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# Stellar Collisions and Mergers in the Galactic Center

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**Abstract.** Stars are most likely to merge or collide in regions of the highest stellar densities, and our own Galactic Center contains many stars packed into a relatively small volume – even the ambient stellar number density in the central 50 $pc$ is quite high, $\sim 10^3$ $stars\ pc^{-3}$. More striking, the three compact young clusters in this region have central densities as high as $10^6$ $stars\ pc^{-3}$. We discuss these extreme environments and the possibility that stellar mergers and collisions have recently occured there. In particular, we predict that at least one massive star in the Arches cluster has already experienced a stellar merger in its short lifetime. Further, the Pistol Star, in the nearby Quintuplet cluster, might owe its apparent relative youth to a rejuvinating stellar merger. Finally, the apparently young stars in the central arcsecond could be products of either collisions, inducing atmospheric stripping, or mergers.

## 1. Introduction

The Galactic Center (GC) is a very dense stellar environment and was recognized early on as a region which might contain products of stellar mergers and collisions. Soon after the identification of the dense stellar cluster in the GC (Becklin et al. 1978), Lacy, Townes, & Hollenbach (1982) suggested that material in the ionized gas in the GC mini-spiral was produced by star-star collisions, but it is now thought that the mini-spiral traces gas pulled in from a wayward molecular cloud, or the nearby circumnuclear ring. Nonetheless, stellar collisions and mergers may still play an important role in describing phenomena in the central parsec. Indeed, a new favorite target for this possibility is the tight cluster of stars in the central arcsecond (Bailey & Davies 1998; Alexander 1999), as its high velocity stars appear (Genzel et al. 1997; Ghez et al. 1998) to be very young (Eckart et al. 1999; Figer et al. 2000).

There are, at least, two other interesting regions, as regards stellar collisions, just 30 $pc$, in projection, from the center: the Arches cluster (Nagata et al. 1995; Cotera et al. 1996; Serabyn, Shupe, & Figer 1997; Figer et al. 1999a), and the Quintuplet cluster (Okuda et al. 1990; Nagata et al. 1990; Glass, Moneti, & Moorwood 1990; Figer, McLean, & Morris 1999b). They are nearly identical to each other, and to the young cluster in the central parsec, except for age – the Arches cluster is ∼2 Myr old, half the age of the other two clusters.

This paper is an introduction to the GC, and objects therein, as it pertains to studies of stellar collisions and mergers. We start by introducing the environment of the GC and finish with 3 case studies of potential mergers or collisions.

## 2. An Introduction to the Galactic Center for Stellar Merger/Collision Astronomers

For this paper, the GC refers to the central 100 *pc* wherein the central mass density approximately follows a power law, with slope $\sim -2$ (Becklin & Negebauer 1968; Lindqvist et al. 1992). The enclosed mass within r∼ 50 *pc* is $\sim\ 3(10^8)\ M_\odot$ (Lindqvist et al. 1992), and the stellar volume density is estimated to be $> 5(10^5)$ *stars* $pc^{-3}$ at r = 1 *pc*. In addition to the molecular gas and largely old stellar population, there is ample evidence of star formation in the GC.

Radio data reveal many embedded HII regions which likely harbor massive stars that are currently forming. Indeed, the Sgr A West Mini-spiral, Sickle, and Thermal Arched Filaments are tracers for gas ionized by spectacular young stellar clusters: 1) the central cluster, 2) the Quintuplet cluster, and 3) the Arches cluster. The central cluster has attracted the most attention over the past 30 years, being the first discovered (Becklin & Negebauer 1968).

The Central cluster contains over 30 evolved massive stars having $M_{\rm initial} > 20\ M_\odot$(Forrest et al. 1987; Allen et al. 1990; Krabbe et al. 1991; Krabbe et al. 1995; Eckart et al. 1995; Libonate et al. 1995; Blum et al. 1995; Genzel et al. 1996; Tamblyn et al. 1996). A current estimate of the young population includes ≈10 WR stars, 20 stars with Ofpe/WN9-like *K*-band spectra, several red supergiants, and many luminous mid-infrared sources in a region of 1.6 pc in diameter centered on Sgr A$^*$ The spatial distribution of the early- and late-type stars has been the subject of several different studies (Becklin & Neugebauer 1968, Allen 1994, Rieke & Rieke 1994, Eckart et al. 1995, Genzel et al. 1996). The continuum surface distribution maps reveal that early-type stars concentrate towards the center, i.e. in the IRS16 sources, but red giants and supergiants are mainly concentrated outside of a $5''$ region near the center.

