The Globular Cluster System of the Canis Major Dwarf Galaxy

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ABSTRACT

Prompted by the discovery of the accreted Canis Major dwarf galaxy and its associated globular cluster (GC) system (Martin et al.), we investigate the contribution of accreted GCs to the Galactic system. The Canis Major GCs, and those associated with the Sagittarius dwarf galaxy, exhibit a range of galactocentric radii, prograde and retrograde motions, and horizontal branch morphologies, indicating that such properties are of limited use in identifying accreted GCs. By contrast, we find that the age-metallicity relation (AMR) of these dwarf galaxies is distinct from that of the main Galactic GC distribution at intermediate-to-high metallicities ([Fe/H] \gtrsim -1.3). The accretion of GCs with a distinct AMR would explain much of the apparent age spread in the Galactic GC system. The Canis Major and Sagittarius AMRs are similar to those of other Local Group dwarf galaxies and are consistent with a simple closed-box chemical enrichment model – a further indication that these GCs formed outside of the Milky Way. The Canis Major GCs all have smaller-than-average sizes for their galactocentric distances, lending further support to their origin outside of the Milky Way. Our findings suggest that accretion of similar mass dwarfs does not appear to have played a major role in building the stellar mass of the thick disk or bulge of the Milky Way.

Subject headings: globular clusters: general – galaxies: individual (Canis Major dwarf) – galaxies: star clusters

1. Introduction

The seminal paper of Searle & Zinn (1978) argued that the formation of the Milky Way galaxy was clumpy and rather chaotic. Furthermore, they suggested that some Galactic globular clusters
(GCs) may not have formed in situ but rather in proto-galactic fragments or dwarf galaxies that were later accreted. Several workers have attempted to identify candidates for these accreted GCs. Methods have included the retrograde motion of some metal-poor GCs (Rodgers & Paltoglou 1984), the variation of horizontal branch (HB) morphology with metallicity in the outer halo (Zinn 1993), the Oosterhoff class (van den Bergh 1993), the size-perigalactic distance relation (van den Bergh 1995) and associations in phase-space (Lynden-Bell & Lynden-Bell 1995).

This subject was given impetus with the discovery of the accreted Sagittarius (Sgr) dwarf galaxy and its system of globular clusters (Ibata, Gilmore & Irwin 1995). It has four clearly identified GCs (Terzan 7, Terzan 8, Arp 2 and M54), with M54 as a prime candidate for the nucleus of the disrupted dwarf (Layden & Sarajedini 2000). Comparing the phase-space distribution of GCs with the expected orbital path of the Sgr dwarf, Bellazzini et al. (2003a) confirmed the status of these four GCs and identified a number of other possible GCs. The closest two GCs to the orbital path are Pal 12 and NGC 4147. Bellazzini et al. (2003b) found evidence for Sgr dwarf ‘tidal debris’ (i.e. stripped stars) around these GCs further supporting their association with the Sgr galaxy. For the third closest GC, Pal 5, Odenkirchen et al. (2003) concluded that it was not part of the Sgr dwarf as it is on a different orbital plane. Thus, we have a sample of six GCs which can be confidently associated with the Sgr dwarf. For a magnitude of \( M_V = -13.8 \), this corresponds to a specific frequency of \( S_N = 18 \), comparable to that of Fornax dwarf (\( S_N = 29 \); Forbes et al. 2000), the highest \( S_N \) galaxy in the Local Group.

Recently, Martin et al. (2003) presented evidence for a second disrupted dwarf galaxy in the Milky Way (Martin et al. 2003). The ‘Monoceros Ring’, discovered earlier by Newberg et al. (2002), is now thought to be the tidal stream of this disrupted dwarf (whose nucleus lies in the direction of Canis Major). Crane et al. (2003) and Frinchaboy et al. (2004) compared the phase-space distribution of Galactic clusters with M giant stars in the Monoceros ring. Assuming a typical thick disk velocity dispersion, they identified five GCs candidates of the disrupted dwarf. They are NGC 2298, NGC 2808, NGC 5286, Pal 1 and BH 176 respectively.

