

Massive Star Formation in the Galactic Center

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The Galactic center is a hotbed of star formation activity, containing the most massive star formation site and three of the most massive young star clusters in the Galaxy. Given such a rich environment, it contains more stars with initial masses above $100 M_{\odot}$ than anywhere else in the Galaxy. This review concerns the young stellar population in the Galactic center, as it relates to massive star formation in the region. The sample includes stars in the three massive stellar clusters, the population of younger stars in the present sites of star formation, the stars surrounding the central black hole, and the bulk of the stars in the field population. The fossil record in the Galactic center suggests that the recently formed massive stars there are present-day examples of similar populations that must have been formed through star formation episodes stretching back to the time period when the Galaxy was forming.

1. Introduction

The Galactic center (GC) is an exceptional region for testing massive star formation and evolution models. It contains 10% of the present star formation activity in the Galaxy, yet fills only a tiny fraction of a percent of the volume in the Galactic disk[†]. The initial conditions for star formation in the GC are unique in the Galaxy. The molecular clouds in the region are extraordinarily dense, under high thermal pressure, and are subject to a strong gravitational tidal field. Morris (1993) argue that these conditions may favor the preferential formation of high mass stars. Being the closest galactic nucleus, the GC gives us an opportunity to observe processes that potentially have wide applicability in other galaxies, both in their centers and in the interaction regions of merging galaxies. Finally, the GC may be the richest site of certain exotic processes and objects in the Galaxy, i.e. runaway stellar mergers leading to intermediate mass black holes and stellar rejuvenation through atmospheric stripping, to name a few.

This review is primarily concerned with massive star formation in the region. For thorough reviews on a variety of topics concerning the Galactic center, see Genzel & Townes (1987), Genzel et al. (1994), Morris & Serabyn (1996), and Eckart et al. (2005).

2. The Galactic center environment and star formation

The star formation efficiency in the GC appears to be high. Plotting the surface star formation rate ($\Sigma_{\text{SFR}} \sim 5 M_{\odot} \text{ yr}^{-1} \text{ pc}^{-2}$) versus surface gas density ($\Sigma_{\text{H}_2} \sim 400 M_{\odot} \text{ pc}^{-2}$) in a “Schmidt plot” suggests an efficiency of nearly 100%, comparable to that of the most intense infrared circumnuclear starbursts in other galaxies and a factor of twenty higher than in typical galaxies (see Figure 7 in Kennicutt 1998). It is also higher than that elsewhere in the Galaxy; commensurately, stars in the GC emit about 5-10% of the Galaxy’s ionizing radiation and infrared luminosity.

[†] For the purposes of this review, the GC refers to a cylindrical volume with radius of ≈ 500 pc and thickness of ≈ 60 pc that is centered on the Galactic nucleus and is coincident with a region of increased dust and gas density, often referred to as the “Central Molecular Zone” (Serabyn & Morris 1996).

Morris & Serabyn (1996) review the content and conditions of the interstellar medium in the “Central Molecular Zone” (CMZ), noting that the molecular clouds in the region are extraordinarily dense ($n > 10^4 \text{ cm}^{-3}$) and warm ($T \sim 70 \text{ K}$) with respect to those found in the disk of the Galaxy. Stark *et al.* (1989) argue that the density and internal velocities of clouds in the GC are a direct result of the strong tidal fields in the region, i.e. only the dense survive. Serabyn & Morris (1996) argue that the inexorable inflow of molecular material from further out in the Galaxy powers continuous and robust star formation activity in the region.

It is still unclear how magnetic field strength affects star formation. If it does matter, then the GC might be expected to reveal such effects. The strength of the magnetic field in the GC has been estimated through far infrared polarized light from aligned dust grains (Hildebrand *et al.* 1993; Chuss *et al.* 2003) and Zeeman splitting of the OH molecule (Plante, Lo, & Crutcher 1995). In both cases, the field is inferred to be of milliGauss strength. However, Uchida & Guesten (1995) argue strongly that these strengths are localized to bundles that delineate the extraordinary non-thermal filaments in the region (Yusef-Zadeh & Morris 1987), and are not representative of the field strength that is pervasive in the region. If this is correct, then the fields inside GC molecular clouds may not be so strong versus those inside disk clouds ($B \sim 3 \mu\text{G}$).

Metals in molecular clouds can provide cooling that aids protostellar collapse, but they also create opacity to the UV flux, winds, and bipolar outflows that emanate from newly formed stars. Measurements of metallicity in the Galactic center span a range of solar, observed in stars (Ramírez *et al.* 2000; Carr, Sellgren, & Balachandran 2000; Najjarro *et al.* 2004), to twice solar, observed in the gas phase (Shields & Ferland 1994), to four times solar, observed through x-ray emission near the very center (Maeda *et al.* 2002). The errors from the stellar measurements are the smallest and suggest that stars in the GC are formed from material with roughly solar abundances.

3. Present-day star formation in the GC

Present-day star formation in the GC is somewhat subdued compared to the episodes that produced the massive clusters we now see. A dozen or so ultra-compact HII regions are distributed throughout the central 50 pc, each containing one or a few O-stars still embedded in their natal environs. Yusef-Zadeh & Morris (1987) identify most of these sources in radio continuum observations (see Figure 1). Zhao *et al.* (1993) and Goss *et al.* (1985) infer Lyman-continuum fluxes that are comparable to that expected from a single O7V star in each of the H1-H5 and A-D UCHII regions. Cotera *et al.* (1999) find that several of the recently formed stars in these regions have broken out of their dust shroud, revealing spectra of young massive stars; see also Figer *et al.* (1994) and Munro *et al.* (2006) for additional examples.

A bit further from the GC, the Sgr B2 molecular cloud harbors a massive star cluster in the making and is home to the most intense present-day star formation site in the Galaxy (Gaume *et al.* 1995; de Pree *et al.* 1995; McGrath, Goss, & De Pree 2004; Takagi, Murakami, & Koyama 2002; de Vicente *et al.* 2000; Liu & Snyder 1999; Garay & Lizano 1999; de Pree *et al.* 1996). Within the next few Myr, this activity should produce a star cluster that is comparable in mass to the Arches cluster (see Figure 2). Sato *et al.* (2000) note evidence in support of a cloud-cloud collision as the origin for the intense star formation in Sgr B2; these include velocity gradients, magnetic field morphology, shock-enhanced molecular emission, shock-induced molecular evaporation from dust grains, and distinctly different densities of certain molecular species throughout the cloud.

