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Detection of Variable Stars in the Galactic Globular Cluster M15

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Abstract

This study reports the discovery of 12 new variable stars in the globular cluster M15 using time series observations from 3.6 m DOT and 2 m class HCT. In total, 198 variable stars were detected in the cluster region, including both known and newly discovered variables. Proper motion data from Gaia EDR3 were used to determine the membership of the identified variable stars. The seven of the new variables are found to be probable members of the cluster. Based on variability characteristics and location in the CMD, two of them are likely RR Lyrae type variables. The majority of the known variables are found to be RR Lyrae type variables.

Keywords: globular cluster M15, variable stars, RR Lyare

1. Introduction

The study of variable stars provides important insights into the formation and evolution of stars, as well as the structure of our Galaxy. Globular cluster M15 is a dense and old globular cluster in our Galaxy, with an age of around 12.5 Gyr (VandenBerg et al., 2016). It is believed that M15 has undergone a core collapse, and has a compact core of ~ 0.14 arcmin (Harris, 2010). It lies at a distance of about at 10 kpc and has a radius of around 9 arcmin. Previous studies show that it contains several variable stars (more than 200), including RR Lyrae and SX Phoenicis variables (Bhardwaj et al., 2021). More than 150 RR Lyrae variables are found to be populated on the horizontal branch of the cluster (Clement et al., 2001). RR Lyrae variables play a crucial role as standard candles in measuring the distance to clusters due to their periodic variations. Moreover, these variables are of particular significance in studying the evolution of

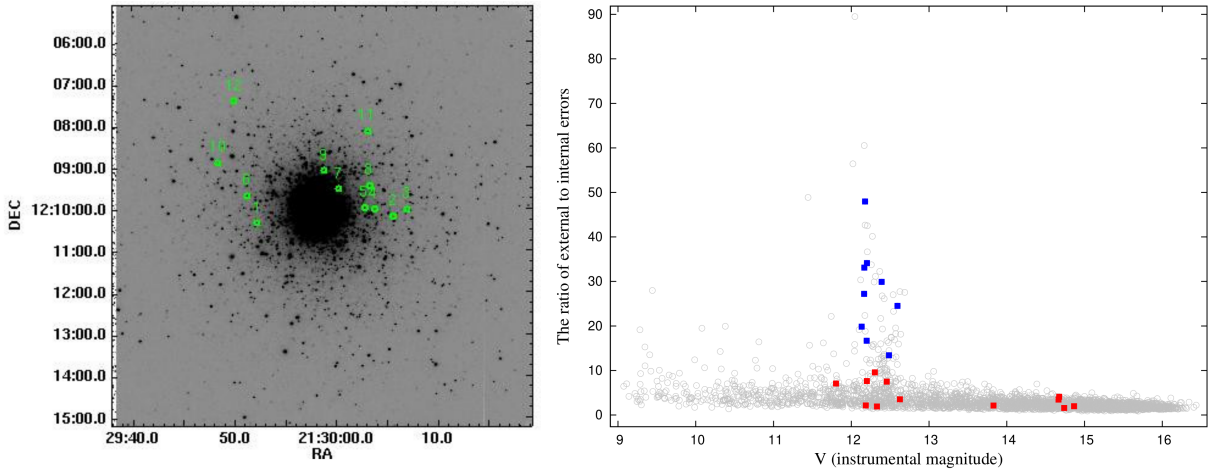

Figure 1: (*Left*) The chart of observed region in V band with M15 in center. The newly identified variables including one detected by Hoffman et al. (2021) are encircled. (*Right*) The ratio of external to internal errors as a function of instrumental magnitude in the V band. The red including one previously known variable and blue squares represent new and a few known variable stars, respectively.

low mass stars (see Sariya et al., 2014). Though, the discovery of various types of variables in globular clusters have been done up to now, RR Lyrae stars continue to dominate the variability populations in these globular clusters (for references see Lata et al., 2019). The time series observations of the M15 were carried out using 3.6 m Devasthal optical telescope (DOT) at the Aryabhatta Research Institute of Observational Sciences (ARIES), Devasthal campus, India for identification of variable stars in the core region of the cluster.

