The Astrophysical Journal, 546:L101–L104, 2001 January 10
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HOW MANY YOUNG STAR CLUSTERS EXIST IN THE GALACTIC CENTER?

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Received 2000 August 31; accepted 2000 October 30; published 2001 January 10

ABSTRACT

We study the evolution and observability of young compact star clusters within ∼200 pc of the Galactic center. Calculations are performed using direct *N*-body integration on the GRAPE-4, including the effects of both stellar and binary evolution and the external influence of the Galaxy. The results of these detailed calculations are used to calibrate a simplified model applicable over a wider range of cluster initial conditions. We find that clusters within 200 pc of the Galactic center dissolve within ∼70 Myr. However, their projected densities drop below the background density in the direction of the Galactic center within ∼20 Myr, effectively making these clusters undetectable after that time. Clusters farther from the Galactic center but at the same projected distance are more strongly affected by this selection effect and may go undetected for their entire lifetimes. Based on these findings, we conclude that the region within 200 pc of the Galactic center could easily harbor some 50 clusters with properties similar to those of the Arches or the Quintuplet systems.

Subject headings: globular clusters: individual (Arches, Quintuplet) — gravitation — methods: *n*-body simulations — stars: evolution — stellar dynamics

1. INTRODUCTION

Two young compact star clusters have been observed within a few tens of parsecs of the Galactic center: the Arches cluster (Object 17, Nagata et al. 1995) and the Quintuplet cluster (AFGL 2004, Nagata et al. 1990; Okuda et al. 1990), for which excellent observational data are available. In terms of structural parameters—size, mass, density profile—and ages, these systems may represent the Galactic counterparts to NGC 2070 (R136), the central star cluster in the 30 Doradus region in the Large Magellanic Cloud (Massey & Hunter 1998). A detailed study of the dynamical evolution of this star cluster is presented in Portegies Zwart et al. (1998). The Arches and Quintuplet clusters lie behind thick layers of absorbing material, hinting that many more such systems may exist. Recently, Dutra & Bica (2000) have reported from the Two Micron All-Sky Survey a total of 58 star cluster candidates within ∼600 pc (in projection) of the Galactic center.

A number of important questions make these clusters worthy of detailed study; among them are: (1) How are such clusters related to globular clusters? (2) How do they contribute to the total star formation rate in the Galaxy? (3) Are their mass functions in reality intrinsically flat, as is suggested by observations? (4) How far are these clusters from the Galactic center? (5) How many are hidden, still waiting to be discovered? In this Letter we summarize the results of a series of *N*-body simulations of young compact star clusters in the vicinity of the Galactic center and address specifically the last item on this list.

We found that the lifetimes of our model clusters depend very sensitively on their distances from the Galactic center. This is mainly due to the larger size of tidally limited clusters lying farther from the Galactic center, resulting in longer relaxation times and therefore longer lifetimes. The majority of our models are visible only for the first part of their lifetimes and are likely to be indistinguishable from the stellar background at later times. We find that the true number of young compact star clusters within 200 pc of the Galactic center is at least 10 but could easily exceed 50.

A more comprehensive paper, exploring all of these questions in more detail and presenting the results of an extensive parameter-space study, is forthcoming (S. F. Portegies Zwart, J. Makino, F. McMillan, & P. Hut 2001, in preparation).

2. INITIAL CONDITIONS

We study the evolution of our model clusters by following the equations of motion of all stars by direct *N*-body integration, at the same time taking into account the internal evolution of both stars and binary systems. The "Starlab" software environment within which this work was performed is described in detail by Portegies Zwart et al. (2001).[5] The special purpose GRAPE-4 system (Makino et al. 1997) was used to accelerate the computation of gravitational forces between stars.

Observed parameters for the Arches and Quintuplet clusters are listed in Table 1. These clusters have masses of $\sim 10^4\ M_\odot$ and are extremely compact, with half-mass radii $r_{\rm hm} \lesssim 1$ pc (Figer, McLean, & Morris 1999b). The projected distance from the Arches to the Galactic center is about 30 pc; the Quintuplet cluster lies somewhat farther out, at ∼35 pc.

