The Magellanic System: Stars, Gas, and Galaxies
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Pulsating variable stars in the Magellanic Clouds

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Abstract. Pulsating variable stars can be powerful tools to study the structure, formation and evolution of galaxies. I discuss the role that the Magellanic Clouds' pulsating variables play in our understanding of the whole Magellanic System, in light of results on pulsating variables produced by extensive observing campaigns like the MACHO and OGLE microlensing surveys. In this context, I also briefly outline the promise of new surveys and astrometric missions which will target the Clouds in the near future.

Keywords. stars: oscillations, Cepheids, delta Scuti, stars: variables: other, Magellanic Clouds, cosmology: distance scale

1. Introduction

The Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) represent the nearest templates where we can study the stellar populations and galaxy interactions in detail, and they are where we set up and verify the astronomical distance scale. The pulsating variable stars can play a fundamental role in this context, offering several advantages with respect to normal stars. The light variation caused by the periodic expansion/contraction of the surface layers makes the pulsating stars easier to recognize than normal stars, even when stellar crowding is severe. Their main parameter, the pulsation period, is measured with great precision, is unaffected by distance and reddening, and is directly related to intrinsic stellar quantities such as the star mass, radius, and luminosity. Among pulsating variables, the Classical Cepheids (CCs) are the brightest stellar standard candles after Supernovae. The Period–Luminosity relation (PL), for which we celebrate this year the 100$^{\rm th}$ anniversary of discovery by Henrietta Leavitt, makes them primary distance indicators in establishing the cosmic distance scale. On the other hand, since pulsating variables of different types are in different evolutionary phases, they can be used to identify stellar components of different ages in the host system: the RR Lyrae stars and the Population II Cepheids (T2Cs) tracing the oldest stars ($t > 10$ Gyr); the Anomalous Cepheids (ACs) tracing the intermediate-age component ($\sim$ 4–8 Gyr); and the CCs tracing the young stellar populations (50–200 Myr). The role of pulsating stars becomes increasingly important in stellar systems like the Magellanic Clouds (MCs) where stars of different age and metal abundance share the same region of the color–magnitude diagram (CMD). The RR Lyrae stars, in particular, belonging to the oldest generation of stars, eyewitnessed the first epochs of their galaxy's formation and thus can provide hints on the early formation and assembling of the MCs system.

Our knowledge of the pulsating variable stars and the census of the MCs variables have made dramatic steps forward thanks to the microlensing surveys which, as a by-product, revealed and measured magnitudes and periods for thousands of variables in both Clouds. The overwhelming amount of information which these surveys have produced, not fully exploited yet, allowed for the first time to study the properties of primary distance

Table 1. Main properties of different types of pulsating variable stars[1].

Class	Pulsation Period (days)	M_V (mag)	Population	Evolutionary Phase
δ Cephei (CCs)[2]	$1 \div 100$[3]	$-7 \div -2$	I	Blue Loop
δ Scuti stars (δ Sc)	< 0.5	$2 \div 3$	I	MS–PMS
β Cephei	< 0.3	$-4.5 \div -3.5$	I	MS
RV Tauri	$30 \div 100$	$-2 \div -1$	I, II	post-AGB
Miras[4]	$100 \div 1000$	$-2 \div 1$	I, II	AGB
Semiregulars (SRs)[4]	> 50	$-3 \div 1$	I, II	AGB
RR Lyrae (RRL)	$0.3 \div 1$	$0.0 \div 1$	II	HB
W Virginis (T2Cs)[5]	$10 \div 50$	$-3 \div 1$	II	post-HB
BL Herculis (T2Cs)[5]	< 10	$-1 \div 0$	II	post-HB
SX Phoenicis (SX Phe)	< 0.1	$2 \div 3$	II	MS
Anomalous Cepheids (ACs)	$0.3 \div 2.5$	$-2 \div 0$	?	HB turnover

Notes:
[1] Adapted from Marconi (2001).
[2] δ Cephei variables are more commonly known as Classical Cepheids (CCs).
[3] A few CCs with periods longer than 100 days are known in both Clouds, in NGC 6822, NGC 55, NGC 300 and in I Zw 18 (Bird *et al.* 2008, and references therein). Unfortunately, CCs with $P > 100$ days are generally saturated in the OGLE and MACHO photometry. They are now being observed with smaller telescopes in order to extend the PL relation to longer periods (W. Gieren, private communication).
[4] Miras and SRs often are jointly refereed to as red variables or long period variables (LPVs).
[5] W Virginis and BL Herculis variables are often referred to as Population II or Type II Cepheids (T2Cs).

indicators such as the CCs and the RR Lyrae stars based on statistically significant numbers, as well as to reveal unknown features and new types of variables. These topics are the subject of the present review.

2. Position on the HR diagram and main properties

Table 1 presents an overview of the currently known major types of pulsating variables, along with their main characteristics (typical period, absolute visual magnitude, parent stellar population and evolutionary phase). Fig. 1 shows the loci occupied by different types of pulsating variables in the HR diagram, along with lines of constant radius and a comparison with stellar evolutionary tracks for masses in the range from 1 to 30 $M_\odot$. The two long-dashed lines running almost vertically through the diagram mark the boundaries of the so-called "classical instability strip". Going from low to high luminosities in its domain we find: δ Scuti variables (luminosity: $\log L/L_\odot \sim 1$, Spectral Type: A0–F0, mass: $M \sim 2$ $M_\odot$), the RR Lyrae stars ($\log L/L_\odot \sim 1.7$, Spectral Type: A2–F2, $M < 1$ $M_\odot$), and the Cepheids (ACs: $\log L/L_\odot \sim 2$, Spectral Type: F2–G6, $M \sim$ 1–2 $M_\odot$; T2Cs: $\log L/L_\odot \sim 2$, Spectral Type: F2–G6, $M \sim 0.5$ $M_\odot$; and CCs: $\log L/L_\odot \sim 3-5$, Spectral Type: F6–K2, $M \sim$ 3–13 $M_\odot$). Once extrapolated beyond the main sequence the instability strip crosses the region of the pulsating hydrogen-rich DA white dwarfs. Red

