ON THE ABSOLUTE MAGNITUDES OF RR LYRAE STARS

THOMAS G. BARNES III AND SUZANNE L. HAWLEY
McDonald Observatory and Department of Astronomy, The University of Texas at Austin
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ABSTRACT

The photometric data base used by Hawley and colleagues in 1986 to determine a mean absolute magnitude for RR Lyrae stars has been examined for systematic errors. Both the magnitudes published by Fitch et al. in 1966 and Clube and Dawe in 1980 for RR Lyrae stars are shown to differ systematically from intensity mean magnitudes. On the basis of new photometry, we determine better relations for inferring intensity mean magnitudes from partial light curves, using both the Fitch et al. and Clube and Dawe methods. In addition, we show that the Fitch et al. photometry requires magnitude-dependent corrections. After correcting the data base for the above effects, we repeated the statistical analysis to determine the mean absolute magnitude for 142 RR\textit{ab} stars with the result \( <M_v> = +0.68 \pm 0.14 \) mag. This is 0.08 mag brighter than the previous determination by Hawley et al.

Subject headings: stars: RR Lyrae — stars: variables

I. INTRODUCTION

Recently, Hawley \textit{et al.} (1986) determined the absolute magnitudes of RR Lyrae stars using a new observational data base and a rigorous maximum likelihood model. They used proper motions from a homogeneous sample of 159 stars published by Wan, Mao, and Ji (1981) and radial velocities from the compilation by Hemenway (1975) improved for 46 stars by new velocities from Hawley and Barnes (1985). Although apparent magnitudes and reddening values were also taken from Hemenway (1975) and Wan \textit{et al.}, these were largely based upon the earlier work of Fitch, Wiśniewski, and Johnson (1966) and Sturch (1966), respectively. The maximum likelihood model was that of Murray (1983). While suggestive trends were found with respect to metallicity and period for subgroups of the sample, the only statistically significant absolute magnitude determined was that for the entire sample of RR\textit{ab} stars: \( <M_v> = 0.76 \pm 0.14 \) mag.

Strugnell, Reid, and Murray (1986) have repeated this analysis using precisely the same data and maximum likelihood model, but with a different mathematical minimization algorithm. Their solution is understandably the same: \( <M_v> = 0.74 \pm 0.13 \) mag. However, Strugnell \textit{et al.} suggest that the magnitude system of Fitch \textit{et al.} (hereafter FWJ) differs systematically from an intensity mean magnitude scale by +0.12 mag. Further, they argue that the Sturch (1966) reddening scale is that of Burstin and Heiles (1982), which would adjust the RR\textit{ab} result by \(-0.09\) mag. The net effect is to leave the Hawley \textit{et al.} result substantially unchanged.

An independent assessment of the FWJ magnitude scale by Pritchet (1986) also supports the need for a correction of order 0.1 mag.

The problem of RR Lyrae reddenings is likely to be with us for some time yet, with various authors preferring one reddening scale or another. The question of an error in the intensity mean magnitudes, however, should be resolved immediately, particularly since it is claimed to cause a 1 \( \sigma \) change in the RR\textit{ab} mean absolute magnitude.

In this Letter, we determine the correction from the FWJ magnitude scale to a true intensity mean magnitude scale. Repeating the statistical analysis for the RR\textit{ab} sample studied by Hawley \textit{et al.} (1986), the mean absolute magnitude is found to change by \(-0.08 \pm 0.01\) mag. This leads to a revised mean absolute magnitude for the RR\textit{ab} stars (with Sturch reddenings) of \( <M_v> = 0.68 \pm 0.14 \) mag.

II. APPROXIMATED INTENSITY MEAN MAGNITUDES

A common problem in statistical studies of RR Lyrae stars is the lack of light curves of sufficient quality to compute reliable intensity mean magnitudes for the sample. Various authors have adopted approximation schemes to make use of the partial light curves.

