

# The Carnegie RR Lyrae Program: The Mid–Infrared RR Lyrae Period–Luminosity Relation in $\omega$ Cen

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## ABSTRACT

Something something metallicity

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## 1 INTRODUCTION

The Carnegie RR Lyrae Program (CRRP) is a Warm *Spitzer* program (PI W. Freedman) with the aim of calibrating the mid–infrared (mid–IR) RR Lyrae period–luminosity (PL) relation. Similar to the Carnegie Hubble Program (CHP) (Freedman et al. 2011), which used mid–IR observations of Cepheids to measure the Hubble constant ( $H_0$  Freedman et al. 2012), the results of the CRRP will be used in to provide an independent, population II calibration of the extragalactic distance scale, and hence an independent measurement of  $H_0$ .

In recent years it has become increasingly important to ob-

tain independent direct measurements of  $H_0$ . The results of Riess et al. (2011) and Freedman et al. (2012), both which use Cepheids and type Ia supernovae (SNe) as their base, agree very well at  $74.4 \pm 2.5$  km s<sup>−1</sup> Mpc<sup>−1</sup> and  $74.3 \pm 2.6$  km s<sup>−1</sup> Mpc<sup>−1</sup>. However, when we consider the latest results from *Planck*, who find  $67.48 \pm 0.98$  km s<sup>−1</sup> Mpc<sup>−1</sup> (Planck Collaboration et al. 2015), there is tension. The *Planck* study derives their measurement from a model of the cosmic microwave background (CMB), so is completely independent of the Riess et al. and Freedman et al. results.

There have been several recent works that have investigated possible sources of uncertainty in the distance ladder that may contribute to the discrepancy between  $H_0$  measurements. For example, Rigault et al. (2015) examine the differences in star formation rates in type Ia SNe host galaxies. They find that the intrinsic brightness

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of a SNe Ia may be affected by the local host environment; i.e. whether the SN occurs in a locally star forming or locally passive environment. [Efstathiou \(2014\)](#) reanalysed the Cepheid data from [Riess et al. \(2011\)](#), and found that different outlier rejection criteria lowered the resultant value of  $H_0$  to  $70.6 \pm 3.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , making it compatible with the value from *Planck*.

The CRRP assess a systematic that was unreachable in the original CHP — the intrinsic accuracy of the mid-IR Cepheid standard candle distance scale when compared to the standard ruler distance scale of CMB and Baryon Acoustic Oscillation (BAO) measurements. With only one “test candle” it is impossible to make any assessment of this accuracy. However, when we have two standard candles with similar precision we can make meaningful comparisons and assess their systematic accuracy.

RR Lyrae variables are intrinsically fainter than Cepheids, and in the optical follow a much shallower, even horizontal, PL relation. Determining an accurate distance to an RRL in the *V* band requires knowledge of its metallicity. However, in more recent years near- and mid-IR observations have shown the true power of RRL as precision distance indicators. In a similar vein to Cepheids, *HST* parallaxes were obtained for several Galactic RRL calibrators ([Benedict et al. 2011](#)) and several groups have been studying the populations of RRL in globular clusters and nearby dwarf spheroidal galaxies (e.g. [Garofalo et al. 2013](#); [Ordoñez et al. 2014](#); [Cusano et al. 2015](#); [Kains et al. 2015](#), and references therein).

In the mid-infrared RRL exhibit similar properties to Cepheids ([Madore et al. 2013](#)). At the wavelengths observed by Warm *Spitzer* (3.6 and 4.5  $\mu\text{m}$ ) we do not see photospheric effects, but only the effects of temperature driving the pulsation. Essentially, the mid-infrared light curve is tracing the change in radius of the star over a pulsation cycle. A by-product of this effect is that the intrinsic width of the RRL PL relation is also minimised in the mid-infrared (mid-IR). The PL relation for pulsational variables can be thought of as a two-dimensional projection of the three-dimensional period–luminosity–colour relation (see figure 3 of [Madore & Freedman \(1991\)](#) for a graphical representation). As the colour–width decreases in the mid-IR, the width of the PL naturally decreases. As one moves from the optical to the mid-IR, the slope of the PL relation steepens and its dispersion dramatically decreases; this phenomenon has been demonstrated in simulations by [Catelan et al. \(2004\)](#), and by several observational efforts, as illustrated in fig. 4 of [Madore et al. \(2013\)](#). The slope should asymptotically approach the predicted slope of the period–radius relation, resulting in a slope between  $-2.4$  and  $-2.8$ . Through this decrease in dispersion we have found that the intrinsic width of the mid-IR PL for RRL is in fact smaller than for Cepheids – 0.05 mag compared to 0.10 mag ([Monson et al. 2015](#), in prep), ([Neeley et al. 2015](#)). This translates to an uncertainty on an individual RR Lyrae star of 2%, compared to 4% for Cepheids.

In this work we focus on the effect of metallicity on the RR Lyrae (RRL) PL relation. Several Galactic Globular Clusters are being observed as part of CRRP, but  $\omega$  Cen is unique in that it exhibits a measureable spread in metallicity ([Freeman & Rodgers 1975](#); [Villanova et al. 2007, 2014](#)).

There are very few metallic or molecular transition lines in the mid-IR at typical RRL temperatures, so the effects of metallicity on luminosity should be minimised. However,  $\omega$  Cen provides the ideal test bed for any effect that we may not have predicted. Such an effect is not out of the realm of possibility; for example, the strength of the CO band head at 4.5  $\mu\text{m}$  has been found to have a significant dependence on metallicity, and has such prevented the IRAC 4.5  $\mu\text{m}$  Cepheid observations from being used for distance measurements

in the CHP. ([Scowcroft et al. 2011](#); [Monson et al. 2012](#); [Scowcroft et al. 2015](#)). As our concern in this program is systematic precision, we must ensure that similar effects do not plague the RRL distance scale.

$\omega$  Cen is ideal for calibrating the RR Lyrae period–luminosity–metallicity relation, as it contains 192 known RR Lyrae ([Kaluzny et al. 2004](#)) with a range of metallicities spanning over 1.5 dex ([Bono 2013](#), priv. comm.); a metallicity spread this wide is not found in any other GGC. One of the advantages of using globular clusters to calibrate PL coefficients is that all stars in a cluster can be considered to be at the same distance from Earth. We can therefore assume that any dispersion in the PL relation is a combination of the a) the intrinsic dispersion of the PL relation, b) the photometric uncertainties, and c) dispersion induced by the spread in metallicity of the RRL. We have measured the intrinsic dispersion of the RRL PL from other clusters (e.g. M4, [Neeley et al. \(2015\)](#)), and our photometric uncertainties are well understood, so the only unknown in this problem is the dispersion due to the spread in metallicity of the cluster.

$\omega$  Cen is unique in that we can also take a second approach to establishing the metallicity effect on the RRL PL relation. As it is such an interesting system,  $\omega$  Cen is extremely well studied and many of its RRL have spectroscopic or photometric metallicities available. As another test of the effect of metallicity, we use these measurements to assess the  $\gamma$  parameter for the GGC, where

$$\gamma = \frac{\Delta \text{mag}}{[\text{Fe}/\text{H}]}, \quad (1)$$

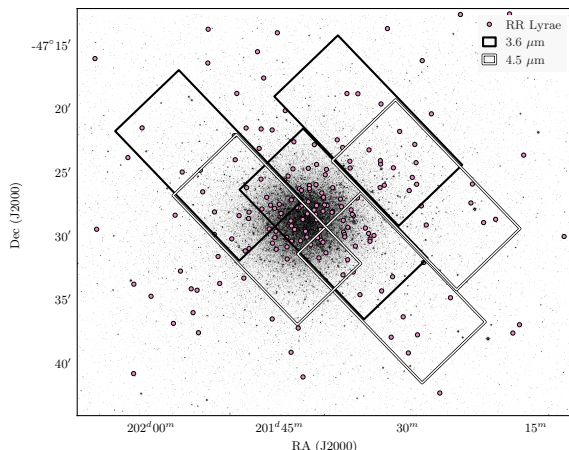
similar to  $\gamma$  used to quantify the effect of metallicity on the zero-point of the Cepheid PL relation.