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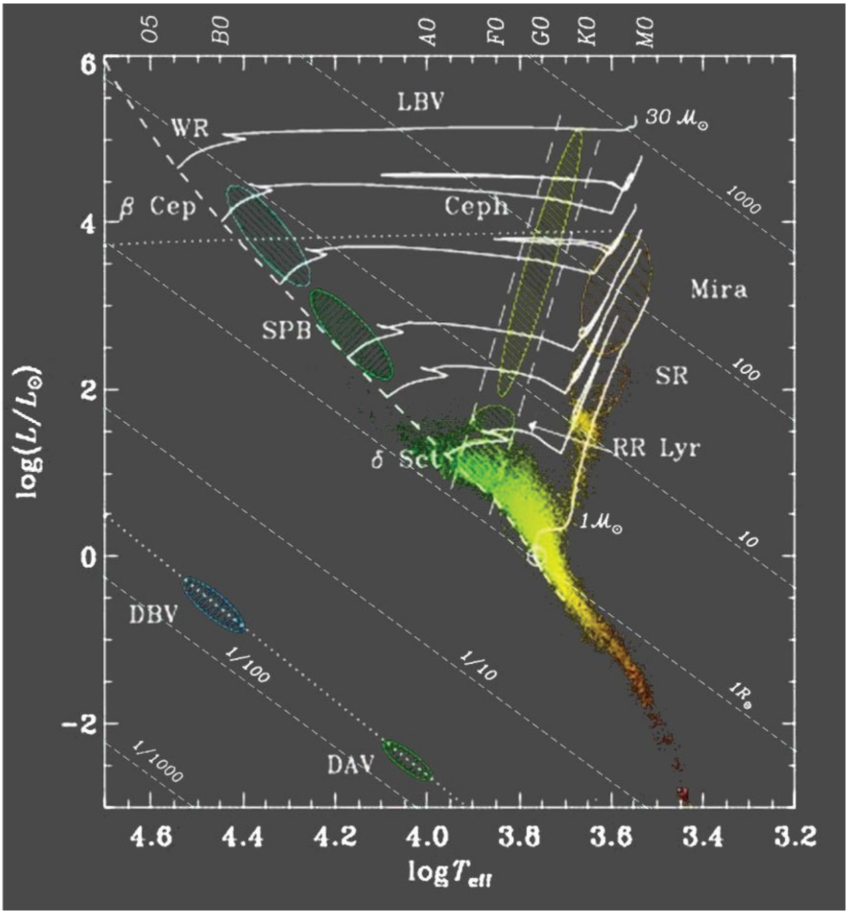

Figure 1. Position of different types of pulsating stars in the HR diagram. The heavy dashed line stretching from the upper left to the lower right is the main sequence of stars with solar abundances. Lines of constant radius (from 1/1000 to 1000 R$_\odot$) are shown, as well as tracks corresponding to masses in the range from 1 to 30 M$_\odot$. The two long-dashed lines indicate the position of the classical instability strip. Different acronyms mean: WR: Wolf-Rayet stars; LBV: luminous blue variables; SPB: slowly pulsating B stars; SR: semiregular variables; DVB, DAV: pulsating He white dwarfs (DB), and hydrogen-rich pulsating white dwarfs (DA). Adapted from Gautschy & Saio (1995).

variables (Miras and SRs) are situated instead below the red edge of the instability strip, at temperatures corresponding to spectral types K–M and luminosities $\log L/\mathrm{L}_\odot \sim 2-4$.

Given their complex stellar populations the MCs host samples of all the various types of pulsating stars shown in Fig. 1, although in varying proportions. As a combination of evolutionary/stellar population effects, but also due to the magnitude limit and time resolution of the currently available variability surveys, up to now RR Lyrae stars, Cepheids and red variables are by far the most frequent and best studied variables in the MCs. This is shown in Fig. 2, which displays the color magnitude diagram of a region close to the LMC bar, from the variability study of Clementini *et al.* (2003), with the different types of pulsating variables (Cepheids, RR Lyrae and δ Scuti stars) marked by different symbols, and the locus of red pulsating variables outlined by a large grey box.

