THE GALACTIC CENTER HE I STARS: REMAINS OF A DISSOLVED YOUNG CLUSTER?

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ABSTRACT

A massive young star cluster, initially embedded in its parent molecular cloud, will spiral into the Galactic Center from \( \lesssim 30n_6^{1/2} \) pc during the life-time of its most massive stars, if the combined total mass is \( \sim 10^6m_6M_\odot \). On its way inwards the system loses most of its mass to the strong tidal field, until the dense cluster core of high-mass stars is finally disrupted near the central black hole. A simple model is presented to argue that this scenario may under plausible conditions explain the observed location and rotation of the Galactic Center HeI stars. Accretion of star clusters into the Galactic Center could be recurrent, and play an important role in regulating the activity of Sgr A*. 

**Subject headings:** Galaxy: center – Galaxy: evolution – galaxies: nuclei – galaxies: star clusters – ISM: clouds – black hole physics

1. INTRODUCTION

The central parsec of the Galaxy contains a cluster of young stars, including some 15 very luminous HeI emission line stars (Krabbe et al. 1995), as well as many less massive O and probably B stars (Eckart et al. 1999). The HeI stars are believed to be part of a sequence supernova of stars of \( \sim 20-100M_\odot \), close to the Wolf-Rayet stage (Najarro et al. 1997). The most massive of these stars have a total age of \( \lesssim 3 \) Myr, while the less luminous stars could have ages up to \( \sim 8 \) Myr. Krabbe et al. (1995) have argued that the most likely origin of these stars is in a small starburst \( \sim 3-7 \) Myr ago, in which \( \gtrsim 10^4M_\odot \) of young stars were created.

In situ formation of these stars is problematic, however, because of the strong tidal field of the Galactic nuclear bulge and central black hole. The tidal forces from the Galactic nucleus alone are sufficient to unbind gas clouds with densities \( n_{\text{crit}} < 10^7 \) cm\(^{-3}\) (1.6 pc/\( R_G \))\(^{1.8} \) at galactocentric radii \( R_G \) (e.g., Morris 1993), while clouds in the nuclear gas disk have densities of \( 10^{-3}-3 \times 10^5 \) cm\(^{-3}\) (Genzel 1989, Güsten 1989). Hence Morris (1993) has argued that the formation of the central star cluster must have been externally triggered to achieve the required high densities, perhaps in a cloud collision. Two clouds coming in from \( \sim 10 \) pc would need to collide near the gravitational radius of the black hole (\( \sim 0.5 \) pc), at a velocity of several hundreds of km s\(^{-1}\); it is unclear whether the required densities and a high efficiency of star formation could be reached. Another model in which the massive stars form through collisions and mergers of lower mass stars in the high-density nuclear cluster now appears unlikely, both because too few massive stars would form (Lee 1994), and because similar stars have been found in the Arches and Quintuplet clusters some 30 pc away from the center (Nagata et al. 1995, Cotera et al. 1996, Figer et al. 1999a).

This letter therefore explores an alternative idea: that the young stars now seen in the Galactic Center (GC) formed further out in a massive star cluster that subsequently spiralled into the nucleus and tidally dissolved. One of the exciting results from HST has been the discovery of young star clusters in a variety of starburst environments (e.g., Whitmore & Schweizer 1995, O’Connell et al. 1995, Oestlin et al. 1998). We also know now that nuclear star clusters are common in spiral galaxies (Carollo et al. 1998, Matthews et al. 1999). The Arches and Quintuplet clusters at \( \sim 30 \) pc distance from the GC testify that a similar star formation mode has been occurring in the nuclear disk of the Galaxy. Both clusters have ages of a few megayears and estimated total masses (extrapolating the IMF to \( 1M_\odot \)) of \( \sim 10^4M_\odot \) (Figer et al. 1999b). The orbits of massive clusters evolve by dynamical friction against field stars in sufficiently dense stellar systems (Tremaine, Ostriker & Spitzer 1975). Here I show that a massive cluster formed well outside the central few parsecs will indeed spiral into the center within the lifetime of its most massive stars, losing much of its mass on the way inwards until finally its dense core is disrupted deep in the nucleus.

2. MASSIVE CLUSTER INFALL

Suppose a massive star cluster is formed at initial galactocentric radius \( R_i = 30R_{30} \) pc. The mass distribution of the nuclear bulge in \( 2 \) pc < \( R_G < 30 \) pc can be approximated as an isothermal sphere (Genzel, Hollenbach & Townes 1994, Fig. 7.1), with circular velocity \( v_c = 130v_{130} \) km s\(^{-1}\) in this range of radii, and

\[
M_G(R_G) = 3.9 \times 10^6v_{130}^2R_G[\text{pc}]M_\odot.
\]

Eq. (1) implies that the mean density within \( 10-30 \) pc corresponds to \( 10^{6.5}-10^{6.5} \) H-atoms per cm\(^3\), so in this region molecular clouds with the densities observed in the GC may indeed collapse and form stars.

