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THE ORIGIN OF IRS 16: DYNAMICALLY DRIVEN IN-SPIRAL OF A DENSE STAR CLUSTER TO THE GALACTIC CENTER?

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ABSTRACT

We use direct *N*-body simulations to study the in-spiral and internal evolution of dense star clusters near the Galactic center. These clusters sink toward the center owing to dynamical friction with the stellar background and may go into core collapse before being disrupted by the Galactic tidal field. If a cluster reaches core collapse before disruption, its dense core, which has become rich in massive stars, survives to reach close to the Galactic center. When it eventually dissolves, the cluster deposits a disproportionate number of massive stars in the innermost parsec of the Galactic nucleus. Comparing the spatial distribution and kinematics of the massive stars with observations of IRS 16, a group of young He I stars near the Galactic center, we argue that this association may have formed in this way.

Subject headings: black hole physics — Galaxy: center — Galaxy: nucleus — globular clusters: individual (Arches, Quintuplet) — methods: *N*-body simulations — stellar dynamics

1. INTRODUCTION

Krabbe et al. (1995) found ~15 bright He I emission line stars within about 1 pc of the Galactic center, accompanied by many less luminous stars of spectral types O and B (Genzel et al. 2000). Genzel et al. (2000) have measured accurate positions and velocities of 41 early-type stars in this region and report proper motions for 26 of them. These stars are part of the comoving group IRS 16, which was apparently formed 7–8 Myr ago in a starburst of mass $\gtrsim 10^4$ $M_\odot$ (Tamblyn & Rieke 1993). They show a high degree of anisotropy; most of the He I stars in the Galactic center are on tangential orbits (Genzel et al. 2000). Detailed spectroscopic analysis of these Galactic center objects (Najarro et al. 1994) indicates that they are highly evolved, with a high surface ratio of helium to hydrogen $n_{\rm He}/n_{\rm H} = 1$–1.67. Allen, Hyland, & Hillier (1990) classify them as Ofpe/WN9 stars, while Najarro et al. (1997) identify them as luminous blue variables (LBVs) with masses between 60 and 100 $M_\odot$.

LBVs are the late evolutionary stages of very massive ($\gtrsim 40$ $M_\odot$) stars (Langer et al. 1994). Massive stars remain in this stage for only a short while ($\sim 3 \times 10^4$ yr) after leaving the main sequence and the helium-rich WN stage, placing these stars in a very narrow age bracket: 3.2–3.6 Myr (Langer et al. 1994). If these objects are lower mass (25–40 $M_\odot$) Wolf-Rayet stars, they may be somewhat older (5–7 Myr; see Testor, Schild, & Lortet 1993), which is consistent with the age estimate of 7–8 Myr obtained from the model calculations of Tamblyn & Rieke (1993) and the independent age determination of 3–7 Myr by Krabbe et al. (1995). In either case, a firm age limit of ~7 Myr is indicated for IRS 16. The absence of detectable X-ray emission from these stars (Baganoff et al. 2001a, 2001b) argues in favor of the LBV interpretation, in which case the age limit drops to ~3.5 Myr.

While the age of the IRS 16 group is fairly well constrained, the location at which it formed is not. One obvious possibility is that the starburst occurred at roughly the Galactocentric radius where the group is now observed. However, this model is problematic, as the formation of stars within a parsec of the Galactic center is difficult. The tidal field of the central black hole is sufficient to unbind gas clouds with densities $\lesssim 10^{10}$ cm^{-3} (Morris 1993). At a distance $\gtrsim 1$ pc star formation is still easily prevented, even though the potential of the bulge starts to dominate over that of the black hole.

Gerhard (2001) proposed that a massive star cluster of mass m formed at a distance of $\lesssim 30(m/10^6\ M_\odot)$ pc from the Galactic center can spiral into the Galactic center by dynamical friction before being disrupted by the tidal field of the Galaxy or its own internal evolution. In order to survive in the Galactic central region, the cluster core density has to exceed $\rho_c \gtrsim 10^7\ M_\odot$ pc^{-3}. It is unlikely that a star cluster would be born with such a high central density, but it may evolve into this state when core collapse occurs. However, even then the cluster must have been initially quite compact. Core collapse of a cluster boosts the central density but can be strongly affected by mass loss from the cluster tidal boundary. In the strong tidal environment of the Galactic center, mass loss from the cluster perimeter may prevent core collapse altogether.

