The infrared JHK light curves of RR Lyr

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Accepted 2007 August ??; Received 2007 August ??; in original form 2007 July ??

ABSTRACT

We present infrared JHK time series photometry of the variable star RR Lyr, that allow us to construct the first complete and accurate infrared light curves for this star. The derived mean magnitudes are $<J> = 6.74 \pm 0.02$, $<H> = 6.60 \pm 0.03$ and $<K> = 6.50 \pm 0.02$. The $<K>$ magnitude is used to estimate the reddening, the mass, the mean luminosity and temperature of this variable star. The use of these RR Lyr data provide a more accurate absolute calibration of the P-L$^K$-[Fe/H] relation, and a distance modulus $(m - M)_0 = 18.48 \pm 0.11$ to the globular cluster Reticulum in the LMC.

Key words: methods: observational – techniques: photometric – stars: variables: RR Lyrae – infrared: stars

1 INTRODUCTION

RR Lyr is the nearest (i.e. brightest) and best studied variable star of its type and therefore plays a crucial role in setting the zero-point of the distance scale. There is a very extensive literature reporting photometric measurements and light curves in all optical bands, as well as spectroscopic measurements and radial velocity curves (see e.g. Preston et al. 1965; Wilson et al. 1989; Szeidl et al. 1997, and references therein). The pulsation period is known to a high degree of accuracy ($P = 0.5668386 \pm 0.0000016$ d, Kolenberg et al. 2006) and it is well established that RR Lyr shows the Blazhko effect (i.e. a modulation of its amplitude) with a period of 38.4 d (Kolenberg et al. 2006). The amplitude of this modulation also varies over a 4-yr period (Detre & Szeidl 1973).

Thanks to its proximity, RR Lyr has the most accurately determined trigonometric parallax. In particular, Benedict et al. (2002) derived the absolute parallax $\pi = 3.82 \pm 0.20$ mas, corresponding to a distance modulus of $(m - M)_0 = 7.09 \pm 0.11$, from the analysis of HST data. A very recent reanalysis of Hipparcos data (van Leeuwen 2007) gives a value $\pi = 3.46 \pm 0.64$ mas.

However, infrared photometric observations are nearly missing for this star, the only published data being the two data points (about half a cycle apart) by Fernley et al. (1993, hereafter FSB93) and the 2MASS single epoch data point.

Based on these very scanty data, the mean K magnitude of RR Lyr has nevertheless been used to calibrate both theoretical and empirical period - K luminosity relations (Bono et al. 2003; Sollima et al. 2006), but the need of a more reliable and accurate determination was strongly felt.

This paper reports on the first infrared (JHK) complete light curves that we have obtained for RR Lyr, derives a new estimate of reddening, distance and physical parameters for this star, provides a more reliable and accurate absolute calibration of the period - K luminosity relation and discusses the implications of these new results on the zero-point of the distance scale.

2 OBSERVATIONS AND DATA REDUCTION

The observations have been made with the AZT24 1.1m telescope of the Campo Imperatore Observatory (L’Aquila, Italy), equipped with the NIR camera SWIRCAM (see Di Paola 2003, Brocato & Dolci 2003 and Del Principe et al. 2005 for a detailed description of the telescope and the camera). The observations have been taken on several nights during the period May-July 2007, in good photometric conditions. The seeing (FWHM) ranged from 1.7 to 3.5 arcsec, with the average value around 2.3 arcsec. We observed a 4.4x4.4 arcmin field around RR Lyr through the J, H and K standard filters. Apart from RR Lyr, 7 fainter 2MASS stars are present in this field. Given the brightness of RR Lyr, the exposure times were as short as possible to avoid...
The photometric analysis has been performed using the SExtractor photometric package (Bertin & Arnouts 1996). For each star we measured the flux contained within a radius corresponding to \(~ \sim 2\) FWHM from the star center. A comparison of the mean magnitudes measured for the 7 stars present in the same RR Lyr field with those reported in the 2MASS catalog indicates the absence of any colour term in the magnitude differences. Therefore, the zero-points to be added to the instrumental JHK magnitudes of RR Lyr have been calculated as the average of the differences between the 2MASS and instrumental JHK magnitudes of the 7 reference stars present in the field. The r.m.s. error on the individual data points is \(\sim 0.01\) mag in all the considered photometric bands. These calibrating stars and their 2MASS catalogue data are listed in Table 1.

