A Carbon-rich Mira variable in a globular cluster: A stellar merger

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ABSTRACT
The membership of Matsunaga’s variable 1, a carbon-rich, mass-losing, Mira variable, in the globular cluster Lynga 7 is discussed on the basis of radial velocities. We conclude that it is a member, the first known C-Mira in a globular cluster. Since such a variable is expected to have an age of \(~ \! 1 \! \! - \! 2\) Gyr and an initial mass of \(~ \! 1.5\) solar masses, we conclude that this star must be the product of a stellar merger.

Key words: stars:AGB and post-AGB - globular clusters:individual; Lynga 7 - stars; variable - stars; carbon.

1 INTRODUCTION
In the course of an extensive infrared survey of Galactic globular clusters for variable stars, Matsunaga (2006) discovered a long period Mira variable near the centre of the globular cluster Lynga 7. The variable has a period of 551 days, a large infrared amplitude ($\Delta K = 1.22$ mag) and very red colours (mean $(J-K) = 4.1$ mag) indicative of mass-loss and a circumstellar dust shell. Sloan et al. (2010) obtained SPITZER mid-infrared spectra of the variable showing it to be a carbon star with strong circumstellar dust emission from SiC and MgS particles as well as absorption from gaseous acetylene. They estimate a mass loss of $2.5 \times 10^{-7}$ solar masses per year. A few carbon rich objects are known in globular clusters, but these have generally been interpreted as cluster examples of the CH stars in the Galactic halo field. These latter stars are believed to be mass exchange binaries. However no carbon Mira has previously been detected in a globular cluster and Matsunaga’s variable, V1, raises a number of problems related both to stellar evolution and to the nature of Mira variables.

In the present paper we derive the radial velocity of V1 and discuss its cluster membership. We then discuss the nature of V1 and its relation to the cluster population.

2 OBSERVATIONS
A medium dispersion (resolution 2.4Å) spectrum of V1 Lynga 7 was obtained on 2012 May 11 (HJD 2456058.6) with the RSS spectrograph on the SALT telescope at SAAO, Sutherland. The spectral region covered was 6000 to 7100Å. Spectra of the planetary nebula Hen 2-146 and the carbon Mira V650 CrA (P = 332 days) were also obtained with the same equipment and settings.

Fig. 1 shows the spectrum of V1 and that of V650 CrA. The spectra match each other well. In both cases the spectrum is dominated by molecules of carbon compounds (particularly CN) and is typical of a carbon-rich Mira (see for instance the atlas of Barnbaum, Stone & Keenan (1996)). In addition V1 shows strong H$\alpha$ emission. This is characteristic of C-Miras at certain phases.

Using the comparison arc we obtain for the planetary nebula Hen 2-146 a radial velocity of $56 \pm 4$ km s$^{-1}$ in good agreement with the catalogue value of $61 \pm 4$ km s$^{-1}$ (Durand at al. 1998). Measured against the comparison arc the H$\alpha$ emission in V1 gives $17$ km s$^{-1}$ with an estimated uncertainty of $\sim 2$ km s$^{-1}$. The night sky lines in this spectrum yield $6 \pm 2$ km s$^{-1}$. Thus we adopt the 11 km s$^{-1}$ as our best estimate of the velocity from the H$\alpha$ emission. This emission originates in shock waves in rising material in the stellar atmosphere. It therefore has, predominately, a negative velocity with respect to the true radial velocity of the star. The best measure (if available) of a C-Mira velocity is obtained from CO lines in the millimetre region, which arise well above the photosphere (see, e.g., Barnbaum 1992 and references therein). Data discussed in Menzies et al. (2006) show that on average Vel(CO(mm)) = Vel(Emission) + 16 km s$^{-1}$, Thus our best estimate of the stellar velocity is 27 km s$^{-1}$. The uncertainty in this figure is not easily determined, but is likely to be 5 km s$^{-1}$ or more.