The paper is set out as follows: Section 2 details the observations and data reduction. Section 3 presents the photometry of the  $\omega$  Cen RRL. Section 4 describes the mid-IR PL relations and Section 5 discusses the application of these to a distance measurement of  $\omega$  Cen. Section 6 and Section 7 examine the effect of metallicity on mid-IR observations of RR Lyrae variables and its implications for distance measurements and the extragalactic distance scale. In Section 8 we present our conclusions.

## 2 OBSERVATIONS & DATA REDUCTION

The Warm *Spitzer* observations for this work were taken as part of the Carnegie RR Lyrae Program (PI W. Freedman, PID 90002). Three fields in  $\omega$  Cen were chosen; their positions and the positions of known  $\omega$  Cen RR Lyrae variables are shown in Figure 1. To obtain optimal RRL light curves we observed each field 12 times over approximately 16 hours, roughly corresponding to the period of the longest period RRL we expected in the field. The observations of all three fields were taken on 2013-05-10 and 2013-05-11. Each field was observed using *Spitzer* IRAC ([Fazio et al. 2004](#)) with a 30s frame time with a medium scale, gaussian 5-point dither pattern to mitigate any image artefacts. Images were collected in both the 3.6 and 4.5  $\mu\text{m}$  channels. The elongated field shapes (seen in Figure 1) come from the design of IRAC; while the [3.6] channel is collecting on-target data, the [4.5] channel collects off target data “for free”, and vice versa. We chose to include these off-target fields to maximise the number of RRL in our final sample and to increase the legacy value of our data set to the community.

The science images were created using MOPEX ([Makovoz et al. 2006](#)), first running overlap correction on the basic calibrated data (cBCDs) then mosaicking them at 0.6 arcsec pixel scale using the



**Figure 1.** A  $K_S$ -band image of  $\omega$  Cen from the FourStar camera, overlaid with the catalog of RR Lyrae (Kaluzny et al. 2004) and footprints of the three IRAC fields.

drizzle algorithm. Mosaicked location–correction images were created at the same time.

PSF photometry was performed using the DAOPHOT and ALLFRAME (Stetson 1987, 1994). The PSF model was created for each field/filter combination using the first epoch data. This was then applied to each other epoch. As the observations were taken so close together the effects of telescope rotation between epochs on the mosaicked PSF were minimal, so making a single good PSF model for each field/filter combination was much more efficient than creating one for every epoch.

Master star lists for ALLFRAME were created for each filter/field combination using a median mosaicked image created by MOPEX. We did not use the same single master star list for both filters as only a small proportion (1/3) of the  $3.6\ \mu\text{m}$  and  $4.5\ \mu\text{m}$  fields overlap each other. Instead we performed separate ALLFRAME reductions for each filter, and combined the results after the fact using DAOMATCH and DAOMASTER. Our photometry is calibrated to the standard system set by Reach et al. (2005).

The primary limiting factor in this data is crowding: 77 RR Lyrae variables out of the original catalog of 192 (Kaluzny et al. 2004) were rejected due to crowding. We compared the *Spitzer* images to a  $K_S$ -band image from the FourStar infrared camera on Magellan (Persson et al. 2013), with a resolution of 0.159 arcsec. This enabled us to see which stars were significantly contaminated.

### 3 RESULTS

Our final photometry catalog, including magnitudes and errors for  $JHK_S$ ,  $3.6\ \mu\text{m}$ , and  $4.5\ \mu\text{m}$  is presented in Table 1.

The average magnitudes are calculated by first converting the individual values into fluxes, then taking the mean flux and converting that back to a magnitude. The photometric errors of the time series data are added in quadrature and divided by the square root of the total number of observations to obtain the final error value.

### 4 PERIOD–LUMINOSITY RELATIONS

For the final PL relations, we use only the stars for which we have photometry in all five bandpasses. Our final RRL sample consists

**Table 1.** Theoretical near- and mid-IR RR Lyrae period–luminosity relations for  $\omega$  Cen; NIR parameters are from Marconi et al. (2015) and MIR parameters are from Braga et al. (in prep.)

Band	Mode	$a$	$b$	$c$	$\sigma$
$J$	FO	−1.070	−2.460	0.150	0.040
	FU	−0.510	−1.980	0.170	0.060
$H$	FO	−1.310	−2.700	0.160	0.020
	FU	−0.760	−2.240	0.190	0.040
$K_S$	FO	−1.370	−2.720	0.150	0.020
	FU	−0.820	−2.270	0.180	0.030
[3.6]	FO	−1.344	−2.718	0.152	0.021
	FU	−0.786	−2.276	0.184	0.035
[4.5]	FO	−1.348	−2.720	0.153	0.021
	FU	−0.775	−2.262	0.190	0.036

of 25 RRL (12 fundamental mode and 13 first overtone). This sample reduces bias by ensuring that the same range of periods and metallicities are sampled for each wavelength.

Our full, uncrowded RR Lyrae sample consists of 96 stars in  $J$  and  $H$ , 98 in  $K_S$ , 36 in  $3.6\ \mu\text{m}$ , and 43 in  $4.5\ \mu\text{m}$ . The PL fits to this sample are shown in Figure 3, and the distance moduli and reddening values obtained from these fits are shown in Figure 6.

We use the near- and mid-infrared PL relation parameters presented in Marconi et al. (2015) and Braga et al. (in prep.) as fiducial in our initial PL fitting. We also use empirical PL relation parameters derived from photometry of RR Lyrae variables in the globular cluster M4 (NGC 6121) from Neeley et al. (2015) for comparison. With the use of preexisting PL relation coefficients, the distance modulus becomes the only free parameter in our fit. We fit all distance moduli using an unweighted least-squares method, and fit the distance modulus to each pulsation mode in each wavelength separately.

Not all stars in our sample have known metallicity values, so we use an average  $[\text{Fe}/\text{H}]$  value for all RR Lyrae variables in the cluster. We use both photometric (Rey et al. 2000) and spectroscopic (Solima et al. 2006) metallicities for comparison. We find that there is little correspondence between individual metallicity measurements for stars which have both spectroscopic and photometric metallicity values, as shown in Figure 2, and that the average metallicities of the spectroscopic and photometric catalogs differ by nearly 0.1 dex. We use a mean photometric  $[\text{Fe}/\text{H}]$  of  $-1.584$  and a spectroscopic  $[\text{Fe}/\text{H}]$  of  $-1.677$ .

The theoretical RRL PL relations for each adopted average metallicity are shown in Figures 4 and 5 and described in Table 1. The relations take the form

$$M = a + b \times \log P + c \times [\text{Fe}/\text{H}] \quad (2)$$

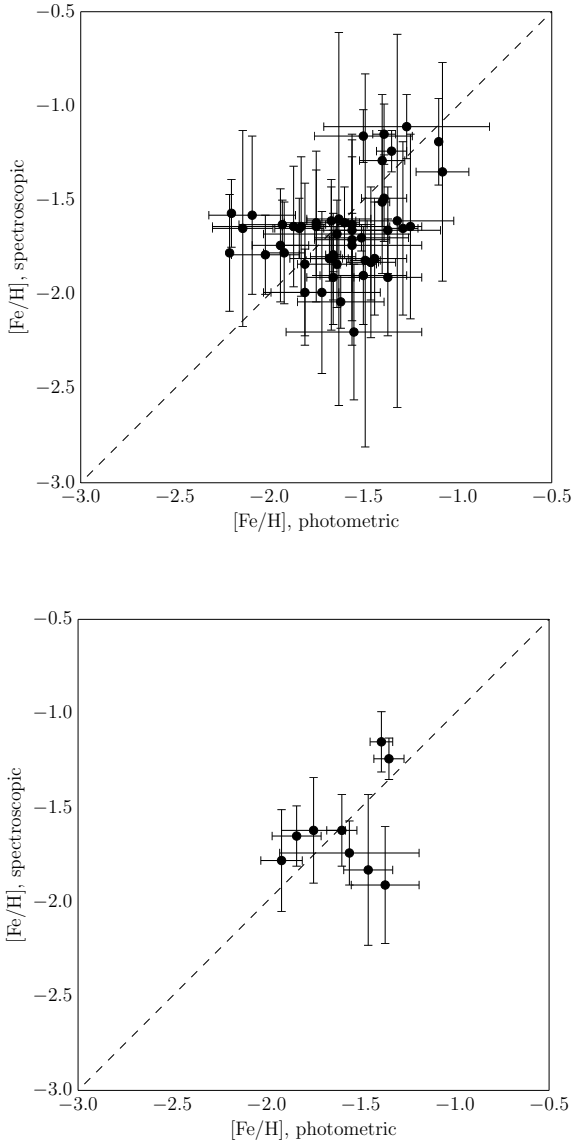
where  $a$ ,  $b$ , and  $c$  are theoretically derived coefficients.

