The [Fe/H] Dependence on the Ca \(\Pi\)-\(M_V\) Relationship

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ABSTRACT. We have examined the Wilson–Bappu effect, a relationship between the absolute magnitude of the star, \(M_V\), and the logarithm of the Ca \(\Pi\) emission width, \(W_0\), over the largest \(M_V\) range to date, +13 to −5, covering \(M\)-dwarfs to type Ia supergiants. We used an extensive literature, the latest \ HIPPARCOS reduction, data from two globular clusters, and new observations from Apache Point Observatory to compile a sample that allowed us to study the effect of [Fe/H] on the Wilson–Bappu relationship. Our results include reporting the deviations from linearity and demonstrating that the Wilson–Bappu relationship is insensitive to metallicity.

1. INTRODUCTION

O.C. Wilson & Vainu Bappu (1957) published a remarkable linear correlation between the logarithm of the Ca \(\Pi\) K emission full width at half-maximum (log \(W_0\)) and the absolute visual magnitude of the star, \(M_V\). They showed that this relationship holds for nonvariable cool stars below type \(F\), regardless of spectral type, [Fe/H], or intensity of the emission line. This correlation is useful to derive an \(M_V\) for cool stars too distant for accurate parallaxes. This relationship can also be found in other spectral lines; Ambruster et al. (1989) published a similar relationship between \(M_V\) and the with of the Mg \(\Pi\) \(k\) line.

The Wilson–Bappu (hereafter WB) effect has aided in studies of variable stars like T Tauri stars as well as main-sequence stars (see Kuhi 1965; Baliunas et al. 1981). The WB effect has been invaluable for our ability to understand chromospheres and heating, see seminal work by Reimers (1973), Neckel (1974), and Ayres (1979). Reimers and Neckel derived a way to relate \(W_0\) to stellar parameters: \(W \sim g^{-2.0}T^{+1.0} [\text{Fe/H}]^{+0.0}\). Ayres was able to establish that the WB effect is largely a result of the surface gravity of the star. The Ca \(\Pi\) line is so optically thick that the increase in width corresponds to an increase in column density in the chromosphere. This relationship between column density and \(W_0\) is predicted to be insensitive to [Fe/H].

Accurate \ HIPPARCOS parallaxes were used for the first time Wallerstein et al. (1999) to study the WB effect for a large number of stars with accurate \(M_V\). Their log \(W_0\) were taken from the large list published by Wilson (1976). Wallerstein et al. (1999) were the first to use \ HIPPARCOS parallaxes and noticed that their small sample of supergiant stars showed unusually large log \(W_0\) and deviated from a linear trend.

Wilson & Vainu Bappu (1957) found that the WB effect has no [Fe/H] dependence. However, they had relatively few stars compared with more recent studies of the WB effect, and there are few metal-poor stars in the solar neighborhood. A chromospheric study of metal-poor giants (Dupree & Smith 1995, hereafter DS95) demonstrated that extremely metal-poor stars ([Fe/H] < −2.0) have a diminished \(W_0\) and did not follow the WB relationship previously established by Wilson (1976). The field giants they studied were too far away to have accurate parallaxes; therefore, they estimated their luminosity by fitting each star’s colors to isochrones of M92, an extremely metal-poor globular cluster. Cacciari et al. (2004) compared stars they studied in the globular cluster NGC 2808 to the study of field stars by Pace et al. (2003) and came to a similar conclusion as DS95, where more metal-poor stars lie above the linear fit derived from more metal-rich stars. However, their result was much more subtle than DS95.

We expand the work by Wallerstein et al. (1999) and DS95 by using the latest \ HIPPARCOS reduction (van Leeuwen 2007) and constraining our sample to stars with parallaxes greater than 3 times the probable error \((\Pi/\sigma_\Pi \geq 3)\)1 instead of \((\Pi/\sigma_\Pi \geq 5)\). We have included all available measurements of \(W_0\) from the

1 When studying individual stars, using parallaxes that are less than 5 times their uncertainty can introduce large errors and unreliable results. For a substantial set of data from which the general behavior of the sample is to be understood, a less strict limit provides sufficient accuracy for the purpose at hand.
literature, additional metal-poor stars observed at the Apache Point Observatory, and Ca II widths of stars from the globular clusters NGC 2808 and ω Cen.

2. THE DATABASE

Parallax is the most reliable and direct method of deriving $M_V$. Hipparcos data constitute the largest sample and most reliable parallaxes, so we used Hipparcos parallaxes (van Leeuwen 2007) for stars that meet our criteria of $\Pi/\sigma_\Pi \geq 3$. The van Leeuwen reduction of Hipparcos data reduced the uncertainty in the parallaxes by a factor of 2 from Perryman (1997), allowing us to study many more stars with acceptable parallaxes.