Our calculations start with 12,288 stars at zero age. We choose stellar masses between 0.1 and 100 $M_\odot$, distributed according to the mass function suggested for the solar neighborhood by Scalo (1986). The median mass of this mass function is about 0.3 $M_\odot$; the mean mass is $\langle m \rangle \simeq 0.6\ M_\odot$. The initial mass of each model is therefore $\sim 7500\ M_\odot$. Initially all stars are single, although some binaries do form dynamically via three-body encounters, in which one star carries away sufficient energy and angular momentum to allow two others to become bound. We adopt three standard distances from the Galactic center, 34, 90, and 150 pc. The initial density profiles and velocity dispersions for our models are generated from anisotropic Heggie & Ramamani (1995) models with $W_0 = 4$. At birth, the clusters are assumed to precisely fill their Jacobi surfaces ("Roche lobes") in the tidal field of the Galaxy and are taken to move in circular orbits around the Galactic center.

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[5] See also http://www.manybody.org.

TABLE 1
OBSERVED PARAMETERS FOR THE ARCHES AND THE QUINTUPLET CLUSTERS

Name	Reference	Age (Myr)	M ($\times 10^3\ M_\odot$)	r_{GC} (pc)	r_{tide} (pc)	r_{hm} (pc)	ρ_{hm} ($\times 10^5\ M_\odot$ pc^{-2})
Arches	1	1–2	12–50	30	1	0.2	0.6–2.6
Quintuplet	2	3–5	10–16	35	1	~0.5	0.08–0.13

NOTE.—Columns list cluster name, reference, age, mass, projected distance to the Galactic center, tidal radius (r_{tide}), and half-mass radius (r_{hm}). The final column presents an estimate of the density within the half-mass radius.

REFERENCES.—(1) Brandl et al. 1996; Campbell et al. 1992; Massey & Hunter 1998; (2) Figer et al. 1999a.

For a circular orbit in the plane of the Galaxy, the distance from the center of the star cluster to the first Lagrangian point (the Jacobi radius) is approximated by

$$r_{L1} \simeq \left[\frac{M}{2M_{Gal}(r_{GC})}\right]^{1/3} r_{GC}. \quad (1)$$

Here M is the mass of the star cluster and the factor of 2 is a correction factor that depends on the density profile; strictly speaking, the factor of 2 is correct only in the case $M_{Gal} \propto r$. (The Jacobi radius is computed consistently with the adopted tidal field in our simulations.) Table 2 presents an overview of our model initial conditions.

The mass of the Galaxy within the clusters' orbit at a distance r_{GC} ($\lesssim$200 pc) is taken to be (Mezger et al. 1999)

$$M_{Gal}(r_{GC}) = 4.25 \times 10^6 \left[\frac{r_{GC}}{(\mathrm{pc})}\right]^{1.2} (M_\odot). \quad (2)$$

This mass distribution determines the strength and geometry of the local Galactic tidal field (for details see S. F. Portegies Zwart, J. Makino, F. McMillan, & P. Hut 2001, in preparation). The evolution of the cluster is followed using the Starlab KIRA N-body integrator and the SeBa binary evolution program (Portegies Zwart et al. 2001). For each selected distance to the Galactic center we carried out three calculations. One series of runs was carried out with identical initial realizations of the N-body system (stellar masses, positions, and velocities, with a total mass of 7432 $M_\odot$). The same initial model can be used at several Galactocentric distances because the shape of the zero-velocity surface does not depend sensitively on distance to the Galactic center. Table 2 gives results of these calculations. For each Galactocentric distance we also performed two additional calculations (for a total of nine runs) with different initial realizations of the N-body systems. These calculations were performed to study the uncertainties in cluster lifetimes and to ascertain the reproducibility of our results. The calculations with different initial realizations produced roughly 10% spreads in core collapse times (t_{cc}) and cluster lifetimes (t_{end}). For reasons of economy, stars were removed from all N-body calculations when they exceeded a distance of $3r_{L1}$ from the cluster center.

3. RESULTS

Figure 1 shows the evolution of cluster mass and number of stars for the models listed in Table 2, which began with identical initial conditions but different Galactocentric distances. Perhaps not surprisingly, clusters located farther from the Galactic center live considerably longer than those closer in. The longer lifetime of the more distant cluster is mainly a consequence of its longer relaxation time. Scaling the relaxation time at the tidal radius of model R34W4 to a distance of 150 pc results in a lifetime of ~52.2 Myr [≡12.7 Myr(218/53)], which is slightly smaller than the ~53.4 Myr lifetime of the model R150W4. Mass loss from stellar evolution, which is more prominent in model R150W4 because the cluster survives longer, seems to be a minor factor in driving the evolution.