2. Observations and Data Reduction

We obtained 229 CCD images of M15 in the V band on October 10, 2020. We used a $4\,\mathrm{K} \times 4\,\mathrm{K}$ CCD imager mounted on the 3.6 m DOT at ARIES. Each image was taken with a 50 s exposure time. The photometric observations of the M15 globular cluster were also done with the Himalaya Faint Object Spectrograph and Camera (HFOSC) mounted on the 2 m Himalayan Chandra Telescope (HCT) in V and R bands from 27 to 29 August in 2010.

The CCD frames obtained in V band were cleaned using IRAF software which includes bias subtraction, flat fielding and cosmic ray removal, and instrumental magnitudes of stars were determined using the DAOPHOT package (Stetson, 1987). Both aperture and PSF photometry have been done, with PSF photometry being preferred for crowded regions. To align the different photometry files, the DAOMATCH and DAOMASTER (Stetson, 1992) routines were used to match the point sources and remove the effects of flux variation in different frames. Using the CCMAP and CCTRAN tasks available in IRAF, we have converted X and Y position of stars into equatorial co-ordinates. The left panel of Fig. 1 shows the observed image of the globular cluster M15 in V band from HCT.

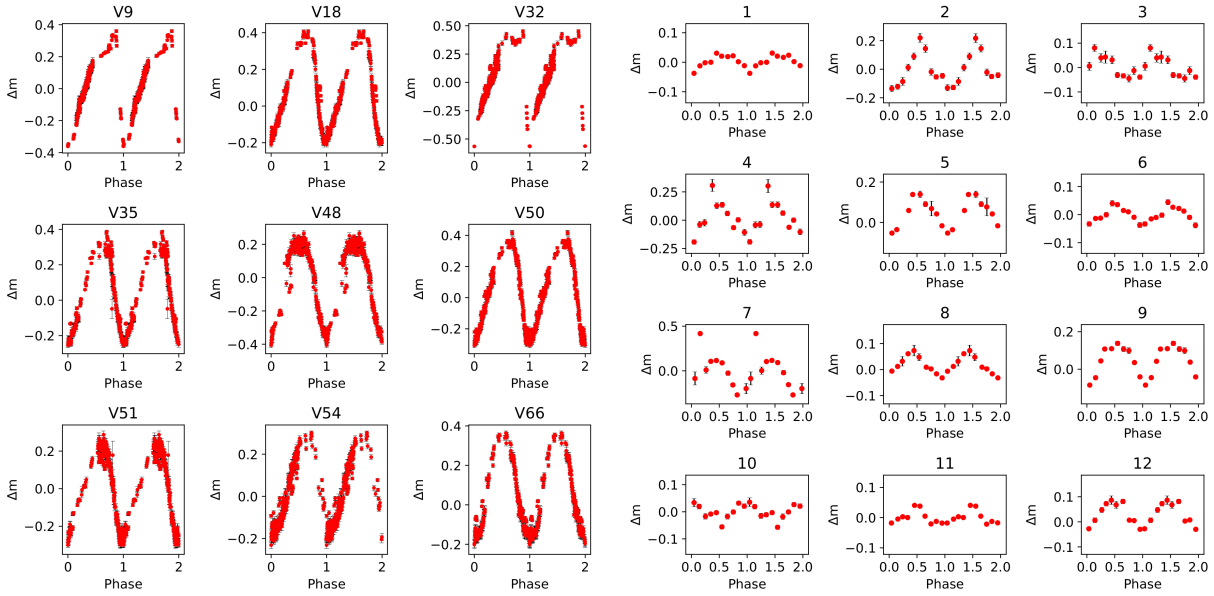

Figure 2: The phased light curves of known variables (*left*) and new variables (*right*) in V band where Δm represents the differential magnitude in the V band.