Najarro et al. (1994) and Najarro et al. (1997) have modelled a half dozen members of the non-WR hot stellar population in the center, finding that they are generally "Ofpe/WN9" stars with strong winds ($\dot{M} \sim 5$ to $80 \times 10^{-5}\ M_\odot\ yr^{-1}$) and relatively small outflow velocities ($v_\infty \sim$ 300 to 1,000 km s$^{-1}$). The effective temperatures of these objects were found to range from 17,000 K to 30,000 K with corresponding stellar luminosities of 1 to $30 \times 10^5\ L_\odot$. These results, together with the strongly enhanced helium abundances ($n_{\rm He}/n_{\rm H} > 0.5$), indicate that the He I emission line stars power the central parsec and belong to a young stellar cluster of massive stars which formed a few million years ago.

The Quintuplet Cluster is equally impressive for its stellar content, containing over 30 stars having $M_{\rm initial} > 20\ M_\odot$, including 4 WC types, 4 WN types, 2 LBVs, and many OBI stars (Figer, McLean, & Morris 1999b). First noted for its five bright infrared sources (Okuda et al. 1990, Nagata et al. 1990,

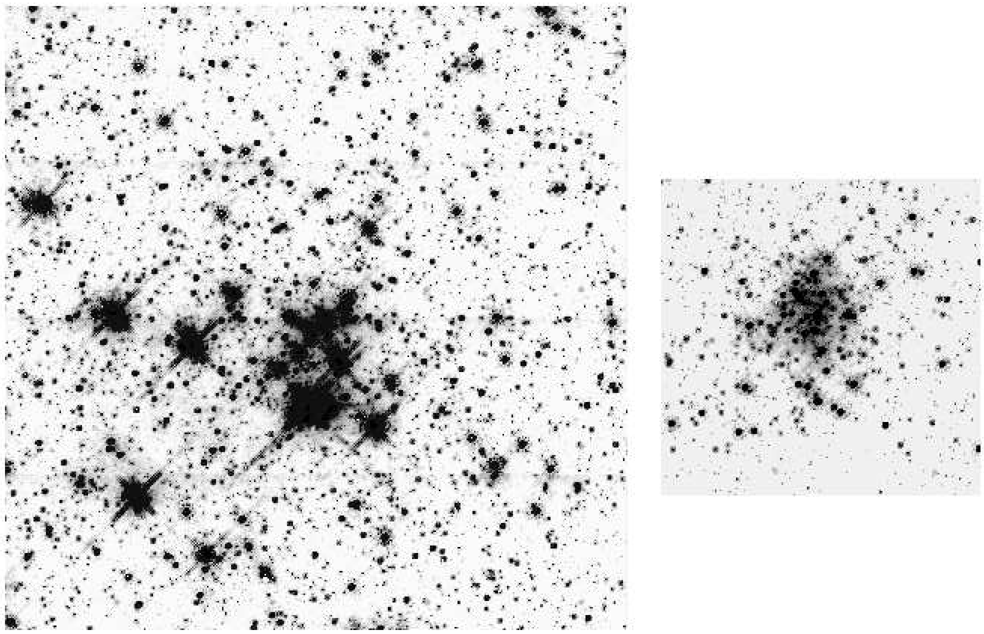

Figure 1. HST/NICMOS images of the Quintuplet (*left*) and Arches (*right*) custers (Figer et al. 1999a).

Glass et al. 1990), the cluster is now known to contain thousands of stars (Figer et al. 1999a; see Figure 1). Of them, the Pistol Star (LBV) is the most luminous, L$\sim 10^{6.6}$ $L_\odot$, and star #362 (LBV) in Figer, McLean, & Morris (1999b; Geballe et al. 2000) is a close second. Given the mix of spectral subtypes for the most luminous stars, Figer, McLean, & Morris (1999b) estimate a cluster age of 3$-$5 Myr, although significant age differences remain, i.e., the Pistol Star is thought to be $\approx$ 2 Myrs old (Figer et al. 1998).

The Arches cluster contains a dense collection of emission-line stars (Nagata et al. 1995; Cotera et al. 1996), and several thousand fainter members within a half-light radius of $\approx$0.2 pc (Figer et al. 1999a). In fact, this cluster is the densest and one of the most massive young clusters in the galaxy, having a central density $> 5(10^5)$ $M_\odot$ $pc^{-3}$, and a total mass $>$ $10^4$ $M_\odot$.

