

The effect of metallicity on Cepheid magnitudes and the distance to M33[★]

V. Scowcroft,^{1†} D. Bersier,¹ J. R. Mould² and P. R. Wood³

¹*Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead CH41 1LD*

²*School of Physics, University of Melbourne, Parkville, VIC 3010, Australia*

³*Research School of Astronomy and Astrophysics, Australian National University, Weston Creek, ACT 2611, Australia*

Accepted 2009 March 24. Received 2009 March 23; in original form 2009 January 27

ABSTRACT

We present the results from a multi-epoch survey of two regions of M33 using the 3.5-m Wisconsin-Indiana-Yale-NOAO (WIYN) telescope. The inner field is located close to the centre of the galaxy, with the outer region situated about 5.1 kpc away in the southern spiral arm, allowing us to sample a large metallicity range. We have data for 167 fundamental mode Cepheids in the two regions. The reddening-free Wesenheit magnitude W_{vi} period–luminosity (PL) relations were used to establish the distance modulus of each region, with $\mu_{\text{inner}} = 24.37 \pm 0.02$ mag and $\mu_{\text{outer}} = 24.54 \pm 0.03$ mag. The apparent discrepancy between these two results can be explained by the significant metallicity gradient of the galaxy. We determine a value for the metallicity parameter of the PL relation $\gamma = \frac{\delta(m-M)_0}{\delta \log Z} = -0.29 \pm 0.11$ mag dex^{−1}, consistent with previous measurements. This leads to a metallicity corrected distance modulus to M33 of $\mu_\gamma = 24.53 \pm 0.11$ mag.

Key words: catalogues – Cepheids – galaxies: distances and redshifts – galaxies: individual: M33.

1 INTRODUCTION

Cepheid variables have been used to determine galactic distances for many decades (e.g. Fernie 1969; Freedman et al. 2001, and references therein). The relationship between their period of pulsation and luminosity has been considered to be well defined at several times during its lifetime. However, the effect of the Cepheid’s chemical composition on the period–luminosity (PL) relation has never been adequately determined, leaving the relation open to systematic uncertainties that have not been fully investigated. Proper calibration of this relation is essential not just to explain how metallicity affects the pulsations of Cepheids, but also to tie down the zero point of the extragalactic distance scale and thus properly measure the Hubble constant.

Metallicity and differential absorption will both change stellar colours (Bell & Rodgers 1969). Theoretical models (e.g. Caputo et al. 2000) show that the metal content of a Cepheid will affect the derived distance modulus. If a star of an unknown metallicity is at an undetermined distance then it is difficult to untangle these two effects on the stars colours. Ideally, the PL relation would remove

this problem as the distance to the star could be found without calculating the colour of the Cepheid. The problem arises as the calibration of the PL relation does not take this effect into account. The distances that were used to calibrate the zero point of the relation were determined without considering how the reddening of the Cepheids was affected by the combination of these two mechanisms, meaning that a systematic offset may have been introduced into the relation.

There has been some investigation into the effect that metallicity has on the PL relation, beginning with Freedman & Madore (1990). Beaulieu et al. (1997) and Sasselov et al. (1997) used the Cepheids detected in the EROS gravitational lensing survey to show that discrepant values of H_0 could be reconciled by applying a metallicity correction to Cepheid distance moduli. Kennicutt et al. (1998) used the *Hubble Space Telescope* (HST) to observe Cepheids in M 101, a nearby spiral galaxy with active star formation regions but low dust extinction properties. Choosing a galaxy with low extinction means that there would be less reddening from dust; any reddening of the colour of the Cepheids could be explained as a metallicity effect. This study found that $\gamma = -0.24 \pm 0.16$ mag dex^{−1} (see also Freedman et al., 2001). However, their conclusions were based on small numbers of Cepheids, combined with the PL relations from Udalski et al. (1999). It is far from ideal to use such a small sample to quantify an effect that could mean that the entire extragalactic distance scale is subject to a systematic offset. Using a similar method but with a larger sample of Cepheids, Macri et al. (2006) found $\gamma = -0.29 \pm 0.09$ mag dex^{−1}. Using a large sample of nearly 700 Cepheids in 17 galaxies, Kochanek (1997) had found a result compatible with these other works.

[★]Based on observations obtained with the WIYN 3.5-m telescope, Kitt Peak National Observatory, National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation. The WIYN Observatory is a joint facility of the University of Wisconsin-Madison, Indiana University, Yale University, and the National Optical Astronomy Observatories.

†E-mail: vs@astro.livjm.ac.uk

Most works use a sample of Cepheids covering a range in metallicity and enforce consistency between distance moduli; this is what Kennicutt et al. (1998) and Macri et al. (2006) did for instance. An alternative approach used, for example, by Sakai et al. (2004) is to assume that the distances to several galaxies are known a priori, from the tip of the red giant branch (TRGB) in their case, and find the correction needed to bring Cepheid distances to these galaxies in agreement with that other standard candle.

There are two possible solutions to the problem of the metallicity-extinction degeneracy. The method followed by Kennicutt et al. (1998) is one possibility, the elimination of extinction from the equation. Theoretically this method should work, but in practice it is not so simple. Kennicutt et al. (1998) chose a galaxy with low extinction, not zero extinction. This implies that the extinction is not entirely eliminated, leaving the degeneracy that we are trying to overcome. However, this degeneracy could be removed by using the reddening-free Wesenheit magnitude W_{vi} PL relation to calculate the distance. By eliminating extinction in this way, any discrepancies in the apparent distance modulus could be explained by the metallicity effect.

The work presented here is based on a multi-epoch survey of M33 conducted with the WIYN 3.5-m telescope. M33 is a well studied galaxy, with observations of Cepheids performed by Hubble as early as 1926 (Hubble 1926). As it is nearby, many studies have determined the distance of M33 using different and independent methods, such as eclipsing binaries (Bonanos et al. 2006), the TRGB (Brooks, Wilson & Harris 2004; Galletti, Bellazzini & Ferraro 2004; McConachie et al. 2004), masers (Brunthaler et al. 2005) and Cepheids themselves (Freedman, Wilson & Madore 1991). Although some of these methods may not provide the same accuracy that a Cepheid distance does, they allow us to have an independent starting point for our analysis of the PL relation of M33. One of the reasons that M33 was chosen for this study is that it is well studied. Its inclination angle is 53° , and so any effect on distance modulus (μ) from the orientation will be extremely small. The effect on μ due to the orientation of the galaxy was found to be very small (less than 0.01 mag). The metallicity gradient across the galaxy is well defined, so the chemical composition of the Cepheids is relatively easy to determine just from their position in the galaxy. These properties inherent to M33 make it the ideal target for a study of this nature.

The paper is organized as follows. Section 2 describes our observations. Section 3 describes the reduction process, including the development of the photometry pipeline and the final calibration and astrometry. Section 4 contains the final catalogues and assesses the accuracy of the photometry, with the final PL relations and distances in Section 5. Finally, we examine the effect of metallicity on our results and derive a value for the metallicity correction parameter γ .