We also use empirical PL relations derived from photometry of RR Lyrae variables in the globular cluster M4 (NGC 6121) from Neeley et al. (2015) for comparison.

The empirical RRL PL relations from Neeley et al. (2015) are described in Table 1. The relations take the form

$$M = a + b \times \log P \quad (3)$$

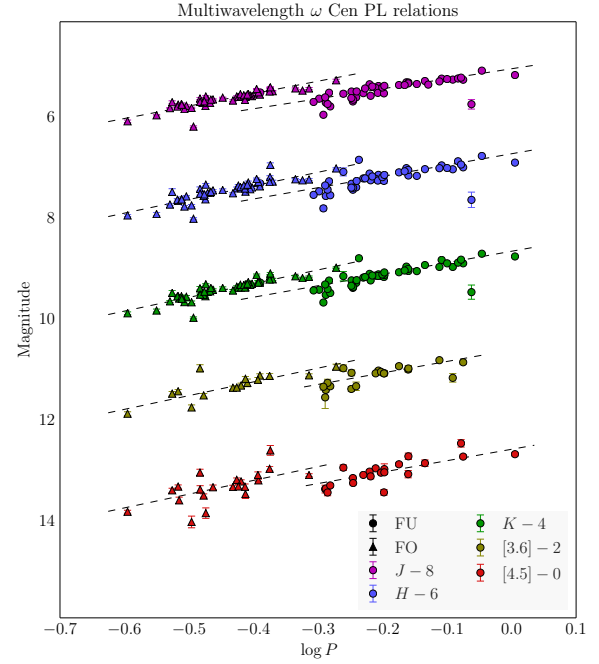
where  $a$  and  $b$  are empirically derived coefficients.



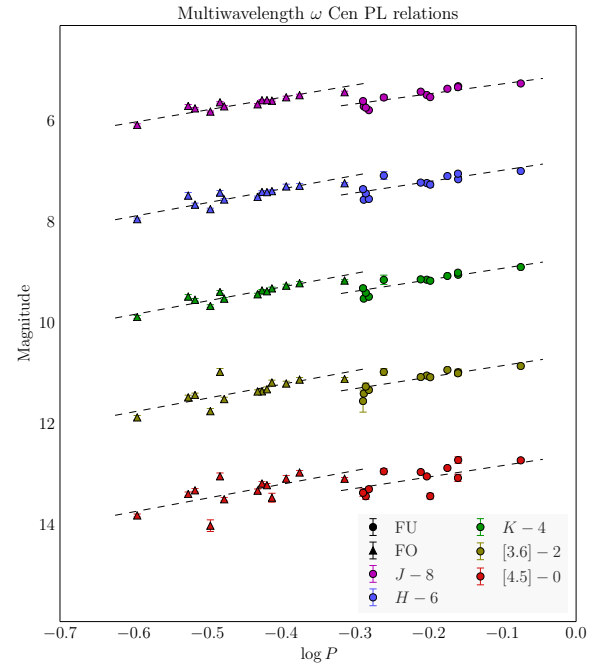
**Figure 2.** Spectroscopic vs. photometric measurements of  $[\text{Fe}/\text{H}]$  for RR Lyrae variables in  $\omega$  Cen. Top: All stars for which both catalogs have  $[\text{Fe}/\text{H}]$  measurements. Bottom: only the stars which appear in our final sample.

**Table 2.** Empirical mid-IR RR Lyrae period–luminosity relations for  $\omega$  Cen from Neeley et al. (2015).

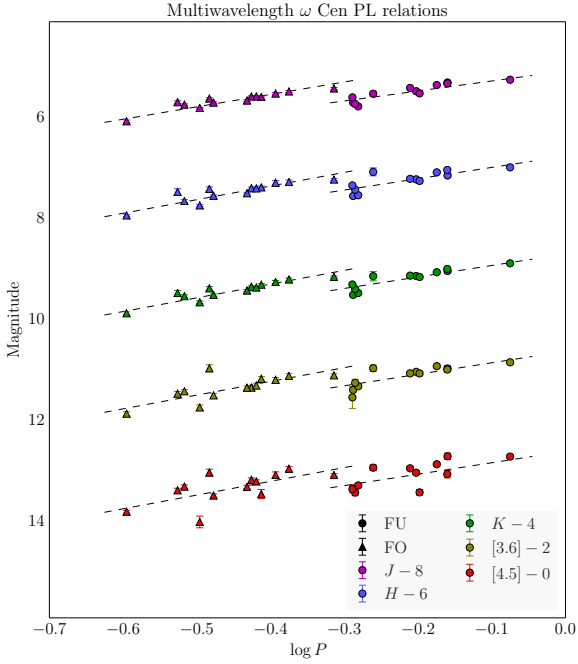
Band	Mode	$a$	$b$	$\sigma$
[3.6]	FO	-1.344	-2.658	0.021
	FU	-0.786	-2.370	0.035
[4.5]	FO	-1.348	-2.979	0.021
	FU	-0.775	-2.355	0.036



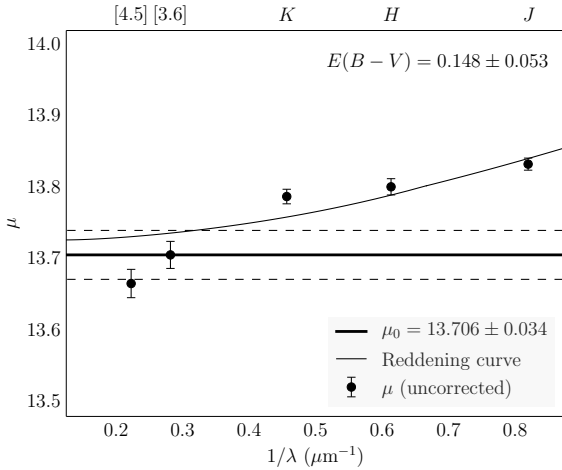
**Figure 3.** PL relations for  $JHK_S$ ,  $3.6\ \mu\text{m}$ , and  $4.5\ \mu\text{m}$  photometry assuming an  $[\text{Fe}/\text{H}] = -1.584$ , corresponding to the average photometric metallicity from Rey et al. (2000). All uncrowded RRL for which we have photometry are included in these fits.



**Figure 4.** PL relations for  $JHK_S$ ,  $3.6\ \mu\text{m}$ , and  $4.5\ \mu\text{m}$  photometry assuming an  $[\text{Fe}/\text{H}] = -1.584$ , corresponding to the average photometric metallicity from Rey et al. (2000). Only those RRL that appear in all five near- and mid-infrared bands are included in the fit.



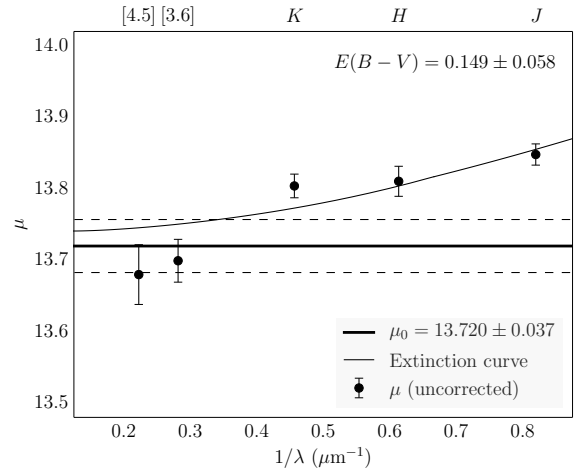
**Figure 5.** PL relations for  $JHK_s$ ,  $3.6\ \mu\text{m}$ , and  $4.5\ \mu\text{m}$  photometry assuming an  $[\text{Fe}/\text{H}] = -1.677$ , corresponding to the average spectroscopic metallicity from Sollima et al. (2006). Only those RRL that appear in all five near- and mid-infrared bands are included in the fit.



