trend, if all six stars have identical amounts of rotational angular momentum and have comparable values of rotational axis inclinations. In that particular case, since \( L \propto R^2 T_{\text{eff}}^4 \) and the rotational angular momentum \( J \propto M R^2 \), then for equal masses, \( V_{\text{rot}} \propto T_{\text{eff}}^2 \). Using a log–log calculation we found that the six RHB stars with \( V_{\text{rot}} \) values in Table 2 define \( V_{\text{rot}} \propto T_{\text{eff}}^2 \), which is shown as the dashed line in Figure 12. However, a straight line, \( V_{\text{rot}} \propto T_{\text{eff}} \), provides almost as good a representation of the limited data, so no definitive conclusions may be drawn.

7.1.3. Comparison of Rotation in BHB and RHB Stars

Finally, we can infer one interesting result, somewhat related to the issue raised above regarding rotational angular momentum as a function of temperature. Kinman et al. (2000) provided estimates of \( V_{\text{rot}} \) for 30 BHB stars. The question we ask is whether the RHB stars we have studied show as large a range in rotational velocities as BHB stars, when allowance is made for the different stellar radii and moments of inertia. Because the method employed by Kinman et al. (2000) was based on the full width at half maximum of the \( \lambda \) 4481 Mg \( \Pi \) line, and their spectral resolving power was only about 15 km s\(^{-1}\), we ask what fractions of their BHB sample were found to have \( V_{\text{rot}} \) values larger than 15 and 20 km s\(^{-1}\), and then ask what fractions of our RHB have similar rotational velocities when allowances are made for the different stellar radii.

We consider first the BHB sample. We derived stellar radii by converting the log \( g \) values into radii, assuming a stellar mass of 0.7 \( M_\odot \). This is a somewhat smaller value than the mass we adopted for the RHB stars, 0.8 \( M_\odot \), and leads to a mean stellar radius of 3.3 \( R_\odot \) (excluding BD+32 2188 because the radius derived from its log \( g \) value, 11.8 \( R_\odot \), suggests it is not a BHB star). Six of the remaining 29 BHB stars (21%) have estimated \( V_{\text{rot}} \) values larger than 20 km s\(^{-1}\), and 10 of them (34%) have \( V_{\text{rot}} \) values larger than 15 km s\(^{-1}\). To compare to the RHB sample of Table 2, we must reduce the \( V_{\text{rot}} \) limits by the ratio of the stellar radii, (3.3/7.5), so the 20 km s\(^{-1}\) limit becomes 8.8 km s\(^{-1}\) and the 15 km s\(^{-1}\) limit becomes 6.6 km s\(^{-1}\). Any difference in mass between the more massive RHB stars and the lower mass BHB stars would lower these limits further. Of the seven RHB stars in Table 2, three (43%) have \( V_{\text{rot}} \) values larger than 8.8 km s\(^{-1}\), and five (71%) have \( V_{\text{rot}} \) values larger than 6.6 km s\(^{-1}\). This small sample would suggest that the RHB stars show a higher fraction of relatively rapid rotators than do the BHB stars, but we reiterate that the stars listed in Table 2 were selected on the basis of large \( V_{\text{rot}} \) values, so we must, in fact, include the 13 other RHB stars, for which we have only estimated \( V_{\text{rot}} \). The mean radius of the 20 RHB stars is 8.0 \( R_\odot \), so the 20 and 15 km s\(^{-1}\) limits for BHB stars are now 8.3 and 6.2 km s\(^{-1}\), respectively, again neglecting mass differences. None of the 13 RHB stars have \( V_{\text{rot}} \) values larger than 4 km s\(^{-1}\), so the percentage of RHB stars with \( V_{\text{rot}} \) values greater than 8.3 and 6.2 km s\(^{-1}\) drops to 15% and 25%, compared to the BHB stars’ values (scaled for radius) of 21% and 34%.

RHB stars may show another similarity to BHB stars in the distribution of their rotational velocities. Peterson et al. (1995) found a bimodal distribution of rotational velocities in the metal-poor globular cluster M13, which has a predominantly blue horizontal branch. Behr (2003) noted an apparent bimodal distribution in the rotational velocities of metal-poor field BHB stars as well. Based only on one star, HD 195636, there might also be a “bimodality” in the rotational velocity distribution of RHB stars.