3. Results

3.1. Variable identification and period determination

To identify variable stars, a code written in python was used to display the light curves of all the cross matched stars in different CCD frames. The light curves were visually inspected, and stars showing periodic or regular brightness variation were identified as variables. In total, 198 variable stars were detected in the region containing M15. Among these, 13 variable stars are newly identified, and the remaining variables are previously known. Hoffman et al. (2021) detected 74 RR Lyrae stars, five Cepheid variables and 34 stars with uncertain classifications in the cluster M15. To compare our newly identified variable stars with Hoffman et al. (2021) ones, we performed a cross-match between present dataset and the data provided by Hoffman et al. (2021). We found one star that is common to both samples, and this star is identified as V106a by Hoffman et al. (2021). Therefore, the variability of this star has been confirmed by our study, which results the total number of newly detected variable stars to 12. The variable nature of stars is also confirmed by the ratio of magnitude scatter observed to that expected from individual standard errors as shown in the right panel of Fig. 1. Table 1 lists the newly identified variable stars.

To determine the most likely periods of the variable stars, we used the Lomb-Scargle (LS) periodogram (Lomb, 1976; Scargle, 1982), which is effective even if data are irregularly sampled. The derived periods have been used to fold the light curves of the variable stars, and the phased light curves were visually inspected to identify the probable period that produced the best folded light curve of the stars. The periods and amplitudes (in V band) of variable stars are given in Table 1. The phased light curves of both known (for a few stars as sample) and newly identified variable stars have been shown in Fig. 2. To represent the phased light curves of the

Table 1: Parameters of new variable stars.

ID	RA (deg)	DEC (deg)	Period (d)	Amplitude (mag)	pmRA (mas yr^{-1})	pmDEC (mas yr^{-1})	BP (mag)	RP (mag)	G (mag)	Prob.
1	322.467972	12.171972	0.169	0.069	-0.545 ± 0.036	-3.809 ± 0.031	15.811	14.934	15.586	0.93
2	322.523444	12.169639	0.195	0.343	-1.055 ± 0.129	-4.456 ± 0.102	17.975	17.046	17.813	0.92
3	322.529083	12.166722	0.109	0.143	-0.993 ± 0.164	-4.802 ± 0.136	18.199	17.307	18.299	0.00
4	322.515861	12.166444	0.241	0.440	-0.809 ± 0.093	-3.740 ± 0.102	17.557	16.549	17.426	0.93
5	322.511583	12.166056	0.564	0.222	-0.319 ± 0.043	-3.643 ± 0.036	15.871	15.379	15.867	0.94
6	322.463833	12.161056	0.167	0.086	-0.771 ± 0.028	-3.550 ± 0.026	15.513	14.393	15.197	0.93
7	322.501180	12.158526	0.351	0.573	—	—	—	—	—	—
8	322.513694	12.157250	0.362	0.101	-0.697 ± 0.042	-3.648 ± 0.036	16.192	15.087	15.830	0.93
9	322.495278	12.151083	0.391	0.209	—	—	—	—	—	—
10	322.451972	12.147833	0.057	0.082	-0.374 ± 0.165	-3.999 ± 0.137	18.401	17.497	18.119	0.00
11	322.513167	12.135556	0.218	0.071	-0.922 ± 0.041	-3.688 ± 0.028	16.060	14.953	15.633	0.93
12	322.458639	12.123167	0.579	0.127	—	—	—	—	—	—

