A Massive Star Odyssey, from Main Sequence to Supernova
Proceedings IAU Symposium No. 212, © 2002 IAU
K.A. van der Hucht, A. Herrero & C. Esteban, eds.

Massive Stars and The Creation of our Galactic Center

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Abstract. Our Galactic Center hosts over 10% of the known massive stars in the Galaxy. The majority of these stars are located in three particularly massive clusters that formed within the past 5 *Myr*. While these clusters are extraordinary, their formation repesents about half of the total inferred star formation rate in the Galactic Center. There is mounting evidence that the clusters are just present-day examples of the hundreds of such similar clusters that must have been created in the past, and whose stars now comprise the bulk of all stars seen in the region. I discuss the massive stellar content in the Galactic Center and present a new analysis that suggests that effects of continuous star formation in the Galactic Center can be seen in the observed luminosity functions newly-obtained HST/NICMOS and Gemini AO data.

1. Introduction

Over 10% of the known massive stars (M_{init}>20 $M_\odot$) in the Galaxy reside in three clusters of young stars located within 30 pc of the Galactic Center. These clusters are the most massive young clusters in the Galaxy and contain approximately 30 Wolf-Rayet (WR) stars, at least 2 Luminous Blue Variables (LBV), approximately a half dozen red supergiants, and approximately 300 O stars. Together, they emit enough ionizing radiation to account for roughly half of the thermal radio emission in the central few degrees of the Galaxy, suggesting that the young clusters contain approximately half of the stars recently formed in this region. An additional collection of young stars exists in the region, with members scattered about the central 50 pc; some have evolved to the WR stage, while others are still deeply embedded within their natal dust cacoons.

The current star formation rate can be approximated by dividing the mass in newly formed stars by their ages, i.e. $5(10^4)$ $M_\odot/5$ *Myr*$\sim$0.01 $M_\odot$/yr, or a star formation rate density of 10^{-7} $M_\odot$/yr pc^{-3}. This rate is approximately 250 times higher than the mean rate in the Galaxy, and about the same factor lower than the rate in starburst galaxies. Clearly, the Galactic Center has formed a plethora of stars in the past 5 *Myr*, but it is less apparent when the millions of stars in the central 50 pc formed. If we assume that the star formation rate in the past was similar to the present rate, then the total mass of stars formed over the past 10 *Gyr* is $\approx 10^8$ $M_\odot$ within a radius of 30 pc of the Galactic Center, or an order of magnitude greater than this amount over the whole Central Molecular Zone, as first suggested by Serabyn & Morris (1996).

This review summarizes the current state of knowledge concerning the massive stars in the Galactic Center, and the history of star formation therein.

2. The Central Cluster

The first young stars discovered in the GC are within the central parsec of the Galaxy (Becklin & Neugebauer 1968). Rieke & Lebofsky (1982) and Lebofsky, Rieke, & Tokunaga (1983) confirmed the identification of blue and red supergiants in the region, claiming that these stars formed in a burst of star formation $\sim$1 *Myr* ago and that their presence could account for the nearby ionized gas and heated dust. Forrest et al. (1987) discovered a blue supergiant in the center having a broad Brackett-α emission line, and Allen, Hyland, & Hillier (1990) identified this same star as having a spectrum similar to those for evolved massive stars in the Magellanic Clouds. Further studies discovered that many of the blue supergiants are evolved massive stars with spectra having prominent He I emission lines, firmly establishing a starburst event roughly 5 *Myr* ago (Krabbe et al. 1991; 1995, Allen 1994, Rieke & Rieke 1994, Blum et al. 1995, Eckart et al. 1995, Genzel et al. 1996, Tamblyn et al. 1996).

