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Preliminary results for RR Lyrae stars and Classical Cepheids from the Vista Magellanic Cloud (VMC) Survey

V. Ripepi[1] • **M.I. Moretti**[2,3] • **G. Clementini**[3] •
M. Marconi[1] • **M.R. Cioni**[*4,5] • **J.B. Marquette**[6] •
P. Tisserand[7]

Abstract The Vista Magellanic Cloud (VMC, PI M.R. Cioni) survey is collecting K_S-band time series photometry of the system formed by the two Magellanic Clouds (MC) and the "bridge" that connects them. These data are used to build K_S-band light curves of the MC RR Lyrae stars and Classical Cepheids and determine absolute distances and the 3D geometry of the whole system using the K-band period luminosity (PLK_S), the period - luminosity - color (PLC) and the Wesenhiet relations applicable to these types of variables. As an example of the survey potential we present results from the VMC observations of two fields centered respectively on the South Ecliptic Pole and the 30 Doradus star forming region of the Large Magellanic Cloud. The VMC K_S-band light curves of the RR Lyrae stars in these two regions have very good photometric quality with typical errors for the individual data points in the range of $\sim$ 0.02 to 0.05 mag. The Cepheids have excellent light curves (typical errors of $\sim$ 0.01 mag). The average K_S magnitudes derived for both types of variables were used to derive PLK_S relations that are in general good agreement within the errors with the literature data, and show a smaller scatter than previous studies.

Keywords stars: variables: Cepheids– stars: variables: RR Lyrae – galaxies: individual: LMC – galaxies: distances and redshifts

1 Introduction

The VISTA near-infrared YJK_S survey of the Magellanic system (VMC; Cioni et al. 2011) is an ESO public survey that is obtaining deep near infrared imaging in the Y, J and K_S filters of a wide area across the Magellanic system, using the VIRCAM camera (Dalton et al. 2006) of the ESO VISTA telescope (Emerson, McPherson, & Sutherland 2006).
The main science goals of the survey are the determination of the spatially-resolved star-formation history (SFH) and the definition of the three-dimensional (3D) structure of the whole Magellanic system. The VMC observations are devised to reach $K_S \sim 20.3$ mag, thus allowing us to measure sources encompassing most phases of stellar evolution: from the main-sequence, to subgiants, upper and lower red giant branch (RGB) stars, red clump stars, RR Lyrae and Cepheid variables, asymptotic giant branch (AGB) stars, post-AGB stars, planetary nebulae (PNe), supernova remnants (SNRs), etc. These different stellar populations will help us assessing the evolution of age and metallicity within the whole MC system.

V. Ripepi
M.I. Moretti
G. Clementini
M. Marconi
M.R. Cioni*
J.B. Marquette
P. Tisserand

[1]INAF-Osservatorio Astronomico di Capodimonte, Via Moiariello 16, 80131, Naples, Italy

[2]INAF-Osservatorio Astronomico di Bologna, via Ranzani 1, Bologna, Italy

[3]University of Bologna, Department of Astronomy, via Ranzani 1, 40127, Bologna, Italy

[4]University of Hertfordshire, Physics Astronomy and Mathematics, Hatfield AL10 9AB, UK

[5]University Observatory Munich, Scheinerstrasse 1, 81679 M unchen, Germany

* Research Fellow of the Alexander von Humboldt Foundation

[6]UPMC-CNRS, UMR7095, Institut d'Astrophysique de Paris, F-75014, Paris, France

[7]Research School of Astronomy & Astrophysics, Mount Stromlo Observatory, Cotter Road, Weston ACT 2611, Australia

In this context, a very significant role is played by the radially pulsating variables, since these stars obey a period-mean density relation that forms the basis of their use as standard candles to measure the distance to the host system. The RR Lyrae stars in particular, in the K band obey a period-luminosity-metallicity (PLZ) relation which is weakly affected by the evolutionary effects, the spread in stellar mass within the instability strip, and uncertainties in the reddening corrections (see e.g. Longmore, Fernley, & Jameson 1986; Dall'Ora et al. 2004; Coppola et al. 2011). Similarly, the Cepheid PL relation in the K band is much narrower than the corresponding optical relations, and less affected by systematic uncertainties in the reddening and metal content (see e.g. Caputo, Marconi, & Musella 2000).