To investigate the WB effect and its dependence on [Fe/H], we have assembled data from a list of previously published CaII emission widths, $W_0$. The value of $W_0$ is defined as the width of the line, $W$, having the instrumental profile removed. See later in Section 2 for an example of how to measure $W$. The $W_0$ values came from the catalogs by Glebocki et al. (1980), Lastennet & Freire Ferrero (1994) as well as Zarro & Rodgers (1983), Wallerstein et al. (1999), and Pace et al. (2003). For the $M$-dwarfs in our sample, we used Ca II K full width at half-maximum (FWHM) measurements from Rauscher & Marcy (2006). The sample of $W_0$ values still lacks a sufficient number of metal-poor stars, so we included the data by DS95 (shown in Table 1). In the case of a star with multiple observations, the most recent value of $W_0$ was used. For consistency, we used only values of $W_0$. Most of these publications used $W_0$, but some published values of $W$. The instrumental profiles of the spectrographs used were quoted in the paper and we subtracted the value from their published $W$ to obtain $W_0$. We compared the different references and methods to look for systematic differences in $W_0$ that would affect our study. There was no difference in the WB effect between the different references. We chose to use the catalog by Cayrel de Strobel et al. (2001) for our values of [Fe/H] for consistency.

To study other main-sequence stars, we analyzed the spectra from the McDonald Observatory archive (Allende Prieto et al. 2004) and measured $W_0$ ourselves. The spectra from McDonald were already reduced and flux calibrated; we only measured the width of the Ca II K line (see Allende Prieto et al. [2004] for the full list of stars). We also expanded the sample of metal-poor stars with observations with the ARC echelle spectrograph (ARCES) on the 3.5 m telescope at Apache Point Observatory (APO). Observations were made with the standard 1.6” × 3.2” slit. Our spectra have a resolution of 31,500, giving us a spectral profile of 7 km/s. ARCES covers a wide spectral range of 3500–10,000 Å. We also observed some metal-poor giants at Kitt Peak National Observatory on 2000 October 14–17. The resolution of the spectrograph used is 18,000. We reduced

| Identifier | log $W_0$ | $M_V$ | $\Pi/\sigma_\Pi$ | Hipparcos $M_V$ | [Fe/H] |
|------------|----------|-------|-----------------|----------------|--------|
| HD6268     | 1.78     | −1.2  |                 |                 | −2.36  |
| HD6833     | 1.83     | −0.9  | 8.5             | 0.31 ± 0.25     | −1.04  |
| HD8724     | 1.92     | −1.3  | 5.5             | 0.47 ± 0.43     | −1.83  |
| HD25532    | 1.90     | −0.1  | 4.1             | 1.36 ± 0.53     | −1.26  |
| HD26297    | 1.83     | −0.9  |                 |                 | −1.68  |
| HD29574    | 1.87     | −2.6  |                 |                 | −1.88  |
| HD63791    | 1.78     | −0.6  |                 |                 | −1.81  |
| HD103036   | 2.00     | −2.2  |                 |                 | −1.78  |
| HD110184   | 1.77     | −2.3  |                 |                 | −2.44  |
| HD110281   | 1.99     | −2.0  |                 |                 | −1.56  |
| HD118055   | 1.87     | −1.9  |                 |                 | −1.76  |
| HD122563   | 1.79     | −1.5  | 12.1            | −0.55 ± 0.18    | −2.74  |
| HD122956   | 1.80     | −0.9  | 5.4             | −0.12 ± 0.41    | 1.63   |
| HIP70199   | 1.90     | −2.3  |                 |                 | −1.99  |
| HIP73960   | 1.86     | −1.7  |                 |                 | −1.37  |
| HD165195   | 1.84     | −1.8  |                 |                 | −2.24  |
| HD166161   | 1.85     | −1.2  | 5.4             | 1.56 ± 0.40     | −2.24  |
| HD175305   | 1.74     | 1.2   | 17.8            | 1.35 ± 0.12     | −1.16  |
| HD184266   | 1.96     | −1.5  | 7.0             | 1.19 ± 0.31     | −1.44  |
| HD187111   | 1.81     | −1.9  |                 |                 | −1.54  |
| HD204543   | 1.92     | −0.3  |                 |                 | −1.84  |
| HD216143   | 1.85     | −1.5  |                 |                 | −2.25  |
| HD221170   | 1.81     | −1.96 | 4.3             | 0.18 ± 0.51     | −2.19  |
| HD232078   | 1.90     | −2.0  |                 |                 | −1.54  |

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our spectra with IRAF using a data reduction guide provided on the APO homepage\(^3\) (and the reduction script written by John Barentine.\(^3\)) We took extreme care to get the wavelength calibration correct, since it is the \(\Delta \lambda\) that determines \(W\). Our measurements, observation dates, and exposure times are presented in Table 2.

