Massive Stars in Interacting Binaries
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Massive Binaries in the Galactic Center

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Abstract. We review the status of massive-star interaction research in the Galactic center (GC). Given the short lifetimes of massive stars, massive binaries will necessarily be located near their formation sites in starburst clusters. The GC contains three recently formed clusters having a very high stellar density, as high as 10^6 *stars* pc^{-3}. We discuss these extreme environments, and possible massive binaries therein. In addition, we argue that they may host the products of massive stellar mergers and collisions. In particular, we predict that at least one massive star in the Arches cluster has already experienced stellar merger events 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: Motivating Topics

This paper is motivated by three related topics: 1) massive-star interactions near the central black hole, 2) massive-star binary evolution in dense clusters, and 3) the most massive stars as binaries/mergers. These are necessarily big topics, so we limit our scope to their relation to phenomena in the Galactic center.

The GC harbors a significant fraction of young stars, and presumably massive binaries. Given the short lifetimes of massive stars, such binaries are likely to be found near the dense concentrations of young stars in the GC. Indeed, soon after the identification of the Central cluster (Becklin, Matthews, Neugebauer, & Willner 1978), Lacy et al. (1982) suggested that the ionized gas in the GC mini-spiral was produced by star-star mergers. While we now know that this gas is pulled from the circumnuclear ring, stellar 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 1999; Alexander 1999), as its high velocity stars (Genzel et al. 1997, 2003; Ghez et al. 1998) appear to be very young (Eckart, Ott, & Genzel 1999; Figer et al. 2000; Ghez et al. 2003). There are two other young clusters near the GC: the Arches cluster (Nagata et al. 1995; Cotera et al. 1996; Serabyn, Shupe, & Figer 1998; Figer et al. 1999a), and the Quintuplet cluster (Okuda et al. 1990; Nagata et al. 1990; Glass, Moneti, & Moorwood 1990; Figer, McLean, & Morris 1999b). 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 ($\sim 10^4\ M_\odot$).

2. Massive-Star Interactions Near the Central Black Hole

The Central cluster contains over 50 evolved massive stars surrounding the central supermassive black hole (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; Genzel et al. 2003). A current estimate of the young population includes at least 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; Krabbe et al. 1995; Genzel et al. 1996; Paumard et al. 2001). Najarro et al. (1994, 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. Ott, Eckart, & Genzel (1999) identify the only apparent massive binary in the Central cluster.

These young stars are superposed on a vast population of older late-type stars, presumably formed through the action of continuous star formation in the GC (Figer et al. 2004a). These stars create a deep CO bandhead in diffuse light in the region, yet Sellgren et al. (1990) and Haller et al. (1996) describe the absence of this feature in spectra of integrated light within 0.6 pc of the GC. They consider the hypothesis that CO in the atmospheres of late-type stars is destroyed by photo-dissociation or stellar collisions in the region. Others suggest altnerate explanations for the CO hole, i.e. stellar mergers/collisions (Lacy et al. 1982; Lee et al. 1996; Alexander 1999; Bailey & Davies 1999; Genzel et al. 1996, 2003), atmospheric stripping (Alexander & Livio 2001), and atmospheric heating (Alexander & Morris 2003). Figer et al. (2003) suggest that the lack of late-type stars may be caused by scattering with massive compact objects near the black hole. Indeed, Miralda-Escudé & Gould (2000) argue that a cluster of ∼24,000 stellar mass black holes should have migrated toward the central parsec through dynamical friction on a timescale of ∼10 *Gyr* (Morris 1993). They find through simulations that this cluster will eject stars on a time-scale of ∼1 *Gyr*. The requisite star formation needed to produce the stellar black holes is supported by the presence of young and intermediate-age stars in the GC: Lebofsky, Rieke, & Tokunaga (1982), Rieke (1987), Lebofsky & Rieke (1987), Haller & Rieke (1989), Haller (1992), Rieke et al. (1993), Blum, Depoy, & Sellgren (1995), Krabbe et al. (1995), Genzel et al. (1996), Narayanan, Gould, & Depoy (1996), Sjouwerman et al. (1999), Figer (2003), and Figer et al. (2004a).

3. Massive-Star Binary Evolution in Dense Clusters

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, Glass et al. 1990), the cluster contains 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. The Arches cluster contains a dense collection of emission-line stars (Nagata et al. 1995; Cotera et al. 1996; Blum et al. 2001; Figer et al. 2002), and several thousand fainter members within a half-light radius of ≈0.2 pc (Figer et al. 1999a). In fact, this cluster is the densest young cluster in the galaxy, having $\rho > 5(10^5)\ M_{\odot}\ pc^{-3}$.

