A Comparison of Photometric Metallicity Calculation Methods Based on OGLE-IV RRab Stars in the Magellanic Clouds

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We use almost 6 500 V- and I-band fine quality light curves of fundamental mode RR Lyrae (RRab) stars from the OGLE-IV survey to compare three different photometric metallicity calculation methods. We calculate [Fe/H] from relations developed for the Johnson V-band, I-band, and for the Kepler Kp-band, and find significant discrepancies between the [Fe/H] distributions. We also show that the relation between the V-and I-band phase parameter φ_{31} used to estimate the iron abundance depends on metallicity, which limits its applicability. Finally, we construct a metallicity map of the Magellanic Clouds and find a metallicity gradient in the Large Magellanic Cloud, but not in the Small Magellanic Cloud.

1 Introduction

In an era of extensive photometric observations, catalogs of RR Lyrae-type variable stars contain tens of thousands of objects. The relation between iron abundance, [Fe/H], and the Fourier parameters of the stars' light curves allows us to investigate mean metallicities and metallicity gradients in various stellar environments, independently of time-consuming spectroscopic observations. For this reason, establishing a reliable relation between [Fe/H] and light curve shape is of great importance. In this paper, we compare known photometric metallicity calculation methods using a large sample of fine quality V-and I-band RRab light curves from the OGLE-IV survey (Udalski et al., 2015).

2 [Fe/H] Calculation Methods

All photometric metallicity calculation methods rely on the period, P, of the star and either the amplitude of variation A or the shape of the light curve, described by the phase parameter $\varphi_{31} = \varphi_3 - 3 \times \varphi_1$, which is calculated from a Fourier series fit to the light curve:

$$I(t) = A_0 + \sum_{k=1}^{n} A_k \times \sin(2\pi kx + \varphi_k) \quad (1)$$

where I is magnitude, $x = (\mathrm{HJD} - \mathrm{HJD}_0)/P$, and n is the order of the fit.

The first formula to calculate [Fe/H] was introduced by Kovacs & Zsoldos (1995) and improved by (Jurcsik & Kovács, 1996, hereafter: JK96) for the V-band data:

$$[\mathrm{Fe/H}]_{\mathrm{JK}} = -5.038 - 5.394P + 1.345\varphi_{31}^{V}\,. \quad (2)$$

It was calibrated with 81 Galactic RRab stars with good quality photometric and spectroscopic data.

The second method for [Fe/H] calculation, also for V-band data, was proposed by Alcock et al. (2000) and Sandage (2004), and used the stars' period P and amplitude A_V. Sandage (2004) provide the following formula:

$$[\mathrm{Fe/H}]_{\mathrm{Sandage}} = -1.453 A_V - 7.990 \log P - 2.145\,. \tag{3}$$

While simpler to use, because it is less sensitive to light curve quality, this method produces a larger scatter and is sensitive to the Oosterhoff dichotomy, so we will not use it in further comparisons.

Motivated by the release of large catalogs of RRab stars by OGLE, Smolec (2005, hereafter: S05) calibrated the $(P, \varphi_{31}) \rightarrow$ [Fe/H] relation for the I-band:

$$\begin{array}{llll} [\mathrm{Fe/H}]_{\mathrm{S}} = & -3.142 & -4.902P & +0.824\varphi_{31}^{I} & \\ & \pm 0.646 & \pm 0.375 & \pm 0.104 & \sigma = 0.18 \end{array} \tag{4}$$

In order to verify the compatibility of the JK96 and S05 formulae, we utilized a catalog of $\sim 27\,000$ RRab in the LMC from OGLE-IV data (Soszyński et al., 2016), and carefully selected $\sim 6\,500$ fine quality light curves. The selection criteria required $I < 19$ mag and $V < 19.6$ mag, at least 80 observations in V and 300 in I-band. In order to remove Blazhko stars from the sample, we rejected RRab with a large scatter around a Fourier model of the light curve, which was adopted to be not higher than 0.07 mag in I and 0.09 mag in V-band.

Figure 1 compares photometric metallicities of the $\sim 6\,500$ RRab stars calculated with the JK96 formula (Eq. 2) for the V-band data with those calculated with the S05 formula (Eq. 4) for the I-band data. We see that the S05 metallicities are on average higher than JK96 metallicities, and the difference is more pronounced at low metallicities. The discrepancy may be due to the fact that the S05 method was calibrated only on 29 stars in the metallicity range $-1.7 <$ [Fe/H] < 0.3, while the JK96 method on 81 stars in the range $-2.0 <$ [Fe/H] < 0.3. Even though the JK96 method gives lower [Fe/H] values at low metallicities, it has been shown that it still overestimates iron abundances in that metallicity range. This is due to the small number of stars at low ([Fe/H] < -2.0) metallicities used for calibration, and wrong spectroscopic iron abundances in some cases (e.g. for X Ari [Fe/H] $= -2.10$ instead of [Fe/H] ~ -2.65, Nemec et al. 2013).

