Is the Galactic center populated with young star clusters?

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Abstract. We study the evolution and observability of young and compact star clusters near the Galactic center, such as the Arches cluster and the Quintuplet. The star clusters are modeled with a combination of techniques; using direct $N$-body integration to calculate the motions of all stars and detailed stellar and binary evolution to follow the evolution of the stars. The modeled star clusters dissolve within 10 to 60 million years in the tidal field of the Galaxy. The projected stellar density in the modeled clusters drops within 5\% to 70\% of the lifetime to a level comparable to the projected background density towards the Galactic center. And it will be very hard to distinguish these clusters at later age among the background stars. This effect is more severe for clusters at larger distance from the Galactic center but in projection at the same distance. Based on these arguments we conclude that the Galactic center easily hides 10 to 40 clusters with characteristics similar to the Arches and the Quintuplet cluster.

1. Introduction

A number of compact and young star clusters have been observed within the inner few ten parsec from the Galactic center. Most noticeable are the Arches cluster (Object 17, Nagata et al. 1995) and the Quintuplet cluster (AFGL 2004, Nagata et al. 1990; Okuda et al. 1990). But it is not excluded that others exist as these clusters are well hidden behind thick layers of absorbing material. The Arches and the Quintuplet clusters form the galactic counterparts of NGC 2070 (or R 136); the central star cluster in the 30 Doradus region in the Large Magellanic Could (Massey & Hunter 1998). The structural parameters of these clusters, size, mass and density profile are quite similar as are their ages. The Arches and the Quintuplet clusters are at a projected distance of $\lesssim 50$ pc from the Galactic center. Their evolution is therefore dramatically affected by the presence of the tidal field of the Galactic bulge and inner disc.

In this paper we report the results of $N$-body simulations of young and compact star clusters, such as the Arches cluster and the Quintuplet cluster in the vicinity of the Galactic bulge. These cluster are particularly interesting because a strong coupling between stellar evolution, stellar dynamics and the tidal field of the Galaxy may exist. In addition to this, excellent observational data are available. Many unusually bright and massive stars are present in both
clusters which, due to the high central density of $10^5$ to $10^6$ stars pc$^{-3}$ are likely to interact strongly with each other.

A number of intriguing question about these clusters makes it worth to model them in great detail, these are 1.) are these clusters the progenitors of globular star clusters, 2.) what is their contribution to the star formation rate in the Galaxy, 3.) are their mass functions intrinsically flat as has been suggested by observations, 4.) how far are these clusters really from the Galactic center and 5.) how many are still hidden, waiting to be discovered. I will address the latter two conundrums in this paper and a more detailed paper is in preparation (Portegies Zwart, Makino, McMillan & Hut, 2000b).

2. The model

We study the evolution of the Arches and Quintuplet cluster by integrating the equations of motion of all stars and at the same time we account for the evolution of the stars and binaries. The adopted N-body integration algorithm, evolution of stars and binaries, and the interface between the dynamical calculations and the stellar evolution are described extensively by Portegies Zwart et al. (2000a, see also http://www.sns.ias.edu/~starlab).

The N-body portion of the simulations is carried out using kira, operating within the Starlab software environment (Portegies Zwart et al. 1998). Time integration of stellar orbits is accomplished using a fourth-order Hermite scheme (Makino & Aarseth 1992). Kira also incorporates block timesteps (McMillan 1986a; 1986b; Makino 1991) special treatment of close two-body and multiple encounters of arbitrary complexity, and a robust treatment of stellar and binary evolution and stellar collisions. The special-purpose GRAPE-4 (Makino et al. 1997) system is used to accelerate the computation of gravitational forces between stars.

The evolution of stars and binaries are carried out by SeBa (see Portegies Zwart & Verbunt, 1996, Sect. 2.1) the binary evolution package which is combined in the starlab software toolset. The treatment of collisions and mass loss in the main-sequence stage for massive stars are described by Portegies Zwart et al. (1998; 1999; 2000a).