The phases of the RR Lyr data points have been calculated using the epoch of maximum light \(T_0=2454025.494\) (selected from the list of maxima for RR Lyr in the GEOS RR Lyr database; La Borgne et al. 2004) and the period \(P=0.5668386\) d (Kolenberg et al. 2006). The corresponding JHK light curves\(^1\) are shown in Figure 1. Note the presence of few outliers in the H light curve at phases \(0.4 \div 0.5\) and \(0.9 \div 1.0\). These measures could be affected by uncertainties in the background determination, which is more unstable in the H band than in the other passbands.

### 3 RESULTS

The mean JHK magnitudes have been derived by Fourier analysis of the light curves, and are \(<J>=6.74 \pm 0.02\), \(<H>=6.60 \pm 0.03\) and \(<K>=6.50 \pm 0.02\). In Table 2 the obtained mean magnitudes are compared with the mean values obtained by FSB93 (average of two magnitudes about half a period apart) and with the single epoch photometry from 2MASS taken at phase \(\phi \sim 0.79\) (i.e. close to the minimum light). The magnitudes measured by FSB93 have been reported in the 2MASS photometric system by adopting the transformations by Carpenter et al. (2001). We note that FSB93’s mean values agree quite well (within \(0.04\) mag) with our results. The 2MASS values reported here for completeness are obviously very different as they are single epoch exposures corresponding to the minimum light phase. Both the FSB93 and the 2MASS data points are shown in Fig. 1 for comparison with our light curves.

Note that significant uncertainties can be present in the phases of the individual data points. On the assumption that the (very accurate) value of the period holds for all data sets, errors in the phase can arise from uncertainties in the definition of the JD of maximum light, and are minimised by the use of maxima as close in time as possible to the data. For the phases of FSB93 data we used an epoch of maximum light \(T_0=2445556.4304\) (Huebscher & Mundry 1984). In this case we estimate that the uncertainty in the phase is less than \(0.02\). For the 2MASS data there are no estimates of maxima very close to the epoch of the observation and the O-C (from visual estimates) of the JD max at that time show strong variations. By averaging the results obtained from JD max estimates in the time range of approximately \(\pm 1\) year of the 2MASS observation we obtain \(\phi=0.79 \pm 0.05\).

In the K panel of Fig. 1 we show also the template K light curve obtained by Jones et al. (1996) from the average behaviour of RR Lyrae variables. The selected template corresponds to a blue light curve amplitude of about \(1\) mag, which is appropriate for RR Lyr (Hardie 1955). The template, shifted to reproduce \(<K>=6.50\), matches our observed data points within \(\pm 0.05\) mag at all phases and the overall agreement is quite good.

### 3.1 Blazhko effect

Our observations cover a range of 48 days, which is more than the Blazhko period of 38.4 d (Kolenberg et al. 2006). This explains why the scatter in the light curves is slightly larger than expected from the photometric errors on the individual data points. However, we could not identify unambiguously light curves corresponding to different Blazhko phases because the nightly coverage of the pulsation cycle was not sufficient.

A study of Blazhko stars by Jurcsik et al. (2002) has shown that RR Lyr displays distorted light curves at all phases of the 4-yr cycle except at low modulation amplitude phase, when the shape of the light curves is similar to that of non-Blazhko stars. Our observations are taken during a period of maximum modulation amplitude, when the light curves are expected to be significantly distorted with respect to the “normal” behaviour. However, according to a study of Blazhko stars in the globular cluster M3 (Cacciari et al. 2005), the Blazhko modulation does not seem to affect significantly the mean magnitude. Therefore, we conclude that the values derived above are a reliable representation of the mean J, H and K magnitudes of RR Lyr.

### 3.2 Reddening

Visual-infrared combined colours present a larger dependence on reddening than optical ones \((E(V-K)/E(B-V)=2.63;\) Cardelli et al. 1989). For this reason, the mean

|       | This work | FSB93 | 2MASS |
|-------|-----------|-------|-------|
| J     | 6.74      | 6.78  | 6.95  |
| H     | 6.60      | 6.57  | 6.69  |
| K     | 6.50      | 6.51  | 6.65  |

\(\phi \sim 0.79\) (Cacciari et al. 1998; Cardelli et al. 1989). For this reason, the mean magnitude of RR Lyr is a reliable representation of the mean J, H and K magnitudes of RR Lyr.