DS95 is of particular interest due to their result of an [Fe/H]-dependent WB effect. However, we choose to only include \(W\) measurements that had a parallax above our \(3\sigma\) criteria. Nine of the twenty-four stars with \(W\) have accurate parallaxes in \textit{Hipparcos}. However, as we show in Table 1 and Figure 1, these stars’ \(M_V\) are on average brighter than \(M_V\) derived from the 2007 parallaxes. DS95 used M92 to estimate the \(M_V\) of all their stars, which have a variety of [Fe/H]. M92 has a luminous and relatively blue RGB due to its low metallicity. When fitting stars of lower metallicity to a bright blue RGB, the stars will have a higher estimated \(M_V\) than the star’s true \(M_V\). We decided to leave out the stars that do not have parallaxes greater than \(3\sigma\) due to the inconsistency of using the RGB to estimate \(M_V\). Many of these metal-poor stars are lost to us since we cannot trust the method used to estimate \(M_V\).

Pace et al. (2003) and Rauscher & Marcy (2006) used Gaussian fitting programs to determine \(W\) because the stars they observed have strong emission profiles. However, our APO sample is very metal-poor and has small Ca II K amplitudes, and is not easily fit with a Gaussian profile. Therefore, we chose to measure the profile emission width using the method of Wilson (1976), as shown in Figure 2. This method was also used on the full sample of spectra from McDonald (Allende Prieto et al. 2004). Allende Prieto used the Harlan J. Smith 2.7 m telescope and the ESO 1.52 m telescope to survey nearby stars with a spectral resolution of \(\sim 50,000\). We compared the WB effect for stars measured by Gaussian fitting versus those stars measured using the FWHM and found that there are no systematic differences in \(W\) space. For the spectra we obtained, we measured the same value of \(W\) (within a tolerance) using the two methods. The tolerance becomes negligible after taking the logarithm.

We include studies of globular clusters NGC 2808 and \(\omega\) Cen to expand our sample of metal-poor stars, allowing us to compare the WB effect among multiple stellar populations. Cacciari et al. (2004) provided measurements of log \(W\) and \(V\) and \((m-M_V)\) of RBG stars in NGC 2808. [Fe/H] values of these stars were published by Carretta et al. (2004). The measurements are shown in Table 3. \(\omega\) Cen has distance modulus of \(\sim 14.07\) (Harris 1996, 2010 edition). The \(V\) and [Fe/H] for stars ROA159, 256, 238, 523, WFI321293, and WFI140419 were published by Vieytes et al. (2011). The identifier ROA stars are from the catalog by Woolley (1966) and the stars identified by WFI were observed with the Wide Field Imaging Camera on the

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\(^3\)See http://www.apo.nmsu.edu/arc35m/Instruments/ARCES/images/echelle_data_reduction_guide.pdf.

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The WB effect was thought to be linear in $\log W_0$ until Wallerstein et al. (1999) demonstrated that the brightest stars have smaller luminosities than their Ca II widths would suggest. $M$-dwarfs showed nonlinearity in Mg II Elgaroy et al. (1990) and Rauscher & Marcy (2006) observed unusual nonlinearity in Ca II FWHM. We used the stars in Rauscher & Marcy (2006) to compare against the other stars in our sample. Rauscher & Marcy (2006) noted that the Ca II FWHM of those stars were within a few km/s of the intrinsic instrumental profile.

Our full sample shown in Figure 3 with a weighted least squares fit of the linear part of the plot (luminosity classes II, III, IV, and bright V’s). Equation (1) is the line of best fit for stars that fall between $1.4 \leq \log W_0 \leq 2.0$ where the errors quoted are the standard deviation of the fit. It is evident that the highest and lowest luminosity class stars do not follow the linear trend of the giants, as previously pointed out by Wallerstein et al. (1999). As a group, the supergiants (and perhaps some misclassified luminosity class II stars), follow a different trend than the rest of the giants. There seems to be a step discontinuity at the transition between the $M$-dwarfs and the $K$-dwarfs ($\log W_0 \approx 1.4$) where there is a spread in $M_V$. Accounting for discrepancies in the dwarfs and supergiants is beyond the scope of this study, and no higher-order polynomial fit was attempted.