The number of stars in each model (see Fig. 1, *dashed lines*) decreases more rapidly than the total mass (*solid lines*). Thus, the mean mass of the stars within the cluster increases gradually with time.

4. DISCUSSION

Although clusters like the Arches and Quintuplet systems are very compact, it may still be hard to see them near the Galactic center because the projected foreground and background stellar density is so high. Integration of the local stellar density (obtained by differentiating eq. [2]) along the line of sight then gives the surface density. S. F. Portegies Zwart, J. Makino, F. McMillan, & P. Hut (2001, in preparation) perform this calculation numerically and arrive at a surface density at 34 pc of about 3000 $M_\odot$ pc^{-2}. While the contrast in the surface density of the cluster relative to that of the background is perhaps an oversimplified measure of the cluster's observability, the results of this simple comparison are quite instructive, and a more comprehensive consideration of luminosity density leads to essentially similar overall conclusions.

TABLE 2
OVERVIEW OF INITIAL CONDITIONS FOR OUR MODEL CALCULATIONS

Model	r_{gc} (pc)	W_0	t_{rxt} (Myr)	t_{rxh} (Myr)	t_{hm} (kyr)	r_{core} (pc)	r_{hm} (pc)	r_{L1} (pc)	t_{cc} (Myr)	t_{end} (Myr)
R34W4	34	4	53	3.2	27	0.05	0.117	0.77	0.8	12.7
R90W4	90	4	134	8.1	68	0.09	0.218	1.42	1.2	32.6
R150W4	150	4	218	13	110	0.14	0.301	1.97	2.0	53.4

NOTE.—Each calculation is performed three times. From left to right, the columns list the model name, the distance to the Galactic center, the initial King parameter W_0, the initial tidal and half-mass relaxation times, half-mass crossing time, core radius, half-mass radius, and distance to the first Lagrangian point in the tidal field of the Galaxy, the time of core collapse, and the time at which the cluster mass drops below 1% of its initial value.

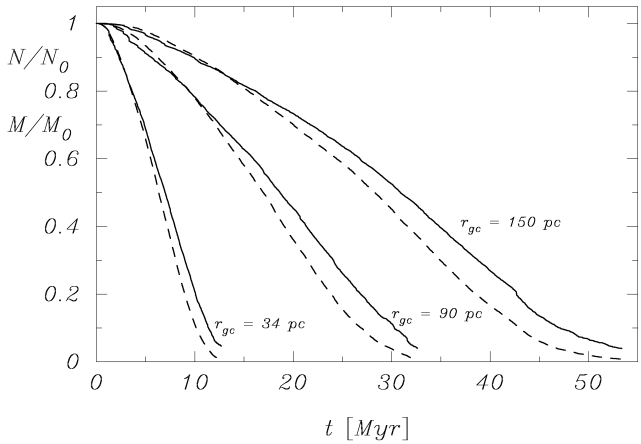

FIG. 1.—Evolution of the total mass M and number of stars N (*solid and dashed lines, respectively*) within the critical zero-velocity surface of selected models at $r_{GC} = 34$ pc (*left*), $r_{GC} = 90$ pc (*middle*), and $r_{GC} = 150$ pc (*right*). The results of the runs with identical initial realizations are presented. All quantities are normalized to their initial values.