We now know that the Central Cluster contains over 30 evolved massive stars having $M_{\rm initial}$ >20 $M_\odot$. A current estimate of the young population includes 9 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* (Genzel et al. 1996). In addition, I estimate that it contains 100 O-stars (O7 and later) still on the main sequence. Najarro et al. (1994) modeled the infrared spectrum of the "AF" star finding that it is a helium-rich blue supergigant/Wolf-Rayet star, characterized by a strong stellar wind and a moderate amount of Lyman ionizing photons. Najarro et al. (1997) expanded this work by analyzing spectra of 8 blue supergiants in the center, finding extremely strong stellar winds ($\dot{M} \sim 5$ to 80 $\times 10^{-5}\, M_\odot\, yr^{-1}$), relatively small outflow velocities ($v_\infty\sim$ 300 to 1,000 km s^{-1}), effective temperatures from 17,000 K to 30,000 K, stellar luminosities of 1 to 30×10^5 $L_\odot$, and spectral characteristics consistent with an "Ofpe/WN9" classification. They concluded 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. More recently, Paumard et al. (2001) reviewed the emission-line stellar population in the central parsec, using new narrow-band infrared imaging. They found that the brightest emission-line stars divide into two categories, bright narrow-line (200 km s^{-1}) and faint broad-line (1000 km s^{-1}) stars, the former being clustered within a few arcseconds of Sgr A*, and the latter being distributed between 5$''$ and 10$''$ from the center.

Eckart et al. (1999) and Figer et al. (2000) identified massives stars within a few AU of the supermassive black hole. Evidently, a significant fraction of this small group of stars are young ($\tau_{\rm age} < 20\ Myr$) and require extraordinarily dense pre-collapse cores ($\rho > 10^{11}\ cm^{-3}$) or formation sites much further away from the central black hole than their present location would suggest. Early results from proper-motion studies suggest that at least some of the stars in this cluster are bound to the black hole and are not on highly elliptical orbits (Ghez et al.

2001; Eckart et al. 2002); therefore they are likely to be near to their formation sites.

3. The Quintuplet Cluster

The Quintuplet Cluster is located approximately 30 pc, in projection, to the northeast of the Galactic Center (Glass, Catchpole, & Whitelock 1987). In addition to the five bright stars for which the Quintuplet was named (Nagata et al. 1990; Okuda et al. 1990), the Quintuplet cluster contains a variety of massive stars, including four WN, five WC (possibly ten, see below), two WN9/Ofpe, two LBV, one red supergiant and several dozen less-evolved blue supergiants (Figer et al. 1999a, 1999c). The five Quintuplet-proper members are massive stars (L $\sim 10^5$ $L_\odot$) embedded within dusty cacoons, although their spectral types and evolutionary status are unknown (Moneti et al. 2001). Figer et al. (1996, 1999a) argue that these stars are dust-enshrouded WCL stars, similar to WR 140 (Monnier et al. 2002) and WR 98A (Monnier et al. 1999). In addition to these post-main sequence stars, it is likely that 100 O-stars still on the main sequence exist in the cluster, assuming a flat to Salpeter IMF. The total cluster mass is estimated to be $\sim 10^4$ $M_\odot$; of this, the stars with certain spectral identifications, i.e. the most massive ones, contribute a few 10^3 $M_\odot$. Given the extended distribution of the cluster, the implied mass density is greater than few thousand $M_\odot$ pc^{-3}. The total ionizing flux is $\sim 10^{51}$ photons s^{-1}, enough to ionize the nearby "Sickle" HII region (G0.18−0.04). The total luminosity from the massive cluster stars is $\approx 10^{7.5}$ $L_\odot$, enough to account for the heating of the nearby molecular cloud, M0.20−0.033.

The two LBVs are added to the list of 6 LBVs in the Galaxy. They include the Pistol Star (Moneti et al. 1994; Figer et al. 1995a, 1995b, 1998, 1999b; Cotera 1995; Cotera et al. 1996), one of the most luminous stars known, and a newly identified LBV (Geballe et al. 2000) that is nearly as luminous as the Pistol Star. Both stars are luminous, "blue," and variable, and the Pistol Star has ejected 10 $M_\odot$ of material in the past $\sim 10^4$ *yrs*, as evidenced by the remarkable Pistol nebula of ionized gas surrounding the star (Figer et al. 1999b; Moneti et al. 2001). Most of the luminous stars in the cluster are thought to be 3−5 Myr old, but significant age differences remain, i.e., the Pistol Star is thought to be $\approx$2 *Myr* old.

