Photometric Determination of the Distance to the RR Lyrae Star YZ Capricorni

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Abstract The RR Lyrae YZ Cap was observed using photometric methods to determine its pulsation period and distance. Light curves in the Bessell B and V and SDSS i' and z' filters were used to determine the period, which was found to be 0.274 ± 0.003 day. The distances calculated using a luminosity-metallicity (V filter) and period-luminosity-metallicity relationship (i' filter and z' filter) were: V: 1107 ± 52 pc, i': 1191 ± 126 pc, and z': 1092 ± 128 pc. These are in agreement with the distance measurement from the second Gaia data release, 1144 ± 90 pc. This demonstrates the potential to use ground-based observations in the visible and near-infrared to determine the distance to RR Lyrae variable stars.

1. Introduction

RR Lyrae stars are periodic variable stars resting on the horizontal band of the Hertzprung-Russell diagram. The prototype for this classification of star, RR Lyrae itself, was discovered by Williamina Fleming in 1901 (Pickering *et al.* 1901). In modern astronomy, RR Lyraes are used as standard candles, meaning that properties of the stars, including their period and metallicity, can be related to their absolute magnitude in order to determine their distance. This distance can be used to analyze and find the distance to other stellar bodies and the globular clusters within which these stars are often found. In the visible bands, fluxes scale as T^4_{eff}, whereas in the near-infrared, the dependence goes as $T^{1.6}_{eff}$ (Catelan and Smith 2015). This reduced sensitivity to temperature in the i' and z' bands has allowed for the development of period-luminosity-metallicity relationships, which are more accurate than the luminosity-metallicity relationships that can be applied in the V band. In an effort to better understand these stars that are critical to modern astronomy, an RR Lyrae star was selected for the determination of its distance and the analysis of its period and magnitude, particularly in the near-infrared bands. The data collected from this star were used to further the usage of previously determined period-luminosity-metallicity relations.

In selecting an RR Lyrae star for analysis, YZ Capricorni, hereafter referred to as YZ Cap, was determined to be a good candidate. The star was present in a variety of astronomical surveys, including the Sloan Digital Sky Survey and the AAVSO Photometric All-Sky Survey, as well as being visible from PanSTARRS. A summary of data regarding YZ Cap is presented in Table 1. YZ Cap is an RRc type star, meaning that it pulsates in the first overtone mode and its light curve can be expected to have a sinusoidal shape (Monson *et al.* 2017).

There are several published values of metallicity for YZ Cap, summarized in Table 2. Since these measurements differ from each other and no singular measurement has been deemed the most accurate, an average of these measurements, [Fe/H] = –1.33 ± 0.17, was used for this analysis. This [Fe/H] value was converted first to a metals-to-hydrogen ratio, [M/H], using the scaling relationship (Equation 1) (assuming $f \simeq 10^{0.3}$, e.g. (Catelan *et al.* 2004) and then to log Z using Equation 2 in order to be utilized in the magnitude and distance analysis (Catelan *et al.* 2004). This gave an [M/H] value of –1.112 and a log Z value of –2.877.

Table 1. Summary of previous published information about YZ Cap.

R.A. (2000) h m s	*Dec. (2000)* ° ' "	*V Mag.*	*Distance*	*Spectral Type*	*Period*
21 19 32.41	–15 07 1.14[1]	11.34[2]	1144 ± 90 pc[3]	F5[4]	0.273 d[5]

Sources: 1. Neeley et al. *(2017). 2. Henden* et al. *(2015). 3. Gaia Collab.* et al. *(2018). 4. Nesterov* et al. *(1995). 5. Bono* et al. *(2020); Neeley* et al. *(2017).*

Table 2. YZ Cap metallicity.