The newly formed cluster will lose orbital energy by dynamical friction against the nuclear bulge stars and spiral into the center on a time-scale

\[
\tau_{df} = \frac{1.17 \times R_G^2v_c}{\ln(0.4N)GM_c} = 3.1 \times 10^6R_{30}v_{130}m_6^{-1}\lambda_{10}^{-1} \text{yr},
\]

where the cluster mass is \( m_c = 10^6m_6M_\odot \) and \( \lambda_{10} = \ln(0.4N)/10 > 1 \) with \( N \) the effective number of field stars (Binney & Tremaine 1987). Thus a massive cluster, \( m_c \sim 10^6M_\odot \), will indeed spiral into the center from
When the entire cluster is finally disrupted at radius \(R_{\text{dis}}\), only a fraction \(\sim R_{\text{dis}}/R_t\) of the initial mass \(m_{\text{ci}}\) will have arrived at \(R_{\text{dis}}\).

We can now write a modified dynamical friction equation using the same arguments as in Binney & Tremaine (1987), and assuming that the instantaneous specific angular momentum loss due to the frictional force is the same for stripped material and material that remains bound to the cluster. This gives \(R_G dR_G/dt = -0.428 G \ln(0.4N) v_c^{-1} m_{\text{ci}} (R_G/R_t)\), the solution of which is

\[
\tau_{\text{df}}(R_t, R_G) = R_t R_G v_c/0.428 \ln(0.4N) G m_{\text{ci}}
\]

Thus in this simple model the total time to spiral in from radius \(R_t\) is just twice that when the mass \(m_{\text{ci}}\) remains constant \([\text{eq. (2)}]\), and the time taken from radius \(R_G < R_t\) for a cluster that started out tidally limited at \(R_t\) is linearly proportional to \(R_G\). To reach the center in \(\sim 3 \times 10^6\) yr from \(R_t \approx 30\) pc (10 pc), a mass-losing cloud-cluster system must have an initial mass \(m_{\text{ci}} \approx 2 \times 10^6 M_\odot\) \((\sim 2 \times 10^5 M_\odot)\). The core of a cluster with initial mass \(2 \times 10^6 M_\odot\) formed at \(R_t \approx 10\) pc would have spiralled into the center after 300,000 years. These time-scales may be slightly overestimated because we have neglected torques from previously stripped material and \(\text{its} ~ \text{wake, left behind on orbits of lower frequency, as well as any additional drag from the nuclear gas disk. Perturbed material within a factor 1.5-2 in galactocentric radius contributes to the frictional drag (Tremaine & Weinberg 1984); over this radial range the cluster loses about half of its mass [eq. (7)].}

One constraint is that the cluster must not evaporate in the strong tidal field of the nuclear bulge before it reaches the center. In the \(m_c = 2 \times 10^4 M_\odot\) evolutionary models for the Arches and Quintuplet clusters by Kim et al. (1999) the evaporation time is several Myr. Evaporation occurs on a time-scale proportional to the half-mass relaxation time

\[
t_{rh} = 2.0 \times 10^8 m_c^{1/2} r_1^{3/2} m_{\odot}^{-1} \lambda_{10}^{-1} \text{ yr},
\]

(Spitzer & Hart 1971) but also strongly on the strength of the tidal field. Here \(r_{rh} = r_1 \text{ pc}\) is the cluster half-mass radius and \(m_s = m_{\odot} M_\odot\) the average stellar mass. \(t_{rh}\) is sensitive to the uncertain half-mass radius. For the Arches cluster Figer et al. (1999a) estimated \(r_{rh} = 0.2 \text{ pc}\) from the observed high-mass stars, i.e., without correction for initial or dynamical mass segregation. We can rewrite \(t_{rh} \propto m_c^{1/2} r_1^{3/2} \propto m_c \rho^{-1/2}\) and consider the mean density to be fixed by the external tidal field. This suggests independently that only clusters significantly more massive or formed at smaller radii than the Arches cluster can reach the central parsec.