$$M_V = -14.7(\pm 0.29) \log W_0 + 27.0(\pm 0.52) \quad (1)$$

### 3.1. Low-Mass Main-Sequence Stars

Main-sequence stars have a strong and well-established relationship between surface gravity, luminosity, and effective temperature. Therefore, we wanted to compare the expected and observed low-luminosity WB effect. Using the $\log g$, $W_0$, $V$ magnitude $[\text{Fe/H}]$ for NGC2808, identifiers from Cacciari et al. (2004), the following table was constructed.

| Identifier | $\log W_0$ | $V$ magnitude | [Fe/H] |
|------------|------------|---------------|--------|
| ROA500     | 1.91       | 13.12         | -0.53  |
| ROA517     | 1.92       | 13.10         | -0.54  |
| WFI139267  | 1.73       | 13.09         | -0.79  |
| WFI263340  | 1.90       | 13.62         | -0.63  |
| WFI305654  | 1.87       | 13.38         | -0.65  |
| ROA159     | 1.89       | 11.98         | -1.72  |
| ROA256     | 1.95       | 12.28         | -1.71  |
| ROA238     | 1.84       | 12.44         | -1.80  |
| ROA523     | 1.82       | 13.39         | -0.65  |
| WFI321293  | 1.88       | 13.69         | -0.72  |
| WFI140419  | 1.86       | 13.49         | -0.68  |

### TABLE 3

| ID no.  | $\log W_0$ | $M_V$  | [Fe/H] |
|---------|------------|--------|--------|
| 3787    | 1.86       | -1.940 | -1.06  |
| 46099   | 1.93       | -1.849 | -1.19  |
| 46580   | 1.89       | -1.900 | -1.03  |
| 47606   | 1.93       | -2.154 | -1.14  |
| 48889   | 1.91       | -2.249 | -1.22  |
| 50119   | 1.87       | -1.704 | -1.21  |
| 50761   | 2.06       | -2.200 | -0.81  |
| 51454   | 1.90       | -2.144 | -1.11  |
| 51499   | 1.99       | -2.155 | -1.24  |

Fig. 2.—Ca II K emission profile of HD64394 observed from McDonald. $W$ is measured as the wavelength difference of the half maximum of the blue and red side of the emission profile at the bottom of the K line. $W$ is measured in km/s. The instrument profile is then subtracted to get $W_0$, modern instruments have an instrumental profile less than 10 km/s.

2.2 m ESO-MPI telescope in Chile (Pancino et al. 2000). We obtained the spectra used in these studies and measured $W_0$ of these stars using the same method as APO and McDonald, described above. The $\omega$ Cen stars are presented in Table 4.

### TABLE 4

| Identifier | $\log W_0$ | $V$ magnitude | [Fe/H] |
|------------|------------|---------------|--------|
| ROA500     | 1.91       | 13.12         | -0.53  |
| ROA517     | 1.92       | 13.10         | -0.54  |
| WFI139267  | 1.73       | 13.09         | -0.79  |
| WFI263340  | 1.90       | 13.62         | -0.63  |
| WFI305654  | 1.87       | 13.38         | -0.65  |
| ROA159     | 1.89       | 11.98         | -1.72  |
| ROA256     | 1.95       | 12.28         | -1.71  |
| ROA238     | 1.84       | 12.44         | -1.80  |
| ROA523     | 1.82       | 13.39         | -0.65  |
| WFI321293  | 1.88       | 13.69         | -0.72  |
| WFI140419  | 1.86       | 13.49         | -0.68  |

Fig. 3.—Wilson–Bappu (WB) effect shown is broken down by luminosity class. The dotted fit is defined in equation (1) and is the weighted least squares fit of the linear region between $1.4 \leq \log W_0 \leq 2.0$. The luminosity class I stars seem to follow a trend that takes them below what equation (1) would predict. The $M$-dwarfs also seem to fall above the fit, having smaller $W_0$ than predicted.
parallaxes, the Pearson’s $r$ correlation coefficient gives a value of $0.09$, indicating that $\Delta \log W_0$ is uncorrelated with [Fe/H]. The study by Cacciari et al. (2004) compare stars from NGC 2808 with the study by Pace et al. (2003) noting that stars in NGC 2808 had a wider spread and tended to be brighter than the fit by Pace et al. (2003) would suggest. However, this could just be a sampling effect. Our study shows conclusively that any dependence on [Fe/H] is has a much smaller effect on the WB effect than $\log g$.