1. The calibrated JHK magnitudes for RR Lyr, along with the Heliocentric Julian Day (HJD) and phase of the observations, are available in electronic form at the CDS (http://cdsweb.u-strasbg.fr/).

2. Sollima et al.
Table 1. The calibrating 2MASS stars. The ID and JHK magnitudes are taken from the 2MASS Catalogue.

| Star ID           | RA (J2000) | Dec (J2000) | J ± err  | H ± err  | K ± err  |
|-------------------|------------|-------------|----------|----------|----------|
| 19252482+4247382  | 291.35429  | 42.79364    | 12.641 ± 0.021 | 12.019 ± 0.017 | 11.876 ± 0.016 |
| 19253010+4248407  | 291.375447 | 42.811321   | 11.977 ± 0.021 | 11.728 ± 0.018 | 11.653 ± 0.018 |
| 19252472+4245382  | 291.353005 | 42.766020   | 11.530 ± 0.021 | 11.280 ± 0.017 | 11.200 ± 0.012 |
| 19252875+4248290  | 291.369824 | 42.808071   | 12.260 ± 0.021 | 11.900 ± 0.018 | 11.807 ± 0.014 |
| 19252995+4247331  | 291.374810 | 42.795258   | 12.806 ± 0.021 | 12.360 ± 0.017 | 12.270 ± 0.018 |
| 19252353+4247403  | 291.348050 | 42.794540   | 12.395 ± 0.022 | 12.177 ± 0.017 | 12.109 ± 0.018 |
| 19252017+4248310  | 291.334045 | 42.808613   | 11.835 ± 0.031 | 11.279 ± 0.029 | 11.133 ± 0.025 |

Figure 1. Light curves of RR Lyr in the J, H and K bands. The dashed curve in the bottom panel show the template from Jones et al. (1996). The two open circles and the open triangle mark the FSB93 and 2MASS data points, respectively.

\[ <V> - <K> \text{ colour can be used to constrain the reddening coefficient } E(B-V) \text{ of RR Lyr. To this purpose, we used the period-colour-metallicity relation obtained from Catelan et al. (2004) period-luminosity-metallicity relations in V and } K^2 \text{ (see their eqn. 6 and 7). After correcting Catelan et al.'s K photometry to the 2MASS system using Carpenter (2001; eq. A.1), this relation predicts:} \]

\[ <V_0> - <K_0> = 2.929 + 2.353 \log P + 0.108 (\log Z)^2 + 0.707 \log Z \tag{1} \]

\[ \quad \text{Using } [\text{Fe/H}] = -1.39 \text{ and } [\alpha/\text{Fe}] = 0.31 \text{ (Clementini et al. 1995) and the value of the period as in Sect. 2 we obtain } <V_0> - <K_0> = 1.20. \text{ The observed mean V magnitude has been obtained by Fourier analysis of the light curve provided by Smith et al. (2003), and is } <V> = 7.75 \pm 0.05. \text{ The difference between the observed and predicted mean colours allows us to estimate the effect of reddening, and to derive } E(V-K) = 0.05 \pm 0.03 \text{ and hence } E(B-V) = 0.02 \pm 0.03. \text{ The uncertainty on the derived reddening coefficient has been estimated by using the standard propagation of the errors in the coefficients given by Catelan et al. (2004), in the mean V and K magnitude and the metallicity. Previous reddening determinations es-}

\[ ^2 \text{We converted the metal mass fraction } Z \text{ in metallicity } [\text{Fe/H}] \text{ using eq. 9 and 10 of Catelan et al. (2004).} \]
timated a value of $E(B-V) = 0.03 \pm 0.02$ (Burstein & Heiles 1978; Blanco 1992) and $E(B-V) = 0.06 \pm 0.03$ (Fernley et al. 1998). On the other hand, Benedict et al. (2002) assumed a reddening coefficient corresponding to $A_V=0.07 \pm 0.03$ as the mean from five field stars close to RR Lyr. This value, however, could be as high as $A_V=0.11 \pm 0.10$ at the location of RR Lyr if a variation across the field was present and a two-dimensional linear interpolation in $A_V$ between the four nearest astrometric reference stars was performed. All of these values are compatible within the errors with the estimate we have derived. In the following we adopt $E(B-V) = 0.02 \pm 0.03$ as derived above, and hence $A_K=0.006$ and $A_V=0.054$ assuming $A_K/E(B-V) = 0.35$ and $A_V/E(B-V) = 3.1$ (Cardelli et al. 1989).

