Calibrating RR Lyrae absolute magnitudes as a function of period shift to correct post-ZAHB evolution systematics

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ABSTRACT. In this contribution we explore calibrating RR Lyrae (RRL) absolute magnitudes as a function of period-shift, as first proposed by Kunder et al. 2009, to correct for evolutionary effects due to evolution off the ZAHB. Period-shift characterises the location in the Period-Amplitude diagram (e.g. Sandage 2006) and correlates with Oosterhoff type, having the potential to account for both the evolutionary and the metallicity dependence of the luminosity. We explore here the performance of the absolute-magnitude-period-shift calibration for the Gaia G-band — the most widely used currently for Galactic structure purposes— using RRLs in globular clusters, and comparing against the traditional absolute-magnitude-metallicity calibration benchmark.

I. THE PROBLEM

- When RRLs evolve off the ZAHB they become more luminous.
- Optical MZ (M-[Fe/H]) relations, used commonly to find RRL distance for Galactic structure studies, are calibrated with RRL samples dominated by RRL in the ZAHB (>75% in the field)
- M-[Fe/H] calibrations cannot account for the evolutionary effect, which can amount to ~0.2 mag in the absolute magnitude
- This translates into a ***systematic*** underestimation of the distance for post-ZAHB RRL by up to ~10%

The problem is then, how to spot post-ZAHB RRLs and to find an observable that correlates with their luminosity (and metallicity)

