The Mass-to-Light Ratios of Galactic Globular Clusters

J. M. Diederik Kruijssen\textsuperscript{1,2} and Steffen Mieske\textsuperscript{3}
\textsuperscript{1}Astronomical Institute, Utrecht University, PO Box 80000, 3508 TA Utrecht, The Netherlands; kruijssen@astro.uu.nl
\textsuperscript{2}Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands
\textsuperscript{3}European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Chile

Abstract. The observed mass-to-light ($M/L$) ratios of globular clusters (GCs) are on average $\sim 20\%$ lower than expected from Simple Stellar Population (SSP) models, which only account for the effects of stellar evolution. We study the $M/L$ ratio evolution of a sample of 24 Galactic GCs using parameterised cluster models. The dynamical evolution of GCs is included by accounting for their dissolution and by using a detailed description of the evolution of the stellar mass function. The ejection of low-mass stars leads to a decrease of $M/L$, which is found to explain the discrepancy between the observations and SSP models.

1 Introduction

Galaxy mergers are thought to have been the formation sites of globular cluster systems (GCSs). As such, globular clusters (GCs) can be used as tracers for studying the early evolution of galaxies and any mergers these galaxies may have experienced. To relate the GCS of a galaxy to its formation history, it is essential to obtain a good consensus on the present masses of the GCs. For obtaining these, (constant) mass-to-light ($M/L$) ratios are commonly used (Fall & Zhang 2001; Jordán et al. 2007; McLaughlin & Fall 2008). However, the observed dynamical $M/L$ ratios of GCs in several galaxies are found to be $\sim 20\%$ lower than the values expected from Simple Stellar Population (SSP) models (Mandushev et al. 1991; McLaughlin & van der Marel 2005; Rejkuba et al. 2007). This complicates the interpretation of GC masses, as it first needs to be understood why their $M/L$ ratios deviate from those predicted by SSP models.\footnote{Interestingly, ultra-compact dwarf galaxies (UCDs), which have been proposed to represent a continuation of the GC mass range to higher masses, have $M/L$ ratios that are $\sim 25\%$ higher than those predicted by SSP models (Rejkuba et al. 2007; Mieske et al. 2008). We separate this discrepancy from the one between GCs and SSP models and only consider GCs.}

It has been proposed that the $M/L$ ratio difference is due to the dynamical evolution of GCs (Kruijssen 2008; Kruijssen & Lamers 2008). The preferential ejection of low-mass, high-$M/L$ stars from dissolving star clusters changes the shape of the stellar mass function (MF) within a cluster (Vesperini & Heggie'}
causing the luminosity to be only marginally affected while the mass decreases. As such, dissolution decreases the $M/L$ ratio with respect to the expected evolution from SSP models, in which it is assumed that the shape of the stellar MF does not vary.

In Kruijssen & Mieske (2009), the hypothesis of low-mass star depletion as an explanation for the low $M/L$ ratios of GCs was tested by considering the sample of 24 Galactic GCs for which the orbits (Dinescu et al. 1999) and observed dynamical $M/L$ ratios (McLaughlin & van der Marel 2005) are known. There, we derived the dissolution timescales from the individual cluster orbits and computed the resulting $M/L$ evolution for the GCs in the sample. It was found that low-mass star depletion can indeed account for the $\sim 20\%$ gap between the observations and SSP models. As a first-order approximation, low-mass star depletion was included by increasing the lower stellar mass limit in the cluster, which was tuned to $N$-body simulations in order to give reliable results. In reality, the stellar MF evolves more gradually. This has been included in new, physical models of the evolution of the stellar MF in dissolving star clusters (Kruijssen 2009). The aim of the present paper is to revisit the calculations of Kruijssen & Mieske (2009) with these new models and to verify whether their conclusions still hold.

### 2 Star cluster evolution and mass-to-light ratio

We use the parameterised cluster model SPACE (Kruijssen & Lamers 2008; Kruijssen 2009), which incorporates the effects of stellar evolution, stellar remnant production, dynamical dissolution and energy equipartition. The dissolution timescale due to evaporation (cf. Baumgardt & Makino 2003) and tidal shocks (cf. Dinescu et al. 1999) is determined for each of the 24 GCs in our sample by considering their individual orbits (Kruijssen & Mieske 2009) and is subsequently converted to a mass loss rate (Lamers et al. 2005).

The evolution of the stellar MF is computed by considering the ejection rate as a function of stellar mass (Kruijssen 2009). The adopted method accounts for mass segregation and dissolution in a tidal field by using the timescale on which energy equipartition is reached for different stellar masses and by comparing the stellar velocities with the escape velocity. The photometry is computed by integrating the MF over the new Padova isochrones (Marigo et al. 2008).