4. The Arches Cluster

First discovered about 10 years ago as a compact collection of a dozen or so emission-line stars (Cotera et al. 1992; Nagata et al. 1995; Figer 1995a; Cotera 1995; Cotera et al. 1996; Blum et al. 2001), the Arches cluster contains thousands of stars, including at least 160 O stars, according to Figer et al. (1999c). Figer et al. (1999c) used HST/NICMOS observations to estimate a total cluster mass ($\gtrsim 10^4$ $M_\odot$) and radius (0.2 pc) to arrive at an average mass density of $3(10^5)$ $M_\odot$ pc^{-3} in stars, suggesting that the Arches cluster is the densest, and one of the most massive, young clusters in the Galaxy. They further used these data to estimate an initial mass function (IMF) which is relatively flat

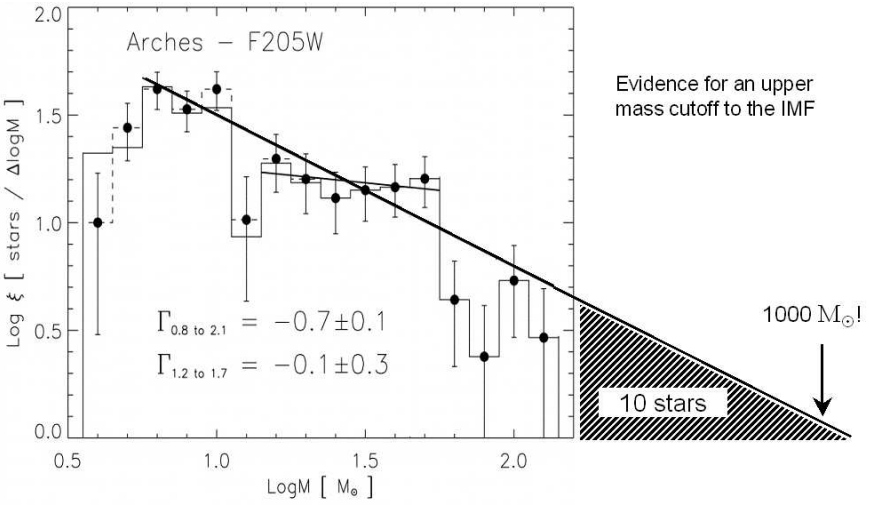

Figure 1. Mass function in the Arches Cluster. Note the absence of stars more massive than $M_{\rm initial}$>300 $M_\odot$, implying the detection of an upper mass cutoff.

($\Gamma \sim -0.6\pm0.1$) with respect to what has been found for the solar neighborhood ($\Gamma \sim -1.35$, Salpeter 1955) and other Galactic clusters (Scalo 1998). Stolte et al. (2002) recently confirmed this flat slope by analyzing the same data and recently obtained Gemini AO data. Figer et al. (2002) estimated an age of 2.5±0.5 *Myr*, based on the magnitudes, colors, mix of spectral types, and quantitative spectral analysis of stars in the cluster. Given the current state of knowledge about this cluster, it now seems apparent that we have observed a firm upper-mass cutoff, as shown in Figure 1. Note that we should expect at least 10 stars more massive than $M_{\rm initial}$=300 $M_\odot$. Indeed, we should even expect one star with an initial mass of 1,000 $M_\odot$! Of course, it is questionable how long such a star would live; however, it is clear that the Arches cluster IMF cuts off at around 150 $M_\odot$. Finally, even if we steepen the IMF slope to the Salpeter value, we still should expect at least 4 stars more massive than 300 $M_\odot$.