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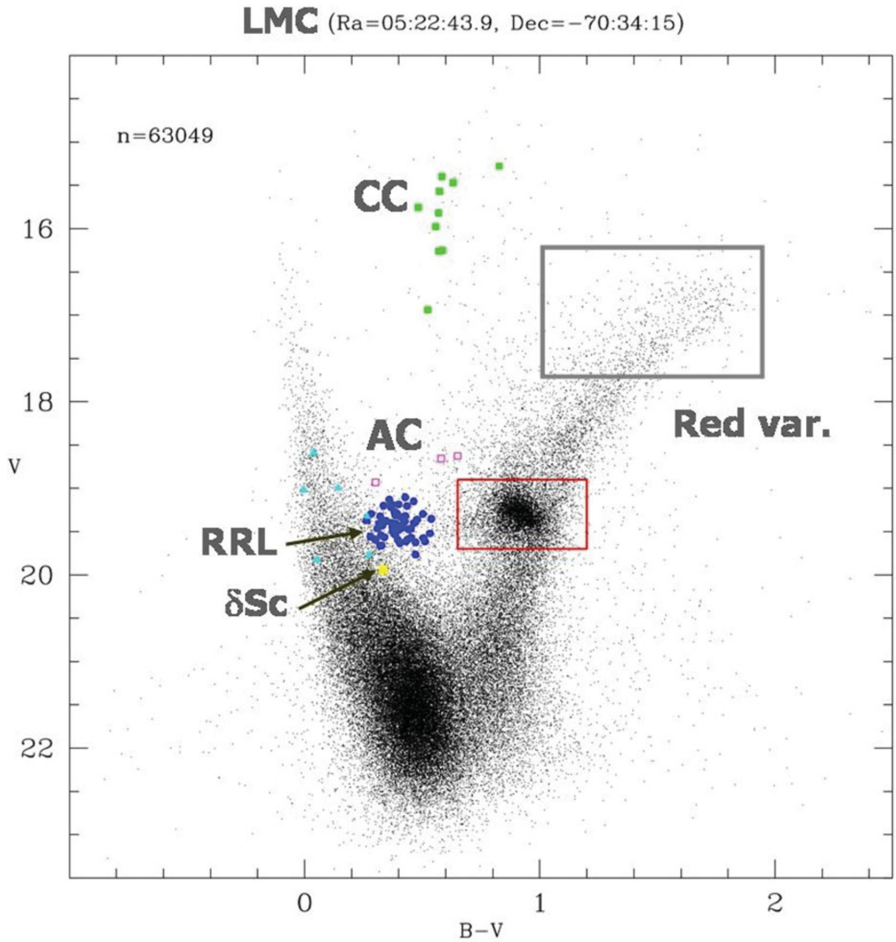

Figure 2. Position of major types of pulsating stars in the CMD of a region close to the LMC bar. Adapted from Clementini *et al.* (2003).

3. The MCs pulsating variables in numbers

Until the last decade of the twentieth century our knowledge of the MCs variables relied mainly upon photographic and photoelectric data and small and inhomogeneous samples. The situation drastically changed at the beginning of the nineties when the MACHO (http://wwwmacho.mcmaster.ca/) and EROS (http://eros.in2p3.fr/) microlensing experiments followed by OGLE (http://ogle.astrouw.edu.pl/) in 1997 began to regularly monitor the MCs for microlensing events and led to the discovery of thousands of pulsating stars. Since then, an increasing number of photometric surveys spanning the whole wavelength spectrum have taken a census of the MCs pulsating variables and allowed to study in detail their pulsation properties on the basis of multiband light curves with hundreds of phase points spanning several years observations. Some of these surveys are summarized in Table 2. Also listed in the table are the relatively few spectroscopic studies available so far for the MCs pulsating variables and, in the last part of the table, the new photometric, spectroscopic and astrometric surveys which are planned for the next decade.

In recent years the photometry of pulsating variables was progressively extended to the infrared region of the wavelength spectrum because the light variation of pulsating stars is smoother, reddening effects become negligible, and calibrating relations such as

Table 2. Surveys of MCs variable stars.

Visual	Infrared	Spectroscopy	Astrometry
EROS[(1)]	*ISO*	Luck & Lambert (1992)	
MACHO[(2)]	DENIS	Luck *et al.* (1998)	
SUPERMACHO[(3)]	SIRIUS	Romaniello *et al.* (2005, 2008)	
OGLE II–III[(4)]	2MASS	Gratton *et al.* (2004)	
MOA[(5)]	SAGE[(6)]	Borissova *et al.* (2004, 2006)	
STEP@*VST*[(7)]	VMC [(8)]	STEP@*VLT*	
Gaia[(9)]		Gaia	*Gaia*
LSST[(10)]			

Notes:
(1) http://eros.in2p3.fr/
(2) http://wwwmacho.mcmaster.ca/
(3) http://www.ctio.noao.edu/∼supermacho/
(4) http://ogle.astrouw.edu.pl/∼ogle/; http://bulge.astro.princeton.edu/∼ogle/
(5) http://www.phys.canterbury.ac.nz/moa/
(6) http://sage.stsci.edu/index.php
(7) http://vstportal.oacn.inaf.it/node/40/
(8) http://star.herts.ac.uk/∼mcioni/vmc/
(9) http://gaia.esa.int
(10) http://www.lsst.org/lsst_home.shtml

the PL relations become tighter when moving to the red region of the spectrum (see Figs. 4 and 6 of Madore & Freedman 1991; Fouqué *et al.* 2003; Ngeow & Kanbur 2008; Freedman *et al.* 2008). The MCs variables make no exception, and several of the past and future surveys listed in Table 2 (e.g., *ISO*, DENIS, VMC) cover in fact the infrared spectral range extending to the mid-infrared domain (3.6–8.0 μm) with the SAGE survey on the *Spitzer* satellite.

The first results from the microlensing surveys of the MCs were published at the end of the nineties. Alcock *et al.* (1996), announced the discovery of about 8000 RR Lyrae stars as a result of the MACHO microlensing survey of the LMC, and Alcock *et al.* (1998, 1999a,b) reported on the identification of about 2000 LMC Cepheids. At same time, large numbers of Cepheids were found in the SMC by the EROS survey (Sasselov *et al.* 1997; Bauer *et al.* 1999), while Wood *et al.* (1999) discovered about 1400 variable stars (Miras, semi-regulars, contact and semi-detached binaries) defining five distinct parallel period-luminosity sequences on the red and asymptotic giant branches of the LMC. OGLE observations of the Clouds started only in 1997. However, the OGLE II and III surveys represent the largest by area-coverage and the deepest and more complete census of the MCs variables. First results from the OGLE III survey of the LMC were recently published by Udalski *et al.* (2008). The new survey extends over about 40 square degrees and is about 1–1.5 magnitudes deeper than the OGLE II survey. Preliminary results on the LMC variables discovered by OGLE III have been presented during this conference by I. Soszynski. They are summarized in Table 3 and compared with results from the OGLE II survey. The number of LMC CCs has been almost doubled by OGLE III, and significant numbers of ACs and δ Scuti stars were also discovered (see Soszyński's talk

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Table 3. Number of pulsating stars in the OGLE surveys of the MCs.