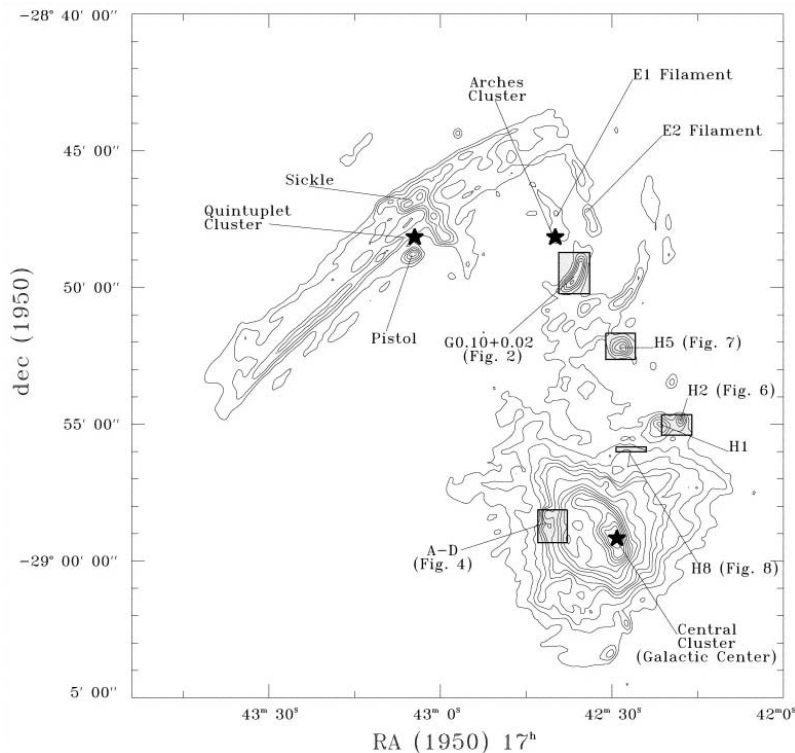


FIGURE 1. Radio emission from the GC region at 6 cm, adapted in Figure 1 by Cotera *et al.* (1999) from Yusef-Zadeh & Morris (1987). The star symbols represent the three massive clusters. Hot stars in the Quintuplet and Arches clusters ionize gas on the surfaces of nearby molecular clouds to produce the radio emission in the “Sickle” and “G0.10+0.02/E1/E2 Filaments,” respectively. The radio emission near the Galactic center is due to a combination of thermal and non-thermal emission. The “H1-8” and “A-D” regions are ultra-compact HII regions surrounding recently formed stars.

4. Continuous star formation in the GC

There is ample evidence for persistent star formation in the GC in the form of upper-tip asymptotic giant branch stars distributed throughout the region (Lebofsky & Rieke 1987; Narayanan, Gould, & Depoy 1996; Frogel, Tiede, & Kuchinski 1999; Sjouwerman *et al.* 1999). Figure 3 shows a plot for some of these stars, based on spectroscopic data, overlaid with intermediate age model isochrones (Blum *et al.* 2003). Note that the giants and supergiants in this plot require ages that span a few Myr to a few Gyr.

One comes to similar conclusions by analyzing photometry of the field population in the GC. Figer *et al.* (2004) use observed luminosity functions to determine that the star formation rate has been roughly constant for the lifetime of the Galaxy in the GC, similar to the suggestion in Serabyn & Morris (1996) based on the sharp increase in unresolved infrared light towards the center and a mass-budget argument. Figure 4 shows model and observed luminosity functions (*right*) for various star formation scenarios (*left*) over the lifetime of the Galaxy, assuming a Salpeter IMF (Salpeter 1955) for masses above $10 M_{\odot}$,

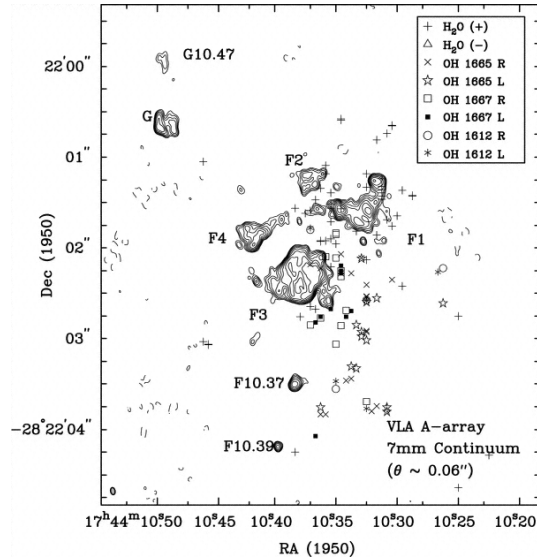


FIGURE 2. Figure 3 from McGrath, Goss, & De Pree (2004) showing H_2O and OH masers overlaid on 7 mm contours for a small portion of the Sgr B2 cloud. The activity in this region is typical of that found near the fifty or so ultra-compact HII regions in Sgr B2.

and a flat slope below this mass. The observations were obtained with HST/NICMOS and have been corrected for incompleteness. The “burst” models (panels 1, 2, 4, and 5) produce unrealistic ratios of bright to faint stars in the luminosity functions, especially for the red clump near a dereddened K-band magnitude of 12. The continuous star formation model (panel 3) best fits the data.

5. Properties of the Three Massive Clusters

The majority of recent star formation activity in the GC over the past 10 Myr produced three massive clusters: the Central cluster, the Arches cluster, and the Quintuplet cluster. The following sections describe the stellar content in the clusters and the resultant implications for star formation in the region. They closely follow recent reviews (Figer *et al.* 1999a; Figer 2003, 2004), with updates, as summarized in Table 1.