We simulate dense star clusters using a direct *N*-body approach, taking the external potential of the Galaxy and the effect of dynamical friction into account. Within this model we study the possibility that a cluster may go into core collapse before dynamical friction causes it to spiral into the Galactic center. We include the dynamical friction term analytically, applying it to the bound cluster mass (see Binney & Tremaine 1987). In § 2 we discuss cluster evolution and dynamical friction in order to interpret the results of our model calculations, which are presented in § 3. We summarize in § 4.

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2. CLUSTER DYNAMICS

2.1. *Timescale for Core Collapse*

The dynamical evolution of a star cluster drives it toward core collapse (Antonov 1962; Spitzer & Hart 1971) in which the central density runs away to a formally infinite value in a finite time. Core collapse occurs at

$$t_{\rm cc} \simeq c t_{\rm rlx} \ , \tag{1}$$

where $t_{\rm rlx}$ is the cluster's " half-mass " relaxation time,

$$t_{\rm rlx} = \frac{r_{\rm vir}^{3/2}}{(Gm)^{1/2}} \frac{n}{8 \ln \lambda} \ . \tag{2}$$

Here G is the gravitational constant, n is the number of stars in the cluster, m is the total cluster mass, and $r_{\rm vir}$ is the cluster's virial radius. The Coulomb logarithm $\ln \lambda \simeq \ln(0.1n) \sim 10$ typically.

In an isolated cluster in which all stars have the same mass, $c \simeq 15$ (Cohn 1980). In a multimass system, core collapse is determined by the accumulation of the most massive stars in the cluster center (Vishniac 1978; see also Chernoff & Weinberg 1990). We have performed direct N-body simulations to determine the moment at which core collapse occurs and hence the value of c in equation (1).

The initial conditions of our model cluster are presented in Table 1. The cluster consists of 65,536 stars distributed initially in a King (1966) model with King parameter $W_0 = 3$. Each of the stars is randomly assigned a mass drawn from a Scalo (1986) initial mass function between 0.3 and 100 $M_\odot$, irrespective of position. The entire cluster is then rescaled to virial equilibrium. We choose a virial radius $r_{\rm vir} = 0.167$ pc. These choices mimic the young Arches and Quintuplet star clusters, which are located somewhat farther ($\sim$30 pc) from the Galactic center. The resulting initial parameters (total mass, core radius, half-mass radius, crossing time, and relaxation time) are also listed in the table.

Visual inspection of the core radius as a function of time indicates that core collapse occurs around $t = 0.76$ Myr, near the moment when the hard binary containing the most massive star reaches a binding energy of $E < -100\ kT$ [where kT is the thermodynamic energy scale of the stellar system; the total kinetic energy of the cluster is $(3/2)nkT$]. This binary was formed somewhat earlier (at $t = 0.58$ Myr), but at that time we could not identify the core as collapsed, as the core radius continued to contract. A little later ($t = 0.84$ Myr), this binary is strongly perturbed by another star, resulting in a collision. On the basis of this information, we conclude that this particular simulation experienced core collapse at $t \sim 0.76$ Myr, so $c \simeq 0.20$, which is consistent with Portegies Zwart & McMillan (2002), but somewhat larger than the $c \simeq 0.15$ found in the Fokker-Planck simulations of Chernoff & Weinberg (1990).

TABLE 1
INITIAL CONDITIONS FOR THE SIMULATED STAR CLUSTERS

Parameter	Value
n	65536
m ($M_\odot$)	62549
W_0 (pc)	3
$r_{\rm core}$ (pc)	0.116
$r_{\rm hm}$ (pc)	0.140
$r_{\rm vir}$ (pc)	0.167
$r_{\rm tide}$ (pc)	0.525
$t_{\rm hm}$ (Myr)	0.0115
$t_{\rm rlx}$ (Myr)	3.87

NOTES.— The parameters are the number of stars, mass ($M_\odot$), the King parameter W_0, the core, half-mass, virial, and tidal radii (all in parsecs). The last two rows give the initial half mass crossing time and the two-body relaxation (both in millions of years).