In the Canis Major discovery paper, Martin et al. (2003) included an N-body simulation of the dwarf’s orbit over the last 2 Gyrs. They simulated both a prograde and retrograde orbit. Although the prograde orbit is favoured, the retrograde orbit could not be ruled out. Further observational constraints and a non-static Galactic potential in the model should help to confirm which orbit is correct. Several GCs were found to have phase-space distributions in common with both models, which led Martin et al. (2003) to conclude they were associated with the Canis Major dwarf. They are: NGC 1851, NGC 1904, NGC 2298 and NGC 2808. For an assumed magnitude similar to the Sgr dwarf (Martin et al. 2003), the four GCs translate into a specific frequency of \( S_N = 12 \). In a follow-up paper, Bellazzini et al. (2003c) argued that the spatial position and stellar populations of the old open clusters AM-2 and Tom 2 imply that they too are associated with the Canis Major dwarf.

Here we derive an updated age-metallicity relation for the Sgr dwarf galaxy and compare it to
the Canis Major and Monoceros ring cluster systems. We show that the Canis Major GCs reveal well-defined age-metallicity and size-galactocentric distance relations. Finally, we briefly discuss the possible thick disk/bulge association of the Canis Major GCs and assess the overall importance of accretion in building the stellar mass of the Milky Way.

2. The Data

In Table 1 we list various properties of the GCs associated with the Sgr and Canis Major dwarf galaxies. We also include the three GC candidates, in addition to NGC 2298 and NGC 2808, put forward by Crane et al. (2003). We will refer to the latter three as the ‘Mono ring GCs’ but remind the reader that the ring is a tidal stream of the Canis Major dwarf observed near the Galactic anti-center. Most ages and metallicities are taken from the homogeneous compilation of Salaris & Weiss (2002). However, metallicities for Terzan 8, M54, NGC 4147, NGC 5286 and Pal 1 come from Harris (1996). The age of Terzan 8 is assumed to be old, i.e. 13 Gyrs old with M54 1 Gyr younger at 12 Gyrs based on the study of Montegriffo et al. (1998), for NGC 4147 and NGC 5286 we assume an old age (13.0 Gyrs) based on the colour-magnitude diagrams of Friel et al. (1987) and Samus et al. (1995) respectively, for Pal 1 we take the age derived by Rosenberg et al. (1998). We note that most of these age estimates are based on the magnitude difference between the horizontal branch and the main sequence turnoff, and thus may suffer from unknown systematic errors due to the second parameter effect. Other properties are from the catalog of Harris (1996).

From Table 1 it can be seen that both the Sgr and Canis Major/Mono ring GC systems have a variety of HB morphologies, with different magnitude and metallicity distributions. The GCs also have both prograde and retrograde motions (Rodgers & Paltoglou 1984). Thus such properties are probably of limited use in separating bona fide Milky Way GCs from those that have been accreted from disrupted dwarfs.

3. The Age-Metallicity Relation of the Sagittarius Dwarf Galaxy

The age-metallicity relation (AMR) of a stellar system provides a key probe of the chemical enrichment history of that system (e.g., Pagel & Tautvaisiene 1995). Here, we derive an updated age-metallicity relation for the Sgr dwarf (see e.g. Layden & Sarajedini 2000) using both the GC system given in Table 1 and studies of field stars.

Ages and metallicities for three field star populations in Sgr were measured by Layden & Sarajedini (2000). Recently, Bonifacio et al. (2004) found a very young and metal-rich stellar component. The mean age-metallicity and range for these four stellar fields, and the six GCs of the Sgr galaxy are shown in Fig. 1.

In Fig. 1, we also overplot a theoretical AMR derived from a simple closed-box chemical
Table 1. Dwarf Galaxy Globular Clusters