We present preliminary results for the RR Lyrae stars and Cepheids contained in the first two "tiles" completely observed by the VMC survey, namely tiles 8_8 and 6_6. These two tiles are centered respectively on the South Ecliptic Pole (SEP) field and on the well known 30 Doradus (30 Dor) star forming region of the Large Magellanic Cloud (LMC). The SEP field is particularly interesting because this region of the sky will be continuously and repeatedly observed during the the commissioning phase of the astrometric Gaia satellite just after the launch in Spring 2013.

2 The VMC data for the variable stars

The VMC observing strategy is described in detail in Cioni et al. (2011) to which the interested reader is referred for more information. Here we focus on the data acquisition for the variable stars.

In order to obtain well sampled light curves and measure accurate parameters (namely K_S average magnitudes) for the variable sources, the K_S observations were split into 12 epochs and distributed along several consecutive months.

We used the v1.0 VMC release "pawprints" (6 "pawprints" form a "tile"). The pawprints were processed by the pipeline (Irwin et al. 2004) of the VISTA Data Flow System (VDFS, Emerson et al. 2004) and retrieved from the VISTA Science Archive (VSA, Hambly et al. 2008)[1].

Usually a variable star is present in two or three not necessarily consecutive pawprints. Hence we first calculated a weighted average of the pawprints' K_S magnitudes to obtain the "tile" K_S, which also represents one epoch of data.

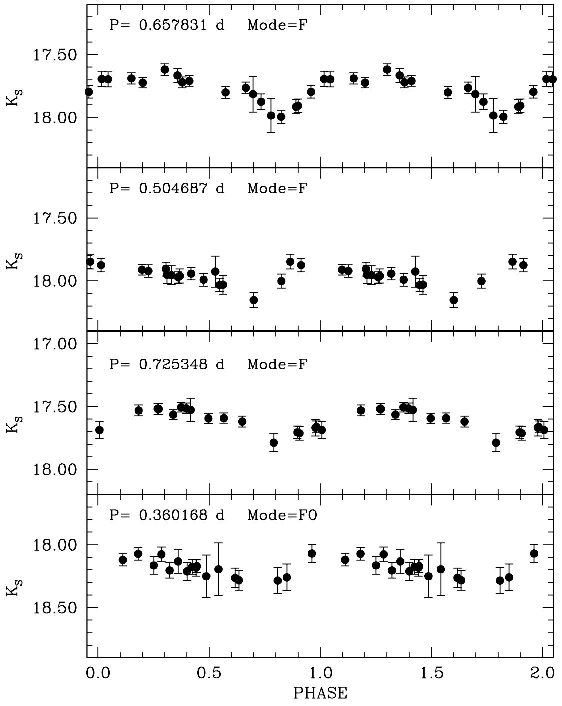

Fig. 1 K_S-band light curves of three fundamental mode (F; 3 upper panels) and one first overtone (FO; bottom panel) RR Lyrae stars in the SEP field. Internal photometric errors of the individual data points are shown, they are typically in the range of 0.02 to 0.05 mag. Periods were taken form the EROS-2 Survey.

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[1] http://horus.roe.ac.uk/vsa/