In general, the three Galactic Center clusters are young ($<$ 5 Myr), compact ($<$ 1 pc), and appear to be as massive as the smallest Galactic globular clusters ($\sim 10^4$ $M_\odot$). However, these compact young clusters have several interesting dynamical characteristics that distinguish them from globular clusters: 1) they have short dynamical timescales ($t_{dyn} \sim 10^{5-6}$ yr and $t_{rh} \sim 10^{6-7}$ yr, respectively); 2) they are situated in strong tidal fields (the tidal radius of $10^4 M_\odot$ cluster located 30 pc from the Galactic center is $\sim$ 1 pc); and 3) mass segregation may occur on a timescale shorter than the lifetimes of the most massive stars in these clusters, i.e. massive stars may play an important role in the dynamical evolution of the cluster.

## 3. Three Galactic Center Testbeds for Studying Mergers and Collisions

### 3.1. The Pistol Star - Is It the "Smoking Gun"?

The "Pistol Star," located roughly at the center of curvature of the Pistol HII region in the Quintuplet cluster, is one of the most luminous and massive stars in the Galaxy (Figer et al. 1998; see Figure 2). Its initial mass, $\sim 150\ M_{\odot}$, is so great, that Figer et al. (1998) predict a very short lifetime of $\sim 2\ Myr$, yet most of the other stars in the Quintuplet are twice as old. The crossing time in the cluster is $\sim 10^5\ yr$, and the cluster has already made a complete orbit around the Galactic Center, assuming a circular orbit. In addition, its natal molecular cloud is nowhere to be seen. Given these facts, we assume that all of the stars in the cluster formed at roughly the same time. This begs the question as to how the Pistol Star, with its extreme high mass, can still be burning so bright after 4 Myr.

Figer et al. (1998) proposed that the star may have had an unusual formation history. They suggest that the star has very little angular momentum, which perhaps allowed its mass to grow so much, consequently, having less-than-average mass-loss towards the cool side of the HR diagram. During core hydrogen burning, it arrived at its Eddington limit and strongly increased its mass-loss rate. While this scenario is possible, it requires an age in the range 1.7−2.1 Myrs.

Another possible explanation relies on a stellar merger to create the Pistol Star. In this scenario, the Pistol Star is the result of a merger between two very massive stars, or, at the very least, a result of accretion-induced collisions between star-forming cores (Bonnell et al. 1998).

### 3.2. Collisions and Mergers in the Quintuplet and the Arches Clusters

The fact that we currently observe only two young clusters near the GC (except the central cluster right at the GC) raises a natural question about the lifetimes of these compact young clusters (CYCs). Using anisotropic Fokker-Planck (F-P) models, Kim, Morris, & Lee (1999; KML hereafter) surveyed lifetimes of CYCs for various initial mass functions (IMFs), cluster masses ($M$), and Galactocentric radii ($R_g$), and found that clusters with $M \lesssim 2 \times 10^4\ M_{\odot}$ and $R_g \lesssim 100$ pc evaporate in $\lesssim 10$ Myr. These unparalleled, short evaporation times ($t_{ev}$) of CYCs are first due to short $t_{dyn}$ and $t_{rh}$, and strong tidal forces, but the mass loss accompanying the evolution of massive stars is also responsible for shortening $t_{ev}$ of clusters that last longer than $\sim 3$ Myr.

F-P models are statistical models involving distribution functions. It is the statistical stability and fast computing time of the F-P models that the survey-type study by KML required. Takahashi & Portegies Zwart (1998) found a good agreement between anisotropic F-P models and N-body simulations for globular clusters by adopting an "apocenter criterion" and an appropriate coefficient for the speed of star removal behind the tidal radius (KML adopted these as well). However, some extreme conditions of CYCs may be inconsistent with the assumptions inherent to F-P models. As discussed in KML, the conditions required by F-P models, $t_{dyn} \lesssim t_{rh}$ and $t_{dyn} \lesssim t_{se}$ ($t_{se}$ is the stellar