These compact young clusters have several interesting dynamical characteristics: 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 a $10^4 M_{\odot}$ cluster located 30 pc from the Galactic center is ~ 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.

We have performed an N-body simulation to follow the evolution of binary systems in a Galactic-center star-cluster, using Aarseth's Nbody6 code and adopting cluster initial conditions for the Arches cluster. Kim et al. (2000) find that the present observations of the Arches cluster are best fit by the following initial values: total mass of $2 \times 10^4\ \mathrm{M}_{\odot}$, mass function slope of 1.75 (Salpeter being 2.35), lower stellar mass limit of $1\,\mathrm{M}_{\odot}$, upper stellar mass limit of $150\,\mathrm{M}_{\odot}$, tidal radius of 1.15 pc, and galacocentric radius of 30 pc. The adopted mass function gives a total stellar number of 2605. The initial number of binary systems adopted is 521, thus the initial fraction of stars in binaries is 40 %. The initial companion mass ratio distribution is obtained by random pairing of stars, and the initial eccentricity distribution is assumed to be thermally relaxed. For the initial period distribution, we adopt equation (8) of Kroupa (1995), which approximates the distribution of binary systems in the Galactic disk. This initial distribution is evolved prior to the start of the N-body integration to account for "pre-main-sequence eigenevolution" (see Kroupa 1995 for details), which reduces the number of initial binary systems to ~ 300.

Figure 1 (*left*) shows that the strong tidal field in the Galactic center makes the cluster lose its mass fairly quickly. The cluster disrupts in ~ 4 Myr. Figure 1 (*right*) also shows the radial distribution of binary systems that contain at least one star heavier than $20\,\mathrm{M}_{\odot}$. The binaries are initially more concentrated in the core, but as the cluster evolves and expands, binaries become rather evenly distributed. Figure 2 shows the evolution of the system mass of binaries. While most of the binaries have system masses less than $200\,\mathrm{M}_{\odot}$, one binary system acquires and maintains a system mass larger than $200\,\mathrm{M}_{\odot}$ for an extended period of time. This binary system has acquired a system mass of $673\,\mathrm{M}_{\odot}$ ($357\,\mathrm{M}_{\odot}$ + $356\,\mathrm{M}_{\odot}$), and is a result of one exchange event followed by three successive merging events. It appears that the most massive binary system has the highest chance of having exchanges or merging events with other massive stars. This is analagous to the runaway merging phenomenon found by Portegies Zwart et al. (1999).

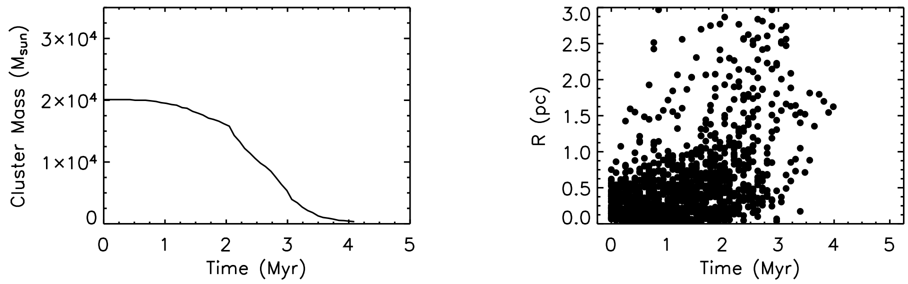

Figure 1. Cluster mass (*left*) and radial location of binary systems (*right*) as functions of time.