2 OBSERVATIONS

The data set consists of 25 epochs of BVI_C images of four fields of M33 obtained between 1998 and 2001 on the 3.5-m WIYN telescope. The first 20 epochs used the WIYN S2KB Imager, a single thinned Tek/STIS 2048×2048 CCD with $21\text{-}\mu\text{m}$ pixel. For the final five epochs, the new Mini-Mosaic (MiMo) camera was used. The MiMo consists of two thinned SITE 2048×4096 CCDs with $15\text{-}\mu\text{m}$ pixel. A single exposure covered 6.8×6.8 arcmin for the Imager, and 9.6×9.6 arcmin for the MiMo, with pixel scales of 0.195 and 0.141 arcsec pixel $^{-1}$, respectively.

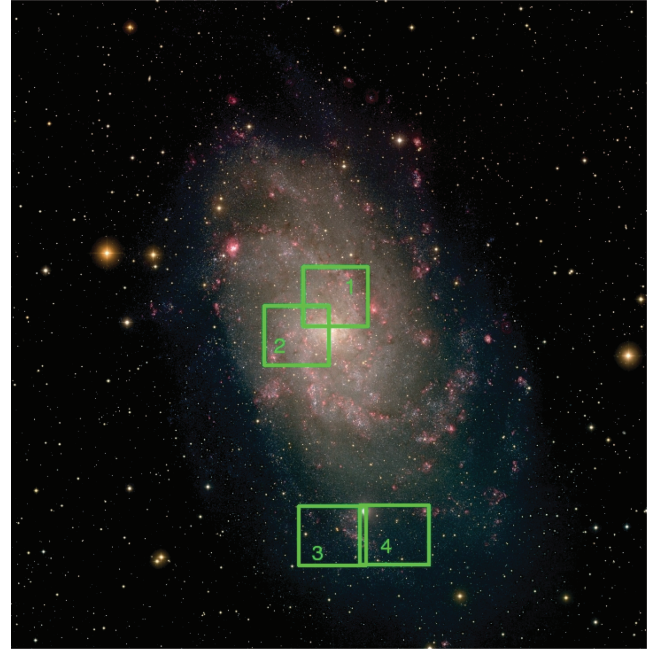


Figure 1. The two regions observed for this survey (Original image copyright: National Optical Astronomy Observatory/Association of Universities for Research in Astronomy/National Science Foundation). The inner region contains fields 1 and 2; the outer region contains fields 3 and 4. The fields were chosen such that they would cover the whole metallicity range of the galaxy. Orientation: north up, east right.

Four fields were observed for the survey, two in the centre of M33 and two in the outer, southern part of the galaxy. The locations of the fields are shown in Fig. 1. The J2000.0 coordinates of the fields are shown in Table 1. All the fields were observed in the B , V and I_C filters with both cameras. The position of the fields were chosen such that the metal-rich population at the centre of the galaxy could be compared with the more metal-poor population in the outer region. Cepheids tend to be concentrated in the spiral arms, so the outer fields were located in the southern part of the galaxy to coincide with the clearest arm. The positions of the fields and the addition of the MiMo camera meant that some objects were observed in either both inner or both outer fields, giving up to 38 observations for objects in the overlap regions. The log of observations is shown in Table 2.

Table 1. J2000.0 coordinates of the four fields. M33-1 and M33-2 are situated in the centre of the galaxy. M33-3 and M33-4 are in the southern spiral arm. Deprojected angular and linear distances of each field to the centre of the galaxy are given, assuming M33 is at a distance of 840 kpc, has an inclination angle of 53° and the major axis has a position angle of 22° .

Field	α	δ	Angular (arcsec)	Linear (kpc)
Imager				
M33-1	1 ^h 33 ^m 49 ^s .12	30°42′56″.48	217.64	0.886
M33-2	1 ^h 34 ^m 06 ^s .13	30°38′52″.50	217.10	0.884
M33-3	1 ^h 33 ^m 48 ^s .99	30°20′24″.58	1242.13	5.059
M33-4	1 ^h 33 ^m 25 ^s .63	30°20′25″.25	1290.30	5.255
Mi-Mo				
M33-1	1 ^h 33 ^m 51 ^s .77	30°45′16″.56	367.50	1.497
M33-2	1 ^h 34 ^m 16 ^s .75	30°36′35″.64	409.13	1.666
M33-3	1 ^h 34 ^m 00 ^s .16	30°21′46″.08	1161.16	4.729
M33-4	1 ^h 33 ^m 21 ^s .13	30°21′52″.20	1220.28	4.970

Table 2. Log of observations. Full table available on request from the author. Cameras: IM = S2KB Imager, MiMo = Mini-Mosaic.

UT date	MHJD	Field	Filter	Cam.	Seeing (arcsec)
1998 August 19	51044.427	M33-1	<i>B</i>	IM	0.53
1998 August 19	51044.433	M33-1	<i>I_C</i>	IM	0.53

3 DATA REDUCTION

Preliminary reduction of the data were performed using the routines in the IRAF¹ CCDPROC package. This consisted of overscan correction, bias subtraction and flat fielding. The photometry was performed using the standalone DAOPHOT (Stetson 1987) and ALLFRAME (Stetson 1994) packages kindly provided by P. Stetson.

3.1 Photometry pipeline

The data set used in this project is fairly large, containing over 300 images of the four fields. To process such a large data set a completely automatic photometry pipeline was developed, covering all the steps from initial star selection to the final point spread function (PSF) photometry.

Initial star lists were compiled using the FIND routine in DAOPHOT with a 3σ detection limit. Aperture photometry was performed on each list to get rough magnitudes using an 11 pixel aperture and sky values from the annulus from 19 to 23 pixels.

The creation of the PSF model is the most important part of the process. The fields are extremely crowded; the inner field has an average density of 890 stars arcmin⁻², or approximately 10 pixels between each centroid position. Of course, these calculations do not take into account the clumpiness of the distribution, the galactic centre has a much higher stellar density than further out. As the fields are so crowded, it is imperative that the PSF model is as accurate a representation of the stellar profile as possible, but it also means that it becomes a more taxing problem. The stars chosen to make the model should be the brightest, least crowded available, and with such heavy crowding these are very rare objects.

The problem was overcome using a combination of the DAOPHOT PICK and PSF routines along with a series of scripts to analyse the resulting fits. The initial model was created by allowing PICK to choose the 200 best stars from the aperture photometry file then using PSF to make six model profiles using the different Gaussian, Moffat and Lorentz functions available, allowing the model to vary linearly across the frames. The residuals of the fit were analysed and any star flagged as saturated or with fitting residuals more than twice the rms residual value were removed. All the stars except the PSF stars were then removed from the images and the PSF was remade with the new star list from the cleaned image. The process of analysing the residuals, removing neighbour stars and remaking the PSF was repeated a further five times and resulted in a clean, well-fitting model. Allowing the model to vary quadratically and repeating the cleaning process more times were both tested but did not significantly improve the results.

Profile fitting photometry was performed on each frame separately using the ALLSTAR routine, which produced an image with all the fitted stellar profiles subtracted. A fitting radius of 0.78 arcsec

was used, corresponding to the typical seeing. This new image was run through the star finding process again to detect any stars that were too faint or crowded to be seen in the first pass. This new star list was appended to the original and run through ALLSTAR again.