FWJ note that “for stars with rapid rise and very asymmetric light curves, mean luminosity lies much nearer to minimum than to maximum.” They use the computed quantity \((M - m)/P\) as a measure of the asymmetry, where \( M \) is the time of maximum light, \( m \) is the time of minimum light, and \( P \) is the period of variation. For an asymmetry parameter of 0.5, FWJ adopt the intensity mean as being midway between the maximum and minimum magnitudes; for 0.1, they adopt an intensity mean one-third of the way from minimum to maximum. Linear interpolation between these extremes gives

\[
<V> = (XV_{\min} + V_{\max})/(X + 1), \tag{1}
\]

where

\[
X = 2.25 - 2.5(M - m)/P. \tag{2}
\]

Clube and Dawe (1980, hereafter CD), also assume an empirical relation between the intensity mean and other, more
easily measured, light curve parameters. They adopt
\[ \langle V \rangle = V_{\text{min}} - 0.39\Delta V - 0.05, \]  \hspace{1cm} (3)
where \( \Delta V \) is the amplitude of the light curve. They estimate the uncertainty in their intensity mean scale to be \( \lesssim 0.1 \) mag.

Strugnell et al. performed a comparison of the FWJ and CD magnitude scales based on 51 stars in common. (Thirteen of the "FWJ" values they use are actually determinations by Hemenway 1975 using eqs. [1] and [2].) They obtain a difference of 0.12 mag in the sense that FWJ are fainter than CD. On the assumption that the CD scale is correct, Strugnell et al. propose a correction to the Hawley et al. mean absolute magnitude for RRab stars of \(-0.12 \) mag.

III. RIGOROUS INTENSITY MEAN MAGNITUDES

For other purposes, we have acquired \( BVRI \) photometry of a selection of RR Lyrae stars with careful attention to complete phase coverage. These data were taken with a high-speed photometer on the 91 cm telescope at McDonald Observatory by the authors in collaboration with M. Frueh, T. J. Moffett, and M. H. Slovak, and will be published elsewhere.

We selected seven RR Lyrae stars which span the relevant range of asymmetry parameter and which do not show the Blazhko effect. For each star, we brought the data into phase agreement and averaged into 0.01 phase bins to form a mean \( V \) magnitude curve. The magnitude curves were converted to intensity curves and numerically integrated to determine the intensity mean magnitude. Using our data we also applied equations (1)–(3) to determine the FWJ and CD mean magnitudes. Table 1 gives comparisons among the various means. Intensity curves for two extreme cases of asymmetry parameter are shown in Figures 1 and 2.

As seen in Table 1, the differences between the intensity mean magnitude and the FWJ approximation to it are correlated with the asymmetry parameter for RRab stars. Let \( \delta V(\text{FWJ}) \) be the correction to the FWJ mean magnitude needed to obtain an intensity mean magnitude. Then the differences for the RRab stars yield
\[ \delta V(\text{FWJ}) = -0.141 + 0.495 \left( M - m \right)/P \, \text{mag}. \]  \hspace{1cm} (4)

The correlation coefficient is 0.83, and the standard deviation of the fit is \( \pm 0.007 \) mag.

<table>
<thead>
<tr>
<th>Star</th>
<th>Intensity Mean (mag)</th>
<th>FWJ Mean (mag)</th>
<th>CD Mean (mag)</th>
<th>( V_{\text{min}} ) (mag)</th>
<th>( V_{\text{max}} ) (mag)</th>
<th>( (M - m)/P ) (phase)</th>
<th>( \Delta V ) (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UU Vir</td>
<td>10.572</td>
<td>10.658</td>
<td>10.554</td>
<td>11.042</td>
<td>9.919</td>
<td>0.13</td>
<td>1.123</td>
</tr>
<tr>
<td>TU UMa</td>
<td>9.809</td>
<td>9.875</td>
<td>9.782</td>
<td>10.206</td>
<td>9.248</td>
<td>0.14</td>
<td>0.958</td>
</tr>
<tr>
<td>SW And</td>
<td>9.713</td>
<td>9.776</td>
<td>9.686</td>
<td>10.102</td>
<td>9.166</td>
<td>0.15</td>
<td>0.936</td>
</tr>
<tr>
<td>V445 Oph</td>
<td>11.025</td>
<td>11.068</td>
<td>10.990</td>
<td>11.375</td>
<td>10.517</td>
<td>0.18</td>
<td>0.858</td>
</tr>
<tr>
<td>DX Del</td>
<td>9.936</td>
<td>9.999</td>
<td>9.926</td>
<td>10.251</td>
<td>9.548</td>
<td>0.18</td>
<td>0.703</td>
</tr>
<tr>
<td>TT Lyn</td>
<td>9.858</td>
<td>9.908</td>
<td>9.837</td>
<td>10.164</td>
<td>9.456</td>
<td>0.19</td>
<td>0.708</td>
</tr>
<tr>
<td>T Sex*</td>
<td>10.054</td>
<td>10.088</td>
<td>10.076</td>
<td>10.300</td>
<td>9.855</td>
<td>0.46</td>
<td>0.445</td>
</tr>
</tbody>
</table>