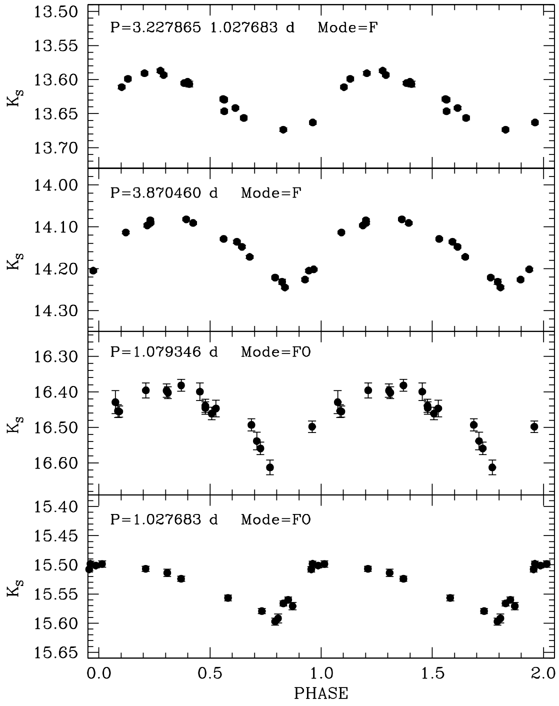

Fig. 2 K_S-band light curve for a sample of Cepheids in the SEP field. Note in the third panel the nice light curve for a faint FO Cepheid. Periods were taken form the EROS-2 Survey.

Particular care was devoted to the determination of a proper Heliocentric Julian Day (HJD) for the K_S value of each “tile”.

The identification, pulsation period and epoch of maximum light of the RR Lyrae stars and Cepheids contained in the SEP and 30 Dor regions are already available in the photometric archives of the Microlensing surveys OGLE and EROS-2.

The OGLE surveys (Soszyński et al. 2008, 2009, and references therein) of which stage IV is in progress, cover an area of the MC system that extends progressively further outside from the bar of each of the Clouds. EROS-2 (Tisserand et al. 2007) is, at present, the most extended of the two surveys and is the only one covering the largest fraction of the VMC field of view including the most peripheral areas such as the SEP region, that in fact only overlaps with EROS-2. Coordinates, periods and optical[2] light-curves of the RR Lyrae and Cepheids in the Gaia SEP field were taken from the EROS-2 catalogue and cross-matched to the VMC catalogues for the SEP tile. The 30 Dor field is covered by both EROS-2 and OGLE-III, but for the present analysis we only employed the periods and optical (Johnson-Cousins V, I bands) light curves from OGLE-III (Soszyński et al. 2008, 2009).
As a result of the matching procedure we found 107 and 1465 RR Lyrae variables, and 11 and 326 Classical Cepheids in the SEP and 30 Dor fields, respectively.

The periods available from EROS-2 for the SEP variables and from OGLE-III for the 30 Dor variables were used to fold the K_S-band light curves produced by the VMC observations and derive average K_S magnitudes for the variables. Examples of the VMC K_S-band light curves of RR Lyrae stars and Cepheids in the SEP and 30 Dor regions are shown in Figs. 1, 2 and 3, 4, respectively. Error bars of the individual K_S measurements are shown in the figures. The uncertainties for the Cepheids are of the same size at the data-points, while they are larger for the RR Lyrae stars, particularly in the 30 Dor region, due to the fainter magnitudes of these variables and the high crowding of the 30 Dor field.

2.1 Determination of the average K_S magnitudes

In the present work we confine our discussion to the RR Lyrae stars in the SEP field and the Cepheids in the 30 Dor region only. This is because of the small number of Cepheids in the SEP tile (only 11), and because the

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[2] The EROS-2 *blue* channel (420-720 nm), overlaps with the V and R standard bands, and the *red* channel (620-920 nm) roughly matches the mean wavelength of the Cousins I band (Tisserand et al. 2007)

high photometric contamination at the magnitude level of the RR Lyrae stars in the 30 Dor field requires a more careful and detailed analysis which is still in progress.

The K_S-band light curves of the RR Lyrae stars are almost sinusoidal and the amplitude of the luminosity variation in K_S is also rather modest. However, the most accurate results for the mean magnitudes are achieved by using the light-curve templates provided by Jones et al. (1996). Note that the use of templates requires accurate ephemeris and V-band amplitudes which, for the SEP RR Lyrae were calculated starting from the EROS-2 database.