Class	**LMC**	**SMC**	**Survey**	Reference
CCs	1416	2144	OGLE II	Udalski *et al.* (1999a,b,c) Soszyński *et al.* (2000)
	3361		OGLE III	Soszyński (this conference)
T2Cs	14		OGLE II	Kubiak & Udalski (2003)
ACs	Yes		OGLE III	Soszyński (this conference)
RR Lyrae stars	7612	571	OGLE II	Soszyński *et al.* (2002, 2003)
Miras & SRs	3221		OGLE II	Soszyński *et al.* (2005)
Small Amplitude Red Giants (SARGs)	15400	3000	OGLE II–III	Soszyński *et al.* (2004, 2005)
δ Scuti stars	Yes		OGLE III	Soszyński (these proceedings)

in this conference). The increased sample of CCs traces very nicely the bar and gas-rich regions of the LMC. The RR Lyrae stars, instead, are evenly distributed on the whole field observed by OGLE III and outline the more spheroidal distribution of the LMC's oldest stellar component. The OGLE III Wesenheit ($W_{\rm I} = I - 1.55(V - I)$) PL diagram spans a total range of about 14 magnitudes, reaching about 1–1.5 magnitudes fainter than the OGLE II PL diagram (see Soszyński 2006). On this diagram the LMC δ Scuti stars locate on the extension to fainter magnitudes of the CCs PL, as suggested by McNamara *et al.* (2007), based on the analysis of the very few δ Scuti stars which were known in the LMC.

In the following, I will specifically address some major results which the surveys listed in Tables 2 and 3 have produced in the study of Cepheids, RR Lyrae stars and red variables and, in turn, in our knowledge of the MCs system.

3.1. *The PL relation of Classical Cepheids*

The CCs are primary standard candles that allow to link the local distance scale to the cosmological distances needed to determine the Hubble constant, H_0.

The CCs PL relation, discovered by H. Leavitt at the beginning of the twentieth century as she was picking up variables on photographic plates of the MCs, is unquestionably one of the most powerful tools at our disposal for determining the extragalactic distance scale. The extraordinary large number of CCs discovered in the MCs by the MACHO and OGLE surveys, allowed to derive the PL relations on unprecedented statistically significant and homogeneous samples of CCs. Udalski *et al.* (1999a) used fundamental-mode (FU) CCs in the LMC and SMC to derive the following PL relations:

$$V_0(\mathrm{LMC}) = -2.760 \log P - 17.042, \quad \sigma = 0.159 \text{ mag}, \quad (649 \quad \text{FU} \quad \text{CCs})$$

$$V_0(\mathrm{SMC}) = -2.760 \log P - 17.611, \quad \sigma = 0.258 \text{ mag}, \quad (466 \quad \text{FU} \quad \text{CCs})$$

The slope of these relations is in very good agreement with the slope of theoretical PL relations computed by Caputo *et al.* (2000) from nonlinear convective pulsation models of CCs ($M_{\rm V} = -2.75 \log P - 1.37, \quad \sigma = 0.18$ mag).

In order to use the PL's of the MCs CCs to measure distances outside the Clouds the zero point of the PL relation is generally fixed by using Galactic CCs whose absolute magnitudes are known from parallax measurements and/or Baade-Wesselink analyses or, alternatively, by assuming a value for the distance to the LMC. In the latter case, the

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zero-point problem thus shifts to the problem of having a robust distance determination for the LMC. The *HST* key program (Freedman *et al.* 2001) used the slope of the CCs *PL* relations by Udalski *et al.* (1999a) and a zero-point consistent with an assumed true distance modulus for the LMC of $\mu_{\rm LMC}$=18.5 mag to measure distances to 31 galaxies with distances from 700 kpc to 20 Mpc. These then served to calibrate other, more far-reaching secondary distance indicators to determine the Hubble constant in a region of constant Hubble flow (see Freedman *et al.* 2001, but also Saha *et al.* 2001, and Tammann *et al.* 2008, for different conclusions on the value of H_0).

In spite of the success in measuring distances up to 20 Mpc, a number of basic questions concerning the CCs *PL* relation still need an answer (see Fouqué *et al.* 2003, for a nice review on this topic). Is the CCs *PL* relation universal, as suggested, for instance, by Fouqué *et al.* (2007), so that we are allowed to apply the LMC *PL* to CCs in other galaxies? Does it depend on metal abundance, as also suggested by nonlinear pulsation models (see, e.g., Marconi *et al.* 2005; Bono *et al.* 2008, and references therein)? Is it linear or does it break at periods around 10 days, as a number of studies (Tammann & Reindl 2002; Tammann *et al.* 2002; Kanbur & Ngeow 2004; Sandage *et al.* 2004; Ngeow *et al.* 2005, 2008) are now suggesting? And, how reliably do we know the distance to the LMC and the distance modulus of $\mu_{\rm LMC}$=18.5 mag adopted by the *HST* key program? I will try to address this latter question in Section 4. Romaniello *et al.* (2008) provide a summary of the rather controversial results on the metallicity sensitivity of the Cepheid distances, in the literature of the past twenty years. These authors use direct spectroscopic measurements of iron abundance for Galactic and MC Cepheids to study the metallicity sensitivity of the CCs *PL* and conclude that the V-band *PL* is metallicity dependent, while no firm conclusions can be reached for the K-band *PL*. However, in their recent paper based on OGLE II and SAGE observations of the LMC CCs, Neilson *et al.* (2008) find that the infrared *PL* relations as well have additional uncertainty due to a metallicity dependence. Clearly, elemental abundance estimates for larger numbers of CCs spanning broad metallicity ranges, increased samples of photometric data in the infrared domain, and a fine tuning of all the parameters involved in the definition of the CCs *PL* relations are needed to quantitatively assess the metallicity dependence of both zero-point and slope of the CCs *PL* relations. Hopefully, most of the questions still pending on the CCs *PL* relation will find more definite answers from the new surveys of the MCs variables planned for the next decade (see Section 5).