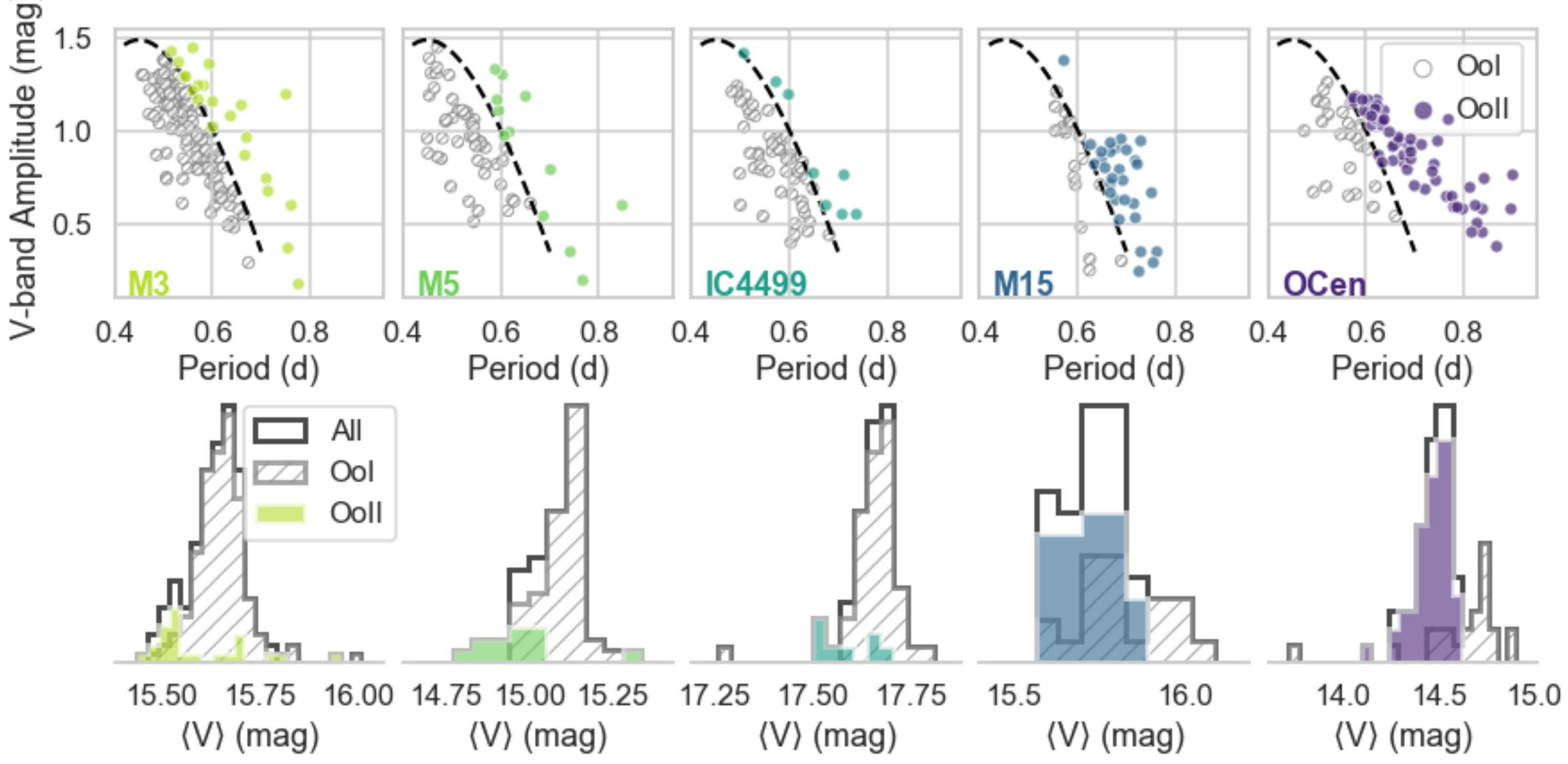

Figure 1. Period-Amplitude (V-band) diagram (**top row**) and apparent intensity-averaged V magnitude distribution (**bottom row**) for RRLs in 5 globular clusters (Clement 2001 catalogue) ranging from Oosterhoff type I (left) to type II and Intermediate (right). The dashed lined separates OoI and II stars. The plot shows in any given cluster, **at fixed metallicity OoII stars are systematically more luminous than OoI counterparts.**

II. THE SOLUTION

The location in the Period-Amplitude diagram correlates both with metallicity and evolution off the ZAHB (Cacciari+ 2005, Lee+ 1990, Clement & Shelton 1999). In globular clusters, where the metallicity is "fixed", the evolutionary effect is evident in the apparent magnitud distribution of RRL, as shown in **Figure 1**.

The "Period Shift", i.e. the period difference at fixed amplitude with respect to the Oosterhoff I (OoI) locus, can be used to calibrate luminosity, as first proposed by Kunder & Chaboyer (2009).

In this contribution we show a first exploration of calibrating the absolute magnitude relation (MZ) for RRab stars in the V and the Gaia G-bands as a function of Period Shift (and Period Shift + [Fe/H]) and compare the performance of this calibration against the widely used M-[Fe/H] benchmark. **The period shift has the advantage of being an entirely photometric observable**, an advantage over M-[Fe/H] for which typically [Fe/H] is unknown and either assumed or estimated via a photometric-metallicity proxy (e.g. [Fe/H]-phi31) leading to much larger uncertainties than if spectroscopic [Fe/H] were used.

III. THE SAMPLE

We used 357 field RRab from the Muraveva et al. 2018 (M18) sample which contains periods, spectroscopic metallicities and V-band intensity-averaged magnitudes. We supplement this data with ASAS-SNII V-band amplitudes (Jayansinghe+ 2018) and updated it with Gaia DR3 parallaxes. **Figure 2** shows the sample's metallicity distribution and Period-Amplitude diagram.