The three clusters are similar in many respects, as they are all young and contain $\gtrsim 10^4 M_\odot$ in stars. They have very high central stellar mass densities, up to nearly $10^6 M_\odot \text{pc}^{-3}$, exceeding central densities in most globular clusters. They have luminosities of $10^7\text{--}10^8 L_\odot$, and are responsible for heating nearby molecular clouds. They also generate $10^{50\text{--}51}$ ionizing photons per second, enough to account for nearby giant HII regions. The primary difference between the clusters is likely to be age, where the Quintuplet and Central clusters are about twice the age of the Arches cluster. In addition, the Central cluster is unique for its population of evolved massive stars that have broad and strong helium emission lines (Krabbe *et al.* 1991, and references therein). While the Quintuplet cluster has a few similar stars (Geballe *et al.* 1994; Figer *et al.* 1999a), the Central cluster has far more as a fraction of its total young stellar population (Paumard *et al.* 2006).

Table 2 summarizes the massive stellar content of the clusters.

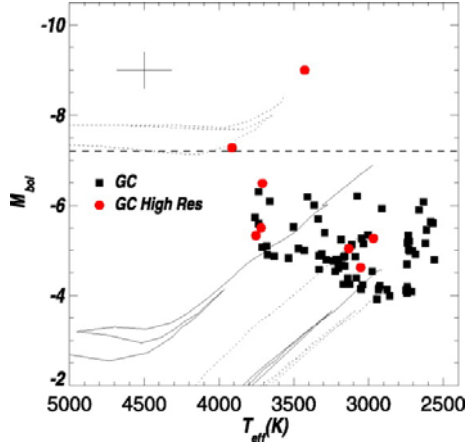


FIGURE 3. Estimates of absolute magnitude versus temperature for stars in the GC from Blum *et al.* (2003). The lines correspond to model isochrones having ages of 10 Myr, 100 Myr, 1 Gyr, 5 Gyr, and 12 Gyr. The supergiants (above the horizontal line) are descendant from stars having $M \approx 15\text{--}25 M_{\odot}$, whereas fainter stars are descendant from lower mass main sequence stars having a few to $15 M_{\odot}$. The presence of these stars in the GC demonstrates intermediate age star formation of massive stars.

TABLE 1. Properties of massive clusters in the Galactic Center

Cluster	Log(M1) M_{\odot}	Log(M2) M_{\odot}	Radius pc	Log($\rho 1$) $M_{\odot} \text{ pc}^{-3}$	Log($\rho 2$) $M_{\odot} \text{ pc}^{-3}$	Age Myr	Log(L) L_{\odot}	Log(Q) s^{-1}
Quintuplet	3.0	3.8	1.0	2.4	3.2	3–6	7.5	50.9
Arches [†]	4.1	4.1	0.19	5.6	5.6	2–3	8.0	51.0
Center [‡]	3.0	4.0	0.23	4.6	5.6	3–7	7.3	50.5

“M1” is the total cluster mass in observed stars. “M2” is the total cluster mass in all stars extrapolated down to a lower-mass cutoff of $1 M_{\odot}$, assuming a Salpeter IMF slope and an upper mass cutoff of $120 M_{\odot}$ (unless otherwise noted) “Radius” gives the average projected separation from the centroid position. “ $\rho 1$ ” is M1 divided by the volume. “ $\rho 2$ ” is M2 divided by the volume. In either case, this is probably closer to the central density than the average density because the mass is for the whole cluster while the radius is the average projected radius. “Age” is the assumed age for the cluster. “Luminosity” gives the total measured luminosity for observed stars. “Q” is the estimated Lyman continuum flux emitted by the cluster.

[†] Mass estimates have been made based upon the number of stars having $M_{\text{initial}} > 20 M_{\odot}$ given in Figer *et al.* (1999b) and the mass function slope in Stolte *et al.* (2003). The age, luminosity and ionizing flux are from Figer *et al.* (2002).

[‡] Krabbe *et al.* (1995). The mass, “M2” has been estimated by assuming that a total $10^{3.5}$ stars have been formed. The age spans a range covering an initial starburst, followed by an exponential decay in the star formation rate.

5.1. Central cluster

The Central cluster contains many massive stars that have recently formed in the past 10 Myr (Becklin *et al.* 1978; Rieke, Telesco, & Harper 1978; Lebofsky, Rieke, & Tokunaga 1982; Forrest *et al.* 1987; Allen, Hyland, & Hillier 1990; Krabbe *et al.* 1991; Najjarro *et al.* 1994; Krabbe *et al.* 1995; Najjarro 1995; Libonate *et al.* 1995; Blum, Depoy, & Sellgren 1995a; Blum, Sellgren, & Depoy 1995b; Genzel *et al.* 1996; Tamblyn *et al.* 1996; Najjarro

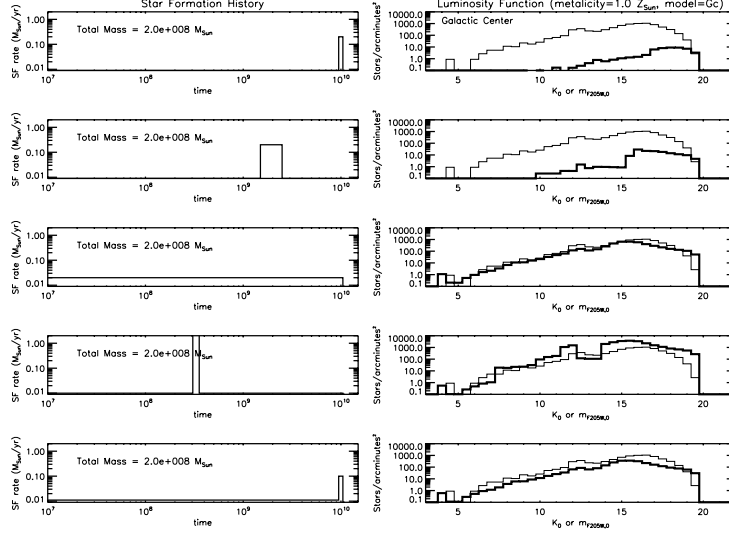


FIGURE 4. A figure adapted from Figer *et al.* (2004) showing various star formation scenarios (*left*), and resultant model luminosity functions (*right, thick*) compared to observed luminosity functions (*right, thin*) in the GC. The models assume a Salpeter IMF slope, an elevated lower-mass turnover of $10 M_{\odot}$, and are additionally constrained to produce $2(10^8) M_{\odot}$ in stars within the region. The observations have been corrected for incompleteness. The third panels from the top, i.e. continuous star formation, best fit the data. The observed turn-down at the faint end appears to be real and is only well fit only by assuming a very high lower mass turnover.