[Fe/H]	*Source*
–1.25	Cacciari *et al.* (1989)
–1.30	Cacciari *et al.* (1989)
–1.06	Feast *et al.* (2008)
–1.54	Govea *et al.* (2014)
–1.48	Govea *et al.* (2014)
–1.33	Average of available sources

$$[M / H] = [Fe / H] + \log(0.638f + 0.362) \quad (1)$$

$$\log Z = [M / H] - 1.765 \quad (2)$$

2. Observations

All observations were made using the Las Cumbres Observatory, which has ten sites around the world with an assortment of 0.4-meter, 1.0-meter, and 2.0-meter telescopes) Brown *et al.* 2013). This distribution of telescopes allows for longer observation times, because when an object is no longer visible to one telescope, the object becomes visible to another.

Test images were taken using the 0.4-meter telescopes to calculate proper exposure times. Optimal times for each band were chosen to ensure ≈100,000 counts for YZ Cap. The exposure times used were 100 seconds for the Bessell B band, 30 seconds for the Bessell V band, 40 seconds for the SDSS i' band, and 130 seconds for the SDSS z' band.

Observations were made between October 19, 2020, and November 1, 2020. A total of 194 images across the four filters was received after an initial processing pass through the Our Solar Siblings (OSS) Pipeline (Fitzgerald 2018). 53 images in B, 48 in V, 47 in i', and 46 z' were retained.

3. Methods

Images gathered from the Las Cumbres Observatory were passed through the Our Solar Siblings (OSS) Pipeline in order to generate photometry files for analysis. From the 194 images that passed through the OSS Pipeline, only 124 were kept for further analysis. In the case of the 70 images that were discarded, YZ Cap and the surrounding comparison stars were either out of focus, too dim, or too blurred. The OSS Pipeline utilizes a variety of photometry methods in order to analyze the images of the stars, and these methods fall into the two main categories of aperture photometry and point-spread function photometry. In aperture photometry, a digital ring is placed around the image of the star, and the magnitude of the star within the ring is measured. This method works well for images in which the star appears very circular and regularly shaped, because an aperture can be accurately placed around a circular-shaped image of a star. The data produced by the SEXtractor method (Bertin and Arnouts 1996), also known as simple aperture method, was the most consistent and was selected for further analysis.

In order to analyze the remaining 124 images, a Python package called Astrosource was utilized (Fitzgerald *et al.* 2020). Astrosource analyzes images and photometry data files of variable stars and identifies comparison stars in the star field for calibration. These calibration comparison stars are identified by having a stable magnitudes and already being present in an accessible database. The catalogues used by Astrosource for the different filters are APASS for B and V (Henden *et al.* 2016), SDSS for i' (Alam *et al.* 2015), and PanSTARRS for z' (Magnier *et al.* 2020; Flewelling *et al.* 2020). The magnitudes of these comparison stars are used to calibrate the magnitude of the variable star being studied, in this case YZ Cap. A list of the coordinates of the identified comparison stars can be found in Table 3. These comparison stars are circled in Figure 1, with YZ Cap circled in the center. After using the comparison stars to calibrate the magnitude, Astrosource produced light curves and period measurements for each filter using the Phase Dispersion Minimization Method (Stellingwerf 1978).

4. Results/discussion

Depicted in Figure 2 are the light curves in the B, V, i', and z' filters. The light curves are relatively consistent with each other and clearly exhibit the characteristic sinusoidal shape of an RRc type star. The period was measured from each light curve using the phase dispersion method minimization algorithm developed by Altunin *et al.* (2020) based on the technique developed by Stellingwerf (1978). The period was measured independently in each filter to be 0.274±0.003 days, which is consistent with previously measured values. The apparent magnitude in each filter is presented in Table 4. The apparent magnitudes were determined by averaging all of the magnitudes from the light curve, which provides sufficiently accurate values because the light curve is highly symmetrical.