2.2. *In-Spiral to the Galactic Center*

The mass M of the Galaxy within the cluster's orbit at distance R ($\lesssim$500 pc) from the Galactic center is taken to be (Sanders & Lowinger 1972; Mezger, Duschl, & Zylka 1996)

$$M(R) = AR^{\alpha} \ , \tag{3}$$

where $A = 4.25 \times 10^6\ M_\odot$ (1 pc)$^{-\alpha}$ and $\alpha = 1.2$. This slope fits the observed light distribution with constant M/L and the rotation curve derived from OH/IR stars and 21 cm line observations (Mezger et al. 1996). Earlier observations, however, claim a slightly shallower slope (Catchpole, Whitelock, & Glass 1990). For clarity we adopt $\alpha = 1.2$ for the remainder of this paper. The density at distance R is then

$$\rho(R) = \frac{1}{4\pi R^2}\frac{dM}{dR} = \frac{A\alpha}{4\pi} R^{\alpha-3} \ . \tag{4}$$

Following Binney & Tremaine (1987), we find that the inspiral of the cluster toward the center owing to dynamical friction is described by (McMillan & Portegies Zwart 2003)

$$\frac{dR}{dt} = -2 \ln \Lambda \frac{\alpha\chi}{\alpha+1}\left(\frac{G}{A}\right)^{1/2} m R^{-(1/2)(\alpha+1)} \ . \tag{5}$$

Here m is constant and $\ln \Lambda \sim \ln(R/\langle r \rangle) \sim 5$ is a Coulomb logarithm (where $\langle r \rangle$ is the object's characteristic radius—roughly the half-mass radius in the case of a cluster), and $\chi \sim 0.3$ is a parameter that depends on the velocity of the cluster and the velocity dispersion of the stellar surroundings. In this case, $\chi \ln \Lambda \sim 1$. The adopted value of $\ln \Lambda$ is consistent with results from N-body simulations (Spinnato, Fellhauer, & Portegies Zwart 2003), who derive $\ln \Lambda = 6.6 \pm 0.6$ for a massive compact object that spirals in, and somewhat smaller than the value $\ln \Lambda \simeq \ln 0.4N$ used by Gerhard (2001), where N is the number of stars with which the cluster interacts. For simplicity we write equation (5) as

$$R^{(1/2)(\alpha+1)} dR = -\gamma\, dt \ . \tag{6}$$

Solving the differential equation (5) with $R(0) = R_i$ at time $t = 0$ results in

$$R(t) = R_i \left[1 - \frac{(3+\alpha)\gamma}{2R_i^{(1/2)(3+\alpha)}} t\right]^{2/(3+\alpha)} \ . \tag{7}$$

Inverting this equation with $R = R_f$ (the disruption radius) at $t = t_{\rm df}$ and substituting equation (3) gives

$$t_{\rm df} = \frac{\alpha+1}{\alpha(\alpha+3)} \frac{1}{\chi \ln \Lambda} m^{-1} \left[\frac{M(R_i)}{G}\right]^{1/2} \left[R_i^{3/2} - \kappa R_f^{3/2}\right] \ , \tag{8}$$

where $\kappa = (R_f/R_i)^{\alpha/2}$. For $\alpha = 1.2$, $\chi \ln \Lambda = 1$, and $R_f \ll R_i$, this becomes

$$t_{\rm df} = 1.34\left(\frac{m}{10^4\ M_\odot}\right)^{-1}\left(\frac{R_i}{1\ {\rm pc}}\right)^{(3+\alpha)/2}\ {\rm Myr}\ . \qquad (9)$$

3. RESULTS

In order to test the hypothesis that a cluster can experience core collapse before reaching the Galactic center, it is instructive to compare the dynamical friction in-spiral timescale with the timescale for internal cluster evolution. We define

$$\eta \equiv \frac{t_{\rm cc}}{t_{\rm df}} \simeq \frac{\alpha(\alpha+3)}{\alpha+1}\frac{c\chi \ln \Lambda}{8 \ln \lambda}\left(\frac{m}{M}\right)^{1/2}\frac{m}{\langle m\rangle}\frac{r_{\rm vir}^{3/2}}{R_i^{3/2} - \kappa R_f^{3/2}}\ . \qquad (10)$$