TABLE 2. Massive Stars in the Galactic Center Clusters

	Age (Myr)	O	LBV	WN	WC	RSG	References
Quintuplet	4	100	2	6	11	1	Figer <i>et al.</i> (1999a); Geballe, Najarro, & Figer (2000); Homeier <i>et al.</i> (2003)
Arches	2	160	0	$\gtrsim 6$	0	0	Figer <i>et al.</i> (2002)
Center	4–7	100	$\gtrsim 1$	$\gtrsim 18$	$\gtrsim 12$	3	Paumard <i>et al.</i> (2006)
Total		360	$\gtrsim 3$	$\gtrsim 29$	$\gtrsim 23$	4	

et al. 1997). In all, there are now known to be at least 80 massive stars in the Central cluster (Eisenhauer *et al.* 2005; Paumard *et al.* 2006), including ≈ 50 OB stars on the main sequence and 30 more evolved massive stars (see Figure 5). These young stars appear to be confined to two disks (Genzel *et al.* 2003; Levin & Beloborodov 2003; Paumard *et al.* 2006; Tanner *et al.* 2006; Beloborodov *et al.* 2006). There is also a tight collection of a dozen or so B stars (the “s” stars) in the central arcsecond, highlighted in the small box in the figure. The formation of so many massive stars in the central parsec remains as much a mystery now as it was at the time of the first infrared observations of the region. Most recently, this topic has largely been supplanted by the even more improbable notion that star formation can occur within a few thousand AU of the supermassive black hole, an idea that will be addressed in Section 7. See Alexander (2005) for a thorough review

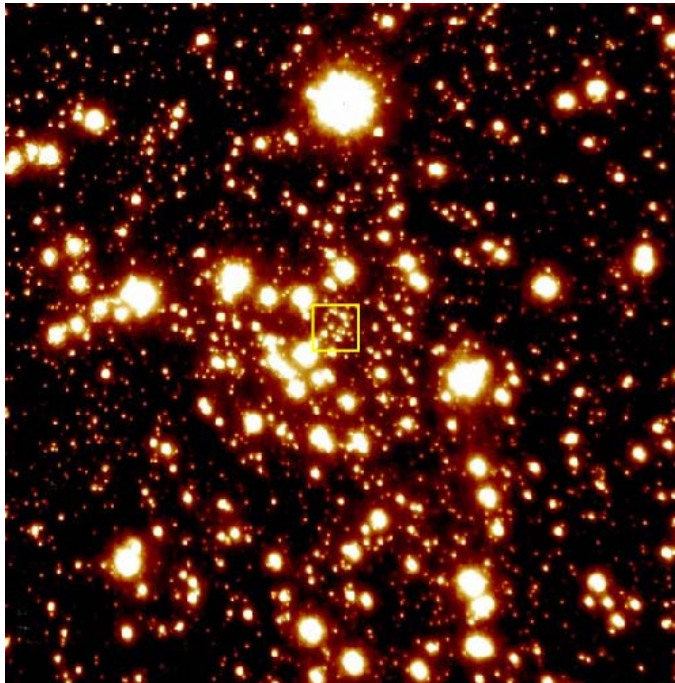


FIGURE 5. K-band image of the Central cluster obtained with NAOS/CONICA from Schödel *et al.* (2006). The 100 or so brightest stars in the image are evolved descendants from main sequence O-stars. The central box highlights the “s” stars that are presumably young and massive ($M_{\text{initial}} \approx 20 M_{\odot}$).

of the “s” stars and Paumard *et al.* (2006) for a review of the young population in the Central cluster.

5.2. *Arches cluster*

The Arches cluster is unique in the Galaxy for its combination of extraordinarily high mass, $M \approx 10^4 M_{\odot}$, and relatively young age, $\tau = 2 \text{ Myr}$ (Figer *et al.* 2002). Being so young and massive, it contains the richest collection of O-stars and WNL stars in any cluster in the Galaxy (Cotera *et al.* 1996; Serabyn, Shupe, & Figer 1998; Figer *et al.* 1999b; Blum *et al.* 2001; Figer *et al.* 2002). It is ideally suited for testing theories that predict the shape of the IMF up to the highest stellar masses formed (see Section 6).

The cluster is prominent in a broad range of observations. Figure 6 shows an HST/NICMOS image of the cluster – the majority of the bright stars in the image have masses greater than $20 M_{\odot}$. The most massive dozen or so members of the cluster have strong emission lines at infrared wavelengths (Harris *et al.* 1994; Nagata *et al.* 1995; Cotera 1995; Figer 1995; Cotera *et al.* 1996; Figer *et al.* 1999b; Blum *et al.* 2001; Figer *et al.* 2002). These lines are produced in strong stellar winds that are also detected at radio wavelengths (Lang, Goss, & Rodríguez 2001; Yusef-Zadeh *et al.* 2003; Lang *et al.* 2005; Figer *et al.* 2002), and x-ray wavelengths (Yusef-Zadeh *et al.* 2002; Rockefeller *et al.* 2005; Wang, Dong, & Lang 2006).

5.3. *Quintuplet cluster*

The Quintuplet cluster was originally noted for its five very bright stars, the Quintuplet Proper Members (QPMs) (Glass, Moneti, & Moorwood 1990; Okuda *et al.* 1990; Nagata *et al.* 1990). Subsequently, a number of groups identified over 30 stars evolved