3. FINAL TIDAL DISRUPTION AND THE HE I STAR CLUSTER

The preceding discussion shows that only the inner parts of a massive young star cluster will spiral into the Galactic center proper, while its outer parts and the cloud envelope will be left behind and distributed further out. There are good reasons to believe that the massive stars will be
concentrated towards the cluster core. There is some evidence that high-mass stars form predominantly in or near the cores of young clusters (Fischer et al. 1998, Bonnell & Davies 1998). After star formation is complete, dynamical mass segregation will further accentuate the central concentration of massive stars, acting on their two-body relaxation time-scale. Thus the most massive cluster stars end up in the GC, as is needed to explain the observed distribution of HeI stars.

Under what conditions is the density of the cluster core high enough to reach the central parsec? The GC HeI distribution of HeI stars is consistent with disruption at radii \( \sim 0.15 \) pc (some tens of arcsec) or further out if the tidal force of the central black hole dominates that from the nuclear bulge. We can thus estimate the required mean density of the cluster core at \( R_{\text{dis}} \) as

\[
\rho_{\text{dis}} = 3m_\alpha(R_{\text{dis}}/4\pi r_i^3) = 6M_\odot/4\pi R_{\text{dis}}^3 \approx 2.2 \times 10^7 M_\odot (R_{\text{dis}}/0.4 \text{ pc})^{-3} M_\odot \text{ pc}^{-3},
\]

where we have written the black hole mass as \( M_\bullet = 3 \times 10^6 M_\odot \) (Genzel et al. 2000). Notice the sensitivity to the disruption radius.

The observed average stellar density in the Arches cluster, extrapolated to include stars down to 1 M\odot, is 6.3 \times 10^3 M_\odot/\text{pc}^3 (Figer et al. 1999a). The 2 \times 10^4 M_\odot models of Kim et al. (1999) show that dynamical evolution and mass segregation lead to the formation of a core of high mass stars with density reaching \( \rho_c \approx 10^7 M_\odot/\text{pc}^3 \) in the mild core collapse stage, after \( \sim 1 \) Myr evolution. Central densities of \( \sim 10^7 M_\odot/\text{pc}^3 \) can thus be reached in later evolutionary stages, high enough for the core to survive to \( R_{\text{dis}} \approx 0.4 \) pc, but significantly larger densities (required for smaller \( R_{\text{dis}} \)) would seem problematic.

The time-scale for this evolution is a small number of relaxation times for the massive stars (Chernoff & Weinberg 1990). If evolution is too fast, the core may reexpand before the cluster has time to reach the GC; this would be the case for the Arches cluster models. For clusters with initial masses \( m_c \gtrsim 3 \times 10^5 M_\odot \), the mass segregation time for 30 M\odot stars is \( \sim 2 \times 10^8 \) yr, using (9) and scaling radii such that \( r_0 \propto m_c^{0.3} \). Thus in the initial stages dynamical evolution is relatively slow. As the cluster spirals in and loses mass, however, the evolution accelerates: the half-mass relaxation time decreases because both the cluster mass and half-mass radius decrease, and the external tidal field becomes stronger, so that the mass evaporating per relaxation time increases. Thus the most rapid dynamical evolution is expected to take place when the stripped-down cluster approaches the center. At the time of final disruption, its mass is a small fraction of the initial mass, comparable to the model clusters studied by Kim et al. (1999) in which the time-scale for core collapse is \( \sim 10^8 \) yr. Thus it is not improbable that such a cluster reaches core collapse shortly before it arrives at the Galactic Center. The high cluster core density required for the core to reach \( R_{\text{dis}} \approx 0.4 \) pc would then most easily be maintained in a phase after core collapse when the energy loss of the core from collisions is compensated by the energy gain from three-body binaries. This requires the core to be dominated by the 100 most massive stars (Binney & Tremaine 1987), previously concentrated into this volume by mass segregation.

After the high-density cluster core has reached \( R_{\text{dis}} \sim 0.4 \) pc and begins to disintegrate, it continues to spiral inwards until torques from its friction wake and the material lost previously (see §2) become ineffective, that is, until the debris has spread in angle by \( \Delta \phi \sim \pi \). The time for the debris within \( \alpha r_i \) of the cluster center to spread by \( \Delta \phi = \pi \)

\[
t_{\text{spr}} \equiv \frac{\pi}{\frac{\alpha}{\alpha_{\text{crit}}}(R_{\text{dis}})} = t_{\text{rot}} \frac{R_{\text{dis}}}{6 \alpha r_i(R_{\text{dis}})},
\]

which gives of order \( t_{\text{rot}}/\alpha \) according to eqs. (5), (6). The rotation period near the black hole is \( t_{\text{rot}} = 13700 M_\odot^{1/2}(R_G/0.4 \text{ pc})^{3/2} \) yr, so for the cluster center \( t_{\text{rot}}/\alpha \) can be several \( 10^4 \) yr. For comparison, the dynamical friction time (2) for \( 10^4 M_\odot \) to spiral from \( R_{\text{dis}} = 0.4 \) pc into the center completely is only 50000 yr. This suggests that the debris of the cluster core will spiral inwards significantly even after the final disruption, and that therefore the rotation pattern observed down to \( R_G \approx 0.15 \) pc is consistent with disruption at radii \( \sim 0.4 \) pc. It will be interesting to simulate this disruption event in the black hole’s tidal field with numerical star cluster models.

