RR LYRAE STARS IN THE GLOBULAR CLUSTER PALOMAR 2

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Received July 8 2022; accepted August 20 2022

ABSTRACT

A CCD \textit{VI} imaging time-series over 11-year is employed to explore the light curves of stars in the field of Palomar 2. We discovered 20 RRab and 1 RRc variables. A revision of \textit{Gaia}-DR3 data enabled us to identify 10 more variables and confirm the RRab nature of 6 of them and one RGB. The cluster membership is discussed, and 18 variables are most likely cluster members. The Fourier light curve decomposition for the 11 best quality light curves of cluster member stars leads to independent estimates of the cluster distance $27.2 \pm 1.8$ kpc and $[\text{Fe/H}]_{ZW} = -1.39 \pm 0.55$. We confirm the cluster as of the Oo I type.

RESUMEN

Empleando una serie temporal de más de 11 años de imágenes CCD \textit{VI}, exploramos las curvas de luz de estrellas en el campo del cúmulo. Descubrimos 20 RRab y 1 RRc. Una revisión de los datos de \textit{Gaia}-DR3 permitió identificar 11 variables más y confirmar la naturaleza RRab de 6 de ellas y una RGB. Presentamos un análisis de membresía y concluimos que al menos 18 de estas variables pertenecen al cúmulo. La descomposición de Fourier de las curvas de luz de mejor calidad de 11 RR Lyrae miembros conduce a estimaciones independientes de la distancia $27.2 \pm 1.8$ kpc y metalicidad $[\text{Fe/H}]_{ZW} = -1.39 \pm 0.55$ medias para el cúmulo. Confirmamos que el cúmulo es del tipo Oo I.

\textbf{Key Words:} globular clusters: individual: Pal 2 — stars: variables: RR Lyrae

1. INTRODUCTION

The globular cluster Palomar 2 is a distant (30 kpc) stellar system in the direction of the Galactic anticenter and close to the Galactic plane ($l = 170.53^\circ$, $b = -9.07^\circ$). It is buried in dust with $E(B - V) \approx 0.93$ and shows evidence of differential reddening (Bonatto & Chies-Santos 2020). It is, therefore, a faint cluster with the HB at about $V \approx 21.5$ (Harris 1996). Most likely due to its faintness no variables in the cluster have ever been reported.

In the present paper we take advantage of an 11-year long time-series of CCD \textit{VI} data, analyzed in the standard Differential Imaging Approach (DIA), to explore the light curves of nearly 500 stars in the field of view (FoV) of the cluster. We have found 21 new RR Lyrae stars (V1-V14 and SV1-SV7 in Table 1). In conjunction with the \textit{Gaia}-DR3 variability index, we confirm the RRab nature of 6 more stars (G3, G11, G12, G13, G18 and G23), plus 1 RGB (G17), for a total of 28 variables in the field of view of our images. In what follows, we argue in favour of the membership of 18 of them and present their light curves and ephemerides. The mean distance and $[\text{Fe/H}]$ of the cluster shall be calculated by the Fourier decomposition of RRab stars with the best quality light curves.

2. OBSERVATIONS AND DATA REDUCTIONS

The data were obtained between December 12, 2010 and February 12, 2021 with the 2.0-m telescope at the Indian Astronomical Observatory (IAO), Hanle, India. The detector used was a SiTe ST-002 2Kx4K with a scale of 0.296 arcsec/pix, for a field of view of approximately $10.1 \times 10.1$ arcmin$^2$. From October 14, 2018 and February 17, 2020 the detector used was a Thompson grade 0 E2V CCD44-82-0-E93 2Kx4K with a scale of 0.296 arcsec/pix, or a FoV of approximately $10.1 \times 10.1$ arcmin$^2$. A total of 197 and 240 images were obtained in the $V$ and $I$ filters, respectively.
2.1. Difference Imaging Analysis

The image reductions were performed employing the software Difference Imaging Analysis (DIA) with its pipeline implementation DanDIA (Bramich 2008; Bramich et al. 2013, 2015) to obtain high-precision photometry of all the point sources in the field of view (FoV) of our CCD. This allowed us to construct an instrumental light curve for each star. For a detailed explanation of the use of this technique, the reader is referred to the work by Bramich et al. (2011).

2.2. Transformation to the Standard System

Since two different detectors were used to achieve the observations as described in the previous section, we treated the transformation to the standard system as two independent instruments. Otherwise, the procedure was the standard one described in detail in previous publications, in summary; we used local standard stars taken from the catalog of Photometric Standard Fields (Stetson 2000) to set our photometry into the VI Johnson-Kron-Cousin standard photometric system (Landolt 1992).

The transformation equations carry a small but mildly significant colour term and are of the form:

\[ V - v = A(v - i) + B \]

and

\[ I - i = C(v - i) + D \]

for each filter, respectively. The interested reader can find the details of this transformation approach in Yepez et al. (2022).