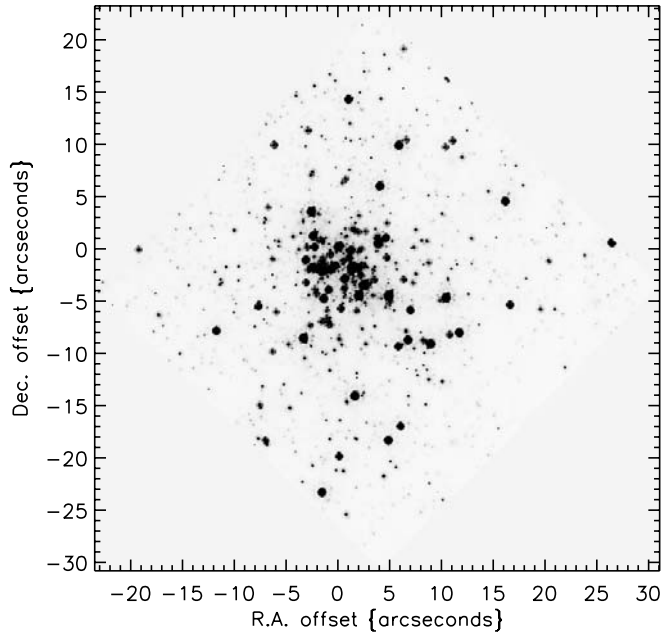


FIGURE 6. F205W image of the Arches cluster obtained by Figer *et al.* (2002) using HST/NICMOS. The brightest dozen or so stars in the cluster have $M_{\text{initial}} \gtrsim 100 M_{\odot}$, and there are ≈ 160 O-stars in the cluster. The diameter is ≈ 1 yr, making the cluster the densest in the Galaxy with $\rho > 10^5 M_{\odot} \text{pc}^{-3}$.

from massive main sequence stars (Geballe *et al.* 1994; Figer, McLean, & Morris 1995; Timmermann *et al.* 1996; Figer *et al.* 1999a). Given the spectral types of the massive stars identified in the cluster, it appears that the Quintuplet cluster is ≈ 4 Myr old and had an initial mass of $> 10^4 M_{\odot}$ (Figer *et al.* 1999a). An accounting of the ionizing flux produced by the massive stars in the cluster conclusively demonstrates that the cluster heats and ionizes the nearby “Sickle” HII region (see Figure 1). The Quintuplet is most similar to Westerlund 1 in mass, age, and spectral content (Clark *et al.* 2005; Negueruela & Clark 2005; Skinner *et al.* 2006; Groh *et al.* 2006; Crowther *et al.* 2006).

Of particular interest in the cluster, the QPMs are very bright at infrared wavelengths, $m_K \approx 6$ to 9, and have color temperatures between ≈ 600 to 1,000 K. They are luminous, $L \approx 10^5 L_{\odot}$, yet spectroscopically featureless, making their spectral classification ambiguous. Figer, Morris, & McLean (1996), Figer *et al.* (1999a), and Moneti *et al.* (2001) argue that these objects are not protostars, OH/IR stars, or protostellar OB stars. Instead, they claim that these stars are dust-enshrouded WCL stars (DWCLs), similar to other dusty Galactic WC stars (Williams, van der Hucht, & The 1987), i.e. WR 104 (Tuthill, Monnier, & Danchi 1999) and WR 98A (Monnier, Tuthill, & Danchi 1999). Chiar *et al.* (2003) tentatively identify a weak spectroscopic feature at $6.2 \mu\text{m}$ that they attribute to carbon, further supporting the hypothesis that these stars are indeed DWCLs. The stars have also been detected at x-ray wavelengths (Law & Yusef-Zadeh 2004), and at radio wavelengths (Lang *et al.* 1999, 2005).

Recently, Tuthill *et al.* (2006) convincingly show that the QPMs are indeed dusty WC stars. Figure 8 shows data that reveal the pinwheel nature of their infrared emission, characteristic of binary systems containing WCL plus an OB star (Tuthill, Monnier,

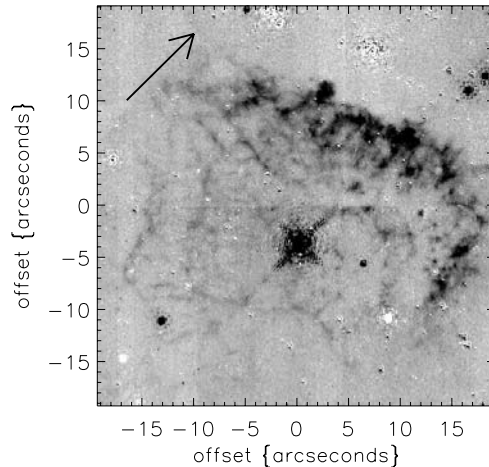


FIGURE 7. Paschen- α image of the region surrounding the Pistol star from Figer *et al.* (1999c). North is to the upper right, and east is to the upper left. The Pistol star ejected $\approx 10 M_{\odot}$ of material approximately 6,000 yr ago to form what now appears to be a circumstellar nebula that is ionized by two WC stars to the north of the nebula. Moneti *et al.* (2001) use ISO data to show that the nebula is filled with dust that is heated by the Pistol star.

& Danchi 1999; Monnier, Tuthill, & Danchi 1999). This identification raises intriguing questions concerning massive star formation and evolution. With their identifications, it becomes clear that every WC star in the Quintuplet is dusty, and presumably binary. There are two possible explanations for this result. Either the binary fraction for massive stars is extremely high (Mason *et al.* 1998; Nelan *et al.* 2004), or only binary massive stars evolve through the WCL phase (van der Hucht 2001).

The Quintuplet cluster also contains two Luminous Blue Variables, the Pistol star (Harris *et al.* 1994; Figer *et al.* 1998, 1999c), and FMM362 (Figer *et al.* 1999a; Geballe, Najarro, & Figer 2000). Both stars are extraordinarily luminous ($L > 10^6 L_{\odot}$), yet relatively cool ($T \approx 10^4$ K), placing them in the “forbidden zone” of the Hertzsprung-Russell Diagram, above the Humphreys-Davidson limit (Humphreys & Davidson 1994). The Pistol star is particularly intriguing, in that it is surrounded by one of the most massive ($10 M_{\odot}$) circumstellar ejecta in the Galaxy (see Figure 7; Figer *et al.* 1999c; Smith 2006). Both stars are spectroscopically (Figer *et al.* 1999a) and photometrically variable (Glass *et al.* 2001). They present difficulties for stellar evolution and formation models. Their inferred initial masses are $> 100 M_{\odot}$, yet such stars should have already gone supernova in a cluster that is so old, as evidenced by the existence of WC stars (Figer *et al.* 1999a) and the red supergiant, q7 (Moneti, Glass, & Moorwood 1994; Ramírez *et al.* 2000). Figer & Kim (2002) and Freitag, Rasio, & Baumgardt (2006) argue that stellar mergers might explain the youthful appearance of these stars. Alternatively, these stars might be binary, although no evidence has been found to support this assertion. Note that in a similar case, LBV1806–20 is also surrounded by a relatively evolved cluster (Eikenberry *et al.* 2004; Figer *et al.* 2005), yet it does appear to be binary (Figer, Najarro, & Kudritzki 2004).