Here $\langle m\rangle$ is the mean mass of cluster stars. For small R_f, this reduces to

$$\eta \simeq \left(\frac{0.29 c\chi \ln \Lambda}{\ln \lambda}\right) n \left(\frac{m}{M}\right)^{1/2}\left(\frac{r_{\rm vir}}{R_i}\right)^{3/2}\ . \qquad (11)$$

There are now three distinct regimes:

1. If $\eta \ll 1$ [far from the Galactic center: $(R/{\rm pc})^{4.2} \gg (n/2.1 \times 10^3)^2[m/M_\odot](r_{\rm vir}/{\rm pc})^3$], the cluster core collapses essentially at its original distance from the Galactic center; thereafter it dissolves, mainly by tidal stripping and mass loss due to stellar evolution, at constant Galactocentric radius.
2. If $\eta \sim 1$ (intermediate distance to the Galactic center), cluster in-spiral and core collapse occur on about the same timescale.
3. If $\eta \gg 1$ (close to the Galactic center), the cluster spirals in without significant internal evolution.

For example, substituting the initial conditions of Table 1 ($m = 65,000\ M_\odot$, $r_{\rm vir} = 0.167$ pc) and equation (3) into equation (11), we can write

$$\eta \simeq 150 c\chi \frac{\ln \Lambda}{\ln \lambda} R^{-2.1}\ . \qquad (12)$$

Taking $c\chi \ln \Lambda/\ln \lambda \sim 0.13$, we find that this cluster will experience core collapse before it reaches the Galactic center if it was born at $R_i \gtrsim 4$ pc.

More generally, Figure 1 shows, as functions of Galactocentric radius, the virial radii (*solid curve*) and an estimate for the initial tidal radii (*dots*) of star clusters with masses and structure parameters as listed in Table 1, for clusters with $\eta = 1$ in equation (11) (core collapse upon arrival at the Galactic center), and take $c\chi \ln \Lambda/\ln \lambda \sim 0.13$. The dashed curve presents an estimate of the Jacobi radius of the star cluster in the Galactic tidal field (see eq. [4] in Gerhard 2001 or eq. [24] in McMillan & Portegies Zwart 2003). A 65,000 $M_\odot$ star cluster that is born with parameters to the right or below the solid curve is expected to experience core collapse before it reaches the Galactic center.

The circles and bullets at $r_{\rm vir} = 0.167$ pc in Figure 1 indicate the outcomes of simulations performed with cluster initial conditions as presented in Table 1, but with varying values of initial Galactocentric radius R_i. The initial models were placed at $R_i = 2$, 3, 4, 5, 6, and 8 pc. Bullets indicate that a model experienced core collapse before reaching the Galactic center; circles indicate disruption before significant contraction of the cluster core.

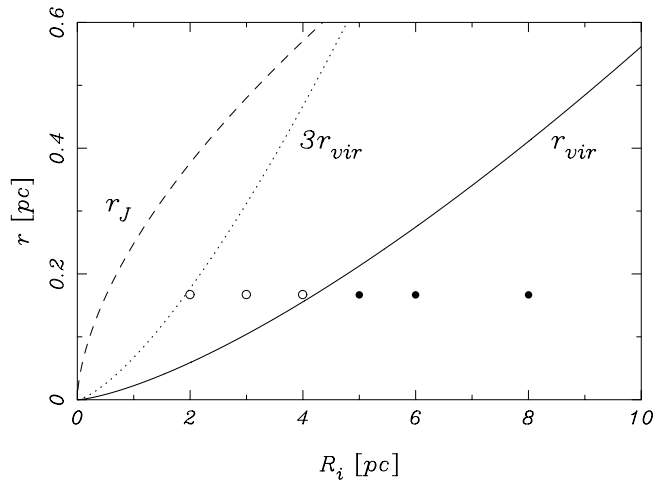

FIG. 1.—Virial radius $r_{\rm vir}$ of a cluster for which core collapse is expected by the time of arrival in the Galactic center (*solid curve*). Here the mass of the cluster is 65,000 $M_\odot$, with 64 k stars. The dotted curve gives 3 $r_{\rm vir}$, which corresponds to the radius where the cluster density goes to zero for a King model with $W_0 = 3$. The dashed line gives the Jacobi radius of the cluster in the tidal field of the Galaxy. Open circles and filled circles show the simulations performed for this study. Open circles indicate that the cluster dissolved before core collapse; filled circles indicate simulations that did experience core collapse.