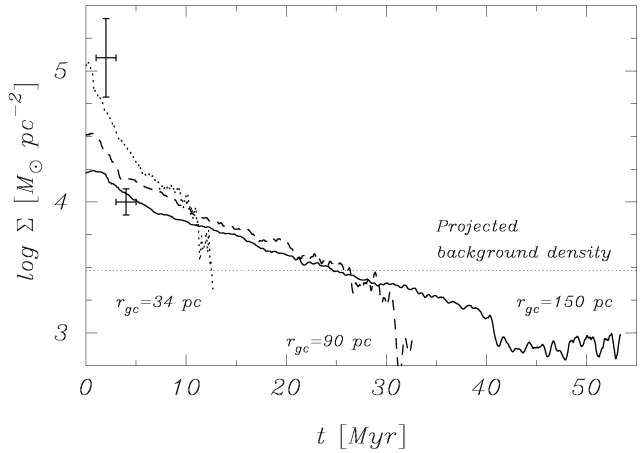

FIG. 2.—Evolution of the surface density within the projected half-mass radius for the models at $r_{GC} = 34$ pc (*dotted line*), at $r_{GC} = 90$ pc (*dashed line*), and at $r_{GC} = 150$ pc (*solid line*). The horizontal dotted line gives the integrated background density at a projected distance of 34 pc from the Galactic center. The results of the runs with identical initial realizations are presented. The two error bars give the observed surface densities of the Arches (*left*) and the Quintuplet (*right*) clusters.

Figure 2 shows the evolution of the surface density within the projected half-mass radius for models R34W4 (*dotted line*), R90W4 (*dashed line*), and R150W4 (*solid line*). The two points with error bars indicate the projected half-mass densities for the Arches (*left*) and Quintuplet (*right*) clusters. The horizontal dotted line gives the background surface density at a projected distance of 34 pc from the Galactic center. The projected densities of the two observed clusters are between 3 (for the Quintuplet) and 50 (for Arches) times higher than the background; clusters with densities below a few times the projected background stellar density may well remain unnoticed.

4.1. *A Simple Model*

A simplified model for the evolution of these star clusters may be constructed as follows. The initial relaxation time at the tidal radius may be calculated using equation (2) and Spitzer's (1987) expression as

$$t_{\rm rxt} \simeq 2.19 \left[\frac{r_{\rm GC}}{\rm (pc)}\right] \ \ {\rm (Myr)}. \tag{3}$$

The constant is obtained by substitution of the appropriate units.

The mass of the cluster decreases almost linearly in time (see Fig. 1) as

$$M = M_0 \left(1 - \frac{\tau}{\tau_c}\right). \tag{4}$$

Here $\tau \equiv t/t_{\rm rxt}$ and $\tau_c \simeq 0.29 t_{\rm rxt}$ is the age at which the cluster dissolves in the tidal field of the Galaxy. The projected surface density within the half-mass radius of the cluster is

$$\Sigma \equiv \frac{M_{\rm hm}}{\pi r_{\rm hm}^2} = \frac{M_{\rm hm}}{\pi w_0^2 r_{\rm L1}^2}. \tag{5}$$

Here $M_{\rm hm} \simeq 0.65M$ is the mass contained within the projected half-mass radius, and $w_0 \equiv r_{\rm hm}/r_{\rm L1}$ depends on the density profile but is always smaller than unity. For a King model with $W_0 = 4$, we find $w_0 \simeq 0.16$. Substitution of equations (1) and (2) into equation (5) gives

$$\Sigma_0 \simeq 7.0 \times 10^6 \left[\frac{r_{\rm GC}}{\rm (pc)}\right]^{-1.2} \ \ (M_\odot \ {\rm pc}^{-2}). \tag{6}$$

The projected surface density Σ decreases with time because the cluster mass decreases and the half-mass radius of the cluster increases. Substitution of equation (4) into equation (5) gives

$$\frac{\Sigma(t)}{\Sigma_0} = \left(1 - \frac{\tau}{\tau_c}\right)\left(\frac{r_{\rm hm,\,0}}{r_{\rm hm}}\right)^2. \tag{7}$$

The half-mass radius $r_{\rm hm}$ increases by about a factor of 2 during the first half-mass relaxation time and remains roughly constant thereafter. In our simple model we implement this by allowing $r_{\rm hm} \approx r_{\rm hm,\,0}$ to increase by a factor of 2 in the first half-mass relaxation time and to remain constant at later times. The fact that the half-mass radius remains roughly constant at late times and does not decrease as $M^{1/3}$, as would be expected for a tidally limited system, is a consequence of our use of the total N-body mass rather than the mass within the Jacobi surface (see Fig. 1) in determining both $r_{\rm hm}$ and Σ. The resulting surface density evolution agrees very well with our N-body calculations.