Figer et al. (2002) conclude that the most massive stars are bona-fide Wolf-Rayet (WR) stars and are some of the most massive stars known, having $M_{\rm initial}$ >100 $M_\odot$, and prodigious winds, $\dot{M}$ >10^{-5} $M_\odot\ yr^{-1}$, that are enriched with helium and nitrogen. These findings are largely based upon the spectra and narrow-band equivalent widths shown in Figure 2, and a detailed quantitative analysis of these data (also see Najarro 2002). Figer et al. (2002) found an upper limit to the velocity dispersion of 22 km s^{-1}, implying an upper limit to the cluster mass of 7(10^4) $M_\odot$ within a radius of 0.23 pc, and a bulk velocity of $v_{\rm cluster}$ ≈+55 km s^{-1} for the cluster. It appears that the cluster happens to be ionizing, and approaching, the surface of a background molecular cloud, thus producing the Thermal Arched Filaments. They estimate that the cluster produces 4(10^{51}) ionizing photons s^{-1}, more than enough to account for the observed thermal radio flux from the nearby cloud. Commensurately, it produces $10^{7.8}$ $L_\odot$ in total luminosity, providing the heating source for the nearby molecular cloud, $L_{\rm cloud} \approx 10^7$ $L_\odot$. These interactions between a cluster of hot stars and

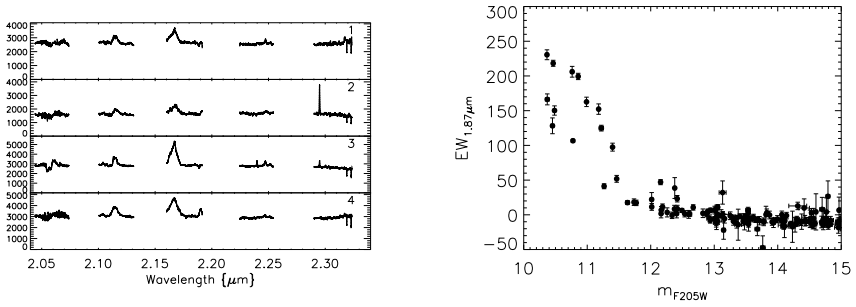

Figure 2. *(left)* K-band spectra of four Wolf-Rayet stars (WNL) in the Arches Cluster from Figer et al. (2002). Emission lines can be seen at 2.058 μm (HeI), 2.104 μm (NIII), 2.112/113 μm (HeI), 2.115 μm (NIII), 2.166 μm (HeI/HI), 2.189 μm (HeII), and 2.224/225 μm (NIII). The sharp feature near 2.32 μm in the spectrum for star #2 is due to a detector defect, and the absorption features longward of 2.33 μm are due to imperfect correction for telluric absorption. *(right)* Equivalent width of the 1.87 μm feature in massive stars of the Arches Cluster (Figer et al. 2002; see also Blum et al. 2001) as a function of apparent magnitude in the HST/NICMOS F205W filter. The feature has contributions from HeI and HI.

a wayward molecular cloud are similar to those seen in the "Quintuplet/Sickle" region. Finally, note that significant work is being done on this cluster at radio and x-ray wavelengths, i.e. shown in Figure 3.

5. The Star Formation History of the Galactic Center

The evidence for recent ($<$10 *Myr*) star formation in the Galactic Center abounds. The Lyman continuum flux emitted in the central few degrees of the Galaxy is about 10^{52} photons/s (Cox & Laureijs 1989), with half coming from stars in the three massive clusters. This flux is about 10% of the that for the whole Galaxy, and the number of massive stars ($M_{\rm initial}$ $>$20 $M_\odot$) in the GC is about 10% of the number in the whole Galaxy. However, note that the star formation rate in the GC is about one one-hundredth of that for the whole Galaxy. Such a low star formation rate as a function of Lyman continuum photon production necessarily follows from the relatively flat initial mass function (IMF) slope used in estimating the mass of stars formed in the young clusters.