* Bailey class RRc.
Similarly, for the CD differences for RRab stars, we find

$$\delta V(CD) = +0.011 + 0.012 \Delta V \text{ mag.} \quad (5)$$

The correlation coefficient is only 0.23, and the standard deviation of the fit is $\pm 0.008$ mag. In this case, the best correlation is clearly a simple shift in the zero point:

$$\delta V(CD) = 0.023 \pm 0.008 \text{ mag.} \quad (6)$$

The RRc star T Sex does not fit either of these relations. The two approximation methods give differences $\delta V(FWJ) = -0.034$ mag and $\delta V(CD) = -0.022$ mag.

IV. IMPROVED APPROXIMATIONS FOR INTENSITY MEANS

The previous section demonstrates that neither the FWJ nor the CD method gives a true intensity mean magnitude. The new data in Table 1 permit revision of the constants in equations (2) and (3) so that more accurate intensity means are produced by each method. We obtain as a replacement for equation (2)

$$X = 1.609 - 1.49(M - m)/P, \quad (7)$$

and for equation (3)

$$\langle V \rangle = V_{\text{min}} - 0.375 \Delta V - 0.040. \quad (8)$$

With these new constants, the FWJ and CD relations reproduce our measured intensity mean magnitudes with standard deviations of $\pm 0.010$ mag, and $\pm 0.008$ mag, respectively.

Unfortunately, the FWJ and CD intensity mean scales still do not agree with each other. Adopting our calibrations of the methods, we have recomputed the intensity means for the 38 stars in common to the original FWJ and CD lists. The mean difference between the new values is $0.028 \pm 0.007$ mag (m.e.) in the sense that FWJ is fainter. While this is a small magnitude difference, it is a $4\sigma$ discrepancy, implying that there is still a problem with one of the magnitude scales.

Examination of the FWJ minus CD differences shows them to be correlated with apparent magnitude. To determine which magnitude scale is in error, we have used the magnitudes near minimum light published by Sturch (1966). For each RR Lyrae in Sturch's list, we have formed the mean apparent magnitude in the phase interval 0.78 to 0.88 as an estimate of $V_{\text{min}}$. Figure 3 shows $V_{\text{min}}(FWJ)$ and $V_{\text{min}}(CD)$ plotted against $V_{\text{min}}(\text{Sturch})$.

FIG. 3.—$V_{\text{min}}$ from FWJ and from CD plotted against Sturch’s values. The lines included have unit slope. The agreement of the CD and Sturch scales is clear, whereas the FWJ scale differs from both of the others.
The FWJ values are seen to be systematically fainter than Sturch's values for the fainter stars. One could argue, as do FWJ, that the Sturch values have simply not achieved minimum light and are therefore too bright. Yet it would be remarkable were the CD values too bright by the same amount as Sturch's values. Furthermore, a comparison of the $V_{\text{max}}$ values of FWJ and CD shows the same trend. We conclude that a magnitude error exists in the FWJ photometry.

Least-squares fits give the following:

$$V_{\text{min}}(\text{FWJ}) = -0.131 + 1.015V_{\text{min}}(\text{CD}), \quad (9)$$

and

$$V_{\text{min}}(\text{FWJ}) = -0.127 + 1.013V_{\text{min}}(\text{Sturch}). \quad (10)$$

We have inverted equation (9) to correct the FWJ photometry for the magnitude effect. Repeating our calculation of intensity mean magnitudes for the corrected FWJ data, we now find the FWJ and CD intensity means to be in agreement. The mean difference for the 38 stars in common is 0.000 ± 0.007 mag (m.e.).