4. DISCUSSION

In summary, the previous sections have shown that under plausible conditions a young star cluster formed in the Galactic nuclear disk may spiral into the GC within the life-time of its most massive stars, and that the density in its core of high-mass stars can be such that it would actually reach and dissolve in the region where the GC HeI stars are observed. The important parameters are the initial galactocentric radius, the cluster mass and radius, and the mass and density of the surrounding molecular cloud. To reach the center from initial radii \( R_i \sim 10-30 \) pc, the cluster must be substantially more massive than the Arches and Quintuplet clusters or the frictional force must at least initially be augmented by the wake of the surrounding molecular cloud, or both. Large cluster masses are also required to avoid too rapid dynamical evaporation and evolution in the strong tidal field.

A prediction of the present model for the origin of the GC HeI stars is that the massive stars in the core of the disrupting young cluster should end up at smaller galactocentric radii than lower mass stars in the cluster envelope. Krabbe et al. (1995) estimate the total stellar mass corresponding to the nuclear HeI star cluster as \( \sim 1.5 \times 10^4 M_\odot \), assuming a mass function \( N(m) \propto m^{-2} dm \) down to \( m_* = 1 M_\odot \). The number of low-mass stars associated with the cluster is unknown, but a standard Salpeter IMF with the same number of the highest mass stars, extrapolated to \( m_* = 0.1 M_\odot \), would give \( \sim 10^5 M_\odot \). Most of these stars should now be found at galactocentric radii of a few parsec (some tens of arcsec) or further out if the cluster was even more massive. Could these stars be related to the young population inferred by Philipp et al. (1999), or was the formation of the cluster just part of a larger-scale starburst?
As in alternative models, the observed counterrotation of the HeI stars with respect to Galactic rotation (Genzel et al. 2000) is not inherent in the present scenario. However, a large molecular cloud entering the nuclear disk with orbital angular momentum roughly antialigned with Galactic rotation would sooner or later suffer a strong collision, and this in fact might be the event triggering the formation of the cluster. The subsequent dynamical friction on the cluster and its surrounding cloud envelope would then tend to circularize the counterrotating orbit while the cluster spirals in, explaining the rotating torus structure of the HeI stars observed now. This observation would be more difficult to explain in models where the GC young stars form in a cloud collision near their present location, because some of these stars should then still reflect the cloud’s initial orbital motion.

How common could cluster accretion events be in the GC? The presence of $\sim 10^8$ yr old AGB stars in the central parsec (Krabbe et al. 1995) suggests that it has happened before, and perhaps one of the massive molecular clouds in the vicinity is the next candidate. Clearly, a cluster accretion rate of $\sim 10^5 M_\odot$ per $3 \times 10^8$ yr would build up substantial mass in the nuclear bulge over time. The total mass inflow rate of $\sim 0.1 M_\odot$/yr inferred from dynamical friction on the GC giant molecular clouds on $x_2$-orbits at $\sim 100$ pc (Stark et al. 1991), and somewhat more from gas flow through the ILR at $\sim 200$ pc (Gerhard 1992, Morris & Serabyn 1996) would supply sufficient gaseous material to maintain this rate of cluster formation in addition to other distributed star formation. Detailed observations of the young stellar population in the GC are needed to see whether the process actually happens recurrently and whether it is a substantial factor in building up the nuclear bulge. Early-on, clusters would spiral in as far as there are field stars to provide the background for dynamical friction. Later clusters would come in further and build up a density gradient (assuming the angular momentum can be further transported outwards), but only some would reach the vicinity of the black hole. In the simple model described in Section 2, where both the nuclear bulge and cluster density profiles are $\propto r^{-2}$, the ingoing cluster’s tidally stripped material would also be distributed $\propto r^{-2}$.

Independent of the rate of cluster accretion, the recent arrival in the GC of a cluster with a large number of massive stars would have profoundly changed the physical conditions in the central parsec and may in fact be responsible for the present lack of activity of Sgr A*. If so, stellar population studies of the frequency of cluster accretion in the GC will have some general impact on understanding the nuclear activity cycles in spiral galaxies.

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