The equations of motion of the 65,536 (64 k) stars in the simulations were computed using the Starlab software environment which combines the *N*-body integrator *kira* and the binary evolution package *SeBa* (Portegies Zwart et al. 2001).[5] The Galactic tidal field and the effects of dynamical friction were taken properly into account by solving equation (5) numerically during the integration of the equations of motion. In these calculations, the clusters could lose mass by tidal stripping, high-velocity stellar ejections, and stellar winds. At any moment in time we determined the total cluster mass from all bound stars; this may slightly underestimate the friction force. The dynamical friction term was then applied to each of the bound stars, but not to unbound stars. The calculations were carried out using the special-purpose GRAPE-6 computer (Makino et al. 1997; Makino 2001).

The results of the simulations in Table 2 may be summarized as follows. The models with $R_i = 2$ and 3 pc both dissolved at $R_f = 1.1$ pc. They did not experience core collapse, nor were any persistent hard binaries formed. (For definiteness, we take a cluster to have dissolved once the bound mass drops below 6000 $M_\odot$.) The model with $R_i = 4$ pc dissolved at $R_f = 1.3$ pc, but core collapse in this case is uncertain. A few hard ($E < -10\ kT$) binaries formed at $t = 0.51$ Myr, at a distance of $R = 2.3$ pc. One of these binaries hardened to $E \lesssim -50\ kT$ at $t = 0.63$ Myr and $R = 1.8$ pc; the cluster dissolved a little later, at $t = 0.83$ Myr. This ambiguity is consistent with the cluster's location close to the solid curve in Figure 1. The models with $R_i \geq$

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

TABLE 2
RESULTS OF MODEL SIMULATIONS

R_i (pc)	t_{cc} (Myr)	R_{cc} (pc)	t_{diss} (Myr)	R_f (pc)
2.....	...	...	1.08	1.1
3.....	...	...	1.01	1.1
4.....	...	...	0.83	1.3
5.....	0.65	3.3	1.19	1.8
6.....	0.68	4.6	>1.44	<2.5
8.....	0.56	7.0	>1.05	<6.4

5 pc all experienced core collapse at $t_{cc} \sim 0.6$ Myr. The $R_i = 5$ pc model dissolved at $t = 1.19$ Myr at a Galactocentric distance of $R_f = 1.8$ pc.[6] The other models were not continued to the point of dissolution.

Figure 2 shows a top view of the orbit of the cluster with $R_i = 5$ pc. The dotted curve indicates the expected orbit of the cluster if its mass would remain constant and was not affected by stellar evolution, internal relaxation, or by the external tidal field. This constant-mass point spirals in slightly more quickly than the cluster in which mass loss is taken into account self consistently (*solid curve*).

Figure 3 shows four subsequent snapshots (*gray scale and contours*) at time intervals of 0.4 Myr for the cluster with $R_i = 5$ pc.[7]

It is at first somewhat surprising that equation (11) agrees so well with the simulation results, as the cluster mass in the latter is a function of time that is neglected in the analytic form. Gerhard (2001) corrects for mass loss using an isothermal model, which implies that the cluster loses mass at a constant rate until disruption. This would result in a factor of 2 increase in the dynamical friction time. It turns out that this overestimates mass loss considerably (see Fig. 2). Most mass in the $W_0 = 3$ King model is lost near the end of the cluster lifetime when the stellar density in the environment becomes comparable to the cluster density near the half mass radius.