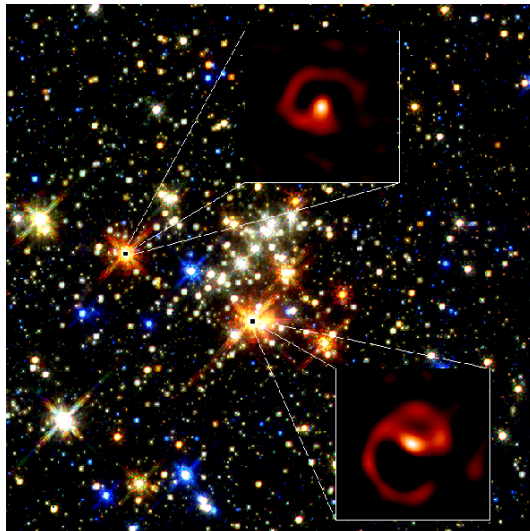


FIGURE 8. Tuthill *et al.* (2006) find that the Quintuplet Proper Members are dusty Wolf-Rayet stars in binary systems with OB companions. The insets in this illustration show high-resolution infrared imaging data for two Quintuplet stars, overlaid on the HST/NICMOS image from Figer *et al.* (1999b). All of the Quintuplet WC stars are dusty, suggesting that they are binary.

6. The initial mass function in the Galactic center

The IMF in the Galactic center has primarily been estimated through observations of the Arches cluster (Figer *et al.* 1999b; Stolte *et al.* 2003), although there have been several attempts to extract such information through observations of the Central cluster (Genzel *et al.* 2003; Nayakshin & Sunyaev 2005; Paumard *et al.* 2006) and the background population in the region (Figer *et al.* 2004). These studies suggest an IMF slope that is flatter than the Salpeter value.

6.1. *The slope*

Figer *et al.* (1999b) and Stolte *et al.* (2003) estimate a relatively flat IMF slope in the Arches cluster (see Figure 9). Portegies Zwart *et al.* (2002) interpret the data to indicate an initial slope that is consistent with the Salpeter value, and a present-day slope that has been flattened due to dynamical evolution. Performing a similar analysis, Kim *et al.* (2000) arrive at the opposite conclusion – that the IMF truly was relatively flat. The primary difficulty in relating the present-day mass function to the initial mass function is the fact that *n*-body interactions operate on relatively short timescales to segregate the highest stellar masses toward the center of the cluster and to eject the lowest stellar masses out of the cluster. Most analysis is needed to resolve this issue.

6.2. *Upper mass cutoff*

The Arches cluster is the only cluster in the Galaxy that can be used to directly probe an upper mass cutoff. It is massive enough to expect stars at least as massive as $400 M_{\odot}$, young enough for its most massive members to still be visible, old enough to have broken out of its natal molecular cloud, close enough, and at a well-established distance, for us to discern its individual stars (Figer 2005). There appears to be an absence of stars with initial masses greater than $130 M_{\odot}$ in the cluster, where the typical mass function

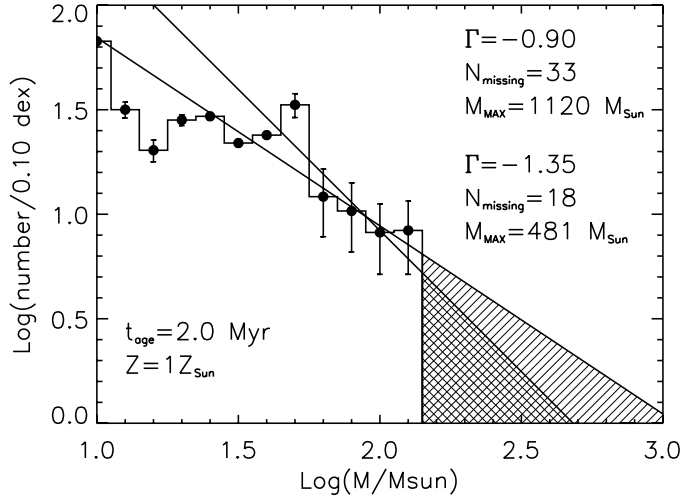


FIGURE 9. Figer (2005) find an apparent upper-mass cutoff to the IMF in the Arches cluster. Magnitudes are transformed into initial mass by assuming the Geneva models for $\tau_{\text{age}}=2$ Myr, solar metallicity, and the canonical mass-loss rates. Error bars indicate uncertainty from Poisson statistics. Two power-law mass functions are drawn through the average of the upper four mass bins, one having a slope of -0.90 , as measured from the data, and another having the Salpeter slope of -1.35 . Both suggest a dramatic deficit of stars with $M_{\text{initial}} > 130 M_{\odot}$, i.e. 33 or 18 are missing, respectively. These slopes would further suggest a single star with very large initial mass (M_{MAX}). The analysis suggests that the probability of there not being an upper-mass cutoff is $\approx 10^{-8}$.

predicts 18 (see Figure 9). Figer (2005) therefore claim a firm upper mass limit of $150 M_{\odot}$. There is additional support for such a cutoff in other environments (Weidner & Kroupa 2004; Oey & Clarke 2005; Koen 2006; Weidner & Kroupa 2006).

6.3. Lower mass rollover

Morris (1993) argue for an elevated lower mass rollover in the GC based on the environmental conditions therein, and only recently have observations been deep enough to address this claim. Stolte *et al.* (2005) claim observational evidence for an elevated cutoff around $6 M_{\odot}$ in the Arches cluster; however, in that case, confusion and incompleteness are serious problems. In addition, even if the apparent turn-down is a real indication of the initial cluster population, the lack of low mass stars might result from their ejection through n-body interactions (Kim *et al.* 2000; Portegies Zwart *et al.* 2002). Field observations should not suffer from such an effect, as the field should be the repository for low mass stars ejected from massive clusters in the GC. Figure 4 reveals a turn-down in the observed luminosity function of the field in the GC at a dereddened K-band magnitude greater than 16. This appears to not be a feature of incompleteness, as the data are greater than 50% complete at these magnitudes (Figer *et al.* 1999b). A more convincing argument, based on this type of data, will await even deeper observations (Kim *et al.* 2006).