The luminosity-metallicity equations in the V (Equation 3) (Catelan *et al.* 2004), and period-luminosity-metallicity equations in the i' (Equation 4) and z' (Equation 5) bands (Caceres and Catelan 2008) were used to calculate the absolute magnitude of YZ Cap in each filter (Table 4). In Equations 4 and 5, the period used was first converted into the "fundamentalized" period using Equation 6 (Caceres and Catelan 2008).

$$M_V = 2.288 + 0.882 \log Z + 0.108 (\log Z)^2 \quad (3)$$

$$M_i = 0.908 - 1.035 \log P_f + 0.220 \log Z \quad (4)$$

$$M_z = 0.839 - 1.295 \log P_f + 0.211 \log Z \quad (5)$$

$$\log P_f = \log P + 0.128 \quad (6)$$

These magnitude values were used to determine the distance to YZ Cap (Table 5), which is compared to the parallax distance

Table 3. Coordinates of comparison stars with magnitude in the B filter.

R.A. (2000) *h m s*	*Dec. (2000)* *° ′ ″*	*B Mag.*
21 20 04	–15 03 41	13.69 ± 0.02
21 19 26	–15 01 56	12.68 ± 0.03
21 19 31	–15 01 13	13.36 ± 0.04
21 19 50	–14 53 20	14.31 ± 0.05
21 19 15	–14 55 03	13.83 ± 0.04
21 20 04	–15 11 12	12.41 ± 0.04
21 19 45	–15 01 58	12.41 ± 0.04
21 19 07	–15 07 25	11.81 ± 0.07
21 19 35	–15 01 30	14.63 ± 0.07
21 19 10	–15 16 47	13.92 ± 0.04

Table 4. Apparent and calculated absolute magnitudes.

Filter	*m*	*M*
B	11.48 ± 0.01	—
V	11.19 ± 0.01	0.721 ± 0.05
i'	11.17 ± 0.01	0.783 ± 0.161
z'	11.15 ± 0.01	0.850 ± 0.192

Table 5. Comparison of distance measurements.

	Distance (pc)	*Error (pc)*
Gaia	1144	90
V	1107	52
i'	1191	126
z'	1092	128
mean	1130	59

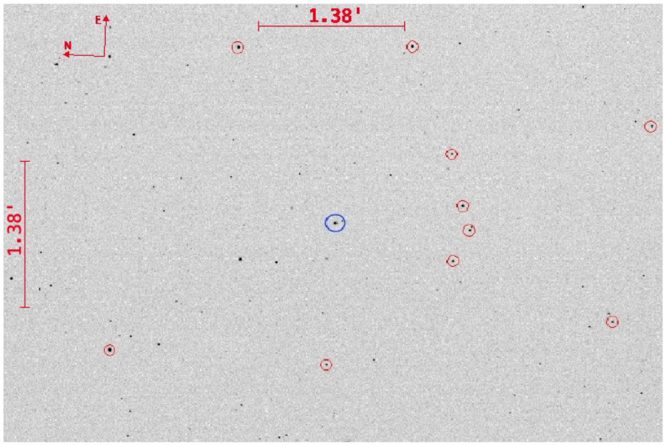

Figure 1. Image taken in the i' filter with circled comparison stars.