Once reasonable PSF magnitudes had been obtained for each frame, the images were combined using MONTAGE2 (Stetson, personal communication) using the best 50 frames to produce two master images, one for the inner and another for the outer fields. These deep, medianed images were then run through the pipeline described above to produce master star lists for the two regions. The master lists contained over 200 000 stars in the inner region and around 100 000 for the outer region. The lists produced from these frames were used rather than the original lists for two reasons. First, a medianed image made from many frames has a much better signal-to-noise (S/N) ratio than a single frame. Second, using identical star lists for each frame and each filter is necessary when using the ALLFRAME package. ALLFRAME was used to calculate the final PSF magnitudes from ‘fixed position’ coordinate lists.

The final step of the instrumental photometry was to calculate the aperture corrections and set all the photometry to the same zero point. Landolt standards were observed on 1999 October 3, so this night was chosen to be the reference night. Aperture corrections were calculated for each frame taken on the reference night (four fields in three filters) using DAOGROW (Stetson 1990). Using the ALLFRAME photometry files as input, all the stars in each frame except the stars used to make the PSF model were subtracted. The PSF stars are ideal for calculating the aperture correction as they are by their nature bright and relatively isolated. The stars remaining in the frame were then measured in nine apertures with radii between 4 and 20 pixels, with the sky measured from an annulus between 25 and 30 pixels. The output photometry was then put into DAOGROW to calculate the growth curves and derive the total magnitudes. The difference between the total magnitude and the PSF magnitude for each star was calculated, and any bad outliers were removed. These stars could have been affected by nearby stars that had been missed, or even nearby PSF stars in the large aperture. The best value of the correction was found using a least squares fit. The corrections were then subtracted from the PSF magnitude to put the ALLFRAME photometry on the same scale as the aperture magnitudes. The aperture corrections for the reference night had an average value of 0.035 mag.

To get correct photometry for every night, the zero-point offset between each frame and its corresponding reference frame was calculated. As the fields overlap, field 1 was chosen as the reference for the inner region and field 3 for the outer region. This ensured that stars that were observed in different fields on the same night were on the same zero point. The zero-point offset of each frame was found by taking the average difference between each magnitude on the reference frame and the frame in question, typically using 1000–2000 stars. The star furthest away from the average was removed and the average recalculated until the dispersion of the differences was less than 0.01 mag. This was found to be a very robust method, distinguishing zero-point differences down to one hundredth of a magnitude.

3.2 Photometric calibration and astrometry

Observations of standard fields (Landolt 1992) were taken on 1999 October 3 with the Imager CCD. Three standard fields were observed repeatedly, with a total of 17 different standard stars. Aperture photometry was performed on the standards with the same settings as the aperture correction, that is a 20 pixel aperture and a

¹ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 3. Photometric solution of 1999 October 3 for the Imager CCD

Filter	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	rms
<i>B</i>	24.1552	0.2760	−0.0682	−0.0062	0.0098
<i>V</i>	24.3051	0.2006	−0.0123	−0.0062	0.0107
<i>I_C</i>	23.7141	0.0903	−0.0545	−0.0026	0.0187

25–30 pixel sky annulus. The PHOTCAL routines in IRAF were used to construct standard solutions of the form

$$m_{\text{inst}} = m_{\text{cal}} + a + b \times X_M + c \times \text{Colour} + d \times UT, \quad (1)$$

where m_{inst} is the instrumental magnitude, m_{cal} is the calibrated magnitude, X_M is the airmass and *Colour* corresponds to $(B - V)$ for the *B* and *V* frames and $(V - I_C)$ for *I_C*. The coefficients for each transformation equation are shown in Table 3. The solution was applied to all Imager frames using INVERTFIT. The *UT* term was included in the solution as the extinction changed very slowly over the reference night. Although the coefficient of this term in the solution is much smaller than the others, we believe that it is still important to include it. The aim of the process is to get the most accurate photometry possible, so if an effect is present and can be measured on a scale comparable to the accuracy we are trying to achieve, then it should be considered.

This calibration is only appropriate for the frames taken with the Imager CCD. Once applied to the Imager frames, the stars on the reference frames could be used as local standards to derive a photometric solution for the two MiMo CCDs. The reference night for the MiMo was chosen to be 2000 October 3 as this had the best image quality for all fields. Stars that appeared in all frames of field 3 on both the photometric reference night and on the Mosaic reference night with $\sigma_V \leq 0.02$ mag were selected as the local standards – around 200 stars for each chip. The PHOTCAL routines were used to find the solution of the transformation equations from the Mosaic instrumental magnitudes to the Imager Landolt calibration. For this transformation, the time dependence and airmass term are absorbed into the zero-point coefficient of this solution and a quadratic colour term was added, resulting in transformation equations of the form

$$m_{\text{MiMo}} = m_{\text{Im}} + a + b \times \text{Colour} + c \times (\text{Colour})^2, \quad (2)$$

where m_{MiMo} refers to the magnitude on the MiMo instrumental scale and m_{Im} refers to the calibrated Imager scale. The quadratic colour term of the MiMo camera is a feature that has been described before by Stetson (2005). The coefficients of the equations are shown in Table 4.

The stacked frames created for making the ALLFRAME master lists were also used to perform the astrometry. For the outer field the USNO-B catalogues (Monet et al. 2003) were used, resulting in a

Table 4. Photometric solution of 2000 October 3 for the Mini-Mosaic camera.

Filter	<i>a</i>	<i>b</i>	<i>c</i>	rms
Chip 1				
<i>B</i>	23.9118	−0.0935	0.0172	0.0494
<i>V</i>	24.1484	−0.0235	0.0079	0.0359
<i>I_C</i>	23.6443	−0.0374	−0.0083	0.0472
Chip 2				
<i>B</i>	23.9120	−0.0587	−0.0143	0.0486
<i>V</i>	24.1465	0.0128	−0.0245	0.0302
<i>I_C</i>	23.6373	−0.0610	0.0042	0.0455

solution with rms values of 0.4 arcsec. The USNO-B catalogue was not appropriate for the inner field as it covers the central part of the galaxy, which is extremely crowded. For this region, the astrometric solution was found by matching by eye to the catalogues published in Massey et al. (2006). They also use USNO-B catalogue for this region but have many fewer stars. This process gave a much better solution, with an rms below 0.07 arcsec.

4 RESULTS

4.1 The catalogues

Two catalogues are available from the WIYN M33 survey. The first contains weighted average *B*, *V* and *I_C* magnitudes for each star. A sample of this catalogue is shown in Table 5.² The second contains all the individual measurements for all the variables cross-identified with the Deep Canada-France-Hawaii Telescope (CFHT) Photometric survey of M33 (Hartman et al. 2006). The catalogues are available in full electronically. They cover the magnitude range between $13.8 \leq V \leq 26.7$, with 75 465 and 146 820 in the final outer and inner field lists, respectively. The magnitude range of the inner field is limited slightly by the degree of crowding, and only contains objects down to $V = 25.7$. Colour–magnitude diagrams for both fields are shown in Fig. 2.