7. The “s” stars

Figure 5 shows a dense collection of about a dozen stars within 1 arcsecond (0.04 pc) of Sgr A* (Genzel *et al.* 1997; Ghez *et al.* 1998, 2000; Eckart *et al.* 2002; Schödel *et al.*

2002; Ghez et al. 2003; Schödel et al. 2003; Ghez et al. 2005). This cluster stands out for its high stellar density, even compared to the already dense field population in the GC. Schödel et al. (2003) and Ghez et al. (2005) (and references therein) have tracked the proper motions of the “s” stars, finding that they are consistent with closed orbits surrounding a massive, and dark, object having $M \approx 2 - 4(10^6) M_{\odot}$, consistent with previous claims based on other methods (Lynden-Bell & Rees 1971; Lacy et al. 1980; Serabyn & Lacy 1985; Genzel & Townes 1987; Sellgren et al. 1987; Rieke & Rieke 1988; McGinn et al. 1989; Lacy, Achtermann, & Serabyn 1991; Lindqvist, Habing, & Winnberg 1992; Haller et al. 1996). The orbital parameters for these stars are well determined, as seen in Figure 10 (*left*), and they require the existence of a supermassive black hole in the Galactic center. While these stars are useful as gravitational test particles, they are also interesting in their own right, as they have inferred luminosities and temperatures that are similar to those of young and massive stars (Genzel et al. 1997; Eckart et al. 1999; Figer et al. 2000; Ghez et al. 2003; Eisenhauer et al. 2003, 2005; Paumard et al. 2006). Figure 10 (*right*) shows the absorption lines that suggest relatively high temperatures.

Oddly, the increased density of the young stars in the central arcsecond is not matched by the density distribution of old stars. Indeed, there is a curious absence of late-type stars in the central few arcseconds, as evidenced by a lack of stars with strong CO absorption in their K-band spectra (Lacy, Townes, & Hollenbach 1982; Phinney 1989; Sellgren et al. 1990; Haller et al. 1996; Genzel et al. 1996, 2003). This dearth of old stars represents a true “hole” in three dimensional space, and not just a projection effect. Even the late-type stars that are projected on to the central parsec generally have relatively low velocities, suggesting dynamical evidence that the region nearest to the black hole lacks old stars (Figer et al. 2003).

The existence of such massive and young stars in the central arcseconds is puzzling, although it is perhaps only an extension of the original problem in understanding the origins of the young stars identified in the central parsec over 20 years ago. Table 3 gives a list of recent papers regarding the origin of the “s” stars. While there are over 30 papers listed in this table, they can be reduced to a few basic ideas. One class of ideas considers the “s” stars as truly young. In this case, the “origin” of the “s” stars is often reduced to the case of massive star formation in the Galactic center region and transportation of the products to the central arcsecond. The other class regards the “s” stars as old stars that only appear to be young, i.e. via atmospheric stripping, merging, or heating. Both classes require new mechanisms that would be unique to the GC, and they both have considerable weaknesses. For example, Figer et al. (2000) argue that stripped red giants would not be as bright as the “s” stars (see Dray, King, & Davies 2006, for detailed confirmation). See Alexander (2005) for a more thorough discussion of the strengths and weaknesses of these ideas.

If the “s” stars are truly young, then that would require massive clumps to form OB stars ($M_{\text{initial}} \gtrsim 20 M_{\odot}$). In addition, the clumps would have to form from very high density material in order for them to be stable against tidal disruption. Assuming that the stars formed as far away from the supermassive black hole as possible, while still permitting dynamical friction to transport them into the central arcsecond during their lifetimes, then the required densities must be $>10^{11} \text{ cm}^{-3}$ (Figer et al. 2000).

The average molecular cloud density in the GC is about five orders of magnitude less, so highly compressive events might be required to achieve the necessary densities. Alternatively, the required densities can be reduced if the stars are gravitationally bound to significant mass, i.e. a surrounding stellar cluster. Indeed, Gerhard (2001), Portegies Zwart, McMillan, & Gerhard (2003), and Kim & Morris (2003) showed that particularly massive clusters could form tens of parsecs outside of the center and be delivered into the

TABLE 3. Chronologically sorted list of references that explore hypotheses on the origin of the “s” stars. Some of the references primarily concern the other young stars in the central parsec and are included in the table because they propose ideas that may relate to the origins of the “s” stars. Contributions to this table have been made by Tal Alexander (priv. communication).

Reference	Description
Lacy, Townes, & Hollenbach (1982)	tidal disruption of red giants
Morris (1993)	compact objects surrounded by material from red giant envelopes (“Thorne-Zytkow objects”)
Davies et al. (1998)	red giant envelope stripping through n-body interactions
Alexander (1999)	red giant envelope stripping through dwarf-giant interactions
Bailey & Davies (1999)	colliding red giants
Morris, Ghez, & Becklin (1999)	duty cycle of formation from infalling CND clouds and evaporation of gas reservoir by accretion and star-formation light
Gerhard (2001)	decaying massive cluster
Alexander & Morris (2003)	tidal heating of stellar envelopes to form “Squeezars”
Genzel et al. (2003)	stellar rejuvenation through red giant mergers
Gould & Quillen (2003)	“exchange reaction” between massive-star binary and massive black hole
Hansen & Milosavljević (2003)	stars captured by inspiraling intermediate mass black hole
Levin & Beloborodov (2003)	formation in nearby gas disk
McMillan & Portegies Zwart (2003); Kim, Figer, & Morris (2004)	inward migration of young cluster with IMBH
Portegies Zwart, McMillan, & Gerhard (2003); Kim & Morris (2003)	inward migration of young cluster
Alexander & Livio (2004)	orbital capture of young stars by MBH-SBH binaries
Milosavljević & Loeb (2004)	formation in molecular disk
Davies & King (2005)	tidal stripping of red giant (AGB) stars (but see critique in Goodman & Paczynski 2005)
Gürkan & Rasio (2005)	decaying cluster with formation of an IMBH
Haislip & Youdin (2005)	formation in disk and orbital relaxation.(but see critique in Goodman & Paczynski 2005)
Levin, Wu, & Thommes (2005)	dynamical interactions with sinking IMBH
Nayakshin & Sunyaev (2005)	<i>in-situ</i> formation within central parsec
Nayakshin & Cuadra (2005)	formation in a fragmenting star disk
Subr & Karas (2005)	formation in disk and accelerated orbital relaxation
Berukoff & Hansen (2006)	cluster inspiral and n-body interactions
Hopman & Alexander (2006)	resonant relaxation of orbits
Freitag, Amaro-Seoane, & Kalogera (2006)	mass segregation through interactions with compact remnants
Levin (2006)	star formation in fragmenting disk
Perets, Hopman, & Alexander (2006)	exchange reactions between massive star binaries induced by efficient relaxation by massive perturbers
Dray, King, & Davies (2006)	tidal stripping of red giant (AGB) stars (but see critique in Figer et al. 2000)

