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The Carnegie RR Lyrae Program: The Mid–Infrared RR Lyrae Period–Luminosity Relation in ω 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 (Freedman et al. 2012a, PID 90002) 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. 2012b), the results of the CRRP will be used 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 obtain independent direct measurements of H_0. The results of Riess et al. (2011) and Freedman et al. (2012b), both which use Cepheids and type Ia supernovae (SNe) as their base, agree very well at 74.4 ± 2.5 km s^{-1} Mpc^{-1} and 74.3 ± 2.6 km s^{-1} Mpc^{-1}, respectivly. However, when we consider the latest results from *Planck*, who find 67.48 ± 0.98 km s^{-1} Mpc^{-1} (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

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in type Ia SNe host galaxies. They find that the intrinsic brightness 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 ± 3.3 km s^{-1} 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 the 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 (Catelan et al. 2004). 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. *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)

Moving to the mid–infrared is well known to minimise the effects of extinction, where $A_{[}3.6]$ and $A_{[}4.5]$ are 16 to 20 times lower than A_V Cardelli et al. (1989); Indebetouw et al. (2005). Additionally, the precision of distances obtained from the RRL PL relation is increased. At the wavelengths observed by Warm *Spitzer* (3.6 and 4.5 μm) 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, and the slope should asymptotically approach the predicted slope of the period–radius relation, resulting in a slope between −2.4 and −2.8 (Madore et al. 2013). 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 ω 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, ω 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 μm has been found to have a significant

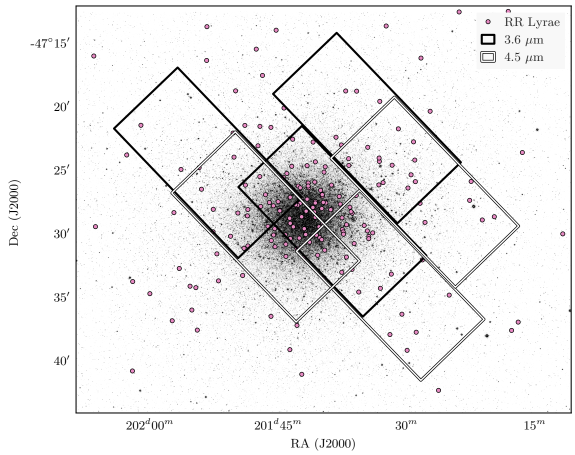

Figure 1. A K_S–band image of ω Cen from the FourStar camera, overlaid with the catalog of RR Lyrae (Kaluzny et al. 2004) and footprints of the *Spitzer* IRAC fields.

dependence on metallicity, and has such prevented the IRAC 4.5 μm 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.

The paper is set out as follows: Section 2 details the observations and data reduction. Section 3 presents the photometry of the ω Cen RRL. Section 4 describes the mid–IR PL relations and Section 5 discusses the application of these to a distance measurement of ω 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

This work combines mid–IR observations from the Warm *Spitzer* mission, with supporting near–IR observations from the FourStar instrument on the Magellan telescope (Persson et al. 2013) **Note for Andy: Which Magellan?**. Figure 1 shows a K_S FourStar image with the *Spitzer* fields outlined, and the positions of known RRL plotted as circles.

2.1 Warm *Spitzer* Data

The Warm *Spitzer* observations for this work were taken as part of the Carnegie RR Lyrae Program. Three fields in ω Cen were chosen; their positions and the positions of known ω 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 μm channels. The elongated field shapes 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 drizzle algorithm. Mosaicked location–correction images were created at the same time.

PSF photometry was performed using 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 temporally 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 μm and 4.5 μm 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 mid–IR photometry is calibrated to the standard system set by Reach et al. (2005).

2.2 FourStar Data

Andy to add text about FourStar data and reduction

2.3 Crowding

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. Our full, uncrowded RR Lyrae sample consists of 96 stars in J and H, 98 in K_s, 36 in 3.6 μm, and 43 in 4.5 μm.