As for the Cepheids, as shown by Figs. 2, 4, the light curves are well sampled and nicely shaped. Hence, to derive the (intensity) average $< K_S >$ we simply used a custom program written in "c" language that performed a spline interpolation to the data.

3 Results

Having derived the mean K_S magnitudes as discussed above, we then computed the PLK_S relations for the SEP RR Lyrae stars and the 30 Dor Classical Cepheids.

3.1 RR Lyrae stars in the SEP field

The PLK_S relation of the 95 RR Lyrae stars with good photometry in the SEP field is shown in Fig. 5, where the periods of the FO RR Lyrae stars were fundamentalized using the formula $\log P_F = \log P_{FO} + 0.127$. The K_S magnitudes were dereddened using the $E(B-V)$ value for the SEP field provided by S. Rubele (private communication) and calculated as described in Rubele et al. (2011).
We then performed a least-square fit to the data, obtaining the following PLK_S relation:

$$K_S^0 = (17.351 \pm 0.035) - (2.450 \pm 0.133) logP \qquad (1)$$

which has an r.m.s.=0.082 mag. The higher dispersion of the SEP RR Lyrae PLK_S with respect to the PLK_S relations followed by the RR Lyrae in Galactic globular clusters (see, e.g. Dall'Ora et al. 2004; Coppola et al. 2011, and references therein) is likely due to a spread in distance among the SEP RR Lyrae along the line of sight, as well as to the possible presence of a metallicity variance among the variables. We have compared our results for the SEP RR Lyrae stars with previous near-infrared observations of RR Lyrae variables in the LMC by Borissova et al. (2009) and Szewczyk et al. (2008). Our Eq. 1 can be compared with Eq. 7 of Borissova et al. (2009) which was calculated using RR Lyrae data from both the above mentioned papers (107 stars in total):

$$K_S^0 = (17.47 \pm 0.07) - (2.11 \pm 0.17) logP \qquad (2)$$

The two equations are only marginally consistent within the errors, and the Borissova et al. (2009) PLK_S has a larger dispersion than ours. These occurrences can be due to both geometrical (depth) effects and a metallicity spread. These aspects will be investigated in a following paper (Moretti et al. in preparation) where we shall also provide our estimate of the LMC distance.

3.2 Classical Cepheids in the 30 Dor Field

The PLK relations of the 172 fundamental mode and the 154 first overtone[3] Classical Cepheids analysed in the 30 Dor field are shown in Fig. 6. Since the saturation level of the VMC survey in K_S limits the length of the periods we are able to measure to a maximum value of about 15-20 days, we decided to complement our data with the sample by Persson et al. (2004) that includes 84 F-mode Cepheids with periods mainly ranging between 10 and 100 days. To merge the two samples we first transformed Persson et al.'s original photometry from the LCO to the 2MASS system using the relations by Carpenter (2001) These data are shown as light blue circles in Fig. 6. To account for the variable reddening that characterizes the 30 Dor field, we adopted the recent evaluations by Haschke, Grebel, & Duffau (2011), while for the Persson et al. (2004) data set we adopted the values provided by the Authors. Finally, we performed least-square fits to the data of F- and FO-modes variables separately, adopting an equation of the form $K_S^0 = \alpha + \beta$ logP. The coefficients derived from the fits are provided in Table 1. The same table also shows a comparison with the literature results of Persson et al. (2004), who only published the PLK_S relation of fundamental-mode pulsators, and of Groenewegen (2000) who also gives the FO PLK_S relation. An inspection of the table reveals that 1) for the F-mode pulsators there is general agreement within the errors among the three studies; 2) the present relation has smaller errors of the coefficients of the PLK_S equation because of the wide range of periods spanned by the Cepheids used to derive the relation, including for the first time in the near-infrared range a significant number of objects with periods smaller than 5 days; 3)

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[3] Double mode pulsators F/FO and FO/SO were included in the F and FO samples, respectively.