### 3 Comparison to observations

The $V$-band $M/L$ ratios from SSP models are compared to the observed values in the left-hand panel of Fig. 1. In the right-hand panel, the modeled $V$-band $M/L$ ratios for the 24 GCs in our sample are compared to the observations. The improvement with respect to the left-hand panel is considerable, but there remains a number of GCs with observed $M/L$ ratios that are lower than the modeled ones. This was explained by Kruijssen & Mieske (2009), who reasoned that some of the observed $M/L$ ratios from McLaughlin & van der Marel (2005) are likely biased due to their use of isotropic single-mass King models to determine the $M/L$ ratios. This method leads to a tendency towards the central $M/L$ ratio rather than the global one for GCs with evolved internal structure.
The Mass-to-Light Ratios of Galactic Globular Clusters

Figure 1. Comparison of $V$-band $M/L$ ratios that are predicted by SSP models (left) with observed $M/L_V$ ratios, and of our modeled $M/L_V$ ratios (right) with the observed values. Error bars denote 1σ standard errors, with diamonds marking GCs for which theory and observation are in 1σ agreement, and dots representing the remaining deviant GCs.

In total, our new models explain the $M/L$ ratios of 17 out of 24 GCs within the 1σ error margins. This is a substantial development with respect to Kruijssen & Mieske (2009), where half of the GCs was explained. The use of the new MF models and of the new Padova isochrones contribute equally to this improvement (three GCs each). The average fraction of the observed $M/L_V$ ratio with respect to the value predicted by SSP models is $0.81^{+0.06}_{-0.08}$, while for our modeled fraction this is $0.79 \pm 0.01$. These values are in excellent agreement. An independent check of our models is provided by comparing the modeled stellar MF slopes to those observed by De Marchi et al. (2007). This is shown in Fig. 2 and confirms the general validity of our models, despite the scatter and large error bars.

4 Discussion

Low-mass star depletion in dissolving GCs explains the ~20% discrepancy between the observed $M/L$ ratios and those predicted by SSP models. The new cluster models (Kruijssen 2009), in which we account for the changing slope of the stellar MF rather than shifting the lower stellar mass limit, show that the results from Kruijssen & Mieske (2009) also hold when more detailed models are applied, and improve the agreement between theory and observations.

Nonetheless, care should be taken when using observed dynamical $M/L$ ratios that neglect a stellar mass spectrum or the variability of $M/L$ from the centre to the outskirts of a cluster. These cannot be interpreted as global $M/L$ ratios if the $M/L$ too strongly varies of radius. Considering the central role GCs play in (extra)galactic astronomy, it essential to obtain an accurate census of their dynamical masses. This would improve the observed globular cluster mass
Figure 2. Observed stellar MF slope $\alpha_{\text{obs}}$ for the stellar mass range $0.3 < m/M_\odot < 0.8$ versus the modeled mean slope in that range $\alpha_{\text{pred}}$. Error bars are 1σ standard errors, mainly caused by the uncertainty in the GC mass.

function \cite{Kruijssen2009}, which can then be more accurately used to trace and interpret the formation history of galaxies.

Acknowledgments. JMDK thanks Henny Lamers for advice, and is grateful to East Tennessee State University for hosting an excellent conference and for financially supporting attendance. The Leids Kerkhoven-Bosscha Fonds is acknowledged for supporting attendance to the conference. JMDK is supported by a TopTalent fellowship from the Netherlands Organisation for Scientific Research (NWO), grant number 021.001.038.

References

Baumgardt, H. & Makino, J. 2003, MNRAS, 340, 227
De Marchi, G., Paresce, F., & Pulone, L. 2007, ApJ, 656, L65
Dinescu, D. I., Girard, T. M., & van Altena, W. F. 1999, AJ, 117, 1792
Fall, S. M., & Zhang, Q. 2001, ApJ, 561, 751
Jordán, A., McLaughlin, D. E., Côté, P., Ferrarese, L., Peng, E. W., Mei, S., Villegas, D., Merritt, D., Tonry, J. L., & West, M. J. 2007, ApJS, 171, 101
Kruijssen, J. M. D. 2008, A&A, 486, L21
Kruijssen, J. M. D., & Lamers, H. J. G. L. M. 2008, A&A, 490, 151
Kruijssen, J. M. D., & Mieske, S. 2009, A&A, 500, 785
Kruijssen, J. M. D., & Portegies Zwart, S. F. 2009, ApJ, 698, L158
Kruijssen, J. M. D. 2009, A&A, accepted, \url{arXiv:0910.4579}
Lamers, H. J. G. L. M., Gieles, M., Bastian, N., Baumgardt, H., Kharchenko, N. V., & Portegies Zwart, S. 2005, A&A, 441, 117
Mandushev, G., Staneva, A., & Spasova, N. 1991, A&A, 252, 94
Marigo, P., Girardi, L., Bressan, A., et al. 2008, A&A, 482, 883
McLaughlin, D. E. & van der Marel, R. P. 2005, ApJS, 161, 304
McLaughlin, D. E., & Fall, S. M. 2008, ApJ, 679, 1272
Mieske, S., Hilker, M., Jordán, A., et al. 2008, A&A, 487, 921
Rejkuba, M., Dubath, P., Minniti, D., & Meylan, G. 2007, A&A, 469, 147
Vesperini, E. & Heggie, D. C. 1997, MNRAS, 289, 898