3 RESULTS

Our final photometry catalog, including magnitudes and errors for JHK_s, 3.6 μm, and 4.5 μm is presented in Table 1. The average magnitudes presented in Table 1 are flux averages, and the photomtric uncertainties of the time series data are the error on the mean.

4 PERIOD–LUMINOSITY RELATIONS

We test both empirical and theoretical parameters as fiducial in our PL fitting. We use the theoretical near– and mid–infrared PL relation parameters presented in Marconi et al. (2015) and Braga et al. (in prep.), along with the 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.

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

Band	Mode	a	b	c	σ
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

Table 2. Empirical mid–IR RR Lyrae period–luminosity relations for ω Cen from Neeley et al. (2015).

Band	Mode	a	b	σ
[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

The theoretical RRL PL relations are described in Table 1. The relations take the form

$$M = a + b \times \log P + c \times [Fe/H] \quad (1)$$

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

We also use the the empirical mid–IR RRL PL relations from Neeley et al. (2015) for comparison. These are described in Table 2. The relations take the form

$$M = a + b \times \log P \quad (2)$$

where a and b are empirically derived coefficients.

The theoretical PL relations for both the near– and mid–IR have a metallicity dependent term. Not all stars in our sample have known metallicity values, so we use an average [Fe/H] value for all RR Lyrae variables in the cluster. We use both photometric (Rey et al. 2000) and spectroscopic (Sollima 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 [Fe/H] of −1.584 and a spectroscopic [Fe/H] of −1.677.

Our full, uncrowded RR Lyrae sample consists of 96 stars in J and H, 98 in K_s, 36 in 3.6 μm, and 43 in 4.5 μm. The PL fits to this sample are shown in Figure 3.

For the final PL relations, we use only the stars for which we have photometry in all five bandpasses. Our final RRL sample consists 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. Figures 4 and 5 show the PL relations fit using the **theoretical??** parameters from Table 1**??**

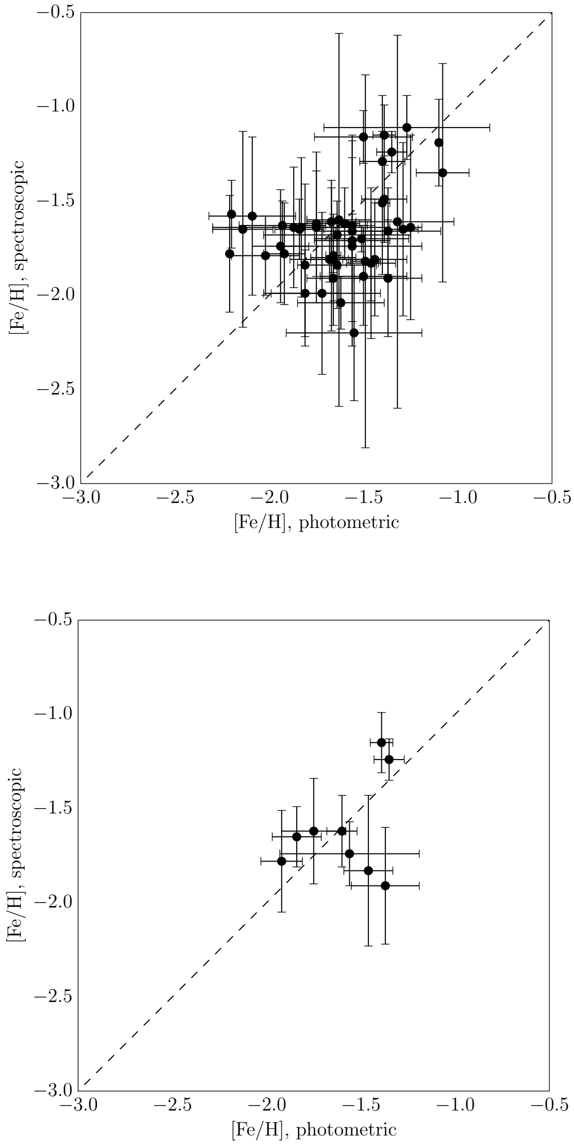

Figure 2. Spectroscopic vs. photometric measurements of [Fe/H] for RR Lyrae variables in ω Cen. Top: All stars for which both catalogs have [Fe/H] measurements. Bottom: only the stars which appear in our final sample.