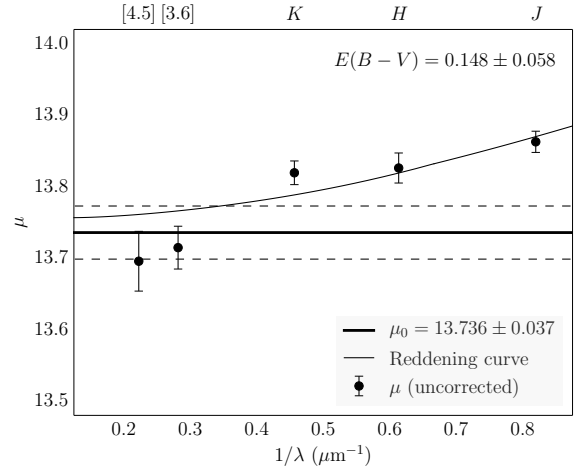
**Figure 6.** Distance moduli for the full sample of  $JHK_s$ ,  $3.6\ \mu\text{m}$ , and  $4.5\ \mu\text{m}$  photometry using the average photometric metallicity from Rey et al. (2000) and theoretical PL relations for all bandpasses

## 5 DISTANCE MODULI

We combine the uncorrected distance moduli from each bandpass to obtain a mean reddening-corrected distance modulus. We fit the near-infrared reddening law from Cardelli et al. (1989) and mid-infrared law from Indebetouw et al. (2005) simultaneously, assuming the ratio of total to selective absorption  $R_V = 3.1$ . (We tested a value of  $R_V = 3.23$  as well, and it changed the results by less than 1%.) The resulting fits are shown in Figures 7 and 8.



**Figure 7.** Distance moduli for the cut sample of  $JHK_s$ ,  $3.6\ \mu\text{m}$ , and  $4.5\ \mu\text{m}$  photometry using the average photometric metallicity from Rey et al. (2000) and theoretical PL relations for all bandpasses

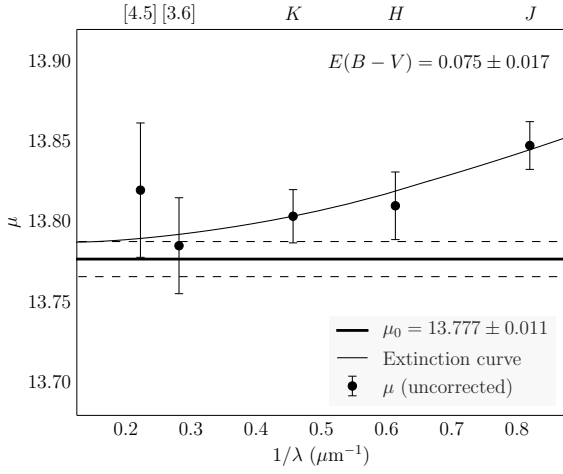


**Figure 8.** Distance moduli for the cut sample of  $JHK_s$ ,  $3.6\ \mu\text{m}$ , and  $4.5\ \mu\text{m}$  photometry using the average spectroscopic metallicity from Sollima et al. (2006) and theoretical PL relations for all bandpasses

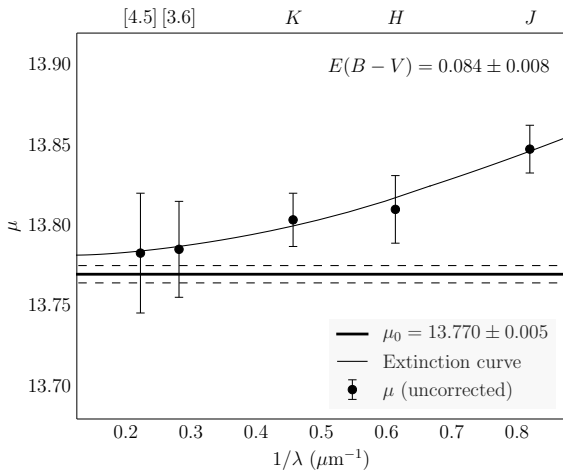
Using photometric metallicities we obtain a mean reddening-corrected distance modulus of  $\mu_0 = 13.720 \pm 0.037$ , and with spectroscopic metallicities we obtain  $\mu_0 = 13.736 \pm 0.037$ . The difference between the two distance moduli is less than 0.02 mag, well within the  $\pm 0.037$  mag errors. The fact that the two distance moduli are indistinguishable is the first indication that the infrared RRL PL relations are not sensitive to metallicity effects.

We average these distance moduli (thus essentially averaging the metallicities as well) to find a true mean distance modulus of  $\mu_0 = 13.728 \pm 0.037$ , which is in excellent agreement with prior measurements using near-infrared RR Lyrae period-luminosity relations (Del Principe et al. 2006), slightly higher than the distance modulus measured using the eclipsing binary OGLEGC17 (Thompson et al. 2001), and significantly higher than the distance modulus measured by dynamical modelling (van de Ven et al. 2006; Watkins et al. 2013).





**Figure 9.** Distance moduli for the cut sample of  $JHK_s$ ,  $3.6 \mu\text{m}$ , and  $4.5 \mu\text{m}$  photometry using the average photometric metallicity from Sollima et al. (2006) and theoretical PL relations for  $JHK_s$  and empirical PL relations for  $3.6 \mu\text{m}$  and  $4.5 \mu\text{m}$

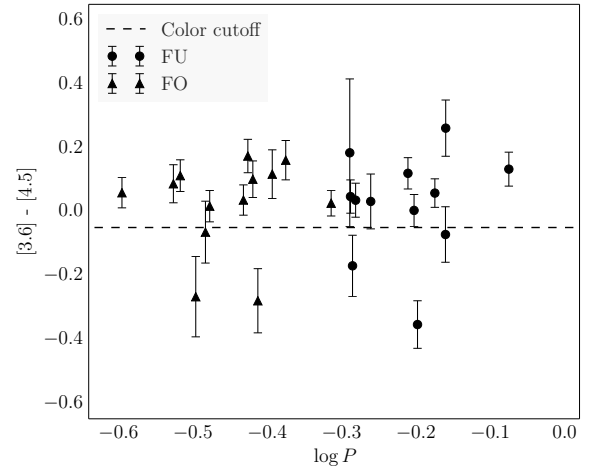


**Figure 10.** Distance moduli for the cut sample of  $JHK_s$ ,  $3.6 \mu\text{m}$ , and  $4.5 \mu\text{m}$  photometry using the average photometric metallicity from Sollima et al. (2006) and theoretical PL relations for  $JHK_s$  and empirical PL relations for  $3.6 \mu\text{m}$  and  $4.5 \mu\text{m}$ , excluding the first overtone pulsators in  $4.5 \mu\text{m}$

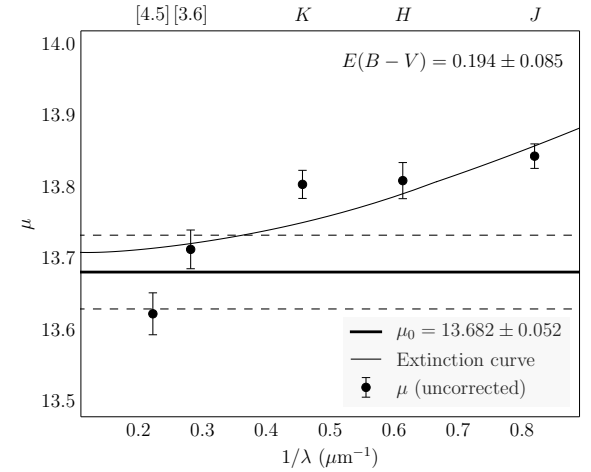
The extinction value we derive from these fits,  $E(B - V) = 0.148 \pm 0.055$  is slightly high but within error of the values of  $E(B - V) = 0.11$  and  $E(B - V) = 0.1212 \pm 0.0021$  derived by Lub (2002) and Schlafly & Finkbeiner (2011) respectively, and in good agreement with the  $E(B - V) = 0.1410 \pm 0.0024$  value derived by Schlegel et al. (1998).