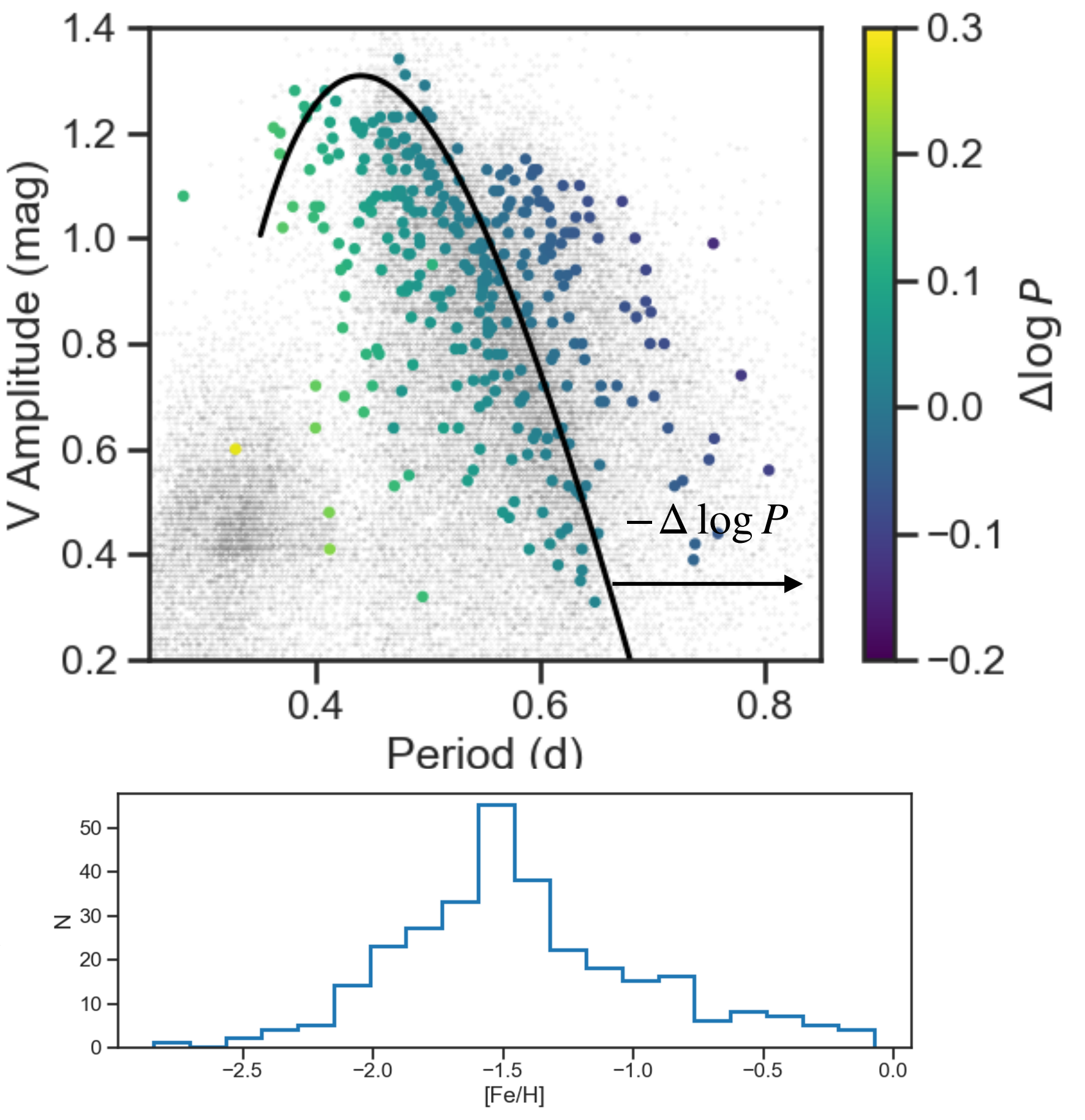

Figure 2. Period-Amplitude diagram (*top*) and metallicity distribution (*bottom*) of the M18 sample (colored circles) of RRL used here (ab stars only).

REFERENCES
Cacciari et al 2005, AJ, 129, 267
Clement & Shelton 1999, ApJ, 515, 185
Clement 2001, AJ, 122, 2587
Kundet & Chaboyer 2009, 138, 1284
Lee et al. 1990, ApJ, 350, 155
Muraveva et al. 2018, MNRAS, 481, 1195

IV. THE INFERENCE

The Period Shift measured with respect to the Oosterhoff I locus, is defined following Clement & Shelton (1999) as

$$\Delta \log P = -0.14\mathrm{Amp_G} - \log P - 0.12$$

The Model. We model the absolute magnitude as a polynomial of the Period Shift of the form

$$M_V = m\Delta \log P + b \quad \text{(Eq. 1)}$$

The Likelihood. We adopt a gaussian likelihood, with an intrinsic dispersion σ_I as a free parameter. For the computation of absolute magnitudes we used the same extinction correction as M18, take the parallax offset $\varpi_0 = -0.033\,\mathrm{mas/yr}$ found by Garofalo et al. 2022 for Gaia DR3 and assume an exponentially decreasing space density prior to compute distances from the parallax (>93% of the sample has parallax errors <20% so, in practice, this does not affect the results).