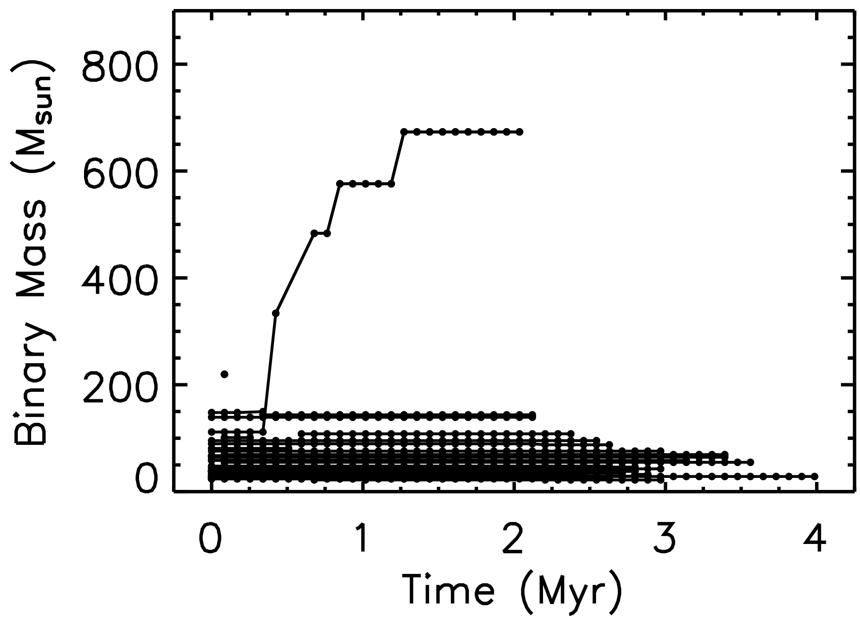

Figure 2. System mass for binaries in simulation as a function of time. Note that one system gains appreciable mass through direct mergers and particle exchange in three-body interactions.

4. The Most Massive Stars as Binaries/Mergers

The "Pistol Star," in the Quintuplet cluster, is one of the most luminous and massive stars in the Galaxy (Figer et al. 1998). Its initial mass, $\sim 150\ M_{\odot}$, suggests a short lifetime of $\sim 2\ Myr$. Oddly, most of the stars in the Quintuplet are twice as old. This discrepancy cannot be explained by continued star formation, given that the cluster crossing time is $\sim 10^5\ yr$, and the cluster has already made a complete orbit around the Galactic Center. This leaves the question as to how the Pistol Star, with its extremely high mass, can still be so bright after 4 *Myr*. One possible resolution relies on a stellar merger to give the Pistol star its present appearance. In this scenario, the Pistol star is the result of a merger between two very massive stars, such as that suggested in Figure 1 (*right*).

There is no direct observational evidence for binarity in the Pistol star; however, another nearly identical star in another region of the Galaxy provides a clue and now appears to be multiple. LBV 1806−20 has a system luminosity in excess of $>10^6\ L_\odot$, for which some have claimed very high mass estimates ($M_{\mathrm{initial}}>200\ M_\odot$) (Eikenberry et al. 2004). Figer, Najarro, & Kudritzki (2004b) show that this star is likely a binary, as shown in Figure 3. Just like the Pistol star, this star is surrounded by WR stars with ages at least 4 *Myr*. Again, if LBV 1806−20 were truly single with so much mass, it would not live longer than $\sim$3 *Myr*. Perhaps this star is "pre-merger" while the Pistol star is "post-merger."

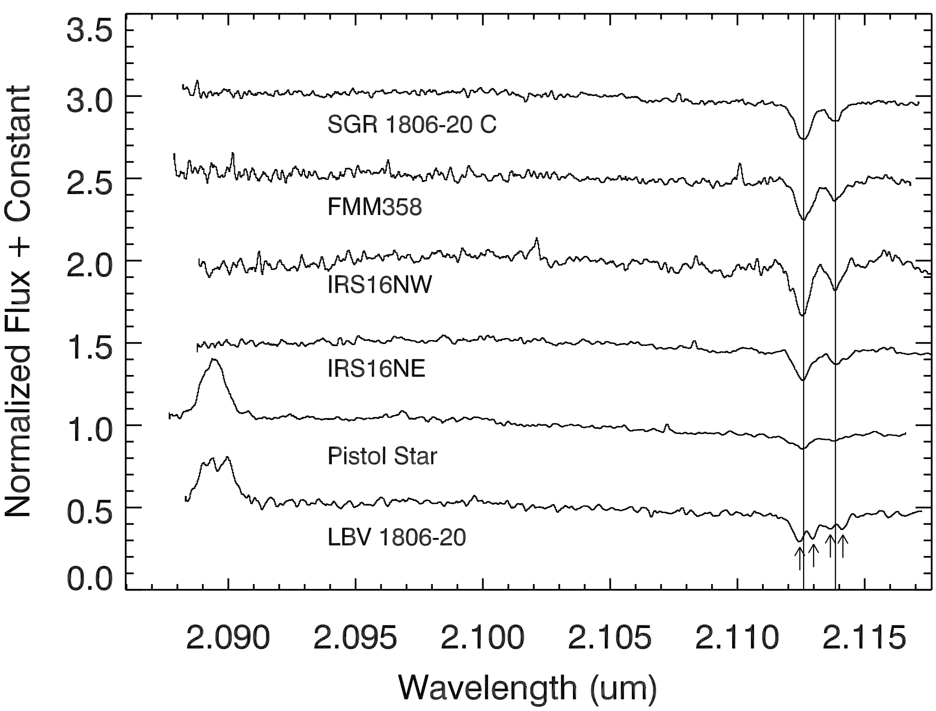

Figure 3. Spectra of massive stars near the 2.112/2.113 μm HeI doublet (Figer, Najarro, & Kudritzki 2004b). The Pistol Star, IRS16NE, and LBV 1806−20 are LBVs or LBV-candidates (Figer et al. 1998; Tamblyn et al. 1996; van Kerkwijk, Kulkarni, Matthews, & Neugebauer 1995), and the remaining stars are B-type supergiants (Figer et al. 1999a; Genzel et al. 1996). All the spectra show a single HeI doublet near 2.1125 μm, except that for LBV 1806−20, in which it is obviously double (marked by arrows). The broad feature near 2.089 μm is common to LBV spectra and corresponds to an FeII transition.