3. Initial conditions

The observed parameters for the Arches and the Quintuplet clusters are presented in Tab. 1. These clusters have masses of about $\sim 10^4 M_\odot$ and are extremely compact $r_{hm} \lesssim 1$ pc (Figer, McLean & Morris 1999). The projected distance from the Arches cluster to the Galactic center is about 34 pc, the Quintuplet cluster is somewhat farther away. If the third component of the projected distance to the Galactic center is zero then the observed distance equals the real distance.

Our calculations start with 12k (12288) stars at zero age. We assign masses to stars between 0.1 $M_\odot$ and 100 $M_\odot$ from the mass function suggested for the Solar neighborhood by Scalo (1986). The median mass of this mass function is about 0.3 $M_\odot$, and the mean mass $\langle m \rangle \simeq 0.6 M_\odot$. For the models with 12k stars this results in a total cluster mass of $\sim 7500 M_\odot$. Initially all stars are
Table 1. Observed parameters for some of these clusters. The columns give the cluster name, reference, age, mass, distance to the Galactic center, the tidal radius and the half mass radius. The last column gives the density within the half mass radius.

| Name         | ref | Age [Myr] | M [$10^3 M_{\odot}$] | $r_{GC}$ [pc] | $r_{\text{tide}}$ | $r_{hm}$ [pc] | $\rho_{hm}$ [$10^5 M_{\odot}/pc^2$] |
|--------------|-----|-----------|----------------------|----------------|------------------|--------------|-------------------------------|
| Arches       | a   | 1–2       | 12–50                | 30             | 1                | 0.2          | 0.3                           |
| Quintuplet   | b   | 3–5       | 10–16                | 50             | 1                | $\lesssim$ 1 | 0.2                           |

References: a) Brandl et al. (1996); Campbell et al. (1992); Massey & Hunter (1998). b) Figer et al. (1999);

single, but binaries may form via three body encounters in which one star carries away the excess energy and angular momentum. We adopt two distances from the Galactic center, 34 pc and 150 pc. The initial density profile and velocity dispersion for the models are taken from a Heggie & Ramamani (1995) model with $W_0 = 4$. At birth the clusters are assumed to perfectly fill the zero velocity surface in the tidal field of the Galaxy. An overview of the initial conditions for the computed models is summarized in Tab. 2.

Table 2. Overview of initial conditions for the calculations. Each row stars with the model name, the distance to the Galactic center and the initial King model $W_0$, then the initial relaxation time, the half mass crossing time and the core radius, half mass radius and the tidal radius. The last two columns give the the time of core collapse and the time the cluster mass drops below 5% in the initial mass (or about $375 M_{\odot}$).

| Model        | $r_{GC}$ [pc] | $W_0$ | $t_{\text{rlx}}$ [Myr] | $t_{\text{core}}$ [Kyr] | $t_{hm}$ [Myr] | $r_{core}$ [pc] | $r_{hm}$ [pc] | $r_{\text{tide}}$ [pc] | $t_{cc}$ [Myr] | $t_{\text{end}}$ [Myr] |
|--------------|---------------|------|-------------------------|--------------------------|---------------|----------------|-------------|----------------|----------------|----------------|----------------|
| R34W1        | 34            | 1    | 5.5                     | 43                       | 0.12          | 0.17           | 0.7         | 1.9            | 9.3            |                |
| R34W4        | 34            | 4    | 3.3                     | 26                       | 0.08          | 0.12           | 0.7         | 0.9            | 12.4           |                |
| R150W4       | 150           | 4    | 12.9                    | 104                      | 0.22          | 0.30           | 1.9         | 3.2            | 58.6           |                |

The tidal field is characterized by the Oort (1927) constants $A$ and $B$ and the local stellar density. The mass within the clusters’ orbit at a distant $r_{GC}$ from the Galactic center is calculated with (Mezger et al. 1999)

$$M_{\text{Gal}}(r_{GC}) = 4.25 \times 10^6 \left( \frac{r_{GC}}{\text{pc}} \right)^{1.2} [M_{\odot}].$$

And with this we can derive the appropriate Oort constants.