Unfortunately, the small sample sizes prohibit any firm conclusions, except that there is no compelling evidence that the rotational angular momentum of RHB stars is any smaller than that of BHB stars.

7.2. Rotation of RGB Stars

7.2.1. CFHT Data

Figure 13 shows the rotational velocities derived from the Fourier transform analyses as a function of visual absolute magnitude for the stars in Tables 2 and 3, including giants, bright giants, and supergiants.
Consider the spread in \( V_{\text{rot}} \sin i \) values for the disk giants. (As before, we exclude \( \beta \) Sge and \( \lambda \) Peg.) Sixteen of the eighteen disk giants have \( V_{\text{rot}} \sin i \) values between 1.5 and 3.5 km s\(^{-1}\), a quite narrow range. The halo giants appear to be more evenly spread out in \( V_{\text{rot}} \sin i \), from about 0 to 5.5 km s\(^{-1}\). Both distributions are puzzling. For example, if we assume that all the halo RGB stars have similar rotational velocities, the distribution in \( V_{\text{rot}} \sin i \) is not consistent with the expected distribution of viewing angles. If \( V_{\text{rot}} = 5.0 \) km s\(^{-1}\), we expect to find almost two thirds of the stars with \( V_{\text{rot}} \sin i \geq 3.0 \) km s\(^{-1}\), but only about one sixth of the stars would have \( V_{\text{rot}} \sin i \leq 2.0 \) km s\(^{-1}\). Instead we find five out of the twelve (42%) with the higher rotational velocities, and half with the lower velocities. While the statistics are weakened by the small sample size, it appears that more is at work here than just geometry.

7.2.2. CfA Data

Equations (1) and (2) allow us, in principle, to estimate \( V_{\text{rot}} \sin i \) for all of the 116 red giants in the CfA program (C2003; C2008). In the case of Equation (1), we must adopt some representation of \( \zeta_{\text{RT}} \), but Equations (4)–(6) appear to be well behaved.

For several reasons, we prefer to explore the behavior of the rotation of this larger sample of metal-poor field red giants in a slightly different fashion. As noted already, projection effects compromise the results for individual stars. Figure 8 shows that the relation between \( \zeta_{\text{RT}} \) and \( M_V \) appears well behaved, but there is scatter among the individual stars, so the correction is best treated in a statistical fashion. Finally, while Figure 9 of C2008 shows that the \( V_{\text{broad}} \) values determined by C2003 and C2008 are good measures of line broadening down to values as low as 3 km s\(^{-1}\) (despite an instrumental resolution of 8.5 km s\(^{-1}\)), uncertainty remains for each individual star. We conclude that it is best to approach the behavior of rotational velocities derived in the above fashion in a statistical manner.

We began our analysis by removing three stars from the CfA sample, all of them binaries with short periods, and hence relatively close separations, where tidal effects of a companion may induce or inhibit the rotation of the primary star. All three stars have unusually small orbital eccentricities, consistent with tidal interactions. With BD+30 2034, BD+18 2890, and CD−37 14010 removed from the sample, we sorted the remaining 113 metal-poor red giants by \( M_V \) and averaged the results within six bins, chosen simply so that the five more luminous bins have equal numbers of stars (20), while the lowest luminosity bin has 13. Table 5 contains the results, including \( \langle M_V \rangle \), \( \langle R/R_\odot \rangle \), and \( \langle V_{\text{broad}} \rangle \). The table also includes the error, \( \sigma \), and the error of the mean, \( \sigma/\mu \), for each quantity. The last two columns of Table 5 include the resultant mean rotational velocity, obtained using \( \langle V_{\text{broad}} \rangle \) and Equations (4) and (1), and Equation (2), respectively. In cases where the macroturbulence value exceeded \( V_{\text{broad}} \), we set \( V_{\text{seg}} \sin i \) to zero. Note that the results for the most luminous stars obtained using Equation (2) agree well with the mean results for the 12 stars observed at the CFHT (\( M_V = -2.0 \); \( V_{\text{seg}} \sin i = 2.3 \) km s\(^{-1}\)).

Figures 14 and 15 show the results. In the former case we have employed Equations (1) and (4), while in the second case we used Equation (2). We have plotted the mean rotational velocities as a function of stellar radius, which we assume, to first order, tracks the rotational angular momentum since all the stars should have very similar masses and mass distributions. The two binned samples show zero or near-zero rotation at all radii (and luminosities) except for the largest radii. This contradicts any stellar evolution that includes conservation of angular momentum, so either the surface has acquired extra rotation from internal sources or from external ones (such as absorption of a large planet), or the line broadening to which we refer as rotation is something else.