central parsec in just a few million years. The efficiency of this method is improved with the presence of an intermediate black hole in the cluster (McMillan & Portegies Zwart 2003; Kim, Figer, & Morris 2004). It is key in any of these cluster transport models that the host system have extremely high densities of $>10^6 M_{\odot} \text{ pc}^{-3}$, comparable to the highest estimated central density of the Arches cluster after core collapse (Kim & Morris

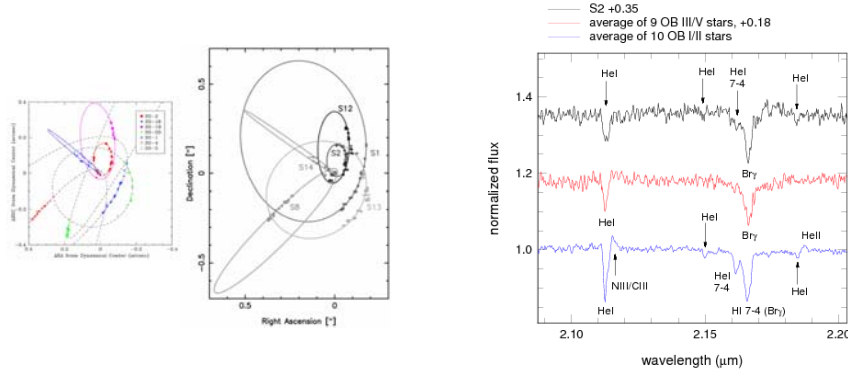


FIGURE 10. (*left*) Figure 2 in Ghez *et al.* (2005) and (*middle*) Figure 6 in Schödel *et al.* (2003), stretched to the same scale. Both figures fit similar model orbits through separate proper motion data sets for the “s” stars. (*right*) Paumard *et al.* (2006) find that one of the “s” stars, S2, has a K-band spectrum that is similar to those of OB stars in the central parsec (see also Ghez *et al.* 2003).

2003). Detailed n-body simulations suggest that while these ideas may be relevant for the origins of the young stars in the central parsec, it is unlikely that they could explain the existence of the “s” stars in the central arcsecond.

8. Comparisons to other massive star populations in Galaxy

There are relatively few clusters in the Galaxy with as many massive stars as in the GC clusters. NGC3603 has about a factor of two less mass than each of the GC clusters (Moffat *et al.* 2002); whereas, W1 has at least a factor of two greater mass (Clark *et al.* 2005; Negueruela & Clark 2005; Skinner *et al.* 2006; Groh *et al.* 2006). The next nearest similarly massive cluster is R136 in the LMC (Massey & Hunter 1998). All of these clusters, and the GC clusters, appear to have IMF slopes that are consistent with the Salpeter value (or slightly flatter) and are young enough to still possess a significant massive star population. It is remarkable to note that these massive clusters appear quite similar in stellar content, whether in the Galactic disk, the GC, or even the lower metallicity environment of the LMC. Evidently, the star formation processes, and natal environments, that gave birth to these clusters must be similar enough to produce clusters that are virtually indistinguishable.

There are probably more massive clusters yet to be found in the Galaxy. The limited sample of known massive clusters is a direct result of extinction, as most star formation sites in the Galaxy are obscured by dust at optical wavelengths. While infrared observations have been available for over 30 years, they have not provided the necessary spatial resolution, nor survey coverage, needed to probe the Galactic disk for massive clusters. Recently, a number of groups have begun identifying candidate massive star clusters using near-infrared surveys with arcsecond resolution (Bica *et al.* 2003; Dutra *et al.* 2003; Mercer *et al.* 2005). Indeed, these surveys have already yielded a cluster with approximate initial mass of 20,000 to 40,000 M_{\odot} (Figer *et al.* 2006), and one would expect more to be discovered from them.

The present-day sites of massive star formation in the Galaxy have been known for some time through radio and far-infrared observations, as their hottest members ionize and heat nearby gas in molecular clouds. As one of many examples, consider W49 which is the next most massive star formation site in the Galaxy compared to Sgr B2 (Homeier

& Alves 2005), and wherein the star formation appears to be progressing in stages over timescales that far exceed the individual collapse times for massive star progenitors. This suggests a stimulus that triggers the star formation, perhaps provided by a “daisy chain” effect in which newly formed stars trigger collapse in nearby parts of the cloud. Similar suggestions are proposed in the 30 Dor region surrounding R136 (Walborn, Maíz-Apellániz, & Barbá 2002). While there is no evidence for an age-dispersed population in Sgr B2, Sato *et al.* (2000) suggest that the cloud was triggered to form stars through a cloud-cloud interaction.

9. Conclusions

Massive star formation in the GC has produced an extraordinary sample of stars populating the initial mass function up to a cutoff of approximately $150 M_{\odot}$. The ranges of inferred masses and observed spectral types are as expected from stellar evolution models, and the extraordinary distribution of stars in the region is a direct consequence of the large amount of mass that has fed star formation in the GC. The origin of the massive stars in the central parsec, and especially the central arcsecond, remains unresolved.

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