The uncertainties given in the average photometry catalogue are the errors on the weighted average magnitudes, calculated from the ALLFRAME results. Fig. 3 shows the relation between magnitude and uncertainty for the *V* band in the outer field. A second series becomes visible around $m_V = 20$ mag. These objects have fewer measurements, a maximum of five, as they appear only on the MiMo frames (which cover a larger field of view than the Imager). However, a comparison between magnitudes calculated from the Imager and the MiMo shows the photometry is compatible. Neglecting the second series, we obtain 1 per cent photometry for objects brighter than $m_V = 22$, and 10 per cent down to $m_V = 24$. The full analysis is shown in Table 6. These results are compatible with theoretical estimates from S/N ratio calculations.

4.2 Comparison with others

To check the accuracy of our results, the average magnitudes were compared with those obtained by Massey et al. (2006). Their survey covers a larger area than the survey presented here but does not go as deep. The comparison for each filter in both fields is shown in Fig. 4. The photometry from this work is considered as the reference, $\Delta\text{mag} = m_{\text{Scowcroft}} - m_{\text{Massey}}$. These plots show that the photometry is sound. Most objects have a difference near zero as expected. For the inner field in particular, there seems to be a secondary sequence near $\Delta\text{mag} \approx -0.8$. We attribute this to misidentifications due to the high level of crowding. By excluding the central 4 arcmin of the galaxy from the comparison the effect was significantly reduced.

The average differences were found using a least squares fit to the brightest three magnitudes in the comparison and are shown in Table 7. Only the brightest stars in the comparison were chosen as the two catalogues are optimized for different magnitude ranges; were we to consider the whole range, we would be basing the fit on the very faintest stars in Massey et al. (2006). However, Δmag gradients were checked for, and the differences for each field-filter combination were found to be constant over the whole

² The full catalogues are available on request from the authors.

Table 5. Sample of the weighted averages catalogue. The uncertainties are from the weighted average calculations derived from the ALLFRAME results. Where no observations were made, the magnitude and error are represented by 99.999 and 9.999, respectively.

ID	α hh:mm:ss	δ dd:mm:ss	B	σ_B	V	σ_V	I_C	σ_I	N_B	N_V	N_I
OUT-14501	1:33:10.21	30:17:22.7	24.946	0.423	23.733	0.161	99.999	9.999	1	1	0
OUT-14510	1:33:10.25	30:17:05.8	22.484	0.155	22.269	0.096	99.999	9.999	2	2	0
OUT-14523	1:33:10.26	30:17:07.2	22.525	0.092	22.872	0.075	99.999	9.999	2	2	0
OUT-14527	1:33:10.19	30:17:50.4	23.608	0.312	24.306	0.248	99.999	9.999	1	1	0
OUT-14532	1:33:10.26	30:17:15.2	23.475	0.109	22.943	0.067	99.999	9.999	2	2	0
OUT-14539	1:33:10.27	30:17:17.2	23.474	0.125	23.576	0.098	23.232	0.335	2	2	1
OUT-14546	1:33:10.27	30:17:23.2	24.193	0.184	23.556	0.092	23.002	0.219	2	2	1
OUT-14551	1:33:10.14	30:18:33.5	24.732	0.373	23.040	0.129	99.999	9.999	1	1	0
OUT-14554	1:33:10.17	30:18:20.5	22.238	0.096	22.313	0.075	99.999	9.999	1	1	0
OUT-14555	1:33:10.20	30:18:06.2	24.940	0.410	23.103	0.084	99.999	9.999	1	1	0

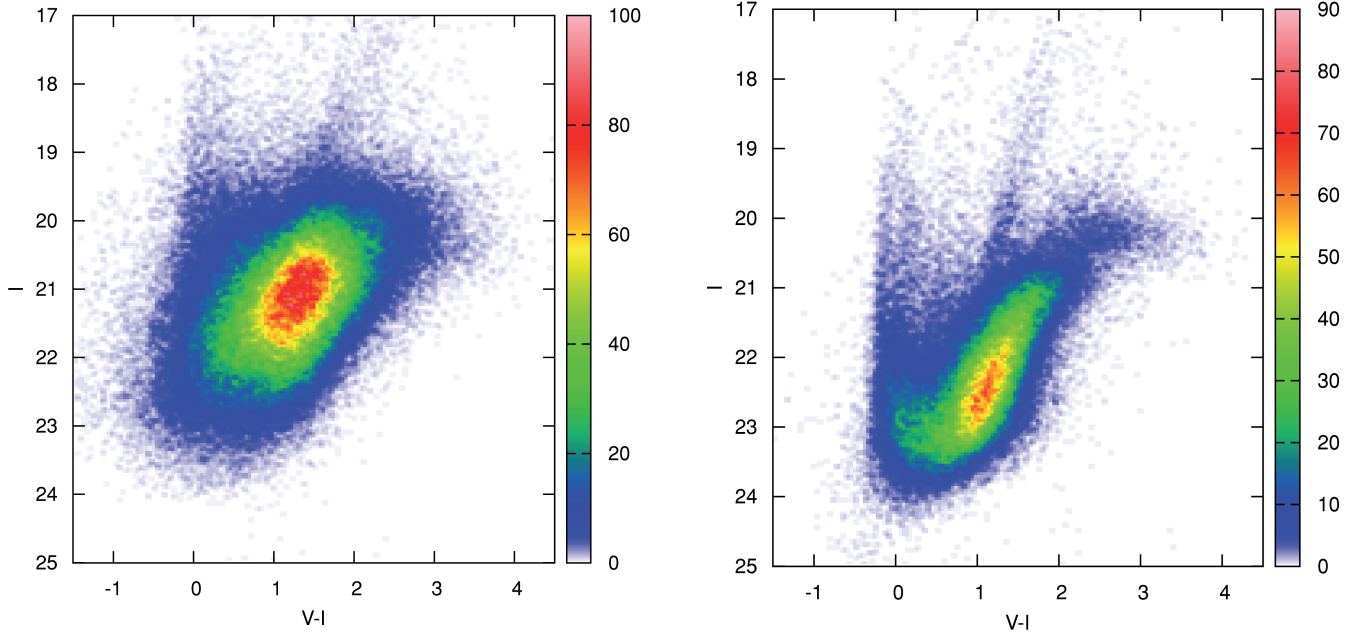


Figure 2. Hess diagrams for the inner (left-hand panel) and outer (right-hand panel) fields, with 0.025 mag bins. The inner field does not go as deep as the outer field as the degree of crowding is much higher. The effects of crowding and differential reddening are obvious in the inner field but are much less so in the outer field.

range of magnitudes. We find a larger average Δmag for I_C which is believed to be because the I_C frames are more crowded than B and V , particularly in the inner field.

5 CEPHEID PERIOD–LUMINOSITY RELATION

The aim of the survey was to detect Cepheids in the two fields and assess the effect that metallicity has on the PL relation. The positions of the two fields were chosen such that the inner field covered the metal-rich centre, which has an $[\text{Fe}/\text{H}]$ value slightly larger than the Milky Way (MW), and the outer field covered the southern spiral arm where the metallicity drops to slightly below that of the Large Magellanic Cloud (LMC).