7.2.3. Discussion

The results of Figures 14 and 15 are hard to understand. C2003 and C2008 discussed the concept of transport of internal angular momentum to the surface layers, but that should appear at the radius and luminosity when the convection zone reaches its deepest penetration. Conceivably, Figure 15 is showing such an effect at \( M_V \approx -0.7 \). But that still does not explain the rotation seen (only) among the largest radii, most luminous stars. The planet search effort of Sozzetti et al. (2006) suggests
that absorption of planets is not sufficiently common to explain the results, either. The appearance of additional (admittedly small) line broadening among only the most luminous metal-poor red giants invites a comparison with two other phenomena that likewise appear favored among such stars: velocity jitter and mass loss.

C2003 and C2008 summarized the appearance of jitter in metal-poor red giants. Jitter becomes increasingly common, with typical velocity variations of about 2 km s\(^{-1}\) for \(M_V < -1.4\). For the stars studied as part of this program, a careful consideration of the results in Tables 2 and 3 shows that all five of the stars with \(V_{\text{rot}} \sin i \geq 3.0\) km s\(^{-1}\) show velocity jitter, defined in C2003 and C2008 as stars with \(P(\chi^2) \leq 10^{-6}\). Of the 12 red giants in Tables 2 and 3, the mean rotational velocity for the 8 stars showing velocity jitter is \(2.9 \pm 0.7\) km s\(^{-1}\), compared to \(1.1 \pm 0.5\) km s\(^{-1}\) for the other 4 stars without detectable velocity jitter.

In Figure 16 we display the results for individual stars that went into the bins of Table 5 and Figure 15. Stars displaying velocity jitter are shown as filled circles. The highest luminosity bin in Figure 15 contains the twenty metal-poor red giants with \(M_V \leq -1.5\). Inspection of Figure 16 shows that 11 of the 17 stars in that bin with \(V_{\text{rot}} \sin i \geq 3.0\) km s\(^{-1}\) show jitter.
Clearly velocity jitter is related in some way to the excess line broadening. Does more rapid rotation among the most luminous stars induce jitter? Does velocity jitter masquerade as rotational broadening in some fashion? Or are both phenomena, excess line broadening and velocity jitter, symptoms of the same cause?

Mass loss may be another key to the puzzle. Smith et al. (1992), Dupree & Smith (1995), and Cacciari et al. (2004) studied Ca II K line profiles in metal-poor giants, finding that for $M_V < -1.7$, the line emission is weaker on the violet side than on the red side, so that the ratio of violet to red emission line flux, $V/R$, is less than unity for the most metal-poor stars. That ratio indicates mass outflow, and it is therefore interesting that we have three phenomena, excess line broadening, velocity jitter, and mass outflow, that appear only at the high luminosities we have studied. As in the case of jitter, it is clear that high luminosity favors both excess line broadening as well as mass loss. Furthermore, as Dupree et al. (2007) stressed, the $V/R$ ratios vary among stars observed by C2003, C2008, and in this paper. As in the case of jitter, it is clear that high luminosity favors both excess line broadening as well as mass loss. Furthermore, as Dupree et al. (2007) stressed, the $V/R$ ratios vary among stars observed by C2003, C2008, and in this paper. As in the case of jitter, it is clear that high luminosity favors both excess line broadening as well as mass loss. Furthermore, as Dupree et al. (2007) stressed, the $V/R$ ratios vary among stars observed by C2003, C2008, and in this paper. As in the case of jitter, it is clear that high luminosity favors both excess line broadening as well as mass loss. Furthermore, as Dupree et al. (2007) stressed, the $V/R$ ratios vary among stars observed by C2003, C2008, and in this paper. As in the case of jitter, it is clear that high luminosity favors both excess line broadening as well as mass loss.

Dupree et al. (2007) also noted that the mass loss decreases at lower metallicities, although the trend is weak. Mass loss remains significant in halo giants, despite the lower metallicities and especially the greater ages of halo giants compared to disk giants. This is unexpected for mass loss driven by magnetic processes, but might be explicable in terms of acoustic shock wave heating of the chromospheres of metal-poor giants (Cuntz et al. 1994). The models employed in that paper suggested velocity variations of a few km s$^{-1}$ with periods probably shorter than pulsation, so this might be a mechanism for producing velocity jitter as well as additional line broadening.