In summary, intensity mean magnitudes may be computed for RR Lyrae stars using either the method of FWJ or that of CD with approximately equal accuracy. Replacing the formulae given in the original references are equations (1) and (7), for FWJ, and equation (8), for CD. In addition, the photometry given by FWJ must be corrected through inversion of equation (9).

V. REVISION OF THE ABSOLUTE MAGNITUDE RESULTS OF HAWLEY ET AL.

Given the above improvements in the intensity mean magnitudes, we have repeated the statistical analyses of the Hawley et al. study. For our photometric data base, we have taken the $V_{\text{min}}, \Delta V$ values of CD; the $V_{\text{min}}, V_{\text{max}}$ values of FWJ, corrected through equation (9); the $V_{\text{min}}, V_{\text{max}}$ values of Hemenway (1975, and private communication); and $V_{\text{min}}, V_{\text{max}}$ values from the General Catalogue of Variable Stars (Kukarkin et al. 1969). The latter two references were used only for stars lacking CD and FWJ data. Intensity means were computed using equation (8). We have used the Sturch (1966) reddening values.

In Table 2 we give our new results for the RR$ab$ groups defined by Hawley et al. The typical mean absolute magnitude changes by −0.08 mag. None of the velocity parameters change by more than 1 km s$^{-1}$. To check whether the inclusion of apparent magnitudes drawn from the General Catalogue of Variable Stars may have degraded our result, we repeated the analysis with those stars omitted. The full RR$ab$ sample, now reduced to 116 stars, yielded $\langle M_V \rangle = +0.27 \pm 0.15$ mag. The increase in uncertainty from 0.14 mag to 0.15 mag is statistically significant, so we adopt as our best estimate the result based on 142 RR$ab$ stars, i.e., $\langle M_V \rangle = +0.68 \pm 0.14$ mag.

Using the same method described in Hawley et al., we have determined a new $\langle M_B \rangle = +0.94 \pm 0.14$ mag. One might argue that the FWJ values of $\langle B - V \rangle$ could also differ systematically from true intensity means as do the FWJ $V$ values which would affect our determination of $\langle M_B \rangle$. We have computed intensity mean values of $\langle B - V \rangle$ for the RR$ab$ stars in Table 1 and compared them to the published FWJ values. The mean difference, in the sense FWJ minus this paper, is $-0.014 \pm 0.009$ (m.e.). We judge this to be not significant and therefore adopt the above $\langle M_B \rangle$ value as our best estimate for the RR$ab$ stars.

The mean absolute magnitude of the RR$c$ group should be changed by $-0.03$ mag to 1.06 ± 0.38 mag according to the comparisons in Table 1. This is an insignificant correction.

VI. CONCLUSION

We have compared the Fitch et al. and Clube and Dawe (1980) methods of approximating intensity mean magnitudes to new measured intensity means for a representative sample of RR Lyrae stars. Both methods are found to be deficient. New calibrations of the methods are determined here and shown to be accurate to better than ±0.01 mag.

In addition, a magnitude-dependent effect has been found in the Fitch et al. photometry. By comparison with Clube and Dawe (1980) and Sturch (1966), a prescription is determined for correction of that photometry.

After revising the photometric data base for the above effects, the Hawley et al. (1986) statistical analysis of RR Lyrae stars was repeated. The new result for 142 RR$ab$ stars is $\langle M_V \rangle = +0.68 \pm 0.14$ mag and $\langle M_B \rangle = +0.94 \pm 0.14$. No other result of the Hawley et al. analysis changes. These values are based on the Sturch (1966) reddening scale. Adoption of other reddening scales will change the absolute magnitudes.

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THOMAS G. BARNES III and SUZANNE L. HAWLEY: McDonald Observatory and Department of Astronomy, University of Texas, RLM 15.308, Austin, TX 78712