3. STAR MEMBERSHIP USING GAIA-EDR3

We have made use of the latest data release Gaia-EDR3 (Gaia Collaboration 2021) to perform a membership analysis of the stars in the field of Pal 2. To this end, we employed the method of Bustos Fierro & Calderón (2019), which is based on the Balanced Iterative Reducing and Clustering using Hierarchies (BIRCH) algorithm developed by Zhang et al. (1996). The method and our approach to it have been described in detail in previous publications, in summary; we used local standard stars taken from the catalog of Photometric Standard Fields (Stetson 2000) to set our photometry into the VI Johnson-Kron-Cousin standard photometric system (Landolt 1992).

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4. DIFFERENTIAL REDDENING AND THE CMD

Palomar 2 is a heavily reddened cluster subject to substantial differential reddening, as it is evident in the crowded and deep HST color magnitude diagram (CDM) shown by Sarajedini et al. (2007). A thorough treatment of the differential reddening in the cluster enabled Bonatto & Chies-Santos (2020) to produce a reddening map, which these authors have kindly made available to us. In Figure 2 the observed CDM and the dereddened versions are shown. To deredden the CDM, the differential reddening map was added to a foreground reddening of \( E(B-V) = 0.93 \).

5. THE VARIABLE STARS IN PAL 2

No variable stars in Pal 2 have been reported thus far. The case of Pal 2 is a particularly challenging one since the cluster is not only distant, but it is also behind a heavy dust curtain; its horizontal branch (HB) is located below 21 mag. We have occasionally taken CCD VI images of Pal 2 since 2010 and until 2021 and we have attempted to take advantage of this image collection to search for variables in the FoV of the cluster. We were able to measure 400-500 point sources in the V and I images that span a range in magnitude and colour shown in the left panel of Figure 2. The HB being located at the bottom of the stellar distribution, we are in fact working at the very limit of our photometry in order to detect cluster member RR Lyrae.

To search for variability we proceeded as follows. By using the string-length method (Burke et al. 1970, Dworetsky 1983), we phased each light curve in our data with a period varying between 0.2 d and 1.0 d, a range adequate for RR Lyrae stars, in steps of \( 10^{-6} \) d. For each phased light curve, the length of the line joining consecutive points, called the string-length and represented by the parameter \( S_Q \), was calculated. The best phasing occurs when \( S_Q \) is minimum, and corresponds to the best period
RR LYRAE STARS IN PAL 2

Fig. 1. VPD and Gaia CMD of Pal 2. In the left panel, black and red points represent field and member stars respectively, as extracted by our analysis of the Gaia DR3 proper motions. In the right panel gray and red symbols are used for non-member and member stars, while black dots represent stars without proper motion information; hence their membership status cannot be assigned (UN). The colour figure can be viewed online.

Fig. 2. The colour-magnitude diagram of Pal 2. The left panel shows all the stars measured in the FoV of our images and illustrates the magnitude and colour ranges of our data. The right panel has been differentially dereddened by adopting the reddening map of Bonatto & Chies-Santos (2020). We adopted from these authors an average foreground reddening of $E(B-V) = 0.93$. As a reference we included two isochrones from the models of VandenBerg et al. (2014) for $[\text{Fe/H}]=−1.6$ and $−2.0$ and a theoretical horizontal branch built by Yepez et al. (2022). Isochrones and HB have been placed at a distance of 26.1 kpc (Bonatto & Chies-Santos 2020). Variable stars are indicated and discussed in § 5. The vertical black lines are the empirical first overtone red edge (FORE) from Arellano-Ferro et al. (2015, 2016). The colour figure can be viewed online.

that our data can provide. A detailed visual inspection of the best phased light curve helped to confirm the variability of some stars. We noticed, however, that the seasonal scatter of the light curve could vary depending mainly on the prevailing seeing conditions and crowdedness of a particular star, a situation that worsens near the core of the cluster. Therefore, it may happen that in some seasons the light curve
TABLE 1
DATA OF VARIABLE STARS IN THE FOV OF OUR PAL 2 IMAGES