Table 1 K_S-band *PL* relations for F and FO Classical Cepheids. The model equation is: $K_S^0=\alpha+\beta$ logP. The first two lines of the table show the coefficients of the least square fit to the data of F and FO Classical Cepheids in the 30 Dor region presented in this paper. The last three lines show the coefficients of the same relations found in the literature.

mode	α	σ_α	β	σ_β	r.m.s.	source
F	16.070	0.017	-3.295	0.018	0.102	This work
FO	15.580	0.012	-3.471	0.035	0.099	This work
F	16.051	0.05	-3.281	0.040	0.108	Persson et al. (2004)
F	16.032	0.025	-3.246	0.036	0.168	Groenewegen (2000)
FO	15.533	0.032	-3.381	0.076	0.137	Groenewegen (2000)

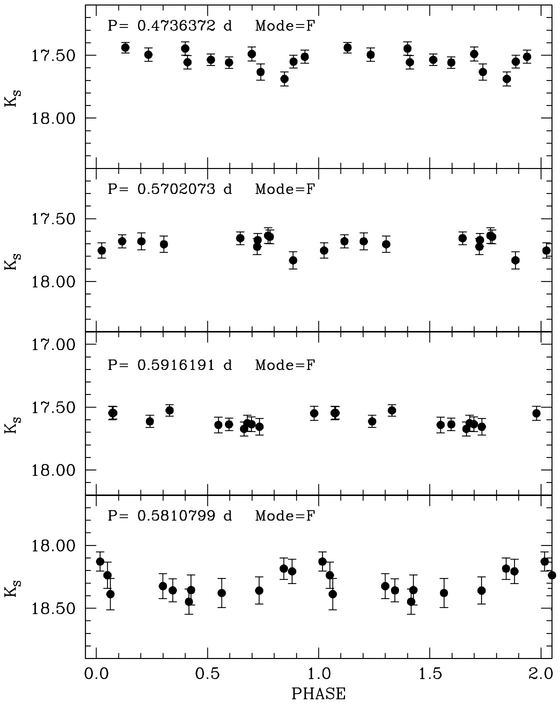

Fig. 3 Same as Fig. 1 for RR Lyrae stars in the 30 Dor region. Periods were taken form the OGLE-III Survey.

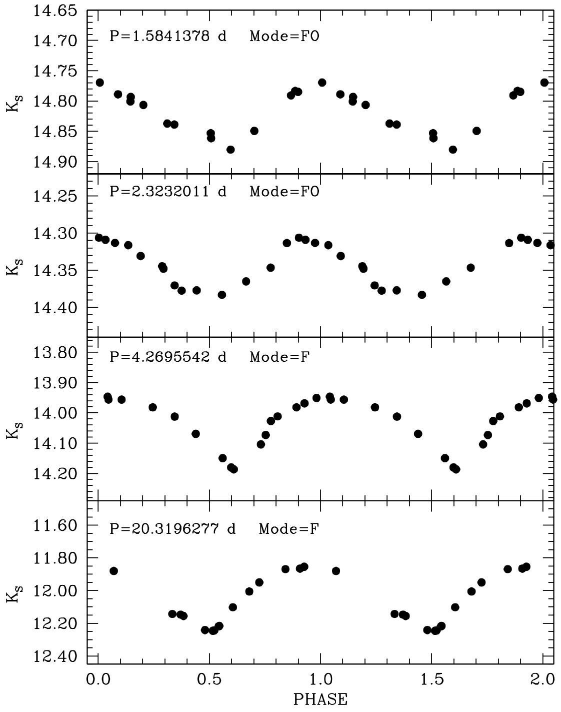

Fig. 4 As in Fig 2 but for Cepheids in the 30 Dor field. Typical errors of the individual data points are of the order of 0.01-0.02 mag, hence have same size as the data points plotted in the figure. Periods were taken from the OGLE-III Survey.