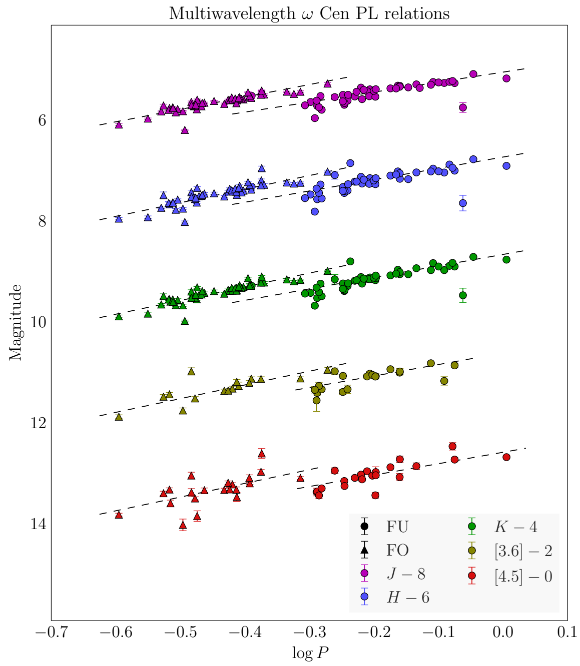

Figure 3. PL relations for JHK_s, 3.6 μm, and 4.5 μm photometry assuming an [Fe/H]= -1.584, corresponding to the average photometric metallicity from Rey et al. (2000). All uncrowded RRL for which we have photometry are included in these fits.

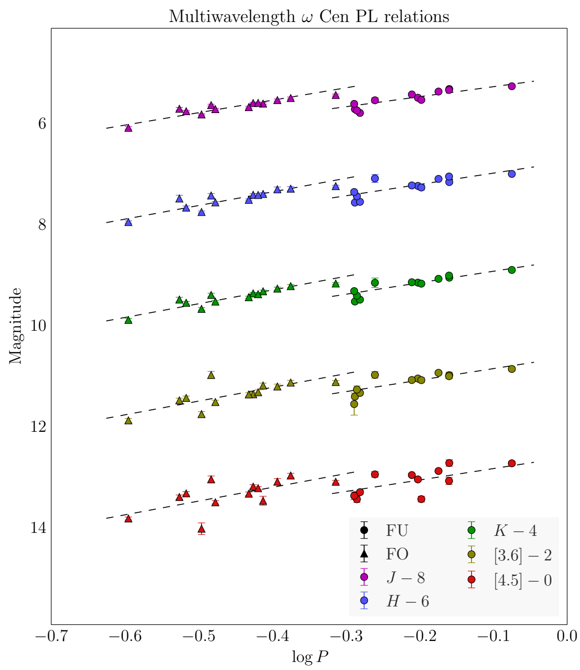

Figure 4. PL relations for JHK_s, 3.6 μm, and 4.5 μm photometry assuming an [Fe/H]= -1.584, corresponding to the average photometric metallicity from Rey et al. (2000). Only those RRL that appear in all five near– and mid–infrared bands are included in the fit.

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.