However, it is apparent from Figures 6, 7, and 8 that the derived distance moduli do not conform well to the fitted extinction curve. We therefore turn to the empirical PL relations derived by Neeley et al. (2015) and Braga et al. (2015).

Using the empirical PL relations for  $3.6 \mu\text{m}$  and  $4.5 \mu\text{m}$  and the theoretical PL relations for  $JHK_s$ , we derive a true dereddened distance modulus of  $\mu_0 = 13.777 \pm 0.011$  and an  $E(B - V)$  of  $0.075 \pm (\text{something})$ , as shown in Figure 9.



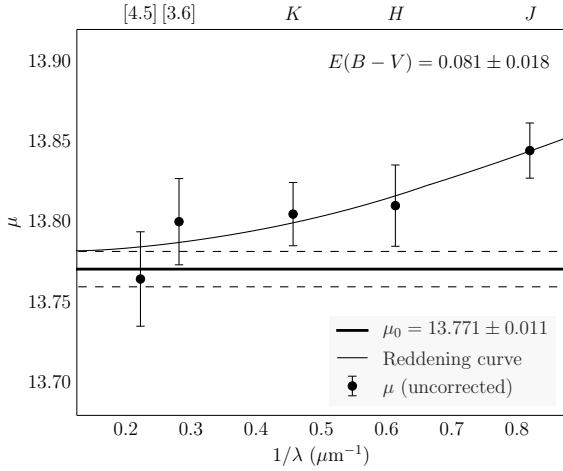
**Figure 11.** Period color nonsense



**Figure 12.** Distance moduli for the cut sample of  $JHK_s$ ,  $3.6 \mu\text{m}$ , and  $4.5 \mu\text{m}$  photometry with the 6 bluest stars excluded, using the average photometric metallicity from Sollima et al. (2006) and theoretical PL relations for  $JHK_s$  and empirical PL relations for  $3.6 \mu\text{m}$  and  $4.5 \mu\text{m}$

The anomalously high distance modulus for  $4.5 \mu\text{m}$  in Figure 9 is caused exclusively by the first overtone pulsators, which have the lowest signal-to-noise measurements and are therefore most vulnerable to crowding effects. If we remove the first overtone pulsators from the  $4.5 \mu\text{m}$  data, the derived distance modulus for  $4.5 \mu\text{m}$  decreases substantially, as shown in Figure 10, resulting in an excellent fit of all points to the reddening curve. From these distance moduli we derive a distance modulus of  $\mu_0 = 13.770 \pm 0.005$  and  $E(B - V) = 0.084 \pm (\text{something})$ .

We also examine the period–color ( $3.6 \mu\text{m} - 4.5 \mu\text{m}$ ) relation for our sample (Figure 11), and find 6 stars with anomalously blue colors ( $3.6 \mu\text{m} - 4.5 \mu\text{m} < -0.05$  mag) in these bandpasses, which may indicate a problem with the  $4.5 \mu\text{m}$  photometry for these stars. We redo the distance modulus fitting with these stars excluded (Figure 12), and find a true distance modulus of ??? do for both m4 and theo PLs



**Figure 13.** Distance moduli for the cut sample of  $JHK_s$ ,  $3.6 \mu\text{m}$ , and  $4.5 \mu\text{m}$  photometry with 6 bluest stars excluded, using the average photometric metallicity from Sollima et al. (2006) and theoretical PL relations for all bandpasses

## 6 METALLICITY

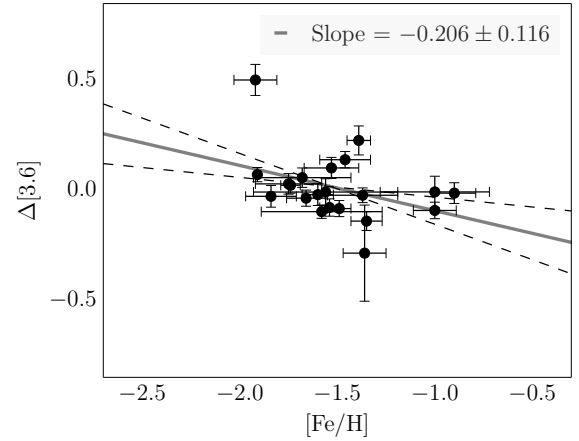
Theoretical models suggest that the metallicity dependence of the RR Lyrae PL relation should decrease monotonically from the optical to the near-infrared (Bono et al. 2001; Catelan et al. 2004). Observational evidence corroborates this; previous investigations performed on WISE data suggest no obvious metallicity dependence in the mid-IR PL relations (Madore et al. 2013).

In the case of Cepheids, Scowcroft et al. (2011) and Scowcroft et al. (2015) have shown that in the  $4.5 \mu\text{m}$  bandpass there is absorption due to a CO bandhead at  $4.65 \mu\text{m}$ , which strengthens the metallicity dependence of the PL relation in this bandpass. However, this effect is due to the low temperature of Cepheid atmospheres and disappears in the hottest, shortest-period Cepheids, as the CO dissociates at temperatures above 6000 K (Monson et al. 2012). As even the coolest RRL have temperatures over 6000 K (?), we expect to see no such CO absorption in the  $4.5 \mu\text{m}$  PL relation. If there are any other unanticipated metallicity effects, they must be smaller than the dispersion of the PL relations themselves.

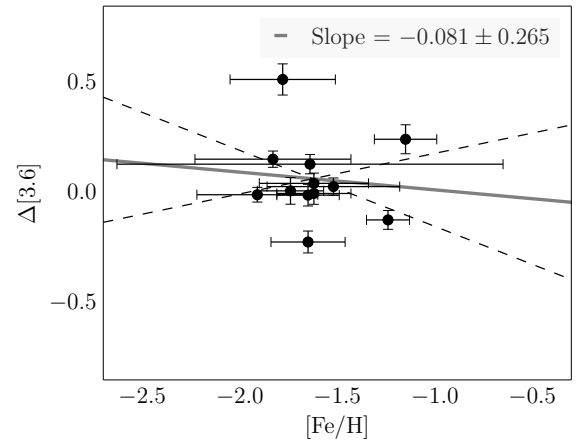
If there is any correlation between  $[\text{Fe}/\text{H}]$  and the PL residuals, we expect it to be a linear one, consistent with the theoretical metallicity terms in the PL relation,  $c \times [\text{Fe}/\text{H}]$ ; we fit a relation of the form

$$\Delta\text{mag} = \gamma \times [\text{Fe}/\text{H}] + d \quad (4)$$

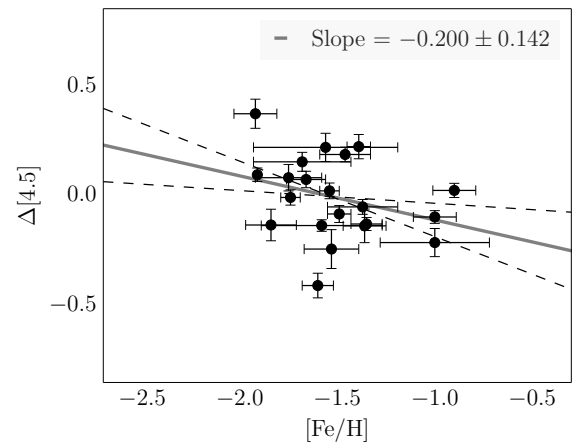
to the  $3.6 \mu\text{m}$  and  $4.5 \mu\text{m}$  PL residuals and metallicity values for stars with known individual metallicity values, as shown in Figures 14, 15, 16, and 17. We find that although the scatter in the  $3.6 \mu\text{m}$  and  $4.5 \mu\text{m}$  PL relations is higher for  $\omega$  Cen than it is for M4 (Neeley et al. 2015; Braga et al. 2015), there is no evidence that it is due to metallicity. When we examine  $[\text{Fe}/\text{H}]$  vs.  $\Delta 3.6 \mu\text{m}$  and  $\Delta 4.5 \mu\text{m}$ ,  $\gamma$  is within  $2\sigma$  of zero for all fits, indicating that there is no significant metallicity dependence in the PL residuals. When the outlier at  $[\text{Fe}/\text{H}] = -2.0$  in Figures 14 and 16 is removed,  $\gamma$  moves within  $1\sigma$  of zero for all  $[\text{Fe}/\text{H}]$  vs. residual fits, as seen in Figures 18 and 19.