| Name            | Age (Gyrs) | [Fe/H]  | R_GC (kpc) | HB  | M_V (mag) | r_h (pc) |
|-----------------|------------|---------|------------|-----|----------|----------|
| Sagittarius     |            |         |            |     |          |          |
| M54             | 12.0 ± 2.0 | −1.79   | 19.2       | 0.75| −10.0    | 3.83     |
| Terzan 7        | 7.5 ± 1.4  | −1.00   | 16.0       | −1.00| −5.1    | 6.56     |
| Terzan 8        | 13.0 ± 1.5 | −2.00   | 19.1       | 1.00| −5.1    | 7.57     |
| Arp 2           | 11.5 ± 1.4 | −1.84   | 21.4       | 0.86| −5.3    | 15.9     |
| Pal 12          | 6.4 ± 0.9  | −0.82   | 15.9       | −1.00| −4.5    | 7.12     |
| NGC 4147        | 13.0 ± 1.5 | −1.83   | 21.3       | 0.55| −6.2    | 2.40     |
| Canis Major     |            |         |            |     |          |          |
| NGC 1851        | 9.1 ± 1.1  | −1.23   | 16.7       | −0.36| −8.3    | 1.83     |
| NGC 1904        | 12.6 ± 1.3 | −1.67   | 18.8       | 0.89| −7.9    | 3.01     |
| NGC 2298        | 12.9 ± 1.4 | −1.85   | 15.7       | 0.93| −6.3    | 2.44     |
| NGC 2808        | 10.2 ± 1.1 | −1.36   | 11.0       | −0.49| −9.4    | 2.12     |
| Monoceros Ring  |            |         |            |     |          |          |
| Pal 1           | 8.0±2.0    | −0.60   | 17.0       | −1.00| −2.5    | 2.15     |
| NGC 5286        | 13.0±2.0   | −1.67   | 8.40       | 0.86| −8.6    | 2.21     |
| BH 176          | 7.0±1.5    | 0.00    | 9.70       | ⋮   | −4.4    | ⋮        |
Fig. 1.— Age-metallicity relation for the Sagittarius dwarf galaxy. The six globular clusters associated with Sgr dwarf are shown by filled circles. The typical error in metallicity is $\pm 0.1$ dex. The Sgr field star populations of Layden & Sarajedini (2000) and Bonifacio et al. (2004) are shown
enrichment model. This model assumes that the stellar system was completely gaseous 13.5 Gyrs ago, and converted gas into stars at a constant rate (set so that the gas supply has just been depleted at the present day). We assume $Z_\odot = 0.02$. We find that using a yield of 0.004 gives a reasonable fit to the data.

The model AMR provides a very good representation of the chemical enrichment history of the Sgr dwarf over the last $\sim 13$ Gyrs. This supports the suggestion of Layden & Sarajedini (2000) that the Sgr dwarf may have formed stars and GCs without significant infall or explosion of gas. Simple closed-box models are also inferred for the Fornax dwarf (Pont et al. 2003) and the LMC/SMC galaxies (Piatti et al. 2002), but more complicated enrichment models are also possible (e.g. Smecker-Hane & McWilliams 2002). We now proceed to compare the Sgr model AMR with cluster and field star data for the Canis Major dwarf.

4. The Age-Metallicity Relation of the Canis Major Dwarf Galaxy

As noted in the introduction, Martin et al. (2003) identified four GCs associated with the Canis Major dwarf and Bellazzini et al. (2003c) added two old open clusters. The open clusters, AM-2 and Tom 2, have approximate ages and metallicities of 5 Gyrs and $[\text{Fe/H}] = -0.5$ (Lee 1997) and 4 Gyrs and $[\text{Fe/H}] = -0.45$ (Brown et al. 1996) respectively.

In Fig. 2 we show these six Canis Major clusters compared to the Sgr model AMR. Given the similar inferred luminosities for the two galaxies (Martin et al. 2003), we might expect the Sgr AMR to be a reasonable approximation for Canis Major. Indeed this appears to be the case. Both galaxies are consistent with a simple closed-box chemical enrichment model, although the stellar yield in the Canis Major galaxy may have been slightly higher than in Sgr.

We also show the three additional Mono ring GCs candidates suggested by Crane et al. (2003). The GCs Pal 1 and NGC 5286 are generally consistent with the high yield AMR, but the very young GC BH 176 deviates significantly (>3$\sigma$) from it. We conclude that BH 176 is unlikely to be a former member of the Canis Major dwarf galaxy.