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 ± 0.037 mag errors. The fact that the two distance

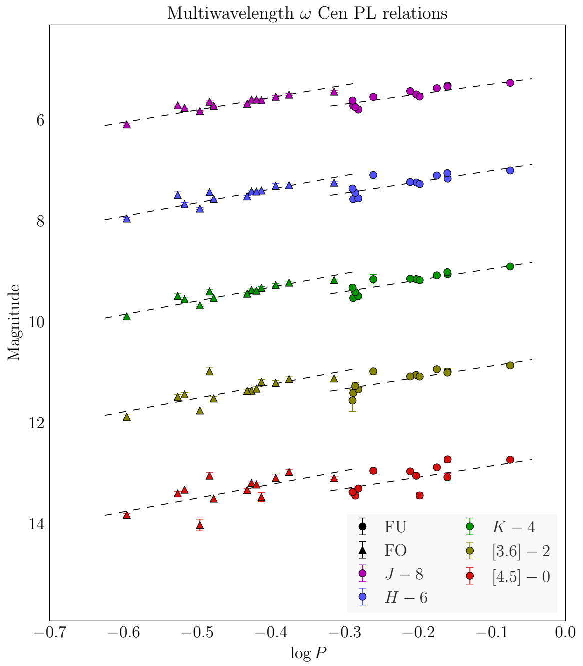

Figure 5. PL relations for JHK_s, 3.6 μm, and 4.5 μm photometry assuming an [Fe/H]= -1.677, corresponding to the average spectroscopic metallicity from Sollima et al. (2006). Only those RRL that appear in all five near– and mid–infrared bands are included in the fit.

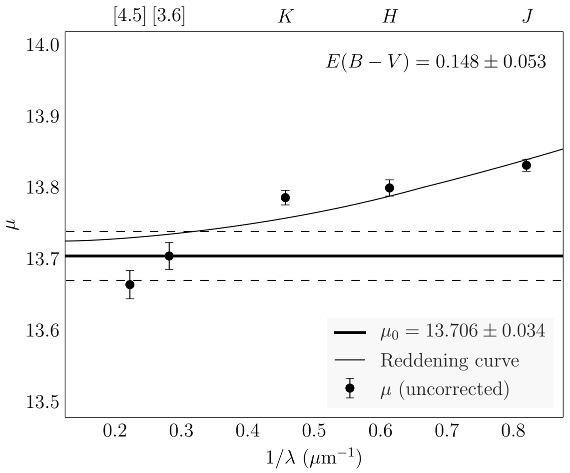

Figure 6. Distance moduli for the full sample of JHK_s, 3.6 μm, and 4.5 μm photometry using the average photometric metallicity from Rey et al. (2000) and theoretical PL relations for all bandpasses

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 moduli

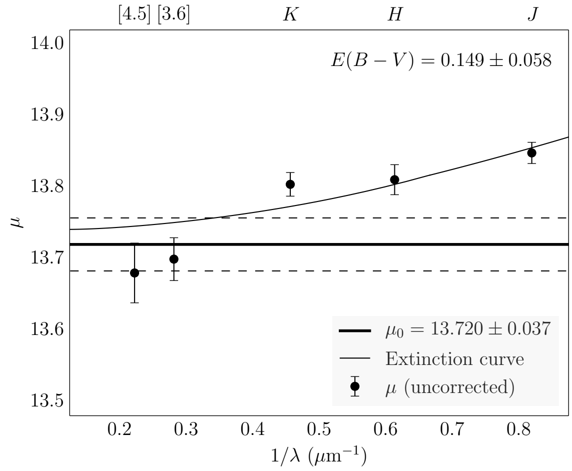

Figure 7. Distance moduli for the cut sample of JHK_s, 3.6 μm, and 4.5 μm photometry using the average photometric metallicity from Rey et al. (2000) and theoretical PL relations for all bandpasses