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Don Figer

Discussion

Sergey Marchenko: Considering the existence of the three clusters that you mentionned, which should disperse very quickly at the same time and at the same place, doesn't it look to you like a mini starburst?

Don Figer: A coordinated starburst?

Sergey Marchenko: Yes, well extended a little bit in time, because they are not exactly the same age. Considering the amount of material which *has* to be brought in to sustain this appearance of the clusters in the Galactic centre over the history of the Galaxy, doesn't it look like a starburst happened a couple of million years ago?

Don Figer: Right, well there's evidence of a build-up over 10 Gyrs of a population through continuous star formation at a level that we see in these three clusters. So it's not quite as extraordinary as you might think. Also, Sgr B2 is creating one of these right now.

Sergey Marchenko: But that will disappear in 5 Myrs from now. Aren't we lucky to see them all together at the same place at the same time?

Don Figer: There will be more in 5 Myrs from now. Sgr B2 will be one in 5 Myrs, because it's being made right now. Also, the Arches is 2 Myrs and the other two are 4 Myrs old. Two and four Myrs is too large a difference in the Galactic centre. That's one orbit of these clusters, so they can't communicate. The Quintuplet and the central cluster - that's odd that there are two that are exactly 4 Myrs.

Simon Portegies Zwart: Don, I'm very intrigued by your initial conditions for the Arches cluster and I know we have had a disagreement on that for 5 years now.

Don Figer: Yes! Which disagreement is this?

Simon Portegies Zwart: The disagreement about the mass function and the one you chose for simulations. Could you comment on that? Is the motivation just from the observations or do you *believe* that there is a lack of, or basically no, low-mass stars?

Don Figer: The mass function I showed had a slope of zero for stars less than 10 $M_\odot$ and then slightly shallower than Salpeter for more massive stars. We used -0.75, where Salpeter is -1.35. I doubt that the results would be much different. In fact you got the same results that I showed using the Salpeter mass function, right?

Simon Portegies Zwart: But the difference is whether or not the star cluster is a 2000, 20 000 or maybe 50 000 particle system. That's a huge difference in number.

Don Figer: Right. So if you integrate the mass function down to zero individual mass, you get roughly 10 000 solar masses, of which 95 % of that is already counted in observations, right? So if you want to say that the initial mass of the Arches cluster was *more*, then you could argue that it was much more massive initially and all that extra mass was kicked out over the years. But we don't have observational evidence for that.

Simon Portegies Zwart: Yes, OK.

Norbert Langer: It took 5 years to disagree, now it takes 5 minutes to agree. [Laughter.]

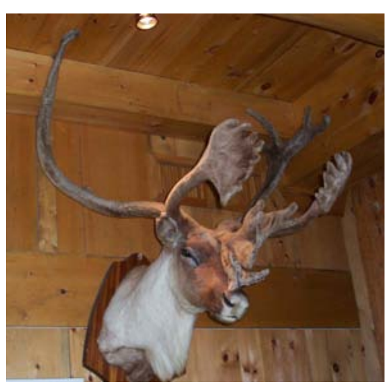
Farhad Yusef-Zadeh: Don, I was interested in what you said that there is nonthermal emission from the Pistol star. Earlier in the week we heard that if you see nonthermal emission, then you have a binary system: it comes from colliding stellar-winds. It's very difficult to get nonthermal emission from a single star.

Don Figer: Right. I clarified that with Stan. That statement, that you couldn't get nonthermal emission from shocks in winds from a single source, should be revised. But they didn't address the question if you could get enough nonthermal emission from circumstellar matter that's being shocked by a wind. It's a very different statement, actually, than the statement that was made. It doesn't mean that it has to be binary.

Farhad Yusef-Zadeh: Right. But in any case I think you have to be careful. There's plenty of extended emission where the Pistol star is. It's very likely that the emission is part of the nebula rather than the Pistol star.

Simon Portegies Zwart: Or from that little bipolar thing.

Farhad Yusef-Zadeh: I wouldn't trust that.



One of the many natural hotel ornaments