### Table 6

**Comparison of Derived Rotational Velocities with Mg II and Ca II Emission line Asymmetries**

| Star      | $M_V$ | $V_{rad}$ | $V_{rad} \sin i$ | $V_{rot}$ (Equation (1)) | $V_{rot}$ (Equation (2)) | Mg II | Ca II |
|-----------|-------|-----------|-----------------|--------------------------|--------------------------|-------|-------|
| HD 2796   | -0.81 | -61.0     | ...             | 7.0                      | 4.1                      | 1.6   | ...   |
| HD 6755a  | 1.50  | -319.2    | ...             | 3.3                      | 0.0                      | 0.0   | $V > R$ |
| HD 6833   | -0.40 | -245.0    | ...             | 7.4                      | 5.0                      | 1.9   | $V < R$ |
| HD 8724   | -1.11 | -113.2    | ...             | 6.0                      | 1.4                      | 0.9   | ...   |
| HD 21022  | -1.17 | 122.3     | ...             | 5.0                      | 0.0                      | 0.3   | ...   |
| HD 23798  | -1.80 | 89.4      | 0.0             | 5.0                      | 0.0                      | 0.3   | $V < R$ |
| HD 2629P  | -1.48 | 14.8      | ...             | 0.5                      | 0.0                      | 0.0   | ...   |
| HD 2957a  | -2.11 | 19.8      | 4.0             | 10.1                     | 7.8                      | 4.3   | $V < R$ |
| HD 36702  | -1.90 | 122.7     | ...             | 6.5                      | 1.5                      | 1.2   | $V > R$ |
| HD 63791  | 0.30  | -108.4    | ...             | 3.7                      | 0.0                      | 0.0   | $V > R$ |
| HD 83212  | -0.90 | 109.1     | ...             | 7.3                      | 4.5                      | 1.8   | $V < R$ |
| HD 88609  | -1.42 | -38.5     | ...             | 4.0                      | 0.0                      | 0.0   | $V < R$ |
| HD 110281 | -2.60 | 141.9     | 5.5             | 11.5                     | 9.3                      | 5.8   | $V < R$ |
| HD 11805d | -1.50 | -100.7    | ...             | 7.4                      | 4.2                      | 1.9   | ...   |
| HD 122956d| -0.70 | 166.0     | ...             | 6.3                      | 2.9                      | 1.1   | $V < R$ |
| HD 126587 | -0.60 | 149.0     | ...             | 4.3                      | 0.0                      | 0.0   | $V > R$ |
| HD 2916   | -1.76 | -12.1     | ...             | 8.2                      | 5.3                      | 2.5   | ...   |
| HD 166161 | 0.79  | 68.3      | ...             | 0.0                      | 0.0                      | 0.0   | $V > R$ |
| HD 17305  | 1.80  | -181.0    | ...             | 7.1                      | 5.8                      | 1.7   | $V < R$ |
| HD 184711c| -2.35 | 102.2     | ...             | 7.7                      | 4.0                      | 2.1   | ...   |
| HDE 232078| -2.15 | 387.2     | ...             | 10.9                     | 8.8                      | 5.2   | $V < R$ |
| HD 187111f| -1.54 | -186.5    | 2.4             | 5.2                      | 0.0                      | 0.4   | ...   |
| HD 204543f| -1.09 | -98.4     | ...             | 5.0                      | 0.0                      | 0.3   | $V < R$ |
| HD 216145 | -1.4  | -116.0    | ...             | 5.5                      | 0.0                      | 0.6   | $V < R$ |
| HD 218732b| -2.80 | -312.2    | 3.1             | 11.1                     | 8.7                      | 5.4   | $V < R$ |
| HD 221170 | -1.70 | -119.0    | 1.0             | 7.4                      | 4.0                      | 1.9   | $V < R$ |
| HD 222434b| -1.20 | 8.8       | ...             | 5.0                      | 0.0                      | 0.3   | ...   |

Notes.

a We employ the $V$ velocity for this binary system.

b Dupree & Smith (1995) cite $V_{rad} = +135$ km s$^{-1}$, which we believe to be incorrect.

c Smith et al. (1992) and Dupree & Smith (1995) both found $V > R$.