The recent star formation history ($\tau_{\rm age} \lesssim 50$ *Myr*) in the Galactic Center is relatively clear. Embedded HII regions trace star formation at the present time (Figer 1995, Cotera 1995, Cotera et al. 1999), while the young clusters trace star formation that occured 2.5$-$5 *Myr* ago. The lack of red supergiants ($\rm M_{Bol} < -6.3$ and $M_{\rm initial}$$>$8 $M_\odot$) in the region provides evidence for a very low star formation rate from 5$-$20 *Myr* ago. Indeed, a burst the size of that seen in the three clusters at 20 Myr ago would have produced 40 red supergiants, yet we see none (other than those associated with the young clusters).

The constraints on this activity are very strong, i.e. there were fewer than $5(10^3)$ $M_\odot$ formed in stars over this time period, assuming the type of star formation that spawned the three massive clusters. Looking beyond 20 *Myr*, the

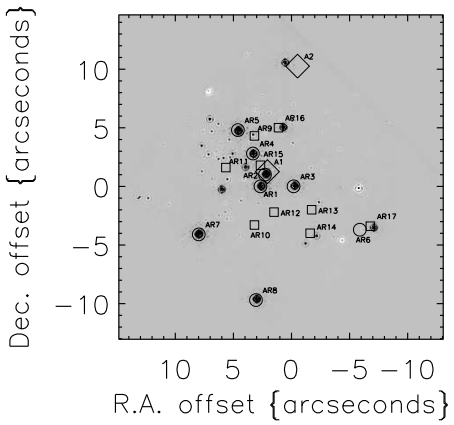

Figure 3. Difference image, F187N−F190N, highlighting stars with excess emission at 1.87 μm. Radio sources ($\nu = 4.9\ GHz$) are shown by circles, as identified in Lang et al. (2001), and as squares, as identified by Figer et al. (2002). X-ray sources are shown by diamonds, as identified by Yusef-Zadeh et al. (2002).

picture becomes less clear because it is difficult to separate old low-mass red giants from much younger high-mass AGB stars with photometric data alone. Using spectroscopy, Blum et al. (1996) have shown that there is a relative dearth of stars with ages between 10 and 100 *Myr* in the central few parsecs. Given their conclusions, I estimate a low star formation rate during this period. These same authors, and Haller (1992), identified stars with ages on the order of a few hundred *Myr* in the central few arcminutes. Sjouwerman (1999) identified a population of OH/IR stars with a narrow range of expansion velocities, indicating intermediate ages and a starburst event a few *Gyr* ago. In addition, Frogel et al. (1999) identified an excess of bright stars in the fields they observed within $0.^{\circ}2$ of the Galactic Center.

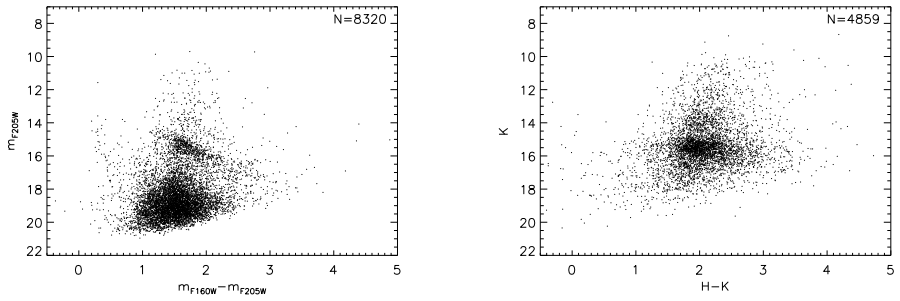

Figure 4. *(left)* Infrared color-magnitude diagram for fields stars in the GC as obtained from NICMOS/HST data. *(right)* Same, but from Gemini/AO data.