Once the tidal field, the mass of the cluster and its density profile are selected the $N$-body system is fully determined. The total mass of the stellar system determines the unit of mass in the $N$-body system, the distance to the
first Lagrangian point $r_{L1}$ in the tidal field of the Galaxy sets the distance unit and the velocity dispersion together with the size of the stellar system sets the time scale. The evolution of the cluster is subsequently followed using the direct $N$-body integration including stellar and binary evolution and the tidal field of the Galaxy (see Portegies Zwart et al. 2000b).

For economic reasons not all stars are kept in the $N$-body system, but stars are removed when they are $3r_{L1}$ from the center of the star cluster.

4. Results

Figure 1. Evolution of the total mass $M$ (dashes), the bound mass (dots) and number of stars $N$ (solids) for the models with $W_0 = 4$ at $r_{GC} = 34\,\text{pc}$ (left) and $r_{GC} = 150\,\text{pc}$ (right). Cluster farther away from the Galactic center live longer.

Figure 1 shows the evolution of the mass and number of stars of two models from Table 2. Star clusters which are located further away from the galactic center live considerably longer than the closer clusters. Estimating the cluster lifetime naively via the initial relaxation time would lead to an age of $48\,\text{Myear}$ ($\equiv 12.4\,\text{Myear} \times 12.9/3.3$) for model R150W4. The weaker tidal field at a distance of $150\,\text{pc}$ from the Galactic center, however, tend to extend the cluster lifetime to about $59\,\text{Myear}$, indicating that the strength of the tidal field has a stronger effect on the cluster lifetime than mass loss from stellar evolution.

The number of stars (solid) in the models (see Fig. 1) decreases more quickly than the total mass (dashes and dots). The mean mass of the stars within the cluster potential therefore increases gradually with time. Near $t = 7\,\text{Myear}$ for
model R34W4 and $t = 32$ Myear for model R150W4 the number of stars drops below the total cluster mass, indicating that the mean mass exceeds $1 M_\odot$. At these moments both models have lost $\sim 65\%$ of their initial mass.

5. Discussion

Although the Arches and Quintuplet clusters are very compact, it may still be hard to notice them near the Galactic center. The local stellar density is high and we can only see these clusters in projection onto the background.

The projected density near the galactic center can be calculated by differentiating Eq. 1 with respect to the distance along line of sight. Portegies Zwart et al. (2000b) perform this calculation numerically and arrive at a projected density of about $3000 M_\odot pc^{-3}$.

![Figure 2](image.png)

**Figure 2.** Evolution of the projected density within the projected half mass radius for models R150W1 (dotes), R34W4 (left solid) and R150W4 (right solid). The two error bars give the observed projected density of the Arches and the Quintuplet clusters.

Figure 2 shows the evolution of the density within the projected half mass radius for models R150W1 (dotes), R34W4 (left solid) and R150W4 (right solid). The two error bars give the projected half mass densities for the observed clus-
ters: Arches (left) and Quintuplet (right). The horizontal dotted line gives the surface density at a projected distance of 34 pc from the Galactic center. The projected densities of the observed clusters are about an order of magnitude higher than the background. Clusters with a lower background density may remain unnoticed among the background stars, as observers may have difficulty to distinguish the cluster from the background.

The projected density of model R34W1 barely exceeds the background and such a cluster easily remains unnoticed throughout its lifetime. The two models which started more concentrated R34W4 and R150W4 have projected densities well above the background, at least initially. The cluster farther away from the Galactic center has a lower density because it is more extended; its tidal radius is larger. After the first few million years this cluster may be hard to notice among the dense stellar background. We adopt a minimum contrast about three times the projected background density, i.e.: $10^4 \, M_\odot \, \text{pc}^{-2}$ required for distinguishing a star cluster among the background. In that case the cluster at a distance of 150 pc would be visible for only about 3 million years ($\sim 5\%$ of its lifetime), and almost 9 million years ($\sim 70\%$ of its lifetime) for the cluster at a distance of 34 pc. Although the cluster far away from the Galactic center (model R150W4) lives much longer, it only remains visible for a small fraction of its lifetime.