In the clusters that did not experience core collapse, stars at disruption were spread over a broad range in radii: $R_f \lesssim R \lesssim R_i$. Stars more massive than 40 $M_\odot$ were not distributed in a significantly different way from low-mass stars. However, in the $R_i = 5$ pc model, which did reach core collapse before disruption, the massive stars became much more centrally concentrated than the other cluster members. The more massive stars penetrated closer to the Galactic center because they sank to the cluster core, whereas low-mass stars were lost from the cluster at an earlier stage, when the cluster was farther from the Galactic center.

While we have shown that core-collapsed clusters preferentially deposit their most massive stars closest to the Galactic center, our models differ in some important ways from the observations reported by Genzel et al. (2000). The end-point of our $R_i = 5$ core-collapse cluster is a tight clump of stars with spatial extent (half-mass radius) comparable to those observed, but the clump was deposited at a radius of almost 2 pc, not within the innermost 1 pc, as is usually assumed (Krabbe et al. 1995). However, we expect that more massive clusters (starting with smaller virial radii or larger Galactocentric radii—see eq. [11]), more centrally concentrated systems or systems on elliptic orbits, penetrate deeper into the Galactic potential.

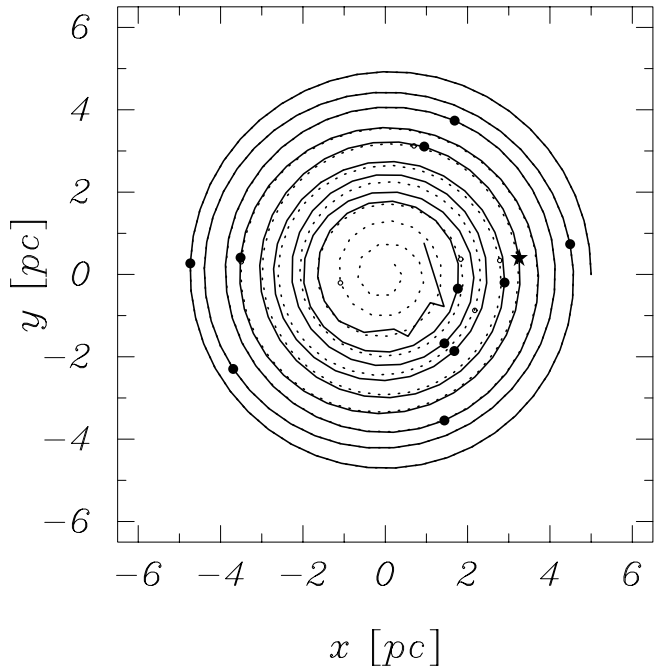

FIG. 2.—Orbital evolution of the star cluster with $R_i = 5$ pc (*solid curve*). The cluster is tracked via its density center, which becomes hard to determine accurately when the cluster contains only a few stars, i.e., near the Galactic center. The star indicated the moment of core collapse. The dotted curve shows the orbit for a constant-mass point with the same mass as the cluster at birth. The bullets in the orbit indicate 10^5 yr time intervals for the cluster orbit. In the dotted curve these intervals are indicated with small circles.

Genzel et al. (2000) present (their Fig. 5) the velocity anisotropy of 12 of the He I stars near the Galactic center. The anisotropy parameter is $\gamma \equiv (v_t^2 - v_r^2)/(v_t^2 + v_r^2)$, where v_t and v_r are the transverse and radial velocity components of the stellar proper motions. The average velocity anisotropy of these stars is $\langle\gamma\rangle = 0.59 \pm 0.48$. When we exclude the one star with an unusually low value of $\gamma = -0.83 \pm 0.33$, the average anisotropy increases to $\langle\gamma\rangle = 0.72 \pm 0.18$. We measured the velocity anisotropy among the star with a mass greater than 40 $M_\odot$ of our $R_i = 5$ pc model at the moment it disrupted and found $\langle\gamma\rangle = 0.79 \pm 0.23$. For all stars in the cluster the mean velocity anisotropy is $\langle\gamma\rangle = 0.04 \pm 0.63$, which is consistent with being isotropic. Likewise the sky-projected radial and tangential velocities of all 104 proper motion stars in the sample of Genzel et al. (2000) is consistent with overall isotropy.