The Prior. We adopt broad uniform priors for all free parameters m, b, σ_I

V. RESULTS

Figure 3 shows the best fit found for the M18 RRab sample. The resulting (MAP) intrinsic dispersion of the MAP $M_V - \Delta \log P$ relation is found to be $\sigma = 0.147$ mag. This is only slightly higher than the intrinsic dispersion of 0.14 mag reported by M18 for the $M_V - \mathrm{[Fe/H]}$ relation.

	MAP
m	2.557 ± 0.192
b	0.621 ± 0.013 mag
σ	0.147 ± 0.011 mag

Table 1. Maximum a Posterior (MAP) parameters for the calibration of Eq. 1

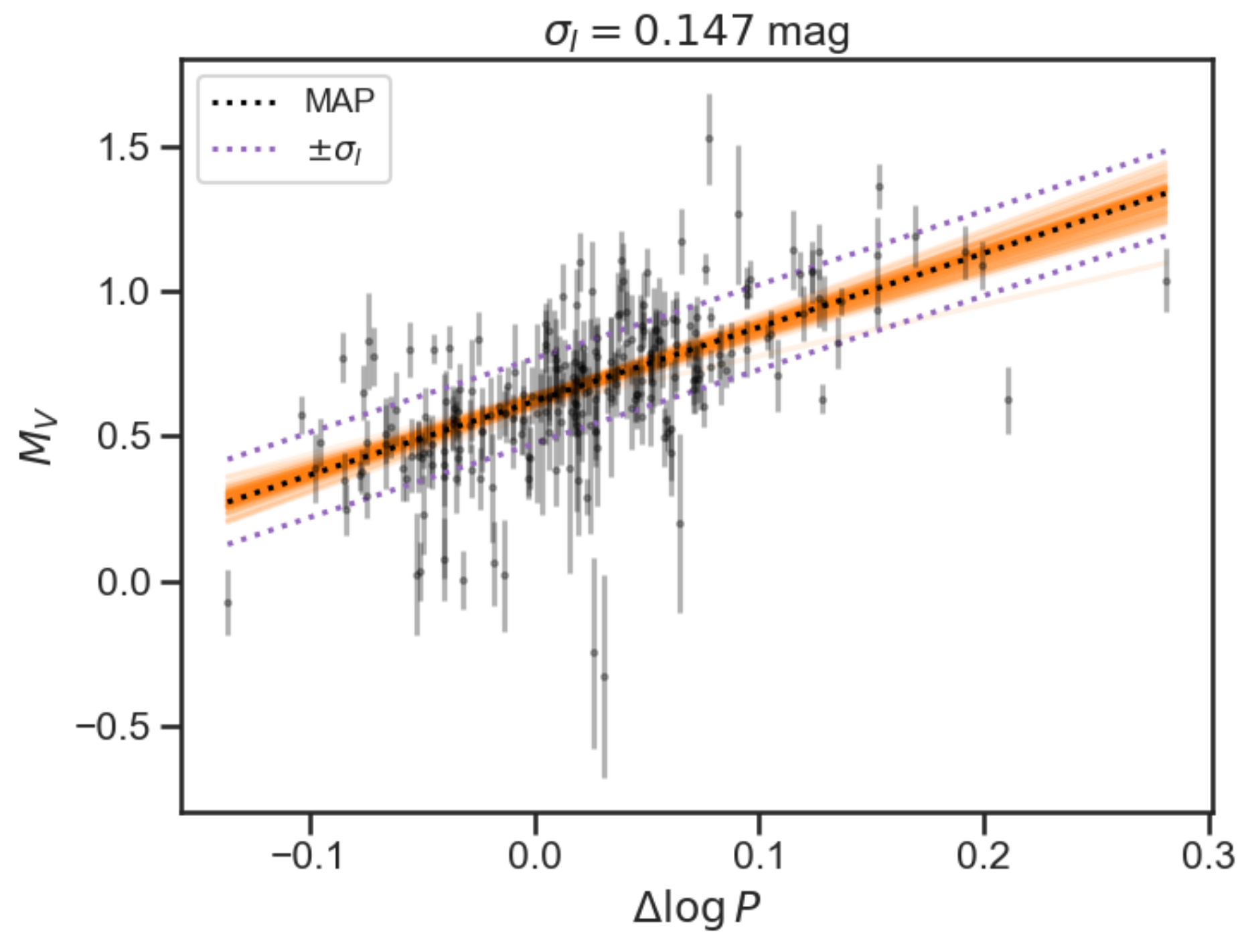

Figure 3. M_V versus period shift $\Delta \log P$ for the M18 RRL sample. The MAP fit is shown (black dotted line), together with 50 random samples from the posterior PDF. The purple dotted lines show the witdh of the (MAP) intrinsic dispersion