Figure 3 shows the evolution of the projected density as a function of distance from the Galactic center for our simple model. Clusters close to the Galactic center are compact enough to be easily visible (*dark shades*) for a large fraction of their lifetimes, but they dissolve quickly. Clusters farther from the Galactic center live much longer, but their surface densities are generally low, lying well below the background for most of their lifetimes. The two well-observed clusters both lie in the lower left corner (high-density region) of Figure 3. The Arches and Quintuplet clusters inhabit only a small portion of the available parameter space. However, the region they populate is most favorable for finding clusters, because the projected surface densities of such clusters are high.

We estimate the number of clusters like the Arches and the

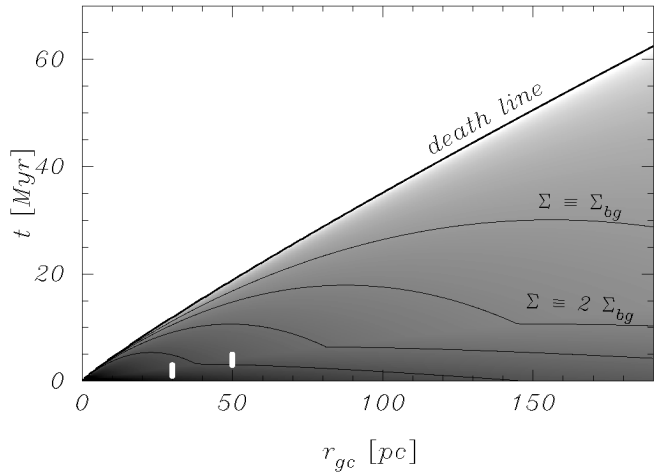

FIG. 3.—Projected cluster density as a function of distance from the Galactic center and time. Gray shading indicates projected surface density; darker shades indicate higher density. Solid lines indicate where the surface density of the cluster equals 1, 2, 4, and 10 times the background density. The background surface density is computed for 34 pc. The two holes to the lower left indicate the locations of the Arches (*left*) and Quintuplet (*right*) clusters on the figure.

Quintuplet based on the fact that both clusters lie at the lower left corner (youngest and most compact) in Figure 3. We assume that all clusters with ages less than ∼5 Myr and within 50 pc (which is about $\sqrt{2}$ 35 pc) of the Galactic center have been found by observers and all outside this region are as yet undetected. We further assume that clusters populate the triangular area in Figure 3 more or less uniformly—probably not a bad assumption since the Galactic mass is roughly proportional to radius (see eq. [2]). With these assumptions, the number of yet-to-be-found clusters is $[\frac{1}{2}\ (60\ \mathrm{Myr})\ (200\ \mathrm{pc})]\ /\ [(5\ \mathrm{Myr})\ (50\ \mathrm{pc})] =$ 24 times more than the number of known clusters. Thus, we expect that the total number of clusters in this region would be around 50.

A conservative lower limit to the number of hidden clusters may be obtained using the same technique but adopting the observed projected density of the Quintuplet system as the limiting contrast at which such clusters can be discovered. The projected density of the Quintuplet exceeds the background density by about a factor of 3. Figure 3 then suggests that about 20% of the available surface area harbors visible clusters. A lower limit to the total number of clusters within 200 pc of the Galactic center would then be around 10.

These estimates are in excellent agreement with the results of Dutra & Bica (2000) mentioned earlier, although the above reasoning suggests that even these 58 candidate clusters may represent only a small fraction of the number actually present.

Finally, we note that a population of 100 clusters with masses of $10^4\ M_\odot$ each and a maximum lifetime of 10^8 Myr implies a star formation rate of 0.01 $M_\odot$ yr^{-1}, enough to build up the entire bulge of $10^8\ M_\odot$ within the 10 Gyr age of the Galaxy.

S. F. P. Z. is grateful to the Institute for Advanced Study, Drexel University, and Tokyo University for their hospitality and the use of their GRAPE-4 hardware. This work was supported by NASA through Hubble Fellowship grant HF-01112.01-98A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, by the Research for the Future Program of Japan Society for the Promotion of Science (JSPS-RFTP97P01102), and by NASA ATP grants NAG5-6964 and NAG5-9264. Part of this Letter was written while S. F. P. Z., S. L. W. M., and P. H. were visiting the American Museum of Natural History. They acknowledge the hospitality of their astrophysics department and visualization group.

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