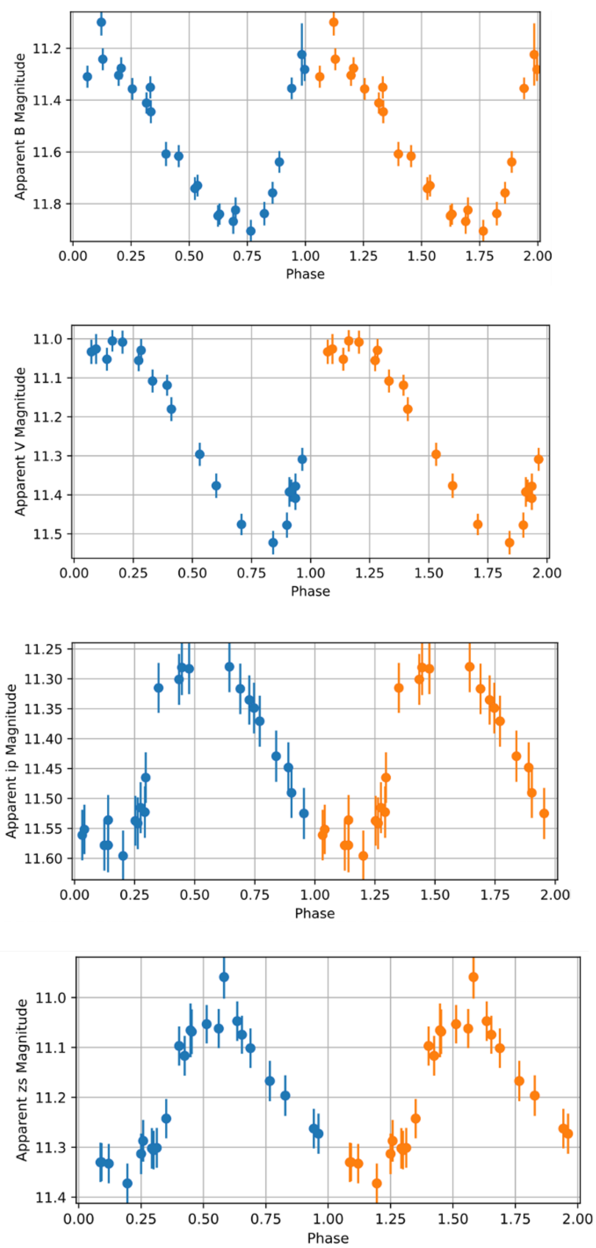

Figure 2. Light curves in the B, V, i', and z' filters, respectively.

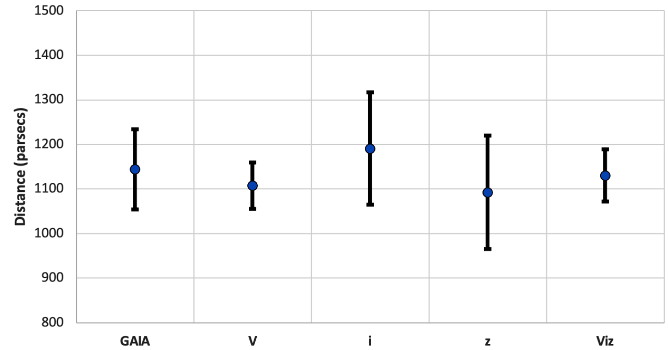

Figure 3. Distance measurements with error after extinction correction. Viz is the mean of all three filters.

measurement published in the second Gaia data release. The interstellar reddening (E(B–V)) of YZ Cap was determined to be 0.14 by minimizing the variance in the values of the true distance moduli for the V (Equation 7), i' (Equation 8), and z' (Equation 9) filters. Extinction values A_m/A_V were calculated using an extinction curve from Cardelli *et al.* (1989), where $R_v = 3.1$ and $A_v = 1$.

$$\mu\ (V) = V - M_V - A_V \tag{7}$$

$$\mu\ (i') = i' - M_i - (A_i / A_v)\ A_V \tag{8}$$

$$\mu\ (z') = z' - M_z - (A_z / A_V)\ A_V \tag{9}$$

Calculated error in the reported distances incorporated errors in the apparent magnitude, period, and metallicity. When the average across all three filters is taken, the distance is found with an error smaller than that reported by Gaia. The distance measurements with error for each filter, the mean of the filters, and the Gaia measured distance are summarized in Figure 3.

5. Conclusion

Using the photometric analysis of the infrared and visible images, the period of YZ Cap was determined to be 0.274 ± 0.003 day, which agrees with previous measurements. Using the equations found in Catelan *et al.* (2004) and Caceres and Catelan (2008), the distance and magnitudes of YZ Cap in the V, i', and z' filters were determined. These values were found to agree with the Gaia measured distance of 1144 ± 90 pc. This study expanded the existing pool of data on RR Lyrae stars, and it provides an example of the ability to apply the infrared period-luminosity relations to an individual star to determine the distance to the star.

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