3.2. *The MCs RR Lyrae stars*

The RR Lyrae stars are the primary distance indicators for stellar systems mainly composed by an old stellar component. They follow an absolute magnitude-metallicity relation in the visual band: M_V − [Fe/H] (Sandage 1981a,b) and a tight ($\sigma \sim 0.05$ mag) Period–Luminosity–Metallicity relation in the K-band: $PL_K Z$, (Bono *et al.* 2003; Catelan *et al.* 2004; Sollima *et al.* 2008, and references therein). Some observational and theoretical studies (see, e.g., Bono *et al.* 2003; Di Criscienzo *et al.* 2004, and references therein) have suggested that the $M_V -$[Fe/H] relation is not linear, becoming steeper when moving to larger metal content.

RR Lyrae stars have been found in all Local Group (LG) galaxies irrespective of morphological type and, although much fainter than the CCs, have been observed and measured as far as in the Andromeda galaxy. Alcock *et al.* (1996) discovered about 8000 RR Lyrae stars in the LMC, among which a fairly large number of double-mode pulsators (Alcock *et al.* 1997). Results from the study of the light curves (Alcock *et al.* 2000, 2003, 2004) showed that the average periods of the LMC RR Lyrae stars differ from what is observed for the Milky Way (MW) variables. Alcock *et al.*'s results were later confirmed and strengthened by the OGLE II studies of the LMC and SMC RR Lyrae stars (Soszyński *et al.* 2002, 2003). These findings suggest differences in the star formation history and rule out both MCs as possible contributors to the assembling of the MW halo.

Spectroscopic data of about 250 LMC RR Lyrae were obtained by Gratton *et al.* (2004), and Borissova *et al.* (2004, 2006). They were used to estimate the metal abundance, radial velocity and radial velocity dispersion of the LMC RR Lyrae population. The LMC RR Lyrae stars are metal-poor, with average metal abundance of $\langle[\mathrm{Fe/H}]\rangle = -1.48/1.54$ dex and spread of about 0.2−0.3 dex. The radial velocity dispersion, $\sigma_{\mathrm{v_r}} = 50$ km s^{-1}, does not vary significantly with increasing distance from the LMC center (Borissova *et al.* 2006 and references therein), and is higher than the velocity dispersion of any other LMC population previously measured, thus providing empirical evidence for a kinematically hot, metal-poor halo in the LMC. Gratton *et al.* (2004) combined their spectroscopic measurements with high accuracy V magnitudes for about a hundred RR Lyrae stars by Clementini *et al.* (2003) to derive the luminosity–metallicity relation of the LMC variables, for which they found the following linear relation: $\mathrm{M_V} = 0.214$ ([Fe/H] + 1.5) + 19.064. The slope of this relation agrees very well with slopes derived for the luminosity-metallicity relation of the MW RR Lyrae stars (Fernley *et al.* 1998) and horizontal branch stars in the globular clusters of M 31 (Rich *et al.* 2005), thus supporting the idea that the luminosity-metallicity relation of the RR Lyrae stars is, in first approximation, linear and universal.

Both the $\mathrm{M_V}$ − [Fe/H] and the $PL_{\mathrm{K}}Z$ relations were extensively used to measure distances to the LMC field and globular cluster's stars (see, e.g., Clementini *et al.* 2003; Dall'Ora *et al.* 2004; Szewczyk *et al.* 2008). Results from these studies are summarized in Table 4.

3.3. *The red variables*

The red variables are, typically, highly evolved stars in the Asymptotic Giant Branch (AGB) phase. Their atmospheres pulsate with typical periods in the range several tens to several hundreds days, and amplitudes ranging from 0.1 up to 6 magnitudes. The class includes the first ever recorded pulsating star: Mira, the prototype of variables with the largest visual amplitudes of any class of pulsating stars: the Miras. The light curves of these variables are often semiregular and multiperiodic, with short brightness outbursts observed sometimes on top of the periodic light change. Mass loss and dust emission, typical of the AGB evolutionary phase, further complicate the scenario, and even the mode of radial pulsation of these stars has long remained a matter of debate. Although the study of these variables most benefited from the long-term photometric monitoring of the Clouds by the microlensing surveys, and then from the combination of the visual data with infrared photometry, still they remain perhaps the least understood of all variable stars.

Wood *et al.* (1999) found that about 1400 red and asymptotic giant branch stars observed in the LMC by the MACHO survey were long period variables. They identified 5 distinct parallel I-band PL sequences, (labeled from "A" to "E" in their Fig. 1), and derived a first tentative classification of the red variables. By combining the MACHO photometry with infrared J and K data Wood (2000) further refined this classification, and definitely identified the Miras as fundamental mode pulsators falling on a single PL_{K} relation corresponding to sequence "C" of Wood *et al.* (1999). The SR variables are instead first to third overtone, or even fundamental mode, pulsators falling on sequence "B", the small amplitude red variables are on sequence "A", the long secondary period variables on sequence "D", and, finally, the contact binaries are on sequence "E". This classification was confirmed by various authors (e.g., Lebzelter *et al.* 2002). Since the Miras are bright, large amplitude variables, their PL relation is an important distance indicator for old and intermediate age populations. A new calibration of the Miras PL_{K}

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relation was recently derived by Whitelock *et al.* (2008) using 53 LMC Miras with periods less than 420 days.