| ID | Gaia variable | Type | P (d) | E₀ (−2450000) | V (mag) | V Amp (mag) | RA (J2000.0) | DEC (J2000.0) | P_Gaia (d) | Membership status | Gaia number |
|----|---------------|------|-------|---------------|---------|-------------|--------------|--------------|-----------|------------------|-------------|
| V1 | RRab          | 0.534838 | 6312.3363 | 20.534 | 0.805 | 4:46:03.57 | +31:22:45.8 | M1 | 15950464014524672 |
| V2 | G5            | 0.551396 | 5422.1114 | 21.342 | 1.056 | 4:46:04:60 | +31:23:45.1 | M1 | 15950474384202336 |
| V3 | RRab          | 0.534863 | 6948.4976 | 21.792 | 0.951 | 4:46:05:53 | +31:23:45.9 | M1 | 1595047438529064 |
| V4 | G14           | 0.561889 | 5912.2228 | 21.413 | 0.814 | 4:46:06:56 | +31:23:43.2 | M1 | 15950474387726464 |
| V5 | G5            | 0.511639 | 8896.2470 | 21.382 | 0.997 | 4:46:07:02 | +31:23:33.5 | M1 | 1595046766794552 |
| V6 | G21           | 0.532592 | 9528.3356 | 21.461 | 1.168 | 4:46:07:38 | +31:23:30:7 | M2 | 15950476768831872 |
| V7 | G16           | 0.558512 | 8407.3827 | 20.925 | 0.914 | 4:46:08:11 | +31:23:37:1 | M1 | 1595047667937024 |
| V8 | G7            | 0.373408 | 5422.1114 | 20.757 | 0.548 | 4:46:08:06 | +31:23:21:7 | M1 | 15950468937041192 |
| V9 | G6            | 0.629016 | 5912.3072 | 20.700 | 0.512 | 4:46:09:11 | +31:23:38:0 | M1 | 15950474384202336 |
| V10| G19           | 0.575280 | 6223.3870 | 20.673 | 0.842 | 4:46:07:38 | +31:23:15:5 | M2 | 1595046766794552 |
| V11| G9            | 0.583630 | 6633.3246 | 20.894 | 0.693 | 4:46:07:21 | +31:23:47:2 | M2 | 1595046766794552 |
| V12| RRab          | 0.546972 | 6948.4441 | 21.327 | 0.887 | 4:46:07:17 | +31:23:15:5 | M2 | 1595046766794552 |
| V13| G1            | 0.574697 | 6948.4591 | 21.842 | 1.610 | 4:46:07:21 | +31:23:47:2 | M2 | 1595046766794552 |
| V14| G12           | 0.508471 | 8781.4301 | 20.918 | 0.323 | 4:46:05:00 | +31:23:21:7 | M1 | 1595046766794552 |
| V15| G13           | 0.587210 | 8407.3175 | 21.585 | 1.363 | 4:46:06:56 | +31:23:27:2 | FS | 1595046766794552 |
| V16| RRab          | 0.588566 | 6634.1554 | 21.267 | 1.024 | 4:46:06:56 | +31:23:27:2 | FS | 1595046766794552 |
| V17| G15           | 0.490941 | 6221.4206 | 21.312 | 1.391 | 4:46:06:56 | +31:23:27:2 | FS | 1595046766794552 |
| V18| G10           | 0.570669 | 6946.4683 | 20.764 | 0.960 | 4:46:06:56 | +31:23:27:2 | FS | 1595046766794552 |
| SV1| RRab          | 0.537325 | 6634.1714 | 21.178 | 1.048 | 4:46:06:56 | +31:23:27:2 | FS | 1595046766794552 |
| SV2| RRab          | 0.545053 | 6633.3810 | 21.178 | 1.048 | 4:46:06:56 | +31:23:27:2 | FS | 1595046766794552 |

1 Out of our FoV. 2 Not measured by our photometry.

variation is dubious, but extremely clear in the runs of best quality, which turned out to be from the 2013 and 2018-2020 seasons.

With the above method we discovered 21 RR Lyrae variables, mostly of the RRab type. Confronting with the membership analysis described in §3, we concluded that 14 of them were likely cluster members. The latest Gaia-DR3 enabled us to search for stellar variability flags in the field of Pal 2. In fact, Gaia flags 22 variables. A cross-match with our variables list shows 12 matches; we found some variables not marked by Gaia and a posteriori we confirmed the variability of a few Gaia sources not previously detected by us.

In Table 1 we list the 32 variables in the field of Pal 2. The table is organized as follows. We have given the name with the prefix “V” only to those stars that seem likely cluster members (status M1 or M2), 18 in total, V1-V18. Arbitrarily, we identified the Gaia variables as G1-G22. This identification is listed in Column 2. In the bottom 14 rows of Table 1 we list the likely non-members (status FS). For non-member variables detected by us, we used the nomenclature with the prefix “SV”.

5.1 Variables in the CMD
In the right panel CMD of Figure 2, all variable stars have been marked with a red circle if they are cluster members or a black circle otherwise. As a reference we included two isochrones from the models of VandenBerg et al. (2014) for [Fe/H]=−1.6 and −2.0 and a theoretical horizontal branch built by Yepez et al. (2022). Isochrones and HB were placed at a distance of 26.1 kpc Bonatto & Chies-Santos (2020). It is heartening to see nearly all the RR Lyrae stars fall in the whereabouts of the HB. In the following section we address some peculiar individual cases.
5.2. Individual Cases

V1. Its position on the CMD above the HB and in the mid-RGB is intriguing since the light curve and period suggest this star to be a member RRab star. An alternative possibility is that the star is a binary. Our data are not sufficient to explore this possibility.