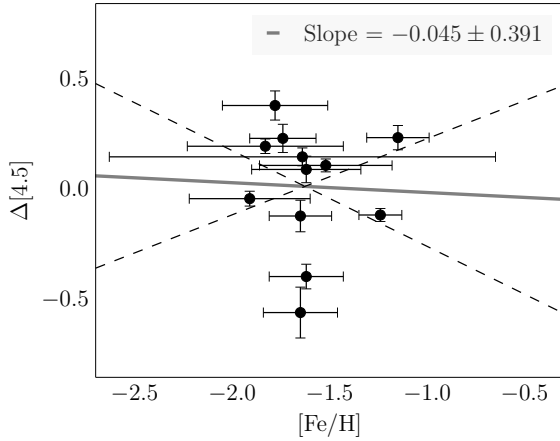
**Figure 14.**  $[\text{Fe}/\text{H}]$  vs.  $\Delta 3.6 \mu\text{m}$  using photometric metallicities



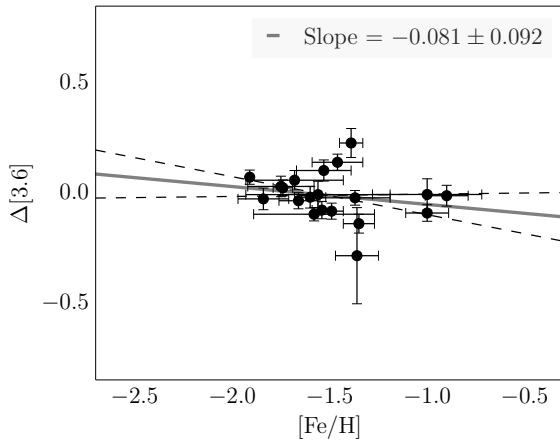
**Figure 15.**  $[\text{Fe}/\text{H}]$  vs.  $\Delta 3.6 \mu\text{m}$  using spectroscopic metallicities



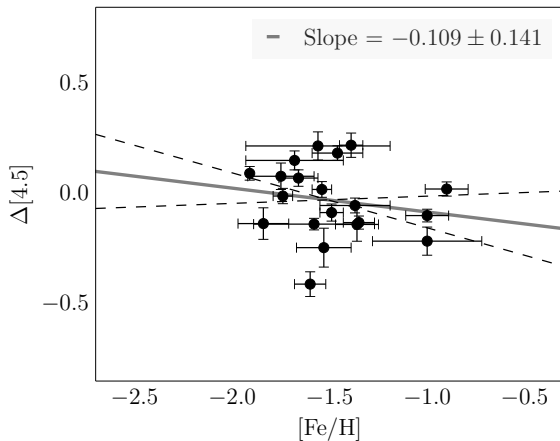
**Figure 16.**  $[\text{Fe}/\text{H}]$  vs.  $\Delta 4.5 \mu\text{m}$  using photometric metallicities



**Figure 17.** [Fe/H] vs.  $\Delta 4.5 \mu\text{m}$  using spectroscopic metallicities



**Figure 18.** [Fe/H] vs.  $\Delta 3.6 \mu\text{m}$  using photometric metallicities, with outlier removed



**Figure 19.** [Fe/H] vs.  $\Delta 4.5 \mu\text{m}$  using photometric metallicities, with outlier removed

## 7 DISCUSSION

The metallicity terms in the theoretical mid-infrared relations are comparable to the metallicity terms in the near-infrared (see Table 1), which is counter to previous predictions that the metallicity dependence should decrease with increasing wavelength (Catelan et al. 2004; Bono et al. 2001). This may be one reason for the  $\sim 0.1$  mag discrepancy between the distance moduli for  $3.6 \mu\text{m}$  and  $4.5 \mu\text{m}$  derived using the theoretical parameters vs. the empirical parameters.

Our investigation into the metallicity effects in the mid-infrared is limited primarily by the quality of the metallicity measurements of individual stars. **Did someone say Eric Persson was working on this at some point...? Should I say we can expect a better dataset at some point?**

## 8 CONCLUSIONS

### ACKNOWLEDGEMENTS

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Table 1:  $JHK_s$ ,  $3.6\ \mu\text{m}$ , and  $4.5\ \mu\text{m}$  photometry of the RR Lyrae variables in  $\omega$  Cen