The number of red variables identified around the tip of the MCs red and asymptotic giant branches has massively increased in the last years. Fraser *et al.* (2005) detected about 22 000 red variables by combining the 8 year light-curve database from the MACHO survey of the LMC, with 2MASS infrared J, H, K photometry. The OGLE II and III surveys detected more than 3000 Miras and SR variables in the LMC (Soszyński *et al.* 2005), and about 15 400 and 3000 small amplitude red giant variables (SARGs) respectively in the LMC and in the SMC. These variables appear to be a mixture of AGB and red giant branch pulsators (Soszyński *et al.* 2004). Ita *et al.* (2004a,b), combining results from the OGLE II and the SIRIUS near-infrared JHK surveys, found that variable red giants in the SMC form parallel sequences on the $PL_{\rm K}$ plane, just like those found by Wood in the LMC. Moreover, Wood's original sequences were found to split into several separate subsequences above and below the tip of the LMC and SMC red giant branches. Slightly different relations were also found for carbon- and oxygen-rich variables. The number of PL sequences identified in the red variable domain was brought to fourteen by Soszyński *et al.* (2007), who also found that the slopes of the PL relation for Miras and SR variables seem to be the same in the LMC and SMC. The number of PLs is expected to increase further once the analysis of the red variables in the OGLE III database will be completed.

4. The distance to the LMC

Because the LMC is the first step of the extragalactic distance ladder, the knowledge of its distance has a tremendous impact on the entire astronomical distance scale. Benedict *et al.* (2002) published an historical summary of distances to the LMC from different indicators. Their Fig. 8 provides an impressive overview of the dispersion in the LMC distance moduli ($\mu_{\rm LMC}$) published during the ten-year span from 1992 to 2001. The last decade has seen dramatic progress in the calibration of the different distance indicators. The dispersion in $\mu_{\rm LMC}$ has definitely shrunk, and values at the extremes of Benedict *et al.*'s distribution (18.1 and 18.8 mag, respectively) are not seen very often in the recent literature.

Table 4 summarizes some recent determinations of LMC distances based on pulsating variables. Far from being exhaustive, this table is only meant to highlight some recent advances in the distance determinations based on major types of pulsating variables found in the LMC. Although systematic differences still exist and need to be worked upon, (for instance the metallicity-corrected PL relation based on revised *Hipparcos* parallaxes for CCs, van Leeuwen *et al.* (2007), gives a somewhat shorter modulus, as does also the PL based on new values for the p-factor used to transform radial velocities into pulsational velocities in the Baade-Wesselink analyses of CCs), the controversy between the so-called "short" and "long" distances to the LMC seems to have largely vanished, and there is now a substantial convergence of the most reliable standard candles on a distance modulus for the LMC around 18.5 mag (Clementini *et al.* 2003; Walker 2003; Alves 2004; Romaniello *et al.* 2008).

5. The new surveys

Among the new photometric surveys, STEP and VMC, expected to start at the end of 2009, will repeatedly observe the Clouds allowing to study variable stars.

STEP (The SMC in Time: Evolution of a Prototype interacting dwarf galaxy, see the poster contribution to this conference by Ripepi *et al.*), will use the *VLT Survey Telescope*

Table 4. Distances to the LMC from pulsating variables.

Method	Distance modulus	Reference
PL, LMC δ Scuti stars	18.50 ± 0.22	McNamara *et al.* (2007)
Model fitting, δ Scuti stars	18.48 ± 0.15	McNamara *et al.* (2007)
Model fitting, Bump Cepheids	18.48 ÷ 18.58 18.55 ± 0.02 18.54 ± 0.018	Bono *et al.* (2002) Keller & Wood (2002) Keller & Wood (2006)
Model fitting, field RR Lyrae stars	18.54 ± 0.02	Marconi & Clementini (2005)
$M_{\rm V}$ − [Fe/H], field RR Lyrae stars	18.46 ± 0.07[(1)]	Clementini *et al.* (2003)
$PL_{\rm K}Z$, field RR Lyrae stars	18.48±0.08	Borissova *et al.* (2004)
$PL_{\rm K}Z$, RR Lyrae stars in Reticulum	18.52±0.01± 0.12	Dall'Ora *et al.* (2004)
$PL_{\rm K}Z$, field RR Lyrae stars	18.58±0.03± 0.11	Szewczyk *et al.* (2008)
$PL_{\rm K}$, CCs $PLC_{\rm J,K}$, CCs $PL_{\rm W}$, CCs $PL_{\rm W}$, CCs	18.47±0.03 18.45±0.04 18.52±0.03 18.39±0.03	van Leeuwen *et al.* (2007) metallicity-corrected

Notes:
[(1)] This distance modulus was derived using values from Clementini *et al.* (2003) for $\langle V(RR)\rangle$ and the reddening, and the assumption of $M_{\rm V} = 0.59 \pm 0.03$ mag for the absolute visual magnitude of RR Lyrae stars at metal abundance [Fe/H] = − 1.5 (Cacciari & Clementini 2003).

(VST) to obtain V, B and i' single-epoch photometry of the SMC, reaching below the galaxy main sequence turn-off; as well as shallow time-series photometry of the Wing and Bridge toward the LMC, for which no previous variability survey exists yet, reaching variables as faint as the RR Lyrae stars.