Expressed in fraction of their lifetime the two models are observable for about 5% to 70% of the time for the clusters at a distance of 150 pc and 34 pc, respectively. We therefore expect that a large population of clusters with characteristics similar to the Arches and Quintuplet may still be hidden in the direction of the Galactic center. Based on our calculations we estimate that more than 40 clusters remain to be found within a projected distance of 50 pc from the Galactic center. Most of these will be older than the Arches and Quintuplet clusters but not exceeding $10^8$ years, as they dissolve on a shorter time scale.

6. Conclusion

We studied the evolution of the two young and compact star clusters near the Galactic center, the Arches cluster and the Quintuplet. Based on the background stellar density towards the Galactic center and the projected density of the modeled and observed clusters we conclude that the number of such clusters must be far greater than observed. Most of these clusters remain hidden in the stellar background and they are observable only in the first few million years of their existence, when they are still very compact. Within a projected distance of 50 pc from the Galactic center between 10 and 40 clusters with characteristics similar to the Arches cluster and the Quintuplet may be hidden. These hidden clusters are likely to be somewhat older and less compact than those already found.

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References

Brandl, B., Sams, B. J., Bertoldi, F., Eckart, A., Genzel, R., Drapatz, S., Hofmann, R., Loewe, M., Quirrenbach, A. 1996, ApJ, 466, 254+

Campbell, B., Hunter, D. A., Holtzman, J. A., Lauer, T. R., Shayer, E. J., Code, A., Faber, S. M., Groth, E. J., Light, R. M., Lynds, R., O’Neil, E. J., J., Westphal, J. A. 1992, AJ, 104, 1721

Figer, D. F., Kim, S. S., Morris, M., Serabyn, E., Rich, R. M., McLean, I. S. 1999a, ApJ, 525, 750

Figer, D. F., McLean, I. S., Morris, M. 1999b, ApJ, 514, 202

Heggie, D. C., Ramamani, N. 1995, MNRAS, 272, 317

Makino, J. 1991, ApJ, 369, 200

Makino, J., Aarseth, S. J. 1992, PASJ 44, 141

Makino, J., Taiji, M., Ebisuzaki, T., Sugimoto, D. 1997, ApJ, 480, 432

Massey, P., Hunter, D. A. 1998, ApJ, 493, 180

Mezger, P. G., Zylka, R., Philipp, S., Launhardt, R. 1999, A&A, 348, 457

McMillan, S. L. W. 1986a, ApJ, 306, 552

McMillan, S. L. W. 1986b, ApJ, 307, 126

Nagata, T., Woodward, C. E., Shure, M., Pipher, J. L., Okuda, H. 1990, ApJ, 351, 83

Nagata, T., Woodward, C. E., Shure, M., Kobayashi, N. 1995, AJ, 109, 1676

Okuda, H., Shibai, H., Nakagawa, T., Matsuhara, H., Kobayashi, Y., Kaifu, N., Nagata, T., Gatley, I., Geballe, T. R. 1990, ApJ, 351, 89

Oort, J. 1927, ban, 3, 275

Portegies Zwart, S. F., Verbunt, F. 1996, A&A, 309, 179

Portegies Zwart, S. F., Hut, P., Makino, J., McMillan, S. L. W. 1998, A&A, 337, 363

Portegies Zwart, S. F., Makino, J., McMillan, S. L. W., Hut, P. 1999, A&A, 348, 117

Portegies Zwart, S. F., McMillan, F., Makino, J., Hut, P. 2000a, submitted to MNRAS [astro-ph/0005248]

Portegies Zwart, S. F., Makino, J., McMillan, F., Hut, P. 2000b in preparation

Scalo, J. M., 1986, Fund. of Cosm. Phys., 11,