Figure 4 shows the apparent magnitud distribution for the RRLs in globular clusters shown in Figure 1, corrected for the difference in the absolute magnitudes due to period shift, computed with the calibration of Eq.1 parameters shown in Table 1. Note how **the systematic offset of OoII (filled) relative to OoI stars is corrected**, the distribution becomes more symmetric and standard deviation is reduced.

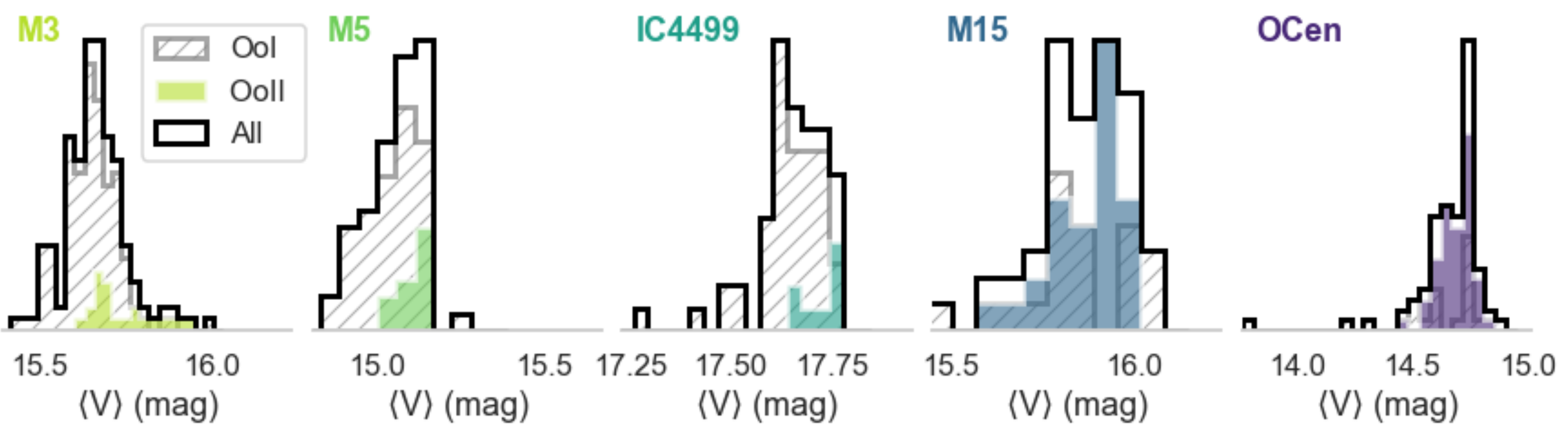

Figure 4. Apparent magnitud distributions for RRLs in globular clusters shown in Fig. 1, corrected for the magnitude difference due to period shift.

V. CONCLUSIONS AND CAVEATS

- We find the $M_V - \Delta \log P$ relation to have an intrinsic dispersion 0.147 mag, only slightly higher than the 0.14 mag of the traditional $M_V - \mathrm{[Fe/H]}$ relation. This shows **the $M_V - \Delta \log P$ relation is competitive for distance calibrations of RRL for Galactic structure purposes**
- The $M_V - \Delta \log P$ relation has the advantage of being based on light curve direct observables (Period and amplitude) **it does not require knowledge (or assumption) of the metallicity**.
- Hierarchical Bayesian Inference that models the OoI reference locus has the potential to yield even better results.

Caveats

- Precise amplitudes are required for the computation of period shifts, which may be a limitation for sparsely sampled surveys.
- The effect of Blazhko modulation in the precision of distances derived using this method will be explored.