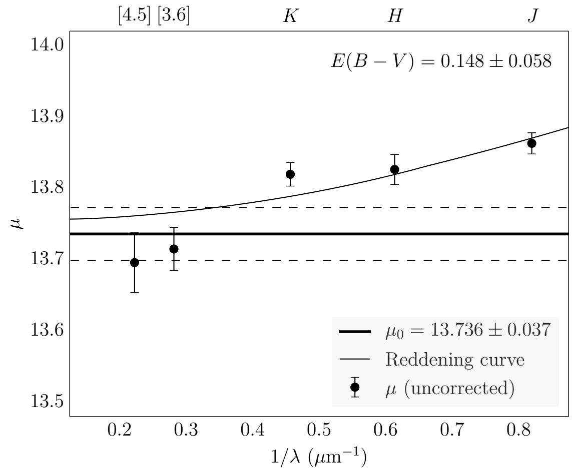

Figure 8. Distance moduli for the cut sample of JHK_s, 3.6 μm, and 4.5 μm photometry using the average spectroscopic metallicity from Sollima et al. (2006) and theoretical PL relations for all bandpasses

measured by dynamical modelling (van de Ven et al. 2006; Watkins et al. 2013).

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 μm and 4.5 μm 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±(something), as shown in Figure 9.

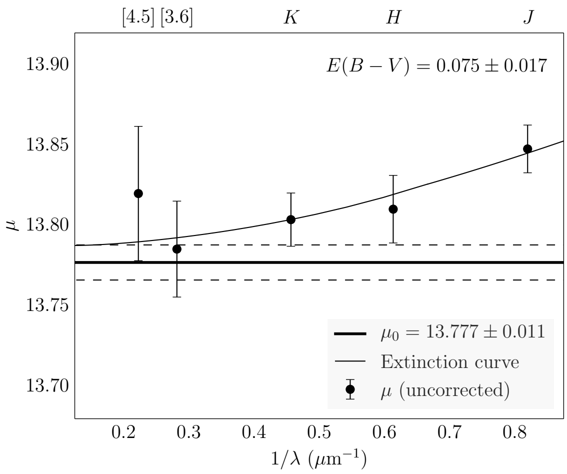

Figure 9. Distance moduli for the cut sample of JHK_s, 3.6 μm, and 4.5 μm photometry using the average photometric metallicity from Sollima et al. (2006) and theoretical PL relations for JHK_s and empirical PL relations for 3.6 μm and 4.5 μm

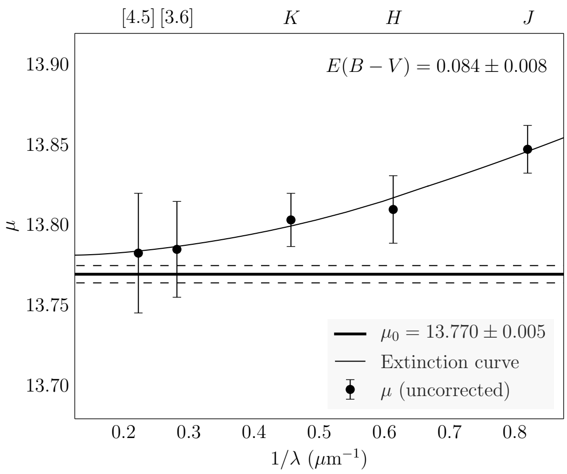

Figure 10. Distance moduli for the cut sample of JHK_s, 3.6 μm, and 4.5 μm photometry using the average photometric metallicity from Sollima et al. (2006) and theoretical PL relations for JHK_s and empirical PL relations for 3.6 μm and 4.5 μm, excluding the first overtone pulsators in 4.5 μm

The anomalously high distance modulus for 4.5 μm 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 μm data, the derived distance modulus for 4.5 μm 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 μ_0 = 13.770 ± 0.005 and $E(B-V)$ = 0.084±(something).