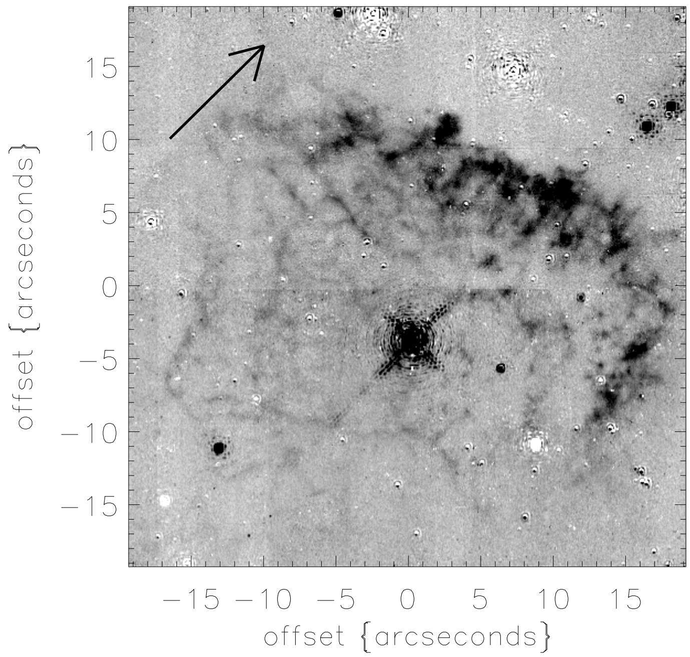


Figure 2. Pa-alpha image of Pistol Star and its surrounding nebula.

evolution timescale) may be violated, especially in the core at certain epochs. Moreover, the active participation of a large mass range of stars in the dynamics, which is another peculiarity of CYCs, is difficult to realize in F-P models that embody a mass spectrum with a restricted number (usually 10-20) of discrete mass components. A greater number of components would better express the mass spectrum, but then the number of stars in each component would become smaller. Since F-P models basically assume an infinite number of stars for each component, they overestimate the role of a component that has too few stars in it. On the contrary, too small a number of components would not properly realize the whole mass spectrum. By fixing the number of stars in the most massive components, KML tried to carefully account for a relatively small number of the most massive stars.

CYCs, estimated to have $\sim 10^{3-4}$ stars, are one of few systems for which real-number N-body simulations are feasible on current workstations. Among many virtues of N-body simulations, the natural realization of the mass spectrum and the tidal fields is particularly beneficial to the study of CYCs. These benefits make N-body simulations treat mass segregation and evaporation of stars exactly, thus providing better density profiles and mass spectra as a function of radius. These are photometric observables, and are partially available from the HST/NICMOS observations of the Arches and Quintuplet by Figer et al. (1999a; partial availability is owed to crowding at the cluster center and to the detection limit at the faint end of the luminosity function). The Arches and Quintuplet are estimated to be only $\sim 2$ and $\sim 4$ Myr old, respectively (Figer et al. 1999a), but their currently observed structures must already have deviated from the initial ones due to their rapid dynamical evolution. With both real-number N-body simulations and HST observations of the two clusters in hand, one has a rare chance of deriving not only the current characteristics of these systems, but their initial conditions as well.

We performed a series of N-body simulations 1) to compare the lifetimes of CYCs with those from F-P models obtained by KML, 2) to find the initial cluster conditions that best match the current observations of CYCs, and 3) to test the effects of initial mass segregation and different initial density profiles on dynamical evolution of the CYCs.

Kim et al. (2000) investigated the dynamical evolution of the Quintuplet and Arches clusters using Aarseth's Nbody6 codes. The simulations used a realistic number of test points (5,000–20,000), and thus represent an improvement over the Fokker-Planck (F-P) models (KML) which surveyed a variety of cluster lifetimes and initial conditions. In general, both the N-body and F-P models indicate that clusters with a mass $\lesssim 2 \times 10^4\,M_\odot$ evaporate in $\sim 10$ Myr. In addition, the N-body simulations were used with the observed projected number density profiles and stellar mass functions from *HST*/NICMOS observations by Figer et al. (1999a) to infer the initial conditions of the Arches cluster: a tidal radius of 1 *pc*, total mass of $2 \times 10^4\,M_\odot$, and mass function slope of $-0.7$ (versus $-1.35$ for Salpeter). We also find that the lower stellar mass limit, the amount of initial mass segregation, and the choice of initial density profile (King or Plummer models) do not significantly affect the dynamical evolution of CYCs.