d Smith et al. (1992) andDupree & Smith (1995) both found $V > R$.

e Smith et al. (1992) found $V < R$ while Dupree & Smith (1995) found it to be uncertain. We adopt the former value.

f Smith et al. (1992) found $V < R$ while Dupree & Smith (1995) found $V < R$.

g Smith et al. (1992) found $V > R$ and Dupree & Smith (1995) found $V < R$. Both suggested $M_V = -0.3$, but we recommend $-1.09$.

h We employ the $V$ velocity for this binary system.

i We employ the $V$ velocity for this binary system.
Another explanation is that pulsation may drive heating and mass loss (Smith & Dupree 1988). Pulsation is an attractive model since it could also explain velocity jitter and possibly extra line broadening due to the accelerations present in a pulsating atmosphere. C2003 drew attention to the apparent periodicity in the velocity jitter of HD 3008 (172 days; amplitude 1.55 km s\(^{-1}\)) and BD+22 2411 (186 days; amplitude 0.96 km s\(^{-1}\)). The periods are long compared to known long-period variables in metal-poor clusters, but the periodicity is certainly suggestive. It would be worthwhile to explore more carefully the line broadening, radial velocity, and mass loss together in metal-poor luminous giants on a variety of timescales.

8. CONCLUSIONS

We have obtained high-resolution, high-S/N spectra for 12 metal-poor field RGB stars and 7 metal-poor field RHB stars. Fourier transform analyses have yielded good estimates for the macroturbulence dispersion, \(\xi\), and the rotation velocity, \(V_{\text{rot}}\sin i\), for all the stars. We obtained consistent results for HD 29574, which was observed during both observing runs, and for \(\eta\) Ser, which had been studied previously by Gray & Pallavicini (1989). It is good to recall that we selected our stars from the C2003 and C2008 samples of 116 RGB stars and 20 RHB stars, and with a bias toward stars with larger line-broadening values (referred to as rotational velocities by C2003). The RGB stars appear to show very similar macroturbulence behavior as a function of luminosity, gravity, and temperature as do disk giants. The twelve RGB stars studied here, however, show a larger range in rotational velocities, with half showing values of 2.0 km s\(^{-1}\) or less, and five having values in excess of 3.0 km s\(^{-1}\). For the seven field RHB stars, we confirm the rapid rotation of HD 195636 discovered by Preston (1997). When allowance is made for the star’s larger radius compared to BHB stars, its rotational angular momentum is comparable to the largest seen in field BHB stars.

We have explored the use of two empirical methods, neither justified physically, to attempt to exploit the more extensive data on line broadening from C2003 and C2008. The derived rotational velocities of the 13 field RHB stars are, as expected from the CfA results, modest. To compare our results with the much lower resolution BHB data from Kinman et al. (2000), we consider the percentages of BHB stars whose rotation rates are comparable to the spectral resolution, and then make allowances for the differences in radii between the BHB stars and our sample of RHB stars. We find that the RHB stars have fewer rapidly rotating stars than does the BHB sample studied by Kinman et al. (2000).

Both algorithms were applied to binned samples of the field RGB stars, so that statistical fluctuations would be diminished. All but the bin containing the most luminous stars (\(M_V \lesssim -1.5\)) showed nearly zero mean rotation, as expected for the large radii. It is clear that the most luminous metal-poor field RGB stars show enhanced rotation or some other source of line broadening, as found initially by C2003. Unlike the results from C2003, however, the line broadening is relatively modest, on average being 2 km s\(^{-1}\) or 4 km s\(^{-1}\), depending on which algorithm is employed. Our CFHT observations did not extend to the lower luminosities, but are consistent with this result. The 12 RGB stars studied had \(\langle M_{\text{rot}} \rangle = -2.0\) and \(\langle V_{\text{rot}}\sin i \rangle = 2.3\) km s\(^{-1}\).

We draw attention to the fact that the transition in luminosity between negligible and significant rotation occurs at about the same \(M_V\) value as the appearance of velocity jitter and mass loss. This is highly suggestive of a common underlying physical origin, which may be a sign of shock waves and acoustic heating of chromospheres (Cuntz et al. 1994) or pulsation (Smith & Dupree 1988). We recommend a dedicated monitoring program of a few key stars to compare timescales and the presence of line broadening, velocity variations, and mass loss.

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