We also examine the period–color (3.6 μm – 4.5 μm) relation for our sample (Figure 11), and find 6 stars with anomalously blue colors (3.6 μm – 4.5 μm < −0.05 mag) in these bandpasses, which may indicate a problem with the 4.5 μm 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**

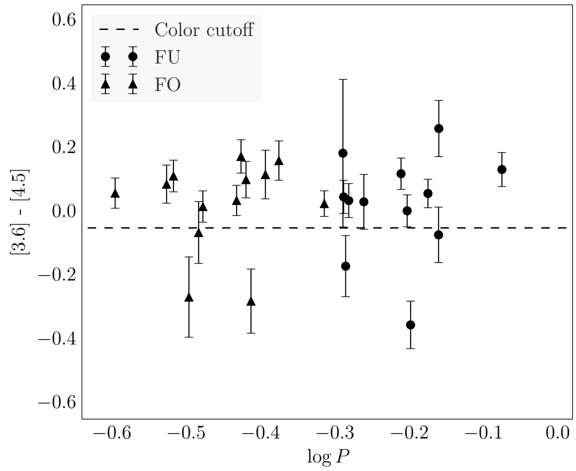

Figure 11. Period color nonsense

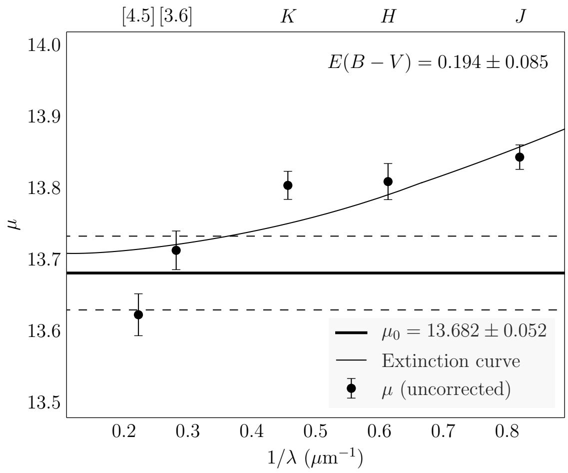

Figure 12. Distance moduli for the cut sample of JHK_s, 3.6 μm, and 4.5 μm photometry with the 6 bluest stars excluded, using the average photometric metallicity from Sollima et al. (2006) and theoretical PL relations for JHK_s and empirical PL relations for 3.6 μm and 4.5 μ

6 METALLICITY

ω 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 Galactic globular cluster. 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. Since we have measured

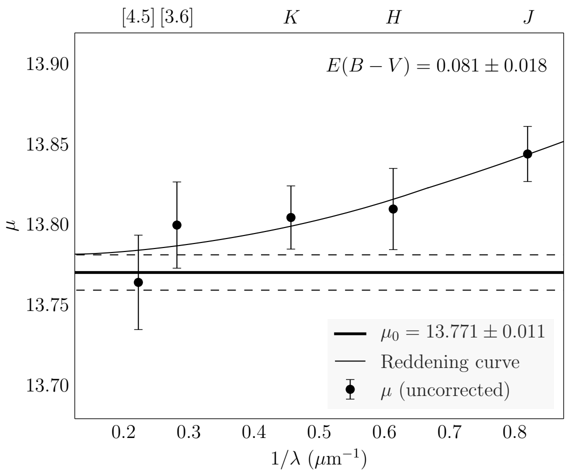

Figure 13. Distance moduli for the cut sample of JHK_s, 3.6 μm, and 4.5 μm photometry with 6 bluest stars excluded, using the average photometric metallicity from Sollima et al. (2006) and theoretical PL relations for all bandpasses

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.

ω 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, ω Cen is extremely well studied and many of its RRL have spectroscopic or photometric metallicities in the literature (e.g. Sollima et al. 2006; Rey et al. 2000). As another test of the effect of metallicity, we use these measurements to assess the γ parameter for the Galactic globular cluster, where

$$\gamma = \frac{\Delta\text{mag}}{[\text{Fe/H}]}, \tag{3}$$

similar to γ used to quantify the effect of metallicity on the zero–point of the Cepheid PL relation (Kennicutt et al. 1998).