VMC ($VISTA$ near-infrared survey of the Magellanic Clouds, see the poster paper by Cioni *et al.* in these proceedings) is instead an *ESO* public survey, which will obtain near-infrared $YJK_{\rm s}$ photometry of the whole Magellanic System (LMC, SMC and Bridge) with the subset of $K_{\rm s}$ exposures taken in time-series fashion to study variable stars.

These two surveys together will provide new multiband data to study the spatially resolved star formation history of the MCs, and will allow to reconstruct the 3-dimensional structure of the whole Magellanic System using various types of pulsating stars (Classical, Type II and Anomalous Cepheids, RR Lyrae, δ Scuti, and Miras).

The astrometric satellite *Gaia*, planned for launch in 2011, is one of the *European Space Agency* (*ESA*) cornerstone missions. During its lifetime of nominally 5 years, *Gaia* will scan the entire sky repeatedly, with an average frequency of about 80 measurements per object over the five-year time span, and will provide astrometry, 2-color photometry, and slit-less spectroscopy in the Ca triplet domain (847–874 nm) for all sources brighter than $V \sim 20$ mag (about 1.3×10^9 stars in total). Expected errors of the Gaia measurements are: σ_π = 10–25 μarcsec at $V \sim 15$ mag for parallaxes, and $\sigma = 15$ km s^{-1} at $V < 6$–17 mag for radial velocities. This is the domain of the bright pulsating variables in the MCs, which, if the satellite performs as expected, will then have their parallax, magnitude, radial velocity and metal abundance directly measured by *Gaia*. The direct measurements via trigonometric parallaxes of distances for Magellanic Cloud CCs and Miras

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will thus allow the calibration with unprecedented precision of these most important primary standard candles.

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References

Alcock, C., Allsman, R. A., Axelrod, T. S., *et al.* 1996, *AJ*, 111, 1146
Alcock, C., Allsman, R. A., Alves, D., *et al.* 1997, *ApJ*, 482, 89
Alcock, C., Allsman, R. A., Alves, D. R., *et al.* 1998, *AJ*, 115, 1921
Alcock, C., Allsman, R. A., Alves, D. R., *et al.* 1999a, *ApJ*, 511, 185
Alcock, C., Allsman, R. A., Alves, D. R., *et al.* 1999b, *AJ*, 117, 920
Alcock, C., *et al.* 2000, *ApJ*, 542, 257
Alcock, C., Allsman, R. A., Alves, D. R., *et al.* 2003, *ApJ*, 598, 597
Alcock, C., Alves, D. R., Axelrod, T. S., *et al.* 2004, *AJ*, 127, 334
Alves, D. 2004, *NewAR*, 48, 659
Bauer, F., Afonso, C., Albert, J. N., *et al.* 1999, *A&A*, 348, 175
Benedict, G., McArthur, B. E., Fredrick, L. W., *et al.* 2002, *AJ*, 123, 473
Bird, J. C., Stanek, K. Z., & Prieto, J. L. 2008, *ApJ*, accepted, (arXiv:0807.4933)
Bono, G., Castellani, V., & Marconi, M. 2002, *ApJ*, 565, L83
Bono, G., Caputo, F., Castellani, V., Marconi, M., Storm, J., & Degl'Innocenti, S. 2003, *MNRAS*, 344, 1097
Bono, G., Caputo, F., Fiorentino, G., Marconi, M., & Musella, I. 2008, *ApJ*, 684, 102
Borissova, J., Minniti, D., Rejkuba, M., & Alves, D., 2006, *A&A*, 460, 459
Borissova, J., Minniti, D., Rejkuba, M., Alves, D., Cook, K. H., & Freeman, K. C. 2004, *A&A*, 423, 97
Cacciari, C. & Clementini, G. 2003, in D. Alloin & W. Gieren (eds.), *Lecture Notes in Physics*, 635, 105
Caputo, F., Marconi, M., & Musella, I. 2000, *A&A*, 354, 610
Catelan, M., Pritzl, B. J., & Smith, H. A. 2004, *ApJS*, 154, 633
Clementini, G., Gratton, R. G., Bragaglia, A., Carretta, E., Di Fabrizio, L., & Maio, M. 2003, *AJ*, 125, 1309
Dall'Ora, M., Storm, J., Bono, G., *et al.* 2004, *ApJ*, 610, 269
Di Criscienzo, M., Marconi, M., & Caputo, F. 2004, *ApJ*, 612, 1092
Fernley, J., Skillen, I., Carney, B. W., Cacciari, C., & Janes, K. 1998, *MNRAS*, 293, L61
Fouqué, P., Storm, J., & Gieren, W. 2003, in D. Alloin & W. Gieren (eds.), *Lecture Notes in Physics*, 635, 21
Fouqué, P., Arriagada, P., Storm, J., *et al.* 2007, *A&A*, 476, 73
Fraser, O. J., Hawley, S. L., Cook, K. H., & Keller, S. C. 2005, *AJ*, 129, 768
Freedman, W. L., Madore, B. F., Gibson, B. K, *et al.* 2001, *ApJ*, 553, 47
Freedman, W. L., Madore, B. F., Rigby, J., Persson, S. E., & Sturch, L. 2008, *ApJ*, 679, 71
Gautschy, A. & Saio, H. 1995, *ARAA*, 34,551
Gratton, R. G., Bragaglia, A., Clementini, G., Carretta, E., Di Fabrizio, L., Maio, M., & Taribello, E. 2004, *A&A*, 421, 937
Ita, Y., Tanabé, T., Matsunaga, N., *et al.* 2004a, *MNRAS*, 347, 720
Ita, Y., Tanabé, T., Matsunaga, N., *et al.* 2004b, *MNRAS*, 353, 705
Kanbur, S. & Ngeow, C. 2004, *MNRAS*, 350, 962
Keller, S. C. & Wood, P. R 2002, *ApJ*, 578, 144
Keller, S. C. & Wood, P. R 2006, *ApJ*, 642, 841