A radial velocity was obtained for V1 by cross-
The position of V1 given by Matsunaga (2006) is $16^h11^m02.0 - 55^\circ 19'14''$ \((J2000)\) together with the cluster centre given by Goldsbury et al. (2010) leads to a distance of the variable from the centre of $\Delta(\text{RA}) = -13.5$ and $\Delta(\text{Dec}) = -10$ arcsecs well within the core of the cluster (core radius 54 arcsecs, half-light radius 72 arcsecs (Harris 1996)).

Radial velocities of 9 cluster stars were measured by Saviane et al. (2012). They find a mean heliocentric velocity of $22 \pm 3$ km $s^{-1}$. Earlier Tavarez & Friel (1995) obtained $6 \pm 13$ km $s^{-1}$ from 4 stars. The high standard error in this case being due to an uncertainty in night to night zero points. In section 2 we obtained a radial velocity for V1 from H$\alpha$ emission $27 \pm 5$ km $s^{-1}$ with a somewhat less certain value of $36 \pm 10$ km $s^{-1}$ from a match to V650 CrA. Given the uncertainties we consider the agreement with the cluster velocity to be satisfactory.

In addition to this, the velocity of V1 differs from that expected for a field C-rich Mira of its period. Long period C-Miras in the solar vicinity are disc objects showing evidence of differential Galactic rotation. The velocity dispersions are moderate, $22 \pm 4$ km $s^{-1}$ in the Galactic radial direction and $18 \pm 3$ km $s^{-1}$ in the direction of Galactic rotation, at the relevant period. (Feast et al. 2006). These dispersions include observational scatter and may be slightly over-estimates. Assuming a flat rotation curve ($\Theta = 220$ km s$^{-1}$ and $R_0 = 8.0$ kpc and with the local solar motion from Feast & Whitelock (1997), the predicted radial velocity for V1 at the distance predicted by a bolometric period-luminosity relation (see section 4) is $-81$ km $s^{-1}$, quite different from the value observed. Also for a member of a disc population with a relatively small velocity dispersion V1 is quite far from the Galactic plane at its predicted distance (445 pc).

3 CLUSTER MEMBERSHIP OF V1

The position of V1 given by Matsunaga (2006) is $16^h11^m02.0 - 55^\circ 19'14''$ \((J2000)\) together with the cluster centre given by Goldsbury et al. (2010) leads to a distance of the variable from the centre of $\Delta(\text{RA}) = -13.5$ and $\Delta(\text{Dec}) = -10$ arcsecs well within the core of the cluster (core radius 54 arcsecs, half-light radius 72 arcsecs (Harris 1996)).

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4 DISCUSSION

Saviane et al.(2012) determined a metallicity for Lynga 7 of [Fe/H] = $-0.57 \pm 0.15$ on the scale of Carretta (2009) and Sarajedini et al. (2007) show that an HST colour-magnitude diagram is well fitted by that of 47 Tuc ([Fe/H] = $-0.76$). Lynga 7 has been claimed to be among the oldest globulars (Marín-Franch et al. 2009). Sarajedini et al. estimate $(m - M)_o = 14.55$ and $E(B-V) = 0.78$ for Lynga 7. This is based on a fit to the 47 Tuc c-m diagram and adopting 13.40 and 0.055 for the latter. There have been some differences in the distance estimates for 47 Tuc (see Gratton et al. 2003) and the uncertainty in the modulus of Lynga 7 is probably not less than $\sim 0.1$ mag.

