The period-luminosity relation of Mira variables in NGC 6388 and NGC 6441

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Abstract. We report a result of our near-infrared repeated observations of Mira variables in the globular clusters NGC 6388 and 6441. These two clusters are known as peculiar clusters with blue horizontal branch stars and RR Lyr variables which are unexpected for their relatively high metallicities. We derive their distance moduli by fitting the Mira variables in the period-luminosity relation. This is the first distance estimates, for these clusters, which is observationally obtained in an independent way from the horizontal branch stars. The obtained distances revealed that the absolute magnitudes of the peculiar RR Lyr variables are similar to the metal-poor ones of [Fe/H] = −2 dex. It is suggested that the constraint we found should be reproduced by any theories to explain the horizontal morphology of these peculiar clusters.

1. Introduction

The globular clusters NGC 6388 and 6441 have attracted many researchers for their peculiar populations of horizontal branch (HB) stars in this decade. In spite of their relatively high abundances ([Fe/H] ~ −0.6), they have extended blue HB stars and RR Lyr variables (Rich et al. 1997, Layden et al. 1999). Furthermore, the red HB slopes upward towards the blue. This feature is quite different from that of the usual HB of globular clusters, and discovered in these clusters for the first time. No canonical theory can reproduce this feature (Sweigart & Catelan 1998). It was discovered that there is (are) non-canonical effect(s) at work (e.g. helium enrichment or rotation), but no final conclusion has yet been reached.

It is important to place and see this interesting feature on the absolute magnitude scale. Different non-canonical process may have different effects on the luminosity. Horizontal branch stars and RR Lyr variables themselves are distance indicators which are most frequently used for globular clusters. However, it is unknown whether the traditional measure is applicable to the peculiar objects. In order to derive their absolute magnitudes, it is necessary to derive distances of the clusters in an independent way. Mira variable can be a good distance indicator especially for relatively metal-rich population (see Feast 2004, for the review). In this contribution, we will utilise Mira variables for the distance estimation, and discuss its impact on the peculiar HB.

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2. Observation and analysis

We are conducting a near-infrared survey by using the Infrared Survey Facility (IRSF) and the Simultaneous three-colour Infrared Imager for Unbiased Survey (SIRIUS) sited at SAAO, Sutherland, South Africa (see Matsunaga et al. 2006a, for some preliminary results). From the monitoring survey, started in the spring of 2002, we obtained an extensive dataset for Mira variables in globular clusters including NGC 6388 and 6441. The frequency of the observations for each cluster is about once a month or more during April–August every year. Many globular clusters have been observed more than 20 times in total. NGC 6388 and 6441 were observed 31 and 40 times, respectively, excluding some unused data with bad conditions (weather or seeing).

The analysis of Mira variables was conducted as follows. At first, 10 or 15 dithered images were combined into one scientific image by using the pipeline software for the standard data reduction (Nakajima, private communication). Photometry was executed by using the DoPHOT software, and a time series of the results were compared with a reference list obtained for the best image for each cluster. The magnitudes were standardised based on those of cluster giants listed in the 2 Micron All-sky Survey (2MASS) point source catalogue. The detail of the procedures was presented in Matsunaga et al. (2006b).

3. Result

3.1. Mira variables in NGC 6388 and 6441

We discovered one and four new Mira variables in NGC 6388 and 6441, respectively. They are named NGC 6388 V1 and NGC 6441 V151–V154 after the list of newly reported variables in Corwin et al. (2006). With all the known Mira variables, we obtained periods and mean magnitudes for five and nine objects in the two clusters. For most of them, such quantities are obtained for the first time. The periods were found with the phase dispersion minimization (PDM) method and the mean magnitudes were adopted by fitting sine curves to light curves. The data will appear in a future paper. The relation between the periods and the mean \(K_s\) magnitudes was plotted in Figure 1. NGC 6441 V151 was not plotted, but is much brighter than expected from the relation. We conclude that this star is not a member of the cluster. The slope of the linear relations overplotted was obtained from the relation of Mira variables in the Large Magellanic Cloud (LMC), as will be described below.

3.2. Distance and the absolute magnitude of horizontal branch

Now, we will derive the distance moduli of the clusters from the period-luminosity relation of the Mira variables. We use the relation of Mira variables in the LMC as a reference one. From the data published by Ita et al. (2004b), we extracted 139 oxygen-rich Mira variables in the LMC with the conditions, \(100 \leq P \leq 350\) (days) and \(J - K_s \leq 1.4\) (mag). Those with the long period \((P > 350)\) were excluded because they are considered to be hot bottom burning stars which are brighter than the period-luminosity relation (Whitelock et al. 2003). The colour condition is to take away carbon-rich Mira variables and those with thick
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Figure 1. Period-luminosity relation of Mira variables in NGC 6388 and 6441.

circumstellar shell. The derived relation for the oxygen-rich objects is,

\[ M_{K_s} = -3.60 \log P + 1.36, \]  

with the LMC distance modulus of 18.50 mag assumed.

Now, we compare the above relation with the relations in Figure 1. After the reddening correction for each cluster, the distance modulus was obtained and listed in Table 1. The reddening values \( E_{B-V} \) were adopted from the catalogue by Harris (1996), and we used the extinction law of \( A_{K_s}/E_{B-V} = 0.365 \) and \( R_V = 3.1 \). We also derived distance moduli for 47 Tuc and NGC 6637, which have similar metallicities to NGC 6388 and 6441. Although the period-luminosity relation may have a metallicity dependence as discussed by Ita et al. (2004a), we can ignore it because the four clusters have similar [Fe/H] values. The listed error sizes include random scatters around the period-luminosity relation and the errors of the reddening which are assumed to be 20 % of \( E_{B-V} \). There is a systematic error from the assumed distance modulus of the LMC, but it has no effect on the relative difference between the four clusters.