A new $(P, \varphi_{31}) \rightarrow$ [Fe/H] relation was derived by Nemec et al. (2013) using 26 *Kepler* field RRab stars with excellent light curves. The formula is nonlinear and agrees very well with spectroscopic iron abundances. Jeon et al. (2014) provide the transformation from φ_{31}^{V} to φ_{31}^{Kp}, which together with the Nemec et al. (2013) relation allows for calculating [Fe/H] from the V-band light curve:

$$\begin{array}{llllll} [\mathrm{Fe/H}]_{\mathrm{N}} = & -8.65 & -40.12P & +5.96\varphi_{31}^{Kp} & +6.27\varphi_{31}^{Kp}P & -0.72(\varphi_{31}^{Kp})^2 \\ & \pm 4.64 & \pm 5.18 & \pm 1.72 & \pm 0.96 & \pm 0.17 \end{array} \tag{5a}$$

$$\varphi_{31}^{Kp} = \varphi_{31}^{V} + 0.174 \quad (\pm 0.085) \tag{5b}$$

This relation is the most up-to-date, and it corrects the problem of the JK96 equation by overestimating [Fe/H] by ~ 0.3 dex at low metallicity values. On the other

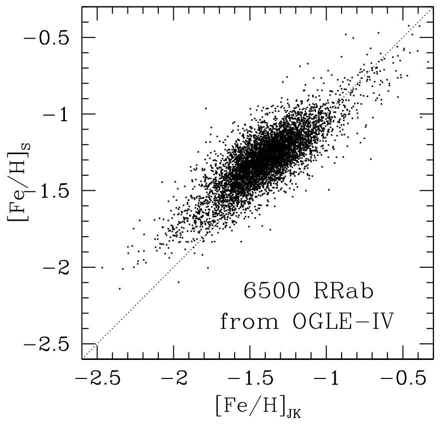

Fig. 1: A comparison of [Fe/H] values from the JK96 method with those from the S05 method.

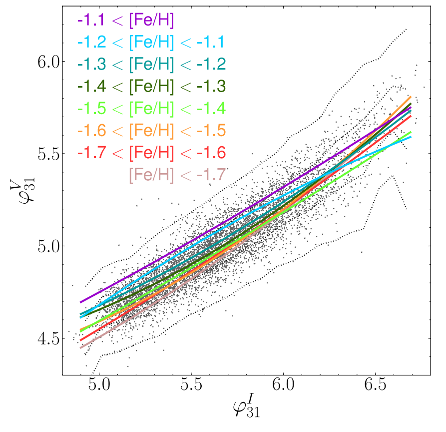

Fig. 2: A metallicity dependent relation between phase parameters φ_{31}^{I} and φ_{31}^{V}.

hand, there are two problems with using the $[\mathrm{Fe/H}]_{\mathrm{N}}$ formula: *a*) the $\varphi_{31}^{V} \rightarrow \varphi_{31}^{Kp}$ transformation (Eq. 5b) has a fairly large error of ± 0.085 and was based on only 34 stars, among which there were a few Blazhko RRab; *b*) there is no analogous transformation from the *I*- to the *Kp*-band, and transforming the phase parameter φ_{31} from the *I*- to the *V*- and then to the *Kp*-band multiplies the errors dramatically.

3 Phase Parameter φ_{31} Interrelations Between Passbands

An alternative approach for determining photometric iron abundances was presented by Deb & Singh (2010) and involved applying the JK96 method to the *I*-band light curves, after transforming the phase parameter φ_{31} from *I* to *V*-band with the equation:

$$\begin{array}{rll} \varphi_{31}^{V} = & 0.568\varphi_{31}^{I} & +0.436 \\ \pm & 0.030 & \pm 0.075 \end{array} \quad (6)$$

The above relation was calibrated with 29 stars in M3 and applied to $\sim 13\,000$ OGLE-III RRab stars in the LMC and revealed that $[\mathrm{Fe/H}]_{\mathrm{S}}$ values are on average 0.07 higher than $[\mathrm{Fe/H}]_{\mathrm{JK}}$ values.

Skowron et al. (2016) attempted to recalibrate Eq. 6, and Figure 2 presents the results, showing a comparison of φ_{31}^{I} calculated from the *I*-band light curves with φ_{31}^{V} calculated from the *V*-band light curves. The authors found that the relation is quadratic rather than linear and more importantly, it depends on metallicity, which limits its applicability to [Fe/H] calculations.