For V1, Matsunaga obtained mean magnitudes of $J = 11.35$, $H = 9.08$ and $K_s = 7.25$ \((J - K_s = 4.10)\) on the IRSF system which is close to the 2MASS system (Kato et al. 2007). Converted to the SAAO system using the transformations given by Carpenter (2001 and web update) and applying a reddening equivalent to $E(B-V) = 0.78$ on the Cardelli system (Cardelli et al. 1989) we obtain $m_{bol} = 9.60$ on the $BC_K - (J - K)$ relation of Whitelock et al. (2006). A main uncertainty is probably the conversion from IRSF (assumed same as 2MASS) to SAAO. Thus with the Sarajedini distance modulus the bolometric absolute magnitude of V1 is $-5.0$. The value predicted from the the period-luminosity \((M_{bol})\) relation of Whitelock et al.(2009) is $-5.2$. This relation is based on LMC C-Miras with bolometric corrections calculated in the same way as for V1 and adopting a modulus of 18.5 for the LMC. Taking into account the various uncertainties including the intrinsic scatter in the period-luminosity relation, the observed and predicted values are in satisfactory agreement. Note that V1 is 0.9 mag fainter at $K$ than predicted by a period-luminosity relation in $K$ (Whiteo et al. 2008), confirming that the star is surrounded by an obscuring dust shell.

Galactic kinematics (Feast et al. 2006) and, particularly, the presence of mass-losing carbon Miras with periods $\sim$ 500 days in intermediate age (1-2 Gyr) clusters in the Magellanic Clouds \((e.g.,\) Nishida et al. 2000) strongly suggests that the initial mass of a C-Mira such as V1 was about 1.5 solar masses. V1 also matches properties of these cluster variables.
well in absolute magnitude and colours. On the other hand, Padova isochrones (Marigo et al. 2008, Girardi et al. 2010 and website) for 10-13Gyr globular clusters indicated that the initial mass of their evolved stars is about 0.8 solar masses.

Since the discovery of a carbon-rich star (a “CH star”) in ω Cen by Harding (1962) several such stars have been discovered. These are taken to be examples of mass exchange binaries of which many are known in the general halo field. In such cases the amount of mass exchanged is likely to have been relatively limited and sufficient only to pollute the stellar atmosphere. Sloan et al. (2010) suggest that V1 could be a CH type object. However, with a predicted initial mass of ∼ 1.5 solar masses this is not possible. The formation of a star of this mass in Lynga 7 requires the merger of two stars near (or beyond) the main sequence turn of point of the cluster.

Sharina et al. (2012) have found a carbon star member in the globular cluster NGC 6426. It has quite strong molecular bands but is relatively blue in JHK. Nothing is known about its variability. The authors discuss whether it is a mass exchange binary or a merger and are not able to come to a certain conclusion (since the mass is not known). A somewhat similar carbon rich star was found in the globular cluster NGC6405 (M15) by Coté et al. (1997), which they consider to be a typical CH star, i.e. a binary with a white dwarf secondary which earlier donated mass to the observed star.

The nature of blue stragglers in the c-m of globular clusters has been much discussed since they were first identified by Sandage (1953). It now seems that there are two types of blue stragglers, mass exchange binaries and stellar mergers (see Ferraro et al. 2009 and references therein). An initial discussion of the evolution of those blue stragglers which are merged stars has been given by Sills et al. (2009). Further theoretical work might allow one to determine whether the properties of V1 require that the merger components be near the main sequence or whether mergers of giant branch stars (whose internal chemical composition has been changed by evolution, e.g. helium enrichment) would also result in a typical long period C-Mira. It would be interesting to know whether there are blue stragglers in Lynga 7. However, radial velocities or proper motions are required for this (Milone et al. 2012). In any case objects like V1 must be very rare since their life time as mass-losing AGB variables is quite short.

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5 CONCLUSIONS
The radial velocity of Matsunaga’s variable V1 is consistent with membership of the globular cluster Lynga 7. Its absolute bolometric magnitude and colours are typical for a long period mass-losing carbon-rich Mira variable. Since such variables have initial masses of ∼ 1.5 solar masses and ages of ∼ 1.5 − 2.0Gyr, we propose that V1 is the evolutionary product of a stellar merger in the cluster ∼ 1.5Gyr ago.

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