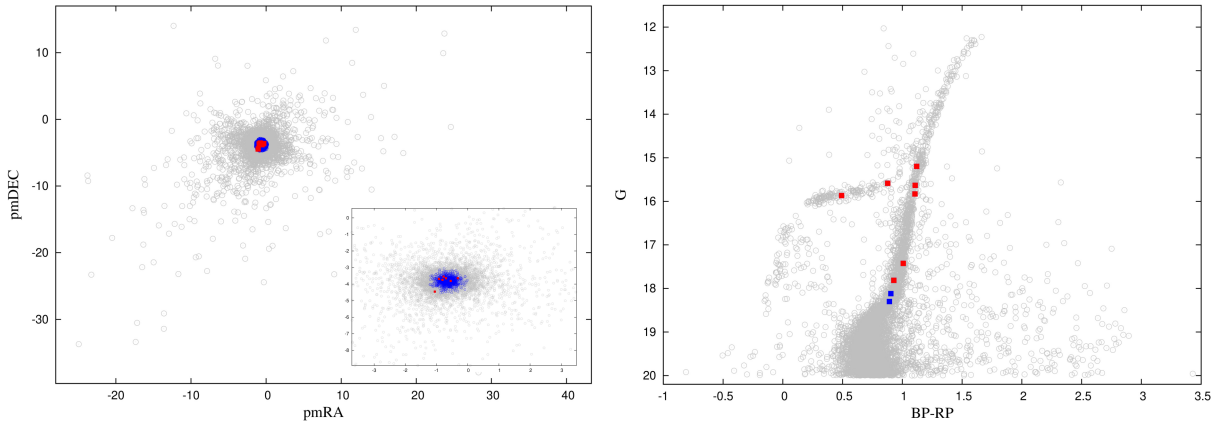

Figure 3: (*Left*) The proper motions for stars lying within cluster radius. The blue colour represents members of the cluster while reds are new member variables. An inset shows the zoomed in portion of the VPD. (*Right*) The G vs. $BP-RP$ CMD for stars lying within cluster radius. The squares represent newly detected variables with one previously known where red and blue squares represent probable cluster members and field star population, respectively.

12 newly identified variables with one previously known variable more effectively, we used a phase bin of 0.1.

3.2. Membership probabilities

The kinematic information of the stars is particularly important to know their association to the cluster. To obtain the membership probabilities of 12 new variables we used proper motions of stars provided by the European Space Agency's Gaia Early Data Release 3 (Gaia EDR3) (Gaia Collaboration et al., 2016, 2021). For this, we used Clusterix 2.0 which is an interactive, web-based tool (http://clusterix.cab.inta-csic.es/clusterix) that enables the determination of membership probabilities in star cluster based on proper motion values using a non-parametric approach (Balaguer-Núñez et al., 2020). This tool determines them empirically from the vector point diagram without any prior assumption about the profiles of the frequency functions. A proper motion cutoff of 10 mas yr^{-1} was applied, and the magnitude limit in the G band was set to 18 mag. The cluster radius was taken as 9 arcmin. In Table 1, the proper motion data and membership probability for nine variable stars are given. We cross-matched the equatorial coordinates of the 12 newly detected variable stars with those from Gaia EDR3, resulting in only nine stars in common. Out of nine variable stars, seven have membership probabilities greater than 90%, and these could be considered probable members of the cluster. The proper motions for stars lying within cluster radius (9 arcmin) are shown in the left panel of Fig. 3 where blue colour represents members of the cluster. The stars plotted with red colour are newly member variables.

3.3. Variability characteristics

In order to characterize the newly identified variable stars with one previously detected variable we have over plotted them in the G versus $BP-RP$ colour-magnitude diagram (CMD) as shown in the right panel of Fig. 3 with squares. We have taken G, BP, and RP data from the Gaia EDR3 catalogue. Only nine new variables have magnitudes in G, BP, and RP passband. In this plot, open circles (grey) represent stars within the cluster radius. Stars no 1 and no 5 are located on the horizontal branch in the CMD of the cluster where RR Lyraes are found. Their periods and shape of light curves also suggest them to be probable RR Lyrae candidates. One star numbered as 10 might be an SX Phe type variable from its period and shape of the light curve. More observations are required to confirm its variability nature. The remaining variables are lying on the red giant branch and these stars could be eclipsing type variables based on their variability characteristics. The most known variables are found to be RR Lyrae stars of RRab and RRc type. The periods of the previously known RR Lyrae stars are consistent with those reported in earlier studies (Clement et al., 2001). To maintain clarity, we did not plot the known variable stars in the present G versus $BP-RP$ CMD. These RR Lyrae stars are found to be populated with other stars on the horizontal branch of the cluster (see Fig. 9 of Bhardwaj et al., 2021).

4. Summary

This work presents the preliminary results for search of variable stars in the region of globular cluster M15. A total of 186 previously known and 12 newly identified variables have been detected in the cluster region. The membership status of the variable stars have been determined using the proper motion data, and seven new variables are identified as probable cluster members, of which two stars could be the probable RR Lyrae stars.

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Further Information

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Author contributions

All the authors have made the significant contributions in this work, which covers observations, data reduction, analysis, and critical review of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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