V16, V17 and V18. Their position on the CMD near the tip of the RGB suggests these stars are red giant variables. However, our photometry was not extensive enough to confirm a long-term variability. Alternatively, we were able to identify short-term variations in V16 and V18 (see Figure 3). The V17 light curve is, in fact, consistent with that of a long-term RGB.

SV1. It is a clear RRab star, falling much to the red of the HB. The star is not a cluster member.

SV7. We have detected clear RRab-like variations in our V data. However, no variation is seen in the I data. While variations might be spurious, we retain the star as a candidate variable to be confirmed.

SV4, SV5, SV6 and G23. These are the four non-member stars, hence identified by black circles or squares in the DCM. However, they lie very near the HB. Their non-membership status was assigned by the statistical approach to their proper motions, but they might be cluster members.

G3 and G20. G3 is a clear RRab star, not a cluster member. For G20 we got a very noisy light curve.
Fig. 4. Light curves of variables in the field of Pal 2. They are most likely field stars, see § 5 for a discussion. The colour code is as in Figure 3. The colour figure can be viewed online.

that makes its classification very difficult; however, the star is likely a non-member.

6. THE OOSTERHOFF TYPE OF PAL 2

The average period of the member RRab star listed in Table 1 is 0.55 days which indicates that Pal 2 is of the Oo I type. We can further confirm this from the distributions of the RRab stars in the Amplitude-Period or Bailey diagram, shown in Figure 5. Given the dispersion of the light curves, the amplitude distribution is also scattered. However, it is clear that the RRab stars follow the expected sequence for unevolved stars typical of OoI clusters (Cacciari et al. 2005), in both the V and I bands. The upper sequence corresponds to evolved stars of the Oo II clusters (Kunder et al. 2013). Hence, Pal 2 is an Oo I type cluster. We note that the stars V16 and V18, whose nature is not clear due to their position in the RGB and short period (§ 5), do not follow the general trend, rather confirming that they are not field RR Lyrae stars. Alternatively, they may be binary stars. Further observations may be required to provide a proper classification.

7. CLUSTER DISTANCE AND METALLICITY FROM MEMBER RR LYRAE STARS

Although the scatter of all these faint cluster member stars may be large, we attempted an estimation of the mean distance and [Fe/H] via the Fourier light curve decomposition. This approach...
has been amply described in previous papers. Both the method details and the specific calibrations for \( M_V \) and [Fe/H] for RRab stars can be found in a recent paper by Arellano Ferro (2022).

We selected the RRab members with the best quality light curves and restricted the Fourier approach to this sample. These are the variables V2-V13 shown in Figure 3. The mean values for the distance modulus \((V - M_V)_0 = 17.18\) and [Fe/H]_{ZW} = \(-1.39 \pm 0.55\) were found. The corresponding distance is \(27.2 \pm 1.8\) kpc for a foreground reddening of \( E(B-V) = 0.93\) plus the differential values according to the reddening map of Bonatto & Chies-Santos (2020). The quoted errors are the standard deviation of the mean; they are a bit too large but given the faintness of the stars and their consequent photometric scatter, the results are in remarkably good agreement with independent determinations: \((V - M_V)_0 = 17.1 \pm 0.1\) and [Fe/H] = \(-1.3\) (Harris et al. 1997); Fe/H]_{ZW} = \(-1.68 \pm 0.04\) (Ferraro et al. 1999); or \(d = 27.2\) kpc and [Fe/H] = \(-1.42\) listed by Harris (1996) (2010 update).

8. SUMMARY

We have found and identified 32 variables in the field of the globular cluster Palomar 2. A membership analysis based on Gaia-DR3 proper motions and the positioning of the variables in the corresponding intrinsic CMD, demonstrates that at least 18 of these variables are cluster members. Most of the detected variables are of the RRab type but one RRc and at least one RGB were identified.

The mean cluster distance and metallicity, estimated from the Fourier light curve decomposition of 11 cluster member RRab stars with the best quality available data, lead to \(d = 27.2 \pm 1.8\) kpc and metallicity \(-1.39 \pm 0.55\), in reasonable agreement with the previous estimates. A detailed finding chart of all these variables is provided.

This project was partially supported by DGAPA-UNAM (Mexico) via grants IG100620. AAF is thankful to Mr. G.A. Garcia Pérez and Mr. G. Ríos Segura for computational help. The facilities at IAO and CREST are operated by the Indian Institute of Astrophysics, Bangalore, we are grateful for the observing time allocated and for the valuable help of the support staff.

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