By using the obtained distance moduli, we plotted their optical colour-magnitude diagrams (CMDs) on the absolute scale (Figure 2). The optical data were from Piotto et al. (2002). We derived the absolute magnitudes red HB stars, \( M_V(\text{RHB}) \), and those of RR Lyr variables, \( M_V(\text{RR}) \). The former was defined as a peak of the distribution in the \((B-V, V)\) diagram. The apparent mean magnitudes of RR Lyr variables were taken from Pritzl et al. (2002) and Pritzl et al. (2003). There is one RR Lyr variable found in 47 Tuc, and we adopted its magnitudes from Carney et al. (1993). There are no RR Lyr variables found in NGC 6637. The results, listed in Table 2, were plotted as horizontal lines; filled lines for \( M_V(\text{RR}) \) and dashed lines for \( M_V(\text{RHB}) \). The sizes of error in these values are also calculated as the combinations of the random scatter and the error of the reddening. The contribution of the reddening error is large in these optical values. We found that \( M_V(\text{RR}) \) and \( M_V(\text{RHB}) \), respectively, are common between the four clusters, and \( M_V(\text{RR}) \) is brighter than \( M_V(\text{RHB}) \) by 0.3–0.4 mag.

4. Discussion

In the previous section, we found that RR Lyr variables are brighter than the red part of the HB in 47 Tuc, NGC 6388 and 6441. Traditionally, it is considered
that metal-rich RR Lyr variables are fainter than metal-poor ones (Caputo et al. 2000). In addition, Clementini et al. (2005) conducted spectroscopic measurements of the metallicities of RR Lyr variables in NGC 6441, and confirmed that the variables are as metal-rich as other cluster stars. However, $M_V(RR)$ listed in Table 1 corresponds to the magnitudes of RR Lyr variables with $[\text{Fe/H}] \sim -2$ dex. It is known that the periods of RR Lyr variables in NGC 6388 and 6441 are longer than what expected for relatively metal-rich RR Lyr variables (see the discussions in Pritzl et al. 2003). This feature implies that they are overluminous if based on traditional pulsational theories, and our result confirms that they are actually as bright as metal-poor RR Lyr variables. The one RR Lyr variable, V9, in 47 Tuc is considered to be a physical member of the cluster (Carney et al. 1993), and it is also brighter than the red part of the HB. Its nature is quite uncertain. It may be an object which has already evolved from the zero-age HB. Although there has been no investigations which connect this object to the peculiar RR Lyr variables in NGC 6388 and 6441, it is interesting to study this anomalous variable in the typical metal-rich cluster 47 Tuc.

Recently, Catelan et al. (2006) reported a remarkable CMD of NGC 6388 in which the turn-off of the main sequence is clearly visible. They showed that the CMD agrees well with that of 47 Tuc in many features, such as the positions

![Figure 2. Optical colour-magnitude diagrams for four clusters. Data from Piotto et al. (2002) were shifted to the absolute scale with the distance moduli obtained in this contribution. RR Lyr variables are plotted as crosses.](image)

Table 1. Estimates of the distance moduli (DM) and absolute magnitudes of the horizontal branch features. RHB and RR indicate red horizontal branch and RR Lyr variables. See the text for the definitions.

| Cluster     | $E_{B-V}$ | $N_{\text{Mira}}$ | DM    | $M_V$(RHB) | $M_V$(RR) |
|-------------|-----------|-------------------|-------|------------|-----------|
| 47 Tuc      | 0.04      | 5                 | 13.15±0.01 | 0.79±0.03  | 0.46±0.03  |
| NGC 6388    | 0.37      | 5                 | 15.44±0.08 | 0.66±0.24  | 0.26±0.24  |
| NGC 6441    | 0.47      | 8                 | 15.65±0.05 | 0.71±0.29  | 0.43±0.29  |
| NGC 6637    | 0.16      | 2                 | 14.71±0.06 | 0.77±0.12  | —         |
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and shapes of the turn-off, RGB and etc, except the the blue HB. They claimed that the peculiar blue HB and RR Lyr variables are overluminous, and presented its interesting implication on their natures. However, they compared the CMDs of both clusters after they added the shift so as to register the red parts of the HB of the two clusters in the same position on the CMDs. On the other hand, our result was obtained in an independent way with Mira variables to shift the CMDs onto the absolute magnitude scale.

5. Summary

We presented the result of our near-infrared observations for Mira variables in NGC 6388 and 6441, which have peculiar HB morphology. We obtained the periods and mean magnitudes for five and nine Mira variables in the clusters, respectively, although one in NGC 6441 is too bright to be a member of the cluster. The data for the other objects were well fitted by the period-luminosity relation in each cluster. The distances of both clusters were then derived by adopting the relation of Mira variables in the LMC as the reference relation at the distance modulus of 18.5 mag. Using the derived distances, we placed the HST optical data on the CMD on the absolute scale, and found that their red HB stars have similar luminosity with those of normal metal-rich clusters as 47 Tuc while RR Lyr variables and blue HB stars are overluminous.

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