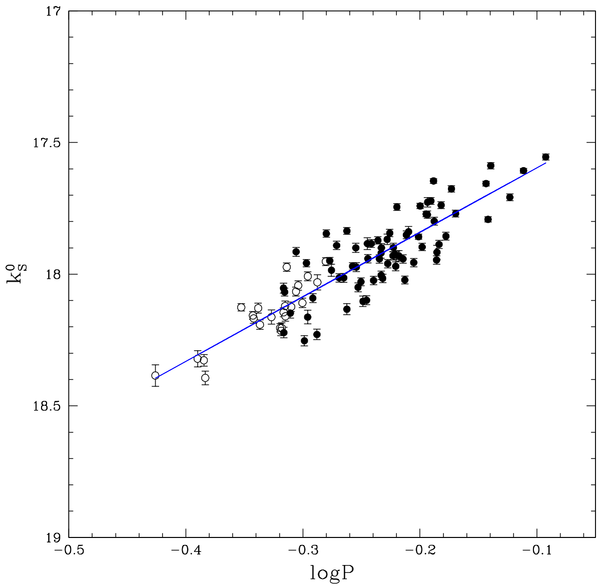

Fig. 5 (K_S)-band Period-Luminosity relation for RR Lyrae variables in the SEP field. Open and filled circles show first overtone and fundamental mode RR Lyrae stars, respectively. The solid line shows the result of the least square fit to the data (see text for details).

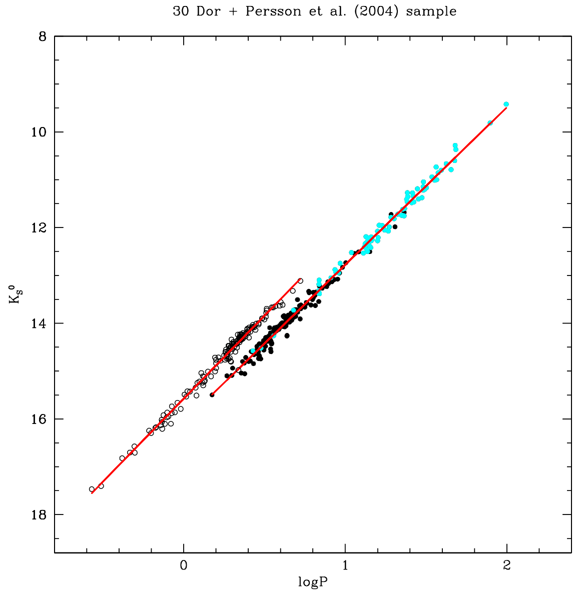

Fig. 6 K_S-band PL relation for Cepheids in the 30 Dor field. Black open and filled circles show FO- and F-mode pulsators, respectively. Light blue filled circles show the F-mode Cepheid sample by Persson et al. (2004). Solid lines are the result of the least square fit to the data (see text for details).

for the FO pulsators the agreement with Groenewegen (2000) is not as good as for the F-mode Cepheids. This could be due to the fact that the deeper photometry of the VMC survey (Groenewegen 2000, relies on 2MASS and DENIS data) allowed us to reach the fainter FO-Cepheids that populate the low-period tail of the PLK_S relation.

The use of the PLK_S relation derived in this paper to estimate the distance of the LMC as well as the discussion of the Wesenheit and PLC relations is deferred to a forthcoming paper (Ripepi et al. 2012, in preparation).

4 Conclusions and future perspectives

We have presented preliminary results on the RR Lyrae stars and the Classical Cepheids observed by the Vista Magellanic Cloud (VMC) survey in two fields of the LMC, centered on the South Ecliptic Pole (SEP) and 30 Dor region, respectively. The K_S light curves of the RR Lyrae variables have very good photometric quality, for the brighter Cepheids we obtained excellent data. The average K_S magnitudes derived for both kind of objects allowed us to derive PLK_S relations which were compared with the literature, finding in general good agreement within the errors. Our data show in any case a smaller scatter with respect to previous studies. We expect much better results when more data from the VMC survey will be available. In particular we will be able to use the PLK_S relation for the RR Lyrae variables and the PLK_S, PLC and Wesenheit relations for Classical Cepheids to investigate both the 3D geometry and the absolute distances to the Magellanic Cloud system.

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