We preserve equation (1) as it stands, adding no term for [Fe/H]. More accurate $M_V$ and a larger sample of $\log W_0$ will be required for a better WB relation. A reanalysis of the [Fe/H] dependence will be possible after the Gaia satellite measures parallaxes down to $5\text{ mas}$ at a limiting magnitude around $V = 10$. By comparison, Hipparcos measured parallaxes better than $0.3\text{ mas}$ out to $V = 20$ and better than $10\mu\text{as}$ at $V = 15\text{mag}$. Compared, Hipparcos measured parallaxes down to $5\text{ mas}$ at a limiting magnitude around $V = 10$.

4. CONCLUSION

We present the largest sample of stars to demonstrate the WB effect over the largest range of $M_V$ to date. The main results of this article are shown in Figures 3 and 5. Our large sample shows that there is a limited range where the WB effect is linear between $+8 \leq M_V \leq -3$ and $1.35 \leq \log W_0 \leq 2.0$. Stars deviate from equation (1) above and below these ranges. To our knowledge, there is no theory of the Ca II emission width that predicts that the relationship should be linear from $13 \leq M_V \leq -6$ or that a higher-order polynomial would be preferable; the issue of what curve should be drawn through the points is not important. What is important is what we can learn from deviation from the luminosity classes. Ayres (1979) was one of the last developments on width–luminosity relationships like the WB effect making arguments that increasing column density leads to an increase in the Ca II width. We can come to the conclusion that the column density of $M$-dwarf chromospheres are

\[ T_{\text{eff}}, \text{ and } M_V \text{ from the zero-age main-sequence isochrones by Girardi et al. (2000) and the relationship } (W_0 \sim g^{-2.0}T^{1.1}) \text{ established by Reimers (1973) and Neckel (1974)} \text{ we can compare expected and observed WB effect. The expected and observed low-luminosity WB effect is shown in Figure 4. The WB effect expected from Reimers (1973) should be linear down to } M_V = 13. \]

Using the conclusions of Ayres (1979), we can speculate that the column depth of $M$-dwarf chromospheres is a lot smaller, leading to the thinner $W_0$ that we observe. We can use the same argument to say that supergiants have a much thicker chromosphere then models predict, leading therefore to a larger $W_0$ than predicted.

3.2. Metallicity Dependence

Because of the large sample and well-behaved linear trend, the luminosity class II, III, IV, and V stars are best suited to examining the effect [Fe/H] has. Figure 5 shows residuals from equation (1), $\Delta(\log W_0)$, as a function of [Fe/H]. The averages of $\Delta \log W_0$ for the metal-poor stars and the metal-rich stars are $-0.034 \pm 0.017$ and $-0.048 \pm 0.042$, respectively. We conclude that, on average, the stars with [Fe/H] $\leq -1.0$ do not deviate significantly from the linear fit. Comparing $\Delta(\log W_0)$ between the metal-poor stars and metal-rich stars shows that they are drawn from the same distribution. A Kolmogorov–Smirnov test between the metal-poor and metal-rich samples yields a value of $0.27$ with a significance of $0.0005$, confirming the null hypothesis that the two groups are drawn from the same parent distribution.

\[ \Delta \log W_0 = 0.027(\pm 0.004) + 0.0005(\pm 0.004)[\text{Fe/H}] \]  

(2)

The lack of [Fe/H] trend disagrees with the conclusions of DS95. The latest Hipparcos $M_V$ differ from the values that they derived using M92 (see Fig. 1). Using only $M_V$ from Hipparcos...
lower than expected, while the supergiants have a larger chromospheric column density than expected.

Modern instrumentation such as the Hipparcos satellite and CCD detectors on ground-based telescopes have permitted the WB effect to be extended to about $M_V = +13$. The value of Figure 3 is the recognition of stars that deviate significantly from the mean so that their chromospheres may be investigated further in detail. Variations in the intensity of the Ca II lines in $G$ and $K$ dwarfs have yielded a great deal of information on their rotation and solar-type cycles of varying chromospheric activity (Baliunas et al. 1981). Our data provides an observing list of stars whose monitoring should produce very interesting results, especially for giants and supergiants of types $G$, $K$, and $M$, regarding their rotations and chromospheric activity variations.

The improved 2007 Hipparcos reduction has allowed us to determine $M_V$ of stars farther away, including more metal-poor stars. High-resolution spectra of metal-poor globular cluster giants allowed us to explore the dependence of [Fe/H] to answer some fundamental questions about the WB effect: Is metallicity the cause of the 0.3 mag spread, or is it responsible for the deviations of the high- and low-luminosity trends? Figure 4 demonstrates clearly the lack of dependence on [Fe/H], as initially asserted by Wilson & Vainu Bappu (1957) and theoretically developed by Ayres (1979).

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