Fig. 2 also shows the ages and metallicities of the remaining (i.e. non Sgr and non Canis Major) Milky Way GCs in the list of Salaris & Weiss (2002). The model AMR deviates from the Milky Way GC distribution at intermediate-to-high metallicities. The Milky Way GCs reveal a much steeper AMR (i.e., they are more chemically enriched at a given age). A closed-box model would require a much higher yield to achieve such an AMR. However, detailed studies of the Milky Way AMR indicates that such a model is a poor representation of reality, and additional processes are required, such as pre-enrichment or infall (e.g., Tinsley 1980).

Some of the metal-poor Milky Way GCs deviate from the mean trend line to younger ages. These GCs typically lie at large galactocentric radii and have been classified as “young halo” GCs (Zinn 1993). These GCs include: Eridanus (age = 8.4 Gyrs, $[\text{Fe/H}] = -1.48$, $R_{GC} = 95.2$ kpc), Pal
Fig. 2.— Age-metallicity relation (AMR) for the Canis Major dwarf galaxy. The four globular clusters (GCs) and two open clusters are shown by filled circles. Three Monoceros ring GCs are shown by filled triangles. The typical error in GC [Fe/H] is ±0.1 dex. The solid curve shows the Sgr galaxy AMR from Fig. 1, and the dashed line a 20% higher yield. The small filled circles show the remaining Milky Way GCs. The GC BH 176 is not consistent with the AMR of the Canis Major galaxy, and therefore unlikely to be a former member.
3 (9.2, −1.57, 95.9), Pal 4 (9.2, −1.58, 111.8), and Rup 106 (10.4, −1.90, 18.5). These, and other
GCs with large galactocentric radii, have been suggested as prime candidates for accreted GCs by
van den Bergh (2000). Thus, Fig. 2 provides further circumstantial evidence that these GCs may
have been accreted from tidally captured galaxies. If these ‘young halo’ GCs and the Canis Major
and Sgr GCs are excluded from a Milky Way analysis, then the age spread of the Salaris & Weiss
(2002) sample of metal-poor GCs is reduced from \( \sim 3 – 4 \) Gyrs to \( \lesssim 1 \) Gyr. This would make any
ELS-type collapse (Eggen, Lyden-Bell & Sandage 1962) very rapid indeed.

5. The Size-Galactocentric Distance Relation

The existence of a size-galactocentric distance relation for Milky Way GCs suggests that the
bulk of the system formed \textit{in situ} (van den Bergh 1995). This point holds because the half-mass
radius of a GC (unlike the core and tidal radii) is expected to be largely unaffected by internal
or external dynamical processes over a Hubble time (Murray & Lin 1992), and any compact GCs
at large galactocentric distances are likely to have survived to the present day (Ashman & Zepf
1998). In Fig. 3 we show the half-mass radius versus galactocentric distance for the Canis Major
GCs compared to other Milky Way GCs. Both quantities are taken from Harris (1996). The Canis
Major GCs have relatively small half-mass radii for their galactocentric distance. This lends further
support to their origin outside of the Milky Way. We note, however, that the Sgr GCs span a large
range in half-mass sizes. This suggests that a small range in GC sizes, while suggestive, is not a
common feature of all dwarf GC systems.

6. The Contribution of Accreted Dwarf Galaxies

It is likely that the Sgr and Canis Major dwarfs are not the only satellites accreted by our
Galaxy. There are good examples in other disk galaxies of \textit{accreting} (Forbes \textit{et al.} 2003) and
\textit{accreted} (Ibata \textit{et al.} 2001) satellite galaxies that contribute to the build-up of galactic halos. For
M31, gas associated with an accreted satellite may have induced some new GC formation (Beasley
\textit{et al.} 2004). How significant are these accretions in the growth of a typical spiral galaxy and to
which galactic component do they contribute?