5.1 Cepheid selection

Cepheids were identified by cross referencing the catalogue with the fundamental mode Cepheid catalogue produced as part of the deep CFHT survey of M33 (Hartman et al. 2006). The fundamental

mode Cepheids were identified using Fourier parameters (Simon & Lee 1981). First overtone Cepheids were excluded from the analysis as they are known to sit slightly higher in the $\log P - \text{Mag}$ plane than fundamental Cepheids and would bias any zero-point fitting towards brighter magnitudes.

To ensure an accurate PL relation, the average magnitudes for each Cepheid were recalculated by fitting Fourier series to the light curves, using the form shown in equation (3), where $m(\phi)$ is the magnitude at phase ϕ and a becomes the phase averaged magnitude:

$$m(\phi) = a + \sum_{i=1}^3 b_i \cos(2\pi i \phi + c_i). \quad (3)$$

The light curve of each Cepheid was examined visually to remove any misidentifications or ones with incorrect periods. The amplitude of each Cepheid was calculated and Cepheids with $A_B > A_V > A_{I_C}$ were included in the final sample, similar to the selection criteria of Pietrzyński et al. (2002). Amplitude ratio selection is an important step as large numbers of classical Cepheids are known to exist in binary systems (Szabados 2003). Very close companions would not

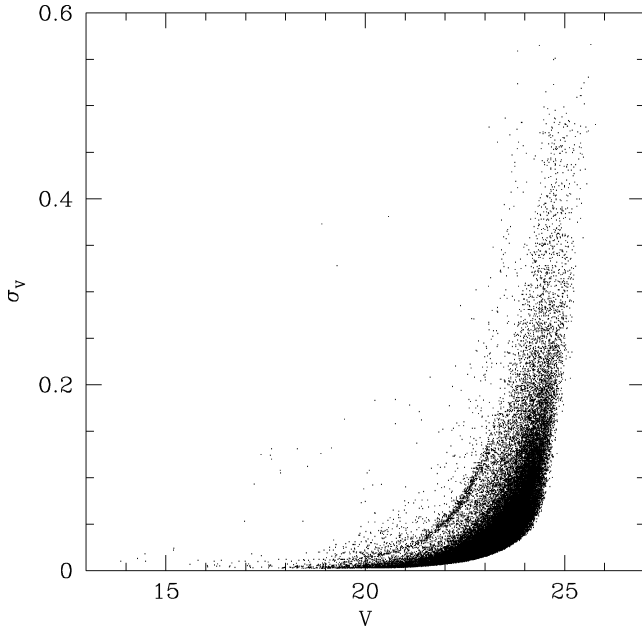


Figure 3. Magnitude – σ relation for V in the outer field. The second series with slightly higher uncertainties for a given magnitude is due to the MiMo magnitudes dominating these objects, as these stars have few measurements.

Table 6. Typical magnitudes and uncertainties from the weighted averages catalogue.

Field	Filter	$\sigma = 0.01$ mag	$\sigma = 0.1$ mag
Inner	B	21.125	24.129
	V	21.693	23.854
	I_C	19.896	22.597
Outer	B	21.336	24.404
	V	22.136	24.195
	I_C	20.840	22.643

be identified as separate stars in the initial photometry. They can however be identified by their characteristic effect on the Cepheid light curve. A Cepheid with an unidentified companion will still appear variable, but the light curve would not reach the minimum value expected. The effect will be seen to different extents in the different photometric bands depending on the colour of the companion. This explanation can also be extended to blending; if a Cepheid is within a background of unidentified faint stars, these objects will affect the shape of the light curve in the same way. By requiring that the amplitudes of the Cepheids follow the criteria set out above, we can remove these effects from the sample. The visual inspection and amplitude selection left 91 and 28 Cepheids in the inner and outer field samples, respectively.

5.2 Metallicity effects

Many attempts have been made to assess the extent of the metallicity effect, with some analysing the effect of Z on μ – and hence the PL zero point – such as Bono et al. (2008) and Sakai et al. (2004), whilst others focus on the effect that Z has on the slope of the PL relation (e.g. Alibert et al. (1999)). In this work, we analyse the effect of Z on the derived distance modulus, which is quantified by

the parameter γ :

$$\gamma = \frac{\delta(m - M)_0}{\delta \log Z}, \quad (4)$$

where $\delta(m - M)_0$ is the difference between distance modulus corrected for the metallicity effect and without correction, in the sense corrected – apparent, and $\delta \log Z$ is the difference between a reference metallicity and the region being studied (Kennicutt et al. 1998). Recent measurements of γ have produced negative values as large as $\gamma = -0.4 \text{ mag dex}^{-1}$, with the average being around $\gamma = -0.25 \text{ mag dex}^{-1}$. Following the methodology of Kennicutt et al. (1998) and Sakai et al. (2004), the value of γ can be calculated using the two distance moduli, μ_{inner} and μ_{outer} , and the $[\text{O}/\text{H}]$ gradient of M33. We adopt the recent $[\text{O}/\text{H}]$ gradient from Magrini et al. (2007):

$$\frac{d[\text{O}/\text{H}]}{dR} = -0.19 \pm 0.08 \text{ dex kpc}^{-1} (R < 3 \text{ kpc}) \quad (5)$$

and

$$\frac{d[\text{O}/\text{H}]}{dR} = -0.038 \pm 0.015 \text{ dex kpc}^{-1} (R \geq 3 \text{ kpc}). \quad (6)$$

The deprojected radial distances of the centres of the two fields are 0.52 and 5.11 kpc, leading to $12 + \log(\text{O}/\text{H}) = 8.852$ and 8.296 for the inner and outer fields, respectively. This gives a value of $\Delta[\text{O}/\text{H}] = -0.556$. To realize the full extent of the correction, we must initially treat the fields as if they had the same metallicity. This is done by using the same model PL relations for both regions.

PL relations were fitted to the Cepheids in both fields in B , V , I_C and the reddening-free Wesenheit magnitude W_{vi} as defined by Fouqué et al. (2007, hereafter F07), assuming the $R_V = 3.23$ reddening law described by Cardelli, Clayton & Mathis (1989):

$$W_{vi} = V - 2.55(V - I_C). \quad (7)$$

The B , V , I_C PL relations are shown in Fig. 5; the W_{vi} relations are shown in Fig. 6. The PL relations take the form $M = a \log P + b$. The values for the slopes, a , were taken directly from the F07 LMC relations, whilst the intercept, b , was derived from an iterative weighted least squares fit for each relation. The values of the W_{vi} zero points are shown in Table 8.

The zero points of the PL relations for W_{vi} can be used to directly infer the distance modulus of M33, without the need to correct for extinction. The distance modulus can be found from the apparent W_{vi} magnitude of a Cepheid with a period of 1 d, such that $\mu = b - M_0$, where b is the zero point of the PL relation and M_0 is the absolute magnitude of a 1 d Cepheid, which is taken directly from the LMC PL relations from F07.

The zero points in Table 8 may at first glance appear discrepant. As they have been derived from the reddening-free W_{vi} PL relations, we can safely rule out an erroneous extinction correction as the source of the difference. There are three other possible explanations for the difference we observe:

- (i) Blending affecting the magnitudes of Cepheids in the inner field.
- (ii) Differing period distributions of the two samples and a possible slope change at $P = 10$ d.
- (iii) Differing metallicity in the two fields.