4 Metallicity in the Magellanic System

Figure 3 shows histograms of photometric metallicities for $\sim 6\,500$ RRab from the LMC, calculated with the three methods described in Section 2: $[\mathrm{Fe/H}]_{\mathrm{JK}}^{\mathrm{I}}$ (Eq. 2 after transforming φ_{31}^{I} to φ_{31}^{V}), $[\mathrm{Fe/H}]_{\mathrm{S}}$ (Eq. 4), and $[\mathrm{Fe/H}]_{\mathrm{N2}}^{\mathrm{I}}$ (Eq. 5 after transforming φ_{31}^{I} to φ_{31}^{V}). The ($\varphi_{31}^{I} \rightarrow \varphi_{31}^{V}$) transformations were calculated from metallicity

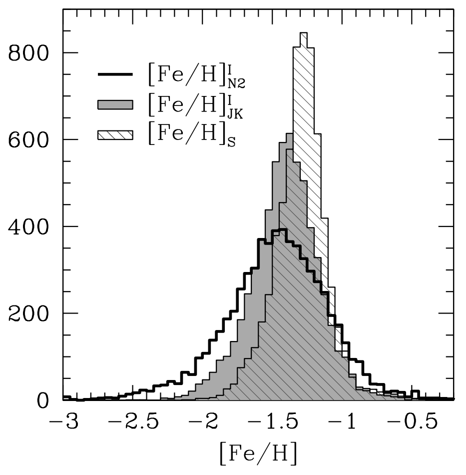

Fig. 3: A histogram of photometric metallicity values that compares three different [Fe/H] calculation methods.

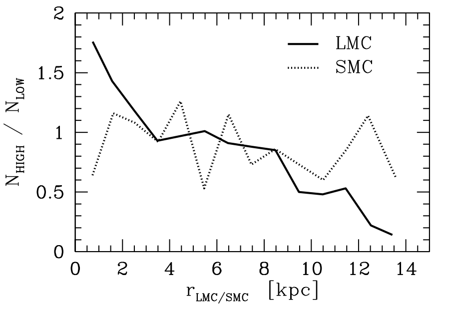

Fig. 4: Ratio of a number of stars vs. distance from the galaxy center for the LMC (solid line) and the SMC (dotted line). N_{HIGH} is the number of stars for which $[Fe/H] > F_1$ while N_{LOW} is the number of stars for which $[Fe/H] < F_2$. In the case of the LMC $F_1 = -0.55$ and $F_2 = -2.0$, while for the SMC $F_1 = -1.3$ and $F_2 = -2.15$.

dependent formulae pictured in Figure 2 rather than from Eq. 6. Mean and standard deviation of the three distributions are as follows: $\langle [Fe/H]^{I}_{JK} \rangle = -1.40 \pm 0.25$, $\langle [Fe/H]_{S} \rangle = -1.30 \pm 0.19$, and $\langle [Fe/H]^{I}_{N2} \rangle = -1.46 \pm 0.38$. The differences between calculated metallicities are immediately visible, both in the mean values and in the distribution shapes. This shows how important it is to be aware of the method that is used for metallicity-related studies and of the effect it has on the final results. It also shows the need to recalibrate these relations with more accurate spectroscopic data.

We then used the full dataset of 32 581 RRab stars from Soszyński et al. (2016) to investigate metal content of the Magellanic Clouds. After careful cleaning of the sample from lower quality and Blazhko light curves, we are left with 24 133 objects in the final sample, of which 20 573 belong to the LMC and 3 560 to the SMC. We calculate [Fe/H] using the most recent method of Nemec et al. (2013) and using the metallicity-dependent transformations of φ_{31} between passbands. To verify whether there is a metallicity gradient in the Magellanic Clouds, in Figure 4 we plot the ratio of a number of stars with high metallicities, N_{HIGH}, to a number of stars with low [Fe/H], N_{LOW}, vs. distance from the center of each galaxy, $r_{LMC/SMC}$. In other words, N_{HIGH} is the number of stars for which $[Fe/H] > F_1$ while N_{LOW} is the number of stars for which $[Fe/H] < F_2$ in a given distance bin. In the case of the LMC, $F_1 = -0.55$ and $F_2 = -2.0$, while for the SMC, $F_1 = -1.3$ and $F_2 = -2.15$. F_1 and F_2 were chosen such that the ratio $N_{HIGH}/N_{LOW} = 1$ for the entire galaxy and the number of stars N_{HIGH} and N_{LOW} in each distance bin was reasonable. Figure 4 shows that the center of the LMC has more metal-rich RRab than the outskirts of this galaxy, suggesting the existence of a metallicity gradient.

5 Conclusions

Our study, based on a subset of $\sim 6\,500$ fine quality light curves of OGLE-IV RRab stars from the LMC, shows that different [Fe/H] formulae give different results, and we conclude that a lot of caution should be used when using photometric [Fe/H] for any astrophysical applications. In fact, a new calibration would be very desirable.

We also show that interrelations between Fourier parameters of the light curves in different filters are metallicity-dependent, which significantly limits their applicability for the [Fe/H] calculation.

Finally, we use a sample of $\sim 20\,500$ OGLE-IV RRab stars in the Magellanic Clouds to show that there is a metallicity gradient in the LMC, but not in the SMC.

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