Martin \textit{et al.} (2003) suggested that the Canis Major dwarf is a major building block of the
Milky Way’s thick disk. This interpretation fits in well with the simulations of Abadi \textit{et al.} (2003),
in which thick disks are the result of satellite accretions in the galactic plane. The thick disk GC
system is traditionally thought to be a flattened, highly rotating system with a relatively high
mean metallicity (Zinn 1985). Today the metal-rich GC system is often considered to be associated
with the bulge of our Galaxy (Minniti 1995), and similarly for external galaxies (Forbes, Brodie
& Larsen 2001). However, the mean metallicity of the four Canis Major GCs identified by Martin
\textit{et al.} (2003) is \([\text{Fe/H}] = −1.5\), i.e. consistent with the mean for the \textit{metal-poor} GC system. Even
Fig. 3.— Globular cluster half-mass radii $r_h$ vs. galactocentric distance $R_{GC}$. The plot shows Milky Way GCs (small filled circles), Canis Major (large filled circles) and the Mono ring GCs Pal 1 and NGC 5286 (filled triangles). Typical errors are $\pm 0.1$ pc in the half-mass radius and $\pm 0.1$ kpc in distance. The Canis Major/Mono ring globular clusters are on average more compact than Milky Way GCs.
the highest metallicity GC, NGC 1851, is still relatively metal-poor with $[\text{Fe/H}] = -1.23$. Such metallicities are not typical of thick disk/bulge GCs but are generally associated with halo GCs. Furthermore, only one Sgr GC (Pal 12), and none of the five Fornax dwarf GCs, have $[\text{Fe/H}] \geq -1$. This suggests that even when satellite accretions do add to the GC system of the Milky Way, such additions are unlikely to contribute significantly to a thick disk or bulge population of GCs. We note also that the alpha-element ratios of thick disk stars (Feltzing et al. 2003) are generally super-solar and so not consistent with (solar ratio) stars found in Local Group dwarfs such as the Sgr dwarf (Bonifacio et al. 2004). Such solar abundance ratios indicate chemical enrichment over an extended time period, as suggested by the AMRs for Sgr and Canis Major (see Figures 1 and 2).

Several studies have placed limits on the importance of dwarf galaxy accretion to the Milky Way’s halo. Based on studies of halo stars, van den Bergh (2000) has argued that 3–7 Sgr-like dwarf accretions may have occurred over the Milky Way’s lifetime. By comparing halo star ages with those from dwarf galaxies, Unavane, Wyse & Gilmore (1996) have argued that only $\sim 10\%$ of the halo mass could have come from dwarfs. Gilmore & Wyse (1998) went on to examine the orbits of halo stars with alpha-element ratios that are similar to dwarf galaxy stars and concluded they were unlikely to have come from accreted dwarfs.

7. Conclusions

The identification of globular clusters (GCs) with the accreted dwarf galaxies Sgr and Canis Major has highlighted the fact that GC properties such as the horizontal branch morphology, prograde or retrograde orbits, range in cluster magnitudes, metallicity and galactocentric distance do not provide a unique signature of an accreted GC.

We have examined the relation between half-mass size and galactocentric distance for the Canis Major GC system, finding that all of the associated GCs have smaller than average sizes. This suggests an origin outside of the Milky Way.

We have derived a simple closed-box age-metallicity relation that provides a good representation of the chemical enrichment history of the Sgr and Canis Major dwarf galaxies. This is consistent with formation of these GCs outside of the Milky Way. The model AMR deviates from the Milky Way GC distribution at intermediate-to-high metallicities, thus providing an alternative and fairly robust method of identifying accreted metal-rich GCs within the Milky Way GC system. Based on the literature age and metallicity measurements for the GC BH 176, we argue it is unlikely to be a former member of the Canis Major galaxy.

We support earlier suggestions that the younger, metal-poor Milky Way GCs are prime candidates for accreted GCs from as yet unidentified galaxies. This would reduce the GC age spread, at a given metallicity, to less than a Gyr and imply that any halo collapse was very rapid. As the age-metallicity relation of the known accreted GCs is distinct from that of other Milky Way GCs
for $[\text{Fe/H}] \geq -1.3$, it suggests that accretion was not a major factor in building the stellar mass of the thick disk or bulge. The majority of the Milky Way GC system and, by implication, the Galaxy itself formed in situ.