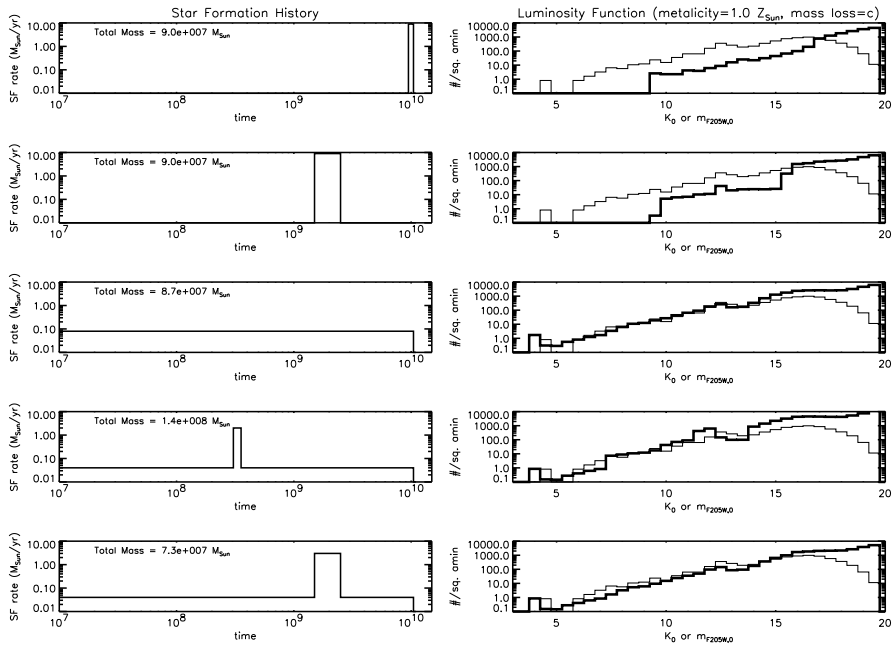

Figure 5. Model luminosity functions (*right, bold*) and observed luminosity functions (*right, light*) for various star formation histories in the Galactic Center (*left*). The models use the Geneva isochrones with solar abundances and canonical mass loss rates.

In order to infer the past star formation rate, I modeled the observed surface number density of stars (Figure 4) as a function of star formation history using the Geneva stellar evolution models, assuming a range of power-law initial mass functions (IMFs), metallicity, and wind mass-loss rates. I considered: an ancient burst, episodic bursts, continuous formation, and combinations of these three. I used these models to produce synthetic luminosity functions for comparison with HST/NICMOS data. The surface number density in the observed luminosity functions has been set by dividing the number of stars per half magnitude bin by the area of the observations. The NICMOS fields vary in location from about 15 pc from the GC to 55 pc, and the sample was culled of forground and background stars by limiting the data to stars with $1.0<m_{\rm F160W}-m_{\rm F205W}<3.0$ ($1.7<A_{\rm K}<6.5$). The results are presented in Figure 5.

In general, I find that the presently observed luminosity function is very well fit by continuous star formation at the level of 0.05 to 0.1 $M_\odot\ yr^{-1}$. The total mass of stars formed is $\sim 10^8\ M_\odot$ in these models, although the present-day mass is less as a result of mass-loss via steady winds or supernovae.

An ancient burst model is not consistent with the presence of bright stars ($K_0<8.0$), nor is it consistent with an enhanced brightness of the red clump (although the observational evidence for such an enhancement is controversial). Episodic bursts are essentially indistinguishable from continuous star formation when using the luminosity function as a metric; clearly, one needs to examine a subset of all stars in distinguishing burst widths and periodicities. The continuous star formation model reproduces the bright end of the luminosity function,

although note that the bulk of the observed bright stars are not red supergiants, so that there must be a gap in significant star formation activity during recent times, excepting the last 5 *Myr*. I find that variations in metallicity, IMF slope, or mass-loss rate, do not qualitatively affect our conclusion that continuous star formation produces synthetic luminosity functions that best fit the observed luminosity function, compared with the other star formation scenarios examined.

I acknowledge very useful discussions with Paco Najarro, Bob Blum, Laurant Sjouwerman, Mike Rich, Mark Morris, Sungsoo Kim, and Jay Frogel.

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