Kubiak, M. & Udalski, A. 2003, *Acta Astronomica*, 53, 117
Lebzelter, T., Schultheis, M., & Melchior, A. L. 2002, *A&A*, 393, 573
Luck, R. E., Moffett, T. J., Barnes, T. G., III, & Gieren, W. P. 1998, *AJ*, 115, 605
Luck, R. E. & Lambert, D. L. 1992, *ApJS*, 79, 303
Madore, B. F. & Freedman, W. L. 1991, *PASP*, 103, 933
Marconi, M. 2001, available at http://www.oa-teramo.inaf.it/scuola2001/ under Contributi Docenti
Marconi, M. & Clementini, G. 2005, *AJ*, 129, 2257
Marconi, M., Musella, I., & Fiorentino, G. 2005, *ApJ*, 632, 590
McNamara, D. H., Clementini, G., & Marconi, M. 2007, *AJ*, 133, 2752
Neilson, H. R., Ngeow, C. -C., Kanbur, S. M., & Lester, J. B. 2008, *ApJ*, in press, arXiv:0810.3001
Ngeow, C. -C., Kanbur, S. M., Nikolaev, S., Buonaccorsi, J., Cook, K. H., & Welch, D. L. 2005, *MNRAS*, 363, 831
Ngeow, C. -C., Kanbur, S. M., & Nanthakumar, A. 2008, *A&A*, 447, 621
Ngeow, C. -C., & Kanbur, S. M. 2008, *A&A*, 679, 76
Rich, M. R., Corsi, C. E., Cacciari, C., Federici, L., Fusi Pecci, F., Djorgovski, S. G., & Freedman, W. L. 2005 *AJ*, 129, 2670
Romaniello, M., Primas, F., Mottini, M., Groenewegen, M. A. T., Bono, G., & François, P. 2005, *A&A*, 429, L37
Romaniello, M., Primas, F., Mottini, M., *et al.* 2008, *A&A*, 488, 731
Saha, A., Sandage, A., Tammann, G. A., Dolphin, A. E., Christensen, J., Panagia, N., & Macchetto, F. D. 2001, *ApJ*, 562, 314
Sandage, A. 1981a, *ApJ*, 244, L23
Sandage, A. 1981b, *ApJ*, 248, 161
Sandage, A., Tammann, G. A., & Reindl, B. 2004, *A&A*,424, 43
Sasselov, D. D., Beaulieu, J. P., Renault, C., *et al.* 1997, *A&A*, 324, 471
Sollima, A., Cacciari, C., Arkharov, A. A. H., Larionov, V. M., Gorshanov, D. L., Efimova, N. V., & Piersimoni, A. 2008, *MNRAS*, 384, 1583
Soszyński, I., Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., Woźniak, P. R., & Żebruń, K. 2000, *Acta Astronomica*, 50, 451
Soszyński, I., Udalski, A., Szymański, M., *et al.* 2002, *Acta Astronomica*, 52, 369
Soszyński, I., Udalski, A., Szymański, M., *et al.* 2003, *Acta Astronomica*, 53, 93
Soszyński, I., Udalski, A., Kubiak, M., Szymański, M., Pietrzyński, G., Żebruń, K., Szewczyk, O., & Wyrzykowski, Ł. 2004, *Acta Astronomica*, 54, 129
Soszyński, I., Udalski, A., Kubiak, M., *et al.* 2005, *Acta Astronomica*, 55, 331
Soszyński, I. 2006, *Mem. S.A.It.*, 77, 265
Soszyński, I., Dziembowski, W. A., Udalski, A., *et al.* 2007, *Acta Astronomica*, 27, 201
Szewczyk, O., Pietrzyński, G., Gieren, W., *et al.* 2008, *AJ*, 136, 272
Tammann, G. A. & Reindl, B. 2002, *ApSS*, 280, 165
Tammann, G. A., Reindl, B., Thim, F., Saha, A., & Sandage, A. 2002, in N. Metcalfe & T. Shanks (eds.), *A New Era in Cosmology*, ASPC 283 (San Francisco: ASP), p. 258
Tammann, G. A., Sandage, A., & Reindl, B. 2008, *A&AR*, 15, 289
Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., Soszyński, I., Woźniak, P. R., & Żebrun, K. 1999a, *Acta Astronomica*, 49, 201
Udalski, A., Soszyński, I., Szymański, M., Kubiak, M., Pietrzyński, G., Woźniak, P. R., & Żebruń, K. 1999b, *Acta Astronomica*, 49, 223
Udalski, A., Soszyński, I., Szymański, M., Kubiak, M., Pietrzyński, G., Woźniak, P. R., & Żebruń, K. 1999c, *Acta Astronomica*, 49, 437
Udalski, A., Soszyński, I., Szymański, M., *et al.* 2008, *Acta Astronomica*, 58, 89
van Leeuwen, F., Feast, M. W., Whitelock, P. A., & Laney, C. D, 2007, *MNRAS*, 379, 723
Walker, A. 2003, in D. Alloin & W. Gieren (eds.), *Lecture Notes in Physics*, 635, 625
Whitelock, P. A., Feast, M. W., & van Leeuwen, F. 2008, *MNRAS*, 386, 313
Wood, P. R., Alcock, C., Allsman, R. A., *et al.* 1999, in T. Le Bertre, A. Lèbre, & C. Waelkens (eds.), *Asymptotic Giant Branch Stars*, IAUS 191, p. 151
Wood, P. R. 2000, *PASA*, 17, 18