This work was supported by NSF grant number AST-0206139 and an NSF Graduate Research Fellowship to JS. We thank R. Proctor for his helpful comments.
REFERENCES

Abadi, M., Navarro, J., Steinmetz, M., Eke, V., 2003, ApJ, 591, 499

Ashman, K. M. & Zepf, S. E. 1998, Globular cluster systems

Beasley, M., Brodie, J., Forbes, D., Barmby, P., Huchra, J., 2004, ApJL, submitted

Bellazzini, M., Ibata, R., Ferraro, F. R., Testa, V. 2003a, A&A, 405, 577

Bellazzini, M., Ferraro, F. R., Ibata, R., 2003b, AJ, 125, 188

Bellazzini, M., Ibata, R., Monaco, L., Martin, N., Irwin, M., Lewis, G., 2003c, MNRAS, in press

Bonifacio, P., Sbordone, L., Marconi, G., Pasquini, L., Hill, V., 2004, A&A, 414, 503

Brown, J., Wallerstein, G., Geisler, D., Oke, J., 1996, AJ, 112, 1551

Eggen, O., Lynden-Bell, D., Sandage, A., 1962, ApJ, 136, 748

Feltzing, S., Bensby, T., Lundstrom, I., 2003, A&A, 397, L1

Forbes D., Masters, K., Minniti, D., Barmby, P., 2000, A&A, 358, 471

Forbes, D. A., Beasley, M. A., Bekki, K., Brodie, J. P., & Strader, J. 2003, Science, 301, 1217

Forbes, D., Brodie, J., Larsen, S., 2001, ApJL, 556, 83

Friel, E., Heasley, J., Christian, C., 1987, PASP, 99, 1248

Frinchaboy, P., et al. 2004, astro-ph/0311101

Gilmore, G. & Wyse, R. F. G. 1998, AJ, 116, 748

Harris, W. E., 1996, AJ, 112, 1487

Ibata, R., Gilmore, G., Irwin, M., 1995, MNRAS, 277, 781

Ibata, R., Irwin, M., Lewis, G., Ferguson, A., Tanvir, N. 2001, 412, 49

Layden, A., Sarajedini, A., 2000, AJ, 119, 1760

Lee, M., 1997, AJ, 113, 729

Lynden-Bell, D., Lynden-Bell, R., 1995, MNRAS, 275, 429

Martin, N., Ibata, R., Bellazzini, M., Irwin, M., Lewis, G., Dehnen, W., 2003, MNRAS, in press

Minniti, D., 1995, AJ, 109, 1663
Montegriffo, P., Bellazzini, M., Ferraro, F., Martins, D., Sarajedini, A., Fusi Pecci, F., 1998, MNRAS, 294, 315

Murray, S. D., Lin, D. N. C. 1992, ApJ, 400, 265

Newberg, H., et al. 2002, ApJ, 569, 245

Odenkirchen, M., et al. 2003, AJ, 126, 2385

Pagel, B., Tautvaisiene 1995, MNRAS, 276, 505

Piatti, A., Sarajedini, A., Geisler, D., Bica, E., Claria, J., 2002, MNRAS, 329, 556

Pont, F., Zinn, R., Gallart, C., Hardy, E., Winnick, R., 2003, astro-ph/0310870

Rodgers, A., Paltoglou, G., 1984, ApJL, 283, L5

Rosenberg, A., Saviane, I., Piotto, G., Aparicio, A., Zaggia, S., 1998, AJ, 115, 648

Samus, N., Ipatov, A., Smirnov, O., Kravtsov, V., Alcaino, G., Liller, W., Alvarado, F., 1995, A&AS, 112, 439

Salaris, M., Weiss, A. 2002, A&A, 388, 492

Searle, L., Zinn, R. 1978, ApJ, 225, 357

Smecker-Hane, T., McWilliam, A., 2002, astro-ph/0205411

Tinsley, B. M. 1980, Fundamentals of Cosmic Physics, 5, 287

Unavane, M., Wyse, R. F. G., & Gilmore, G. 1996, MNRAS, 278, 727

van den Bergh, S., 1993, MNRAS, 262, 588

van den Bergh, S. 1994, AJ, 108, 2145

van den Bergh, S. 1995, AJ, 110, 1171

van den Bergh, S., 2000, ApJ, 530, 777

Zinn, R., 1985, ApJ, 293, 424

Zinn, R., 1993, The Globular Cluster-Galaxy Connection, ASP Conf. Series 48, ed. G. Smith & J. Brodie (San Francisco, ASP), p38

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