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 μm bandpass there is absorption due to a CO bandhead at 4.65 μm, 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 (Iben 1971), we expect to see no such CO absorption in the 4.5 μm 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 [Fe/H] and the PL residuals, we expect it to be a linear one, consistent with the theoretical metallicity terms in the PL relation, $c \times [Fe/H]$; we fit a relation of the form

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

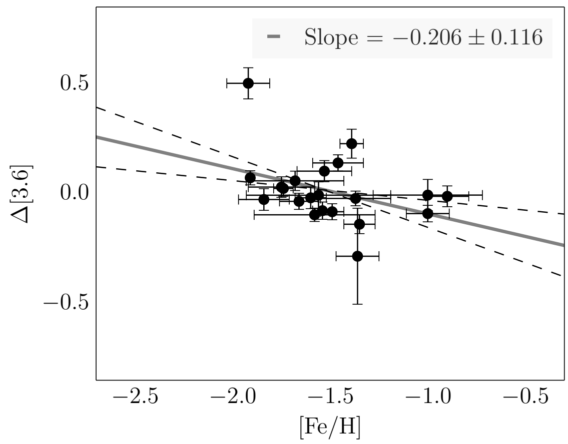

Figure 14. [Fe/H] vs. Δ3.6 μm using photometric metallicities

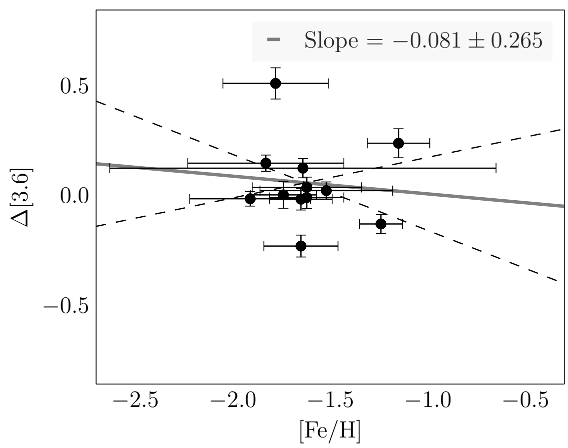

Figure 15. [Fe/H] vs. Δ3.6 μm using spectroscopic metallicities

to the 3.6 μm and 4.5 μm 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 μm and 4.5 μm PL relations is higher for ω 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 [Fe/H] vs. Δ3.6 μm and Δ4.5 μm, γ is within 2σ of zero for all fits, indicating that there is no significant metallicity dependence in the PL residuals. When the outlier at [Fe/H] = −2.0 in Figures 14 and 16 is removed, γ moves within 1σ of zero for all [Fe/H] vs. residual fits, as seen in Figures 18 and 19.

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 ~0.1 mag discrepancy between the distance moduli for 3.6 μm and