3.3 Mean Temperature and Luminosity

The $V-K$ colour is one of the best temperature indicator. Indeed, it has a larger sensitivity to the photospheric temperature and a smaller dependence on metallicity with respect to optical colours (Alonso et al. 1999).

To estimate the mean temperature of RR Lyr we used the color-temperature transformations by Castelli (1999) and Montegriffo et al. (1998). For this purpose, we corrected the measured mean colour $<V-K> = 1.25$ for the reddening $E(V-K) = 0.05$ and applied a further correction of $-0.02$ mag to account for non-static atmospheric effects (Bono et al. 1995a). The resulting intrinsic static colour $<V-K> = 1.18$ in the 2MASS system assumes the values of 1.14 in the Bossell & Brett (1988) system adopted by Castelli (1999), and 1.15 in the system adopted by Montegriffo et al. (1988). Therefore the corresponding temperatures are $T_{eff}=6423$ K, 6253 K and 6313 K using Castelli (1999) calibration, and Montegriffo et al. (1998) empirical and theoretical calibrations, respectively (see Table 4 in Cacciari et al., 2005). The mean of these values is $<T_{eff}> = 6330 \pm 50$ K.

The luminosity of RR Lyr can be estimated once a distance modulus is known. Considering the two determinations of trigonometric parallax quoted in Sect. 1, we adopt the value by Benedict et al. (2002) for its much smaller error, and hence $(m-M)_0 = 7.09 \pm 0.11$ and $M_K = -6.00 \pm 0.03$. Using $BC_K=1.15$ from Montegriffo et al. (1998) and $M_{bol}=4.75$ (the IAU convention) we then derive the luminosity of RR Lyr $\log L/L_\odot = 1.68 \pm 0.05$. This estimate is in good agreement with that reported by Bono et al. (2003) using a theoretical period-K luminosity relation ($\log L/L_\odot = 1.689 \pm 0.030$).

In Fig. 2 we show the location of RR Lyr in the theoretical Hertzprung-Russel diagram. For comparison, the theoretical Zero Age Horizontal Branch (ZAHB) interpolated to $[Fe/H]=-1.39$ from the set of ZAHB models by VandenBerg et al. (2000) is overplotted along with the red edge of the instability strip predicted by Bono et al. (1995b). As can be noted, RR Lyr appears to be located close to the theoretical ZAHB and not far from the red edge of the instability strip. Given the uncertainties both on the data and on the theoretical models, this indicates that the star has not yet significantly evolved from the phase of core helium burning. A further confirmation of this result is provided by the location of RR Lyr in the B amplitude-period relation (see Cacciari et al. 2005). Indeed, in this diagram the maximum

![Figure 2](image_url)

**Figure 2.** Location of RR Lyr in the Hertzprung-Russel diagram. The theoretical ZAHB of VandenBerg et al. (2000) and the red edge of the instability strip by Bono et al. (1995b) are overplotted.

4 THE ZERO-POINT OF THE DISTANCE SCALE

In Sollima et al. (2006) RR Lyr was used to set the zero-point of the period - infrared luminosity relation derived from the analysis of 544 RR Lyrae variables in 16 globular clusters. To that purpose, the $M_K$ magnitude of RR Lyr was estimated to be $-0.57$ mag based on the data and knowledge then available. We can now provide a more reliable and accurate value, based on the present infrared light curves and updated values of reddening, namely $M_K = -0.60$ mag. This value is $0.03$ mag brighter than the previous one, and the eq.s (4) and (5) in Sollima et al. (2006) become:

$$M_K = -2.38(\pm 0.04) \log P_F + 0.08(\pm 0.11) [Fe/H]_{CG} -1.07(\pm 0.11)$$

where $P_F$ is the fundamental period and $[Fe/H]_{CG}$ the metallicity in the Carretta & Gratton (1997) metallicity scale.