5.2.1 Blending

The most obvious suggestion to explain discrepant values for the distance moduli is the fact the inner field is extremely crowded, and there may be Cepheids with undetected companions in the

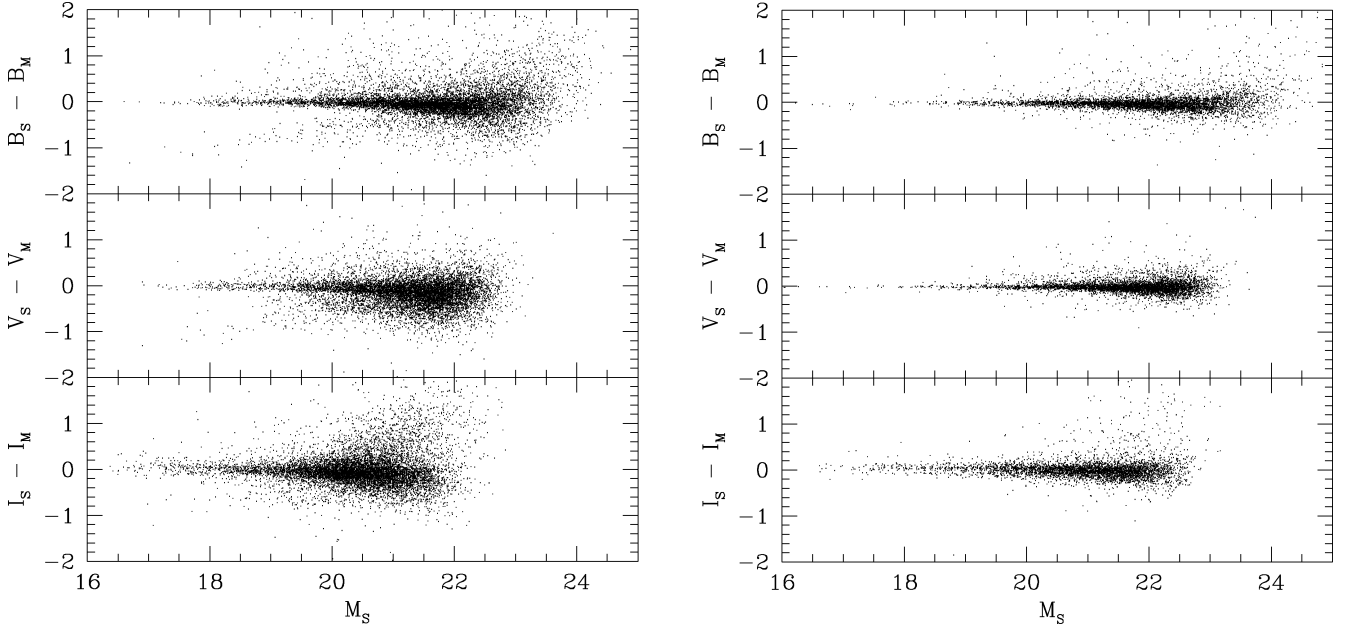


Figure 4. Comparison between this work and the catalogues of Massey et al. (2006) for the inner field (left-hand panel) and the outer field (right-hand panel). This work is considered to be the reference and is denoted by M_S , Massey et al. (2006) by M_M and $\Delta\text{mag} = M_S - M_M$. The average number of stars compared is 9700 for the inner field and 5100 for the outer field, corresponding to roughly 5 per cent of our catalogues. All matched stars with $\sigma < 0.5$ mag that were outside the central 4 arcmin were included. The secondary $M_S - M_M < 0$ trends that are visible in the left-hand panel are believed to be due to the severe crowding of the region, as the matching algorithm used will tend to match to slightly brighter stars in highly crowded regions.

sample which will affect any PL relation zero point that we try to fit. However, we do not believe that this is the cause of the observed deviation.

First, our procedure is based on ALLFRAME which uses a deep image, made by stacking many individual exposures, to do the photometry on each individual frame. When the photometry is done on this deep reference frame, the S/N ratio for each object is much higher than on individual images, allowing us to better recognize, and classify as such, stars that may be blended. Second, our comparison of the photometry with Massey et al. (2006) shows excellent agreement. They use images with individual exposure times of 60 s in BV and 150 s in I ; in other words, they are up to five times less deep than our data. This means that the level of crowding and blending will be less severe than in our case. Yet, our photometry is found to be in excellent agreement with theirs, for both fields, over the whole magnitude range covered by both surveys. If we were sensitive to blending levels that Massey et al. do not see, there

should be a systematic offset between the two catalogues. However, as we do not see a quantifiable offset in either Fig. 4 or Table 7, we can safely rule out blending as the cause of the difference in distance modulus for the two fields.

We can also rule out blending as the cause on a theoretical level. Ferrarese et al. (2000) addressed this issue, in the context of the *HST* Key Project, with artificial star tests. They did this for two galaxies with fairly different levels of crowding. Their main conclusion was that this has little impact on distance moduli, provided the Cepheids used to derive the distance are carefully selected, as the ones in our final sample were. It is useful to note, however, we found the same $\Delta\mu$ between our outer and inner fields using both the raw and selected Cepheid samples, although the PL relation constructed from the selected sample has a much lower dispersion than that of the raw sample. This reduces the uncertainty on the fit, but also provides indirect evidence that blending is not an issue in our sample.

Table 7. Differences between weighted average magnitudes in this catalogue and Massey et al. (2006). Δmag was found from a least squares fit to the brightest end of the comparison, the range is given in column 4. $\sigma_{\Delta\text{mag}}$ is the uncertainty on Δmag . Outliers with $\Delta\text{mag} > \pm 0.5$ were rejected, as they are most likely misidentifications due to the crowding in the inner field.

Field	Filter	Δmag	$\sigma_{\Delta\text{mag}}$	Range
Inner	B	0.008	0.005	16–19
	V	−0.009	0.008	15–18
	I_C	0.031	0.008	15–18
Outer	B	−0.013	0.008	16–19
	V	−0.014	0.005	16–19
	I_C	0.021	0.005	16–19

5.2.2 Period distribution and slope changes

The second possibility for the differing values for the distance modulus of M33 is the period range of the two samples. The distribution of periods in the final, selected sample is shown in Fig. 7. It is quite clear that the period distribution of the two regions is not the same. This is for two reasons. First, the short-period Cepheids are fainter so we detect more of them in the outer field where the detection limit is lower. Second, long-period Cepheids are rarer than their short-period counterparts. Therefore, we expect the ratio of long-period Cepheids to total number of stars detected to be quite low, hence they will be preferentially detected in the region with a higher number of stars; in this case, the inner region.

There is some observational evidence that the slope of the V and I_C PL relations change around 10 d (e.g. Ngeow et al. 2009).