If IRS 16 is indeed a remnant cluster core, our simulations provide no easy explanation of the rather broad stellar distribution perpendicular to the supposed cluster orbit plane, nor for the large dispersion in their velocities. The stars in our simulations are eventually spread out in the orbit plane; they are quite tightly confined in the direction perpendicular to this plane. The dispersion in the velocity distribution of these stars then would be on the order of the cluster velocity dispersion: on the order of 10 km s^{-1}, rather than the observed dispersion of a few 100 km s^{-1}. The disruption of

[6] An animation of this simulation is available at http://manybody.org/starlab.html. See also http://www.ids.ias.edu/~starlab/animations/.

[7] See http://manybody.org/stalab.html for an animation.

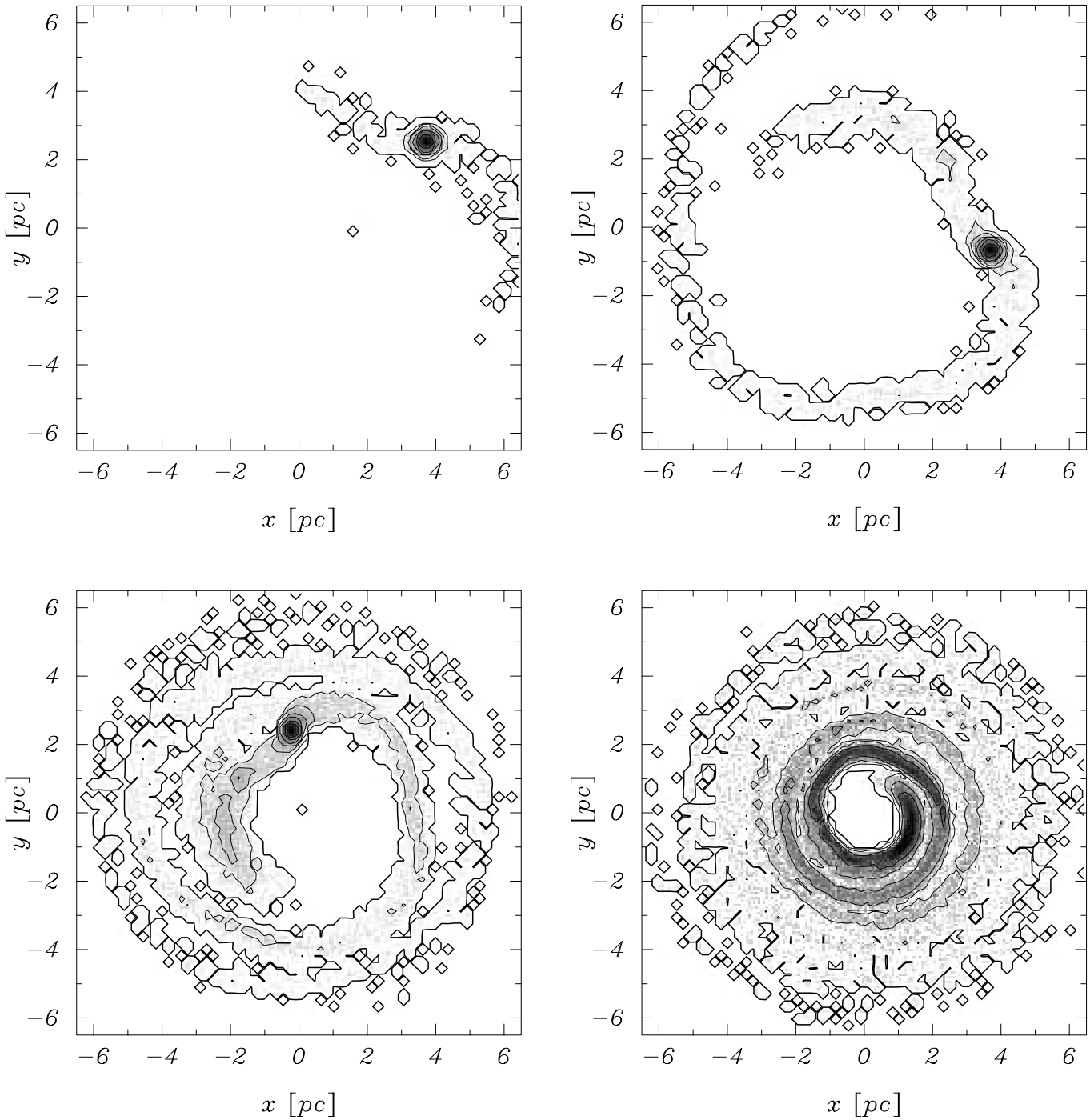

FIG. 3.—Top view of model $R_i = 5$ pc at $t = 0.1$, 0.4, 0.8, and 1.2 Myr. Density is gray-scaled linearly between maximum (*dark*) and zero density (*light*) scaled individually to each panel. The contours indicate a constant stellar density of 10 stars pc^{-3}, 50 stars pc^{-3}, 100 stars pc^{-3}, etc. (Note that this calculation was performed with a different value of ln Λ than was adopted in Fig. 2.)

two star clusters in short succession would not reproduce all kinematic information. We speculate that other dynamical processes, such as the effects of primordial binaries, the presence of a central black hole binary or possible inhomogeneities in the background potential, might have operated in IRS 16 to increase its scale height out of the plane and to drive the velocity dispersion to its observed values. At present, however, we have no ready solution to this conundrum.

4. SUMMARY

We have critically examined the hypothesis proposed by Gerhard (2001) that the group IRS 16 may be the remnant of a much larger cluster that formed farther from the Galactic center and sank toward the center via dynamical friction. IRS 16 contains about 40 early-type stars, including at least 15 very luminous He I stars, all lying within ~0.4 pc of the Galactic center.

We have studied this possibility by performing a series of direct N-body simulations in which dynamical friction is taken into account in a semianalytic fashion and included self-consistently in the equations of motion of the cluster stars. The N-body calculations were performed with 65,536 stars and were run on the GRAPE-6. Stellar masses were selected from a realistic mass function, and stars were initially distributed as a $W_0 = 3$ King model with virial radius $r_{\rm vir} = 0.167$ pc. We find that, in order for a clump of massive stars to survive, the cluster must have experienced core