The application of these log $P$-$M_K$-$[Fe/H]$ relations to the RR Lyrae stars in the globular cluster Reticulum in the LMC leads to a distance modulus ($m-M)_0 = 18.48 \pm 0.11$, using the K data by Dall’Ora et al. (2004) and $[Fe/H] = -1.71$ and $E(B-V) = 0.03$ (Suntzeff et al. 1992). On the other hand, the absolute $V$ magnitude of RR Lyr derived here ($M_V = 0.61 \pm 0.12$) can be also used to set the zero point of the period - $V$ luminosity relation.
Assuming $\delta V / \delta [Fe/H] = 0.214$ (Clementini et al. 2003) we derive $M_V = 0.54$ at $[Fe/H] = -1.71$ (as appropriate for Reticulum). This value, together with the mean dereddened V magnitude $< V_0 > = 18.98$ for these variable stars (from Walker 1992) implies a distance to the Reticulum of $(m - M)_0 = 18.44 \pm 0.14$. The agreement of the V and K results make us confident that we have provided the most reliable and accurate JHK data presently available for RR Lyr.

As an interesting application of this infrared relation, we can estimate the distance to the set of RR Lyrae stars observed by Borissova et al. (2004) in the inner regions of the LMC (see Sollima et al. 2006), which turns out to be $(m - M)_0 = 18.56 \pm 0.13$. Similarly, we can estimate the distance to the bar of the LMC, where about 100 RR Lyrae stars with an average metallicity of $[Fe/H] = -1.5$ (Clementini et al. 2003) have a mean dereddened V magnitude $< V_0 > = 19.064$. Using the absolute V magnitude of RR Lyr derived above we obtain $(m - M)_0 = 18.48 \pm 0.13$. This result is also in good agreement with the most recent studies of Cepheid variables (Persson et al. 2004; Gieren et al. 2005; van Leeuwen et al. 2007; Fouqué et al. 2007). The difference between the distance to the bar (from the V relation) and to the inner field (from the K relation), which is larger than the difference found for the Reticulum, may indicate that the two fields are not exactly at the same distance.

5 CONCLUSIONS

In this paper we provide the first light curves of the variable star RR Lyr in the infrared JHK passbands, yielding to the mean magnitudes $<J> = 6.74 \pm 0.02$, $<H> = 6.60 \pm 0.03$ and $<K> = 6.50 \pm 0.02$.

The mean temperature and luminosity of RR Lyr have been derived. These quantities have been used to estimate the mass of this star and its evolutionary stage by comparison with theoretical ZAHB models of appropriate metallicity. This comparison indicates that RR Lyr is located on or very near the ZAHB locus, and so it is still burning helium in its core.

The excellent quality of the present infrared data allowed us to use RR Lyr as a reliable and accurate infrared standard candle to set the zero point of the distance scale. In particular, the mean $M_K = -0.60$ magnitude was used to calibrate the period - K luminosity - metallicity relation for RR Lyrae stars.

The most important aspects of these results are:

i) With the present calibration we derive a distance modulus to the globular cluster Reticulum of the LMC of $(m - M)_0 = 18.48 \pm 0.11$. This value, obtained from the $< K >$ of RR Lyr, is comparable to the value obtained from the $< V >$ ($(m - M)_0 = 18.44 \pm 0.14$) within the errors. This indicates that the mean V and K magnitudes of RR Lyr are accurate and self-consistent.

ii) The estimated distances to the bar and an inner field of the LMC are also in good agreement with the most recent studies of Cepheid variables (Persson et al. 2004; Gieren et al. 2005; van Leeuwen et al. 2007; Fouqué et al. 2007) although there is some indication that the inner field is slightly more distant.

ACKNOWLEDGEMENTS

We warmly thank Paolo Montegriffo for assistance during catalogs cross-correlation and Mauro Dolci for his technical support for the observations and data reduction procedures. We are grateful to the anonymous referee for his comments and suggestions that have contributed to improve the paper. This research was supported by contract ASI-INAF I/023/05/0 and PRIN-INAF 2006.

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