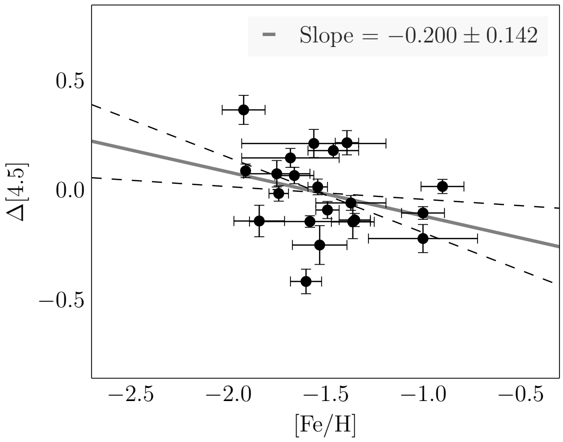

Figure 16. [Fe/H] vs. Δ4.5 μm using photometric metallicities

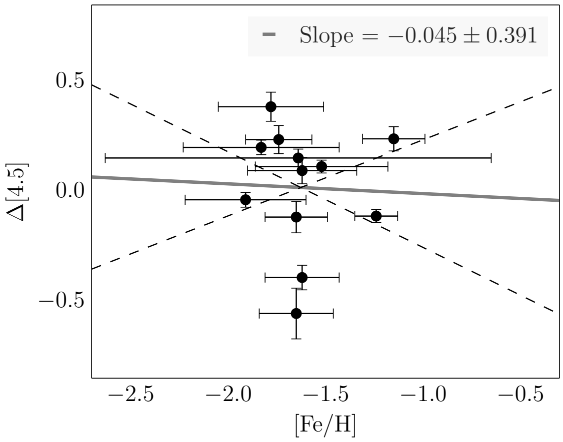

Figure 17. [Fe/H] vs. Δ4.5 μm using spectroscopic metallicities

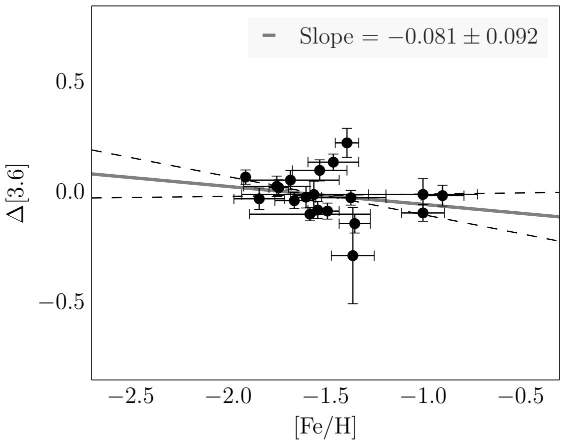

Figure 18. [Fe/H] vs. Δ3.6 μm using photometric metallicities, with outlier removed

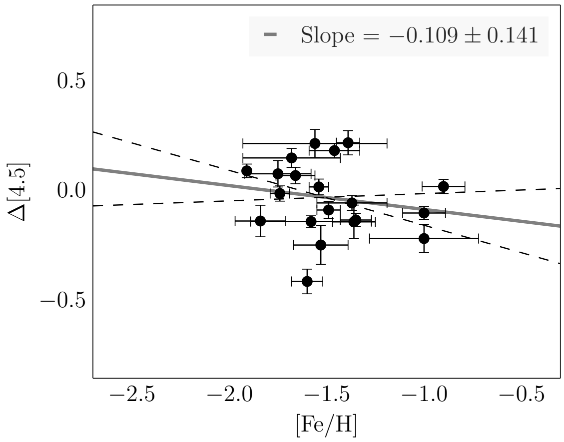

Figure 19. [Fe/H] vs. Δ4.5 μm using photometric metallicities, with outlier removed

4.5 μm 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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APPENDIX A: APPENDIX: PHOTOMETRY OF RR LYRAE VARIABLES

Table A1: JHK_s, 3.6 μm, and 4.5 μm photometry of the RR Lyrae variables in ω Cen

ID	RA (J2000)	Dec (J2000)	J	σ_J	H	σ_H	K_s	σ_K	[3.6]	$\sigma_{[3.6]}$	[4.5]	$\sigma_{[4.5]}$	P (days)	Mode	[Fe/H], p	$\sigma_{[Fe/H]}$, p	[Fe/H], s	$\sigma_{[Fe/H]}$, 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 A1 – *Continued from previous page*

ID	RA (J2000)	Dec (J2000)	J	σ_J	H	σ_H	K_s	σ_K	[3.6]	$\sigma_{[3.6]}$	[4.5]	$\sigma_{[4.5]}$	P (days)	Mode	[Fe/H], p	$\sigma_{\rm [Fe/H]}$, p	[Fe/H], s	$\sigma_{\rm [Fe/H]}$, 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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