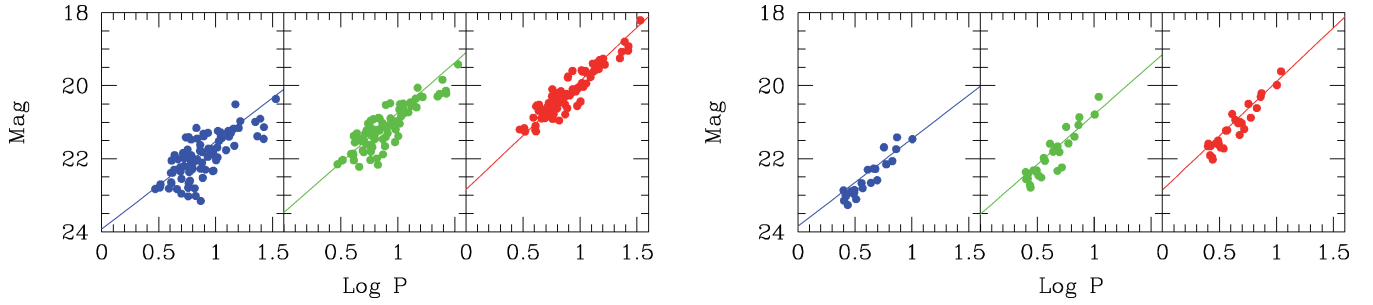


Figure 5. PL relations for the inner field (left-hand panel) and the outer field (right-hand panel), B , V and I_C go from left to right. The lines correspond to the LMC PL relations described in Fouqué et al. (2007). The magnitudes have not been corrected for reddening.

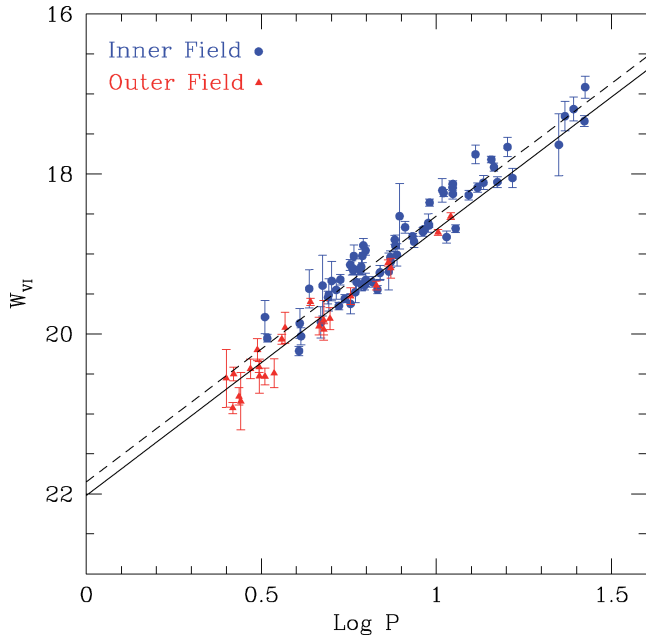


Figure 6. Reddening-free Wesenheit W_{vi} PL relations for the inner field (blue circles) and the outer field (red triangles).

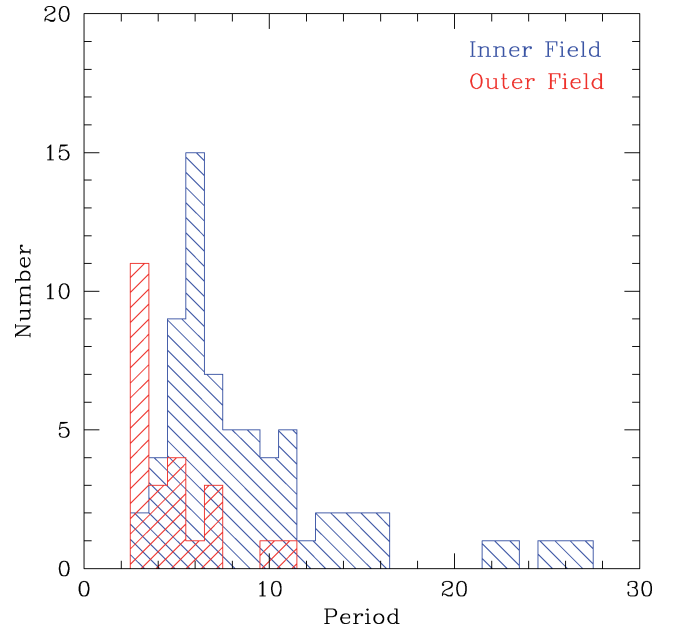


Figure 7. Period distribution of the two Cepheid samples used to fit the W_{vi} PL relations.

However, there is still debate about whether this effect is real, and if the same non-linearity will appear in the W_{vi} relation. To rule out any possible slope change as the cause of the discrepant distance moduli, the samples were both cut to $\log P < 1$ and the PL relations refitted. Note that no attempt is made to determine if any non-linearity is present or to quantify the effect, just to eliminate the possibility; such tests would require a much larger Cepheid sample than is used in this work. As a first test, both the slope and zero point of the fits were allowed to vary. The two slopes had the same

value, as expected, but again the two zero points were different. To bring the uncertainty on the zero points down, the slope was then fixed and the zero points refitted. The resulting fit is shown in Fig. 8. Using the fixed slopes gives zero points of 21.90 ± 0.02 and 22.03 ± 0.04 for the inner and outer fields, respectively.

The fact that the zero points are still discrepant at the 3σ level when we use a fixed period range demonstrates that this effect, whatever the cause, is universal over the period range and is not due to the possible non-linearity of the PL relation.

Table 8. Distance moduli from the W_{vi} PL relations using the whole Cepheid sample and the period limited sample.

Field	b_{LMC}	μ
All P		
Inner	21.85 ± 0.02	24.37 ± 0.02
Outer	22.01 ± 0.03	24.54 ± 0.03
$\log P < 1$		
Inner	21.90 ± 0.02	24.42 ± 0.02
Outer	22.03 ± 0.04	24.55 ± 0.04

5.2.3 Metallicity

As we have successfully ruled out blending and the period distribution as causes of the discrepant distance modulus, the only remaining explanation is the differing chemical abundances in the two environments. The zero points and distance moduli for each fit are shown in Table 8.

To quantify the effect of metallicity, we use γ , as defined in equation (4). We can substitute $\delta(m - M)_0$ for $\Delta\mu = 0.16 \pm 0.04$ mag, using the full sample distance moduli, and $\delta Z = -0.556 \pm 0.101$ dex. This leads to a metallicity correction of $\gamma = -0.29 \pm 0.11$ mag dex $^{-1}$. This is compatible with recent

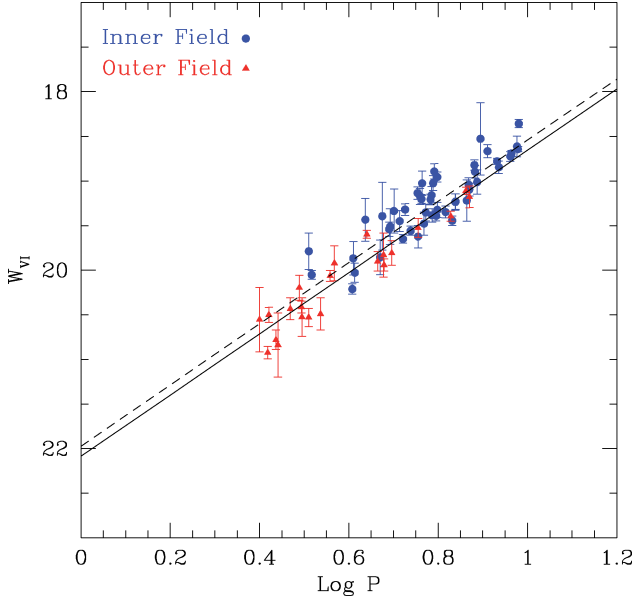


Figure 8. W_{vi} PL relation fit using $\log P < 1$ criteria. The two slopes were found to be identical, however the zero points still differ at the 3σ level.