ID	RA (J2000)	Dec (J2000)	$J$	$\sigma_J$	$H$	$\sigma_H$	$K_s$	$\sigma_{K_s}$	[3.6]	$\sigma_{[3.6]}$	[4.5]	$\sigma_{[4.5]}$	$P$ (days)	Mode	[Fe/H], p	$\sigma_{[\text{Fe/H}]}$ , p	[Fe/H], s	$\sigma_{[\text{Fe/H}]}$ , s
3	13:25:56.15	-47:25:53.8	13.247	0.017	12.982	0.018	12.882	0.017	12.841	0.039	12.708	0.036	0.841	ab	-1.54	0.05	—	—
4	13:26:12.93	-47:24:18.8	13.475	0.016	13.219	0.021	13.133	0.020	13.030	0.036	13.026	0.035	0.627	ab	-1.74	0.05	—	—
5	13:26:18.33	-47:23:12.4	13.700	0.017	13.549	0.020	13.507	0.027	13.387	0.043	13.340	0.030	0.515	ab	-1.35	0.08	-1.24	0.11
7	13:27:00.90	-47:14:00.5	13.333	0.009	13.151	0.031	13.036	0.018	—	—	—	—	0.713	ab	-1.46	0.08	—	—
8	13:27:48.45	-47:28:20.3	13.505	0.015	13.258	0.016	13.223	0.014	—	—	—	—	0.521	ab	-1.91	0.28	—	—
9	13:25:59.58	-47:26:24.0	13.776	0.017	13.534	0.021	13.470	0.016	13.315	0.036	13.279	0.039	0.523	ab	-1.49	0.06	—	—
10	13:26:06.99	-47:24:36.6	13.579	0.014	13.395	0.023	13.345	0.019	13.342	0.037	13.168	0.037	0.375	c	-1.66	0.10	—	—
11	13:26:30.59	-47:23:01.6	13.481	0.014	13.307	0.028	13.219	0.025	13.050	0.058	—	—	0.565	ab	-1.67	0.13	-1.61	0.22
12	13:26:27.21	-47:24:06.2	13.590	0.018	13.379	0.028	13.305	0.025	13.168	0.048	13.448	0.088	0.387	c	-1.53	0.14	—	—
13	13:25:58.18	-47:25:21.6	13.353	0.019	13.081	0.022	13.058	0.017	12.918	0.032	12.860	0.031	0.669	ab	-1.91	0.000	—	—
14	13:25:59.74	-47:39:09.6	13.588	0.011	13.343	0.020	13.365	0.016	—	—	13.299	0.045	0.377	c	-1.71	0.13	—	—
15	13:26:27.11	-47:24:38.0	13.245	0.018	13.020	0.031	12.954	0.025	13.149	0.084	—	—	0.811	ab	-1.64	0.39	-1.68	0.18
16	13:27:37.69	-47:37:34.8	13.680	0.015	13.502	0.022	13.437	0.018	—	—	—	—	0.330	c	-1.29	0.08	-1.65	0.46
18	13:27:45.11	-47:24:56.6	13.371	0.010	13.131	0.024	13.100	0.016	13.006	0.043	—	—	0.622	ab	-1.78	0.28	—	—
20	13:27:14.05	-47:28:06.3	13.410	0.015	13.210	0.036	13.125	0.025	13.060	0.039	12.940	0.029	0.616	ab	—	—	-1.52	0.34
21	13:26:11.17	-47:25:58.8	13.578	0.016	13.399	0.027	13.361	0.020	13.301	0.047	13.200	0.032	0.381	c	-0.90	0.11	—	—
22	13:27:41.04	-47:34:07.6	13.572	0.012	13.380	0.016	13.288	0.017	—	—	—	—	0.396	c	-1.63	0.17	-1.60	0.99
23	13:26:46.50	-47:24:39.5	13.941	0.025	13.794	0.048	13.658	0.033	13.325	0.064	—	—	0.511	ab	-1.08	0.14	-1.35	0.58
24	13:27:38.32	-47:34:14.5	13.419	0.012	13.218	0.014	13.138	0.014	—	—	—	—	0.462	c	-1.86	0.03	—	—
30	13:26:15.94	-47:29:56.0	13.521	0.021	13.287	0.046	13.251	0.030	13.188	0.047	13.071	0.060	0.404	c	-1.75	0.17	-1.62	0.28
32	13:27:03.32	-47:21:38.9	13.508	0.009	13.244	0.018	13.132	0.018	—	—	—	—	0.620	ab	-1.53	0.16	—	—
33	13:25:51.60	-47:29:05.8	13.338	0.015	13.106	0.022	13.091	0.019	—	—	13.006	0.035	0.602	ab	-2.09	0.23	-1.58	0.42
34	13:26:07.21	-47:33:10.4	13.273	0.014	13.018	0.014	12.916	0.013	—	—	12.838	0.065	0.734	ab	-1.71	0.000	—	—
35	13:26:53.21	-47:22:34.7	13.586	0.012	13.463	0.024	13.356	0.023	—	—	—	—	0.387	c	-1.56	0.08	-1.63	0.36
36	13:27:10.11	-47:15:29.8	13.534	0.007	13.372	0.019	13.307	0.014	—	—	—	—	0.380	c	-1.49	0.23	—	—
38	13:27:03.30	-47:36:30.2	13.226	0.015	12.943	0.019	12.814	0.018	—	—	—	—	0.779	ab	-1.75	0.18	-1.64	0.40
39	13:27:59.77	-47:34:42.3	13.560	0.009	13.415	0.014	13.308	0.014	—	—	—	—	0.393	c	-1.96	0.29	—	—
40	13:26:24.56	-47:30:46.2	13.517	0.022	13.250	0.051	13.153	0.033	13.062	0.049	13.416	0.056	0.634	ab	-1.60	0.08	-1.62	0.19
44	13:26:22.39	-47:34:35.3	13.677	0.014	13.425	0.023	13.368	0.018	—	—	13.132	0.036	0.568	ab	-1.40	0.12	-1.29	0.35
45	13:25:30.88	-47:27:21.0	13.513	0.015	13.201	0.015	13.164	0.014	—	—	13.070	0.028	0.589	ab	-1.78	0.25	—	—
46	13:25:30.23	-47:25:51.8	13.299	0.016	12.998	0.017	12.947	0.014	—	—	—	—	0.687	ab	-1.88	0.17	—	—
47	13:25:56.46	-47:24:12.0	13.420	0.020	13.223	0.018	13.150	0.018	13.099	0.030	13.073	0.026	0.485	c	-1.58	0.31	—	—
49	13:26:07.78	-47:37:55.5	13.566	0.012	13.238	0.019	13.220	0.016	—	—	13.099	0.049	0.605	ab	-1.98	0.11	—	—
50	13:25:53.94	-47:27:35.8	13.647	0.014	13.402	0.015	13.362	0.014	—	—	13.305	0.056	0.386	c	-1.59	0.19	—	—
51	13:26:42.66	-47:24:21.4	13.597	0.014	13.378	0.033	13.270	0.029	13.315	0.083	—	—	0.574	ab	-1.64	0.21	-1.84	0.23
54	13:26:23.54	-47:18:47.7	13.281	0.016	12.998	0.017	12.954	0.015	12.799	0.030	—	—	0.773	ab	-1.66	0.12	-1.80	0.23
56	13:25:55.53	-47:37:44.1	13.643	0.009	13.386	0.022	13.353	0.017	—	—	13.232	0.035	0.568	ab	-1.26	0.15	—	—
57	13:27:49.38	-47:36:50.5	13.234	0.015	12.995	0.018	12.882	0.014	—	—	—	—	0.794	ab	-1.89	0.14	—	—
58	13:26:13.05	-47:24:03.0	13.660	0.017	13.495	0.018	13.421	0.021	13.345	0.033	13.309	0.034	0.370	c	-1.37	0.18	-1.91	0.31
59	13:26:18.43	-47:29:46.7	13.727	0.023	13.424	0.043	13.391	0.033	13.248	0.071	13.418	0.064	0.519	ab	-1.00	0.28	—	—
63	13:25:07.96	-47:36:54.1	13.223	0.017	12.862	0.017	12.869	0.012	—	—	—	—	0.826	ab	-1.73	0.09	—	—
64	13:26:02.22	-47:36:19.2	13.638	0.013	13.438	0.022	13.407	0.022	—	—	13.314	0.044	0.344	c	-1.46	0.23	—	—
66	13:26:33.08	-47:22:25.2	13.542	0.011	13.359	0.022	13.264	0.020	13.103	0.035	—	—	0.407	c	-1.68	0.34	—	—
67	13:26:28.62	-47:18:46.9	13.610	0.014	13.384	0.016	13.326	0.015	13.368	0.047	—	—	0.564	ab	-1.10	0.000	-1.19	0.23
68	13:26:12.80	-47:19:35.7	13.258	0.021	13.004	0.015	12.970	0.015	12.928	0.050	—	—	0.535	c	-1.60	0.01	—	—
69	13:25:11.02	-47:37:33.5	—	—	—	—	13.112	0.014	—	—	—	—	0.635	ab	-1.52	0.14	—	—
70	13:27:27.76	-47:33:42.7	13.529	0.013	13.282	0.029	13.254	0.022	—	—	—	—	0.391	c	-1.94	0.15	-1.74	0.30
72	13:27:33.11	-47:16:22.9	13.554	0.010	13.339	0.017	13.311	0.014	—	—	—	—	0.385	c	-1.32	0.22	—	—
73	13:25:53.75	-47:16:10.8	13.480	0.018	13.251	0.017	13.215	0.016	—	—	—	—	0.575	ab	-1.50	0.09	—	—
74	13:27:07.22	-47:17:33.9	13.622	0.008	13.457	0.016	13.405	0.015	—	—	—	—	0.503	ab	-1.83	0.36	—	—
75	13:27:19.70	-47:18:46.5	13.410	0.011	13.175	0.028	13.137	0.025	—	—	—	—	0.422	c	-1.49	0.08	-1.82	0.99
76	13:26:57.23	-47:20:07.7	13.634	0.012	13.488	0.017	13.449	0.020	—	—	—	—	0.338	c	-1.45	0.13	—	—
77	13:27:20.89	-47:22:05.6	13.474	0.013	13.264	0.028	13.199	0.021	—	—	—	—	0.426	c	-1.81	0.000	-1.84	0.43
79	13:28:24.99	-47:29:25.2	13.382	0.010	13.162	0.016	13.123	0.015	—	—	—	—	0.608	ab	-1.39	0.18	—	—
81	13:27:36.68	-47:24:48.3	13.542	0.012	13.326	0.033	13.286	0.025	13.248	0.076	—	—	0.389	c	-1.72	0.31	-1.99	0.43
82	13:27:35.61	-47:26:30.3	13.579	0.016	13.324	0.024	13.296	0.018	—	—	13.827	0.104	0.336	c	-1.56	0.20	-1.71	0.56
83	13:27:08.42	-47:21:34.1	13.603	0.010	13.431	0.024	13.370	0.022	—	—	—	—	0.357	c	-1.30	0.22	—	—
84	13:24:47.45	-47:29:56.5	—	—	12.833	0.017	12.781	0.016	—	—	—	—	0.580	ab	-1.47	0.10	—	—
85	13:25:06.49	-47:23:34.0	13.344	0.011	—	—	—	—	—	—	—	—	0.743	ab	-1.87	0.31	—	—