The number of events in the cluster core may be calculated by

$$\int N_c n_c \sigma_{event} v_c dt, \tag{1}$$

where $N_\mathrm{c}$, $n_\mathrm{c}$, and $v_\mathrm{c}$ are number of stars, number density, and velocity in the core, and $\sigma_\mathrm{event}$ is the cross section of a certain event. $N_\mathrm{c}$ is roughly constant over time and does not vary much from cluster to cluster (from CYCs to globular clusters). We know that $n_\mathrm{c}$ and $v_\mathrm{c}$ of CYCs are similar to that of globular clusters (except for the Quintuplet which is thought to be in its final disruption phase). The largest difference comes from $\sigma_{event}$ which depends mostly on the size (in case of tidal interaction) of stars at the high density region. While the massive stars in globular clusters disappear before the corecollapse takes place, those in CYCs survive until the epoch of central density peak due to very short relaxation time. Since a significant mass segregation takes place during the first 1 Myr of the CYCs due to an exceptionally wide mass spectrum, the mean mass at the core quickly becomes very large. Thus $\sigma_{event}$ at the center of CYCs will be signicantly larger than that of globulars. But, the number of merger events in our most recent n-body calculations for the Arches (IMF slope = $\Gamma = -0.7$, initial mass = $2(10^4)$ $M_\odot$) is only a few (1-5). This is basically because the cluster does not live long (with high central densities). In any case, several runs predict a merger which results in a total mass larger than 200 $M_\odot$. This may exlain the existence of the Pistol Star.

If we put the Arches cluster to a place where the tidal radius would be 10 times larger than the current value, i.e. farther away from the Galactic center, the lifetime of the cluster would be 100 times longer. But this does not mean we would observe 100 times more merger events because the cluster would live with relatively small central densities for most of its lifetime. This is due to the rapid expansion of the core after 2 *Myr* when the stellar evolution stars. So, the number of events would be only slightly larger than at the current location of the Arches.

Note that our comparison between the N-body simulation and HST observations suggests a relatively flat IMF ($\Gamma = -0.7$). Massive stars have larger radii and thus larger collision cross sections. So those who do hydrodynamical simulations of close stellar encounters might consider encounters between very massive stars. We refer the reader to Kim & Lee (1999) for theoretical cross sections of tidal capture events between two stars with a large mass contrast.

### 3.3. The Central Parsec and the Stellar Cluster Near the Black Hole

The Central cluster has drawn the most attention regarding stellar collisions and mergers for obvious reasons, given its high stellar density and the region's strong gravitational field which produces high stellar velocities. From an observational point of view, Sellgren et al. (1990) noted an absence of bright red giants near the central $5''$, suggesting that stellar collisions might have disrupted the outer layers of such stars. While it is true that bright red giants are preferentially located outside the central few arcseconds, Figure 4 in Genzel et al. (1996) and Figure 2 in Figer et al. (2000) clearly show that spectra of background flux in the central few arcseconds exhibits CO absorption bandheads suggestive of K giants. The observational evidence, then, for collision-induced disruption of stellar atmospheres is strongest for the brightest red giants, for which Genzel et al. (1996) calculate that a core density of $10^{6.5}\ M_\odot\ pc^{-3}$ would be sufficient to generate the requisite number of star-star interactions; however, the impact parameter they used was too large to effect a complete ejection of the red giant atmosphere. Alexander (1999) revisited this issue, considering close interactions which could lead to the depletion of red giant atmospheres in the central few arcseconds. He concluded that it is possible to explain the lack of bright red giants in that region due to close encounters, but that this conclusion is critically dependent on a cusp-like distribution of those stars, i.e. a density of $> 5(10^7)\ M_\odot\ pc^{-3}$. Bailey & Davies (1999) performed a similar simulation, finding that stellar collisions are unlikely to have produced the apparent depletion of red giants in the center $5''$. In particular, they find that the collision rate is likely to have been too low. A final determination on this issue will await higher resolution imaging which would sample the distribution of stars in the center.

Another candidate for products of stellar mergers/collisions in the center lies in the dense cluster of stars in the central arcsecond (Genzel et al. 1997; Ghez et al. 1998). Genzel et al. (1997) first claimed that some of these dozen or so stars are similar in their K-band spectral morphology and brightnesses to OB main sequence stars. Using much higher spectral resolution, Eckart et al. (1999) and Figer et al. (2000) arrived at similar conclusions. Such stars only remain on the main sequence for 20 Myr, so they must have formed quite close to their current location; however, bound cores so near to the central black hole require extremely high densities, $> 10^{11}\ cm^{-3}$. In addition, OB main sequence stars have relatively high masses, $\sim\ 20\ M_\odot$, so the protostellar cores must have been very massive. An alternate possibility relies on stellar collisions to produce objects which only appear to be so hot. However, this is unlikely, given that the same requirements discussed above for the red giants pertain. In addition, it is questionable that a stripped red giant would have such large luminosities.

## 4. Conclusions

In conclusion, we find that the three young stellar clusters in the Galactic Center are prime proving grounds for stellar merger and collision theories. In particular, these clusters are the densest and most massive young clusters in the Galaxy. They have individual members which might be products of stellar mergers, i.e. the Pistol Star, and they may contain products of near-misses, or collision, i.e. in the Central cluster.

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