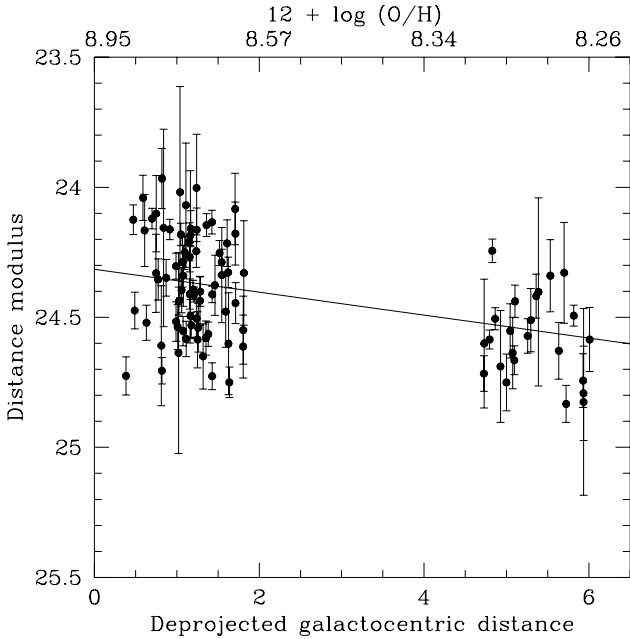


Figure 9. Measured distance moduli for each Cepheid as a function of deprojected galactocentric distance and metallicity. The line is a weighted least squares fit to the individual data points.

measurements, such as that of Sakai et al. (2004). Our final distance measurement for M33 is calculated by assuming an LMC metallicity of 8.34 (Sakai et al. 2004). Using $\gamma = -0.29 \pm 0.11$, we find that the metallicity corrected distance modulus to M33 is $\mu_\gamma = 24.53 \pm 0.11$, consistent with recent TRGB distance measurements. The individual distance moduli derived for each Cepheid are shown in Fig. 9.

The uncertainty on our result is significant. By using a larger Cepheid sample, the contribution from the distance moduli could be reduced. Also, the sample only covers the two extremes of the metallicity gradient. We will investigate the effect further using the

data from Hartman et al. (2006). Their sample contains over 2000 Cepheids spread over the entire galaxy, and hence the entire [O/H] range. This will allow us to fully investigate the effect over a wide range of [O/H], rather than just fitting a straight line to two points, and the use of so many Cepheids will bring the random uncertainty down considerably.

We note that the largest contribution to the error budget is the uncertainty on the metallicity gradient of M33. This could be reduced using a large sample of Cepheids. Recent work by Beaulieu et al. (2006) has shown that the two periods of double mode Cepheids can be used to calculate their metallicity. By using a large sample of these stars across the whole galaxy, in combination with observations of fundamental mode Cepheids covering the same area, it would be possible to calculate γ with a much higher degree of accuracy.

6 CONCLUSIONS

We have produced a photometric catalogue in B , V and I_C for over 200 000 objects in two regions of M33, identifying 167 fundamental mode Cepheids. Using the reddening free Wesenheit LMC PL relations, we have established distances to the two regions as $\mu_{\text{inner}} = 24.37 \pm 0.02$ mag and $\mu_{\text{outer}} = 24.54 \pm 0.03$ mag. The difference in these two distance moduli is believed to come from the effect of metallicity on the zero point of the PL relation, and hence its effect on Cepheid distances. We have quantified this effect by the parameter $\gamma = \frac{\delta(m-M)_0}{\delta[\text{O}/\text{H}]}$ and find a value of $\gamma = -0.29 \pm 0.11$ mag dex $^{-1}$, consistent with other recent estimates. For the range of metallicities discussed here, it is appropriate to include γ in the PL relation. This leads to the numerical PL shown in equation (8), assuming an LMC distance modulus of 18.4 mag. The metallicity of the region in question is denoted by $[\text{O}/\text{H}]_{\text{mes}}$:

$$W_{vi} = -3.320(\pm 0.011) \log P + 22.01(\pm 0.03) + 0.29(\pm 0.11)([\text{O}/\text{H}]_{\text{LMC}} - [\text{O}/\text{H}]_{\text{mes}}). \quad (8)$$

The analysis presented here assumes that *only* the zero point of the PL relation changes with metallicity; the slope does not significantly change between the MW and LMC metallicities. We have repeated the analysis using the MW slope of the W_{vi} PL relation from F07 and we found the same value for γ . This is an important result as it means that we can find reddening- and metallicity-corrected Cepheid distances for any population from two colour (V and I_C) photometry without the time consuming task of calculating internal A_V values for other galaxies.

As noted above, the final result and particularly the errors are significantly affected by the value of metallicity one uses for each region. We have used the recent results from Magrini et al. (2007). Crockett et al. (2006) found a much shallower gradient however. Using their values of metallicity in our two fields, we find $\gamma = -2.899 \pm 0.065$ mag dex $^{-1}$, incompatible with other determinations of this parameter. Such a large value of γ would have dramatic effects on the distance scale. In particular, it would change the distance to the LMC by so much that the Cepheid distances would become incompatible with all other measurements. The difference in distance moduli between the two fields is an argument in favour of a rather large metallicity gradient in M33. However, the metallicity gradient of M33 is still subject to strong debate and, to quote Kudritzki et al. (2008), ‘... the expectation of homogeneous azimuthal metallicity in patchy star-forming spiral galaxies seems naive...’. Our extension of the work of Beaulieu et al. (2006) based on double-mode Cepheids in M33 will shed light on this discrepancy by measuring the metallicity and its gradient using many more

positions. Hopefully this paper serves as an example of the need for better determinations of the metallicities of *all* galaxies where Cepheids have been observed.

It is also important to note the correlation between this work and the Hubble Key Project (Freedman et al. 2001); although the M33 Cepheids have shorter periods than the average in the *HST* project, the value of γ that we find is consistent with their work.

We will further investigate the effect of metallicity by applying the methodology described above to the catalogues from Hartman et al. (2006). With the large number of Cepheids, we will be able to sample the whole [O/H] range of the galaxy and the whole $\log P - \text{Mag}$ parameter space, finally calibrating the effect that has plagued the Cepheid PL relation and distance scale for many decades.

ACKNOWLEDGMENTS

We would like to profusely thank J.-P. Beaulieu and J.-B. Marquette for the M33 fundamental mode Cepheid catalogues which have proved to be invaluable to this work. We are indebted to P. Stetson and K. Stanek for their assistance with creating and testing the photometry pipelines. We thank the referee, P. Fouqué, for his swift and thorough report that significantly improved the content and presentation of this paper. VS is supported by an STFC studentship.

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