Continued on next page

Table 1 – Continued from previous page

ID	RA (J2000)	Dec (J2000)	$J$	$\sigma_J$	$H$	$\sigma_H$	$K_s$	$\sigma_K$	[3.6]	$\sigma_{[3.6]}$	[4.5]	$\sigma_{[4.5]}$	$P$ (days)	Mode	[Fe/H], p	$\sigma_{[\text{Fe/H}], p}$	[Fe/H], s	$\sigma_{[\text{Fe/H}], s}$
94	13:25:57.06	-47:22:46.1	14.070	0.024	13.934	0.022	13.870	0.027	13.858	0.038	13.799	0.029	0.254	c	-1.00	0.11	–	–
95	13:25:24.95	-47:28:53.2	13.497	0.015	13.269	0.017	13.264	0.017	–	–	13.178	0.024	0.405	c	-1.84	0.55	–	–
97	13:27:08.49	-47:25:30.9	13.302	0.010	13.143	0.029	13.034	0.022	12.964	0.061	12.702	0.064	0.692	ab	-1.56	0.37	-1.74	0.17
101	13:27:30.24	-47:29:51.0	13.708	0.016	13.484	0.030	13.436	0.023	–	–	–	–	0.341	c	-1.88	0.32	–	–
102	13:27:22.11	-47:30:12.3	13.320	0.012	13.033	0.022	12.993	0.020	12.984	0.049	13.056	0.072	0.691	ab	-1.84	0.13	-1.65	0.16
103	13:27:14.29	-47:28:36.3	13.620	0.018	13.409	0.040	13.377	0.034	12.960	0.071	13.024	0.066	0.329	c	-1.92	0.11	-1.78	0.27
104	13:28:07.76	-47:33:44.9	13.732	0.096	13.626	0.154	13.452	0.141	–	–	–	–	0.867	ab	-1.83	0.18	–	–
105	13:27:46.02	-47:32:43.9	13.768	0.014	13.615	0.020	13.533	0.018	–	–	–	–	0.335	c	-1.24	0.18	–	–
107	13:27:14.05	-47:30:57.9	13.597	0.017	13.340	0.038	13.301	0.030	13.535	0.219	13.351	0.076	0.514	ab	-1.36	0.11	–	–
115	13:26:12.30	-47:34:17.5	13.401	0.012	13.176	0.017	13.103	0.013	–	–	–	–	0.630	ab	-1.87	0.01	-1.64	0.32
117	13:26:19.91	-47:29:21.0	13.480	0.020	13.274	0.043	13.202	0.031	13.110	0.044	12.949	0.043	0.422	c	-1.68	0.25	–	–
120	13:26:25.52	-47:32:48.6	13.525	0.049	13.072	0.079	13.135	0.094	12.958	0.066	12.927	0.055	0.549	ab	-1.39	0.06	-1.15	0.16
121	13:26:28.17	-47:31:50.5	13.741	0.016	13.648	0.033	13.531	0.026	13.414	0.037	13.302	0.033	0.304	c	-1.46	0.13	-1.83	0.40
122	13:26:30.31	-47:33:02.2	13.369	0.018	13.132	0.042	13.062	0.024	13.057	0.052	13.019	0.043	0.635	ab	-2.02	0.18	-1.79	0.21
123	13:26:51.17	-47:37:13.2	13.462	0.016	13.239	0.019	13.174	0.017	–	–	–	–	0.474	c	-1.64	0.01	–	–
124	13:26:54.49	-47:39:07.5	13.708	0.013	13.510	0.018	13.482	0.023	–	–	–	–	0.332	c	-1.33	0.23	–	–
125	13:26:48.92	-47:41:03.7	13.420	0.015	13.200	0.016	13.153	0.015	–	–	–	–	0.593	ab	-1.67	0.22	-1.81	0.38
126	13:28:08.03	-47:40:46.7	13.642	0.011	13.467	0.017	13.370	0.016	–	–	–	–	0.342	c	-1.31	0.13	–	–
127	13:25:19.36	-47:28:37.6	–	–	–	–	13.579	0.018	–	–	13.573	0.063	0.305	c	-1.59	0.08	–	–
128	13:26:17.75	-47:30:13.0	13.207	0.018	12.927	0.032	12.810	0.020	–	–	12.445	0.074	0.835	ab	-1.88	0.04	–	–
130	13:26:09.93	-47:13:40.0	13.688	0.021	13.527	0.032	13.418	0.025	–	–	–	–	0.493	ab	-1.46	0.17	–	–
147	13:27:15.86	-47:31:09.2	13.397	0.012	12.934	0.041	13.083	0.022	–	–	12.585	0.096	0.423	c	-1.66	0.14	–	–
149	13:27:32.94	-47:13:43.6	13.354	0.015	13.061	0.035	13.024	0.024	–	–	–	–	0.683	ab	-1.21	0.24	–	–
150	13:27:40.21	-47:36:00.1	13.068	0.019	12.757	0.025	12.692	0.018	–	–	–	–	0.899	ab	-1.76	0.34	–	–
151	13:28:25.40	-47:16:00.2	13.501	0.013	13.301	0.020	13.265	0.016	–	–	–	–	0.408	ab	-1.30	0.24	–	–
163	13:25:49.42	-47:20:21.5	13.763	0.019	13.557	0.016	13.545	0.025	–	–	–	–	0.313	c	-1.18	0.27	–	–
168	13:25:52.78	-47:32:02.9	14.176	0.015	14.000	0.020	13.960	0.018	–	–	–	–	0.321	c	–	–	–	–
169	13:27:20.47	-47:23:59.1	13.805	0.013	13.735	0.019	13.652	0.025	13.734	0.050	14.001	0.116	0.319	c	–	–	-1.65	0.19
184	13:27:28.50	-47:31:35.4	13.778	0.012	13.624	0.028	13.536	0.019	–	–	–	–	0.303	c	–	–	–	–
185	13:26:04.13	-47:21:45.0	13.701	0.016	13.545	0.018	13.508	0.023	13.496	0.036	13.479	0.033	0.333	c	–	–	–	–
261	13:27:15.41	-47:21:29.5	13.431	0.009	13.212	0.019	13.113	0.020	–	–	–	–	0.403	c	–	–	-1.50	0.35
263	13:26:13.13	-47:26:09.7	13.155	0.017	12.888	0.017	12.746	0.016	–	–	12.660	0.034	1.012	ab	–	–	-1.73	0.19
274	13:26:43.73	-47:22:48.2	13.828	0.011	13.758	0.023	13.650	0.022	–	–	–	–	0.311	c	–	–	–	–
276	13:27:16.51	-47:33:17.6	13.727	0.021	13.614	0.046	13.533	0.024	–	–	–	–	0.308	c	–	–	–	–
280	13:27:09.33	-47:23:05.7	13.951	0.012	13.905	0.026	13.816	0.029	–	–	–	–	0.282	c	–	–	–	–
285	13:25:40.20	-47:34:48.4	13.687	0.017	13.504	0.027	13.503	0.015	–	–	13.358	0.074	0.329	c	–	–	–	–
288	13:28:10.32	-47:23:47.8	13.809	0.011	13.719	0.016	13.635	0.019	–	–	–	–	0.295	c	–	–	–	–
289	13:28:03.68	-47:21:27.9	13.743	0.013	13.618	0.015	13.584	0.022	–	–	–	–	0.308	c	–	–	–	–
291	13:26:38.52	-47:33:28.0	13.674	0.018	13.518	0.044	13.444	0.026	–	–	–	–	0.334	c	–	–	–	–
357	13:26:17.77	-47:30:23.4	13.692	0.027	13.468	0.064	13.468	0.045	13.462	0.044	13.375	0.041	0.298	c	–	–	-1.64	0.99

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