collapse during the in-spiral. Core-collapse deposits the observed high proportion of early-type stars close to the Galactic center and prevents a spread of massive stars to larger distances. The anisotropy observed for the early-type stars in IRS 16 is consistent with our model calculations. However, the spatial extent and high dispersion in the velocities of the observed cluster are not satisfactorily explained with the current simulations. The presence of primordial binaries or a binary of intermediate mass black holes in the cluster center may be required to explain these observations.

Our approximation to the dynamical friction term has some limitations, as the parameter $\chi \ln \Lambda$ is fixed in our simulations. In reality, this term may differ from the adopted value, will probably vary with time, and may depend on a number of external factors. More accurate measurements of this parameter are presented by Spinnato et al. (2003). Regardless of this uncertainty, we are still able to draw some firm conclusions. We find that dense star clusters in a strong tidal field experience core collapse on a timescale similar to that for an isolated cluster and that core collapse can occur before a cluster near the Galactic center is tidally disrupted.

When the cluster experiences core collapse, the fraction of massive stars deposited near the center is much greater than when core collapse is averted by tidal disruption. Our simulated clusters dissolve when their core densities fall below a few million $M_\odot$ pc^{-3}, more than an order of magnitude higher than the local background stellar density. Our calculations were performed using rather low concentration $W_0 = 3$ clusters. We expect that clusters with higher initial concentrations would penetrate deeper and more easily to the Galactic center. Variations in the initial orbit of the cluster may also prove to be efficient in transporting stars closer to the Galactic center. Note that our choice of initial conditions are possibly among the least favorable to explain the observations. The parameter space for clusters which experience core collapse before reaching the Galactic center may therefore be even larger than suggested here.

Our model calculations support the scenario proposed by Gerhard (2001) to explain the presence of a population of early-type stars within a parsec of the Galactic center. If born at a distance of $\sim$5 pc, the primordial cloud from which the cluster formed should have had an initial density on the order of 10^6 cm^{-3}, but this density might be lower if the stars in IRS 16 originated in a somewhat more massive cluster at a greater distance.

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