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The Pistol Star and Massive Stars in the Galactic Center

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Abstract.

A significant portion of the massive stars in the Galaxy are located within 50 pc of the Galactic Center. The stars have a variety of ages between 1 and 10 Myr, giving rise to Wolf-Rayet and red supergiant types. Most of these stars reside in three massive clusters: the Central Cluster, Quintuplet Cluster, and Arches Cluster. The clusters have similar masses, $\approx 10^4\ M_\odot$, but the first two are substantially older (3-5 Myr) than the last (1-2 Myr). This spread in age, with most other parameters being equal, gives us a unique opportunity to test models which predict massive star evolution. We discuss the content in these clusters, with a particular emphasis on how well they fit into our current understanding of stellar evolution. In particular, we discuss the Pistol Star, one of the most luminous, and, therefore, initially most massive, stars in the Galactic Center. Its evolutionary status places the star in the unstable Luminous Blue Variable stage, providing an extraordinary opportunity to test stellar evolution models for massive stars near their Eddington limits. We find a lower luminosity limit of $10^{6.6}\ L_\odot$, $T_{\rm eff} \approx 10^{4.15}$ K, and a helium-enriched surface, consistent with the star's advanced evolutionary status. Our evolutionary tracks suggest an initial mass of $\sim 200\ M_\odot$ and age of $1.7-2.1$ Myrs. We interpret the star and its surrounding nebula as an LBV which has recently ejected large amounts of material. We expect that many of the massive stars in the Galactic Center will soon progress through an LBV stage and eventually become supernovae at a rate of ≈ 1 per 20,000 years for the next several Myr.

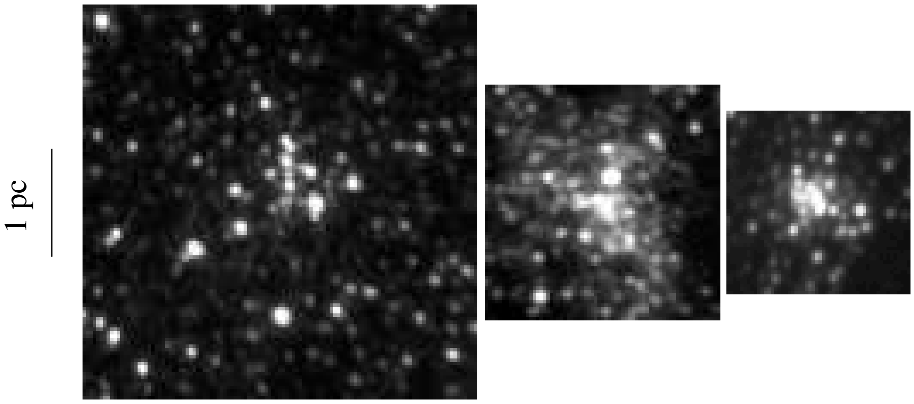

Figure 1. K′-band images of the Quintuplet, Central, and Arches clusters (left to right). See Figer 1995 for details.

1. Introduction

Massive stars represent one of the last great frontiers of stellar evolution theory. Because of their incredible burning rate, their interiors evolve much more quickly than those of lower mass stars. Due to their prodigious winds, their outward appearance changes drastically over short timescales, i.e., changes in $T_{\rm eff}$ by factors of two or three in a time span of hundreds of years. The combination of these factors makes it difficult to model the evolution of massive stars, so their evolutionary progressions are largely uncertain.

Massive stars also present interesting test points for star formation theories, i.e., how can stars which emit so much radiation accrete so much matter? Current theories suggest that massive stars begin hydrogen burning while still accreting matter. Indeed, these theories suggest that massive stars with $M_{\rm initial}$ $\sim$ 85$-$150 $M_\odot$ have accretion times which are comparable to their hydrogen burning times, i.e., their photospheres are unobservable throughout their main sequence lifetimes (Bernasconi & Maeder 1996). Presently, the best estimate of the most massive star which can form (and be seen) is constrained by observation.

The Galactic Center is a remarkable laboratory for studying massive star birth and evolution. While occupying just 1% of the Galactic volume, the Galactic Center harbors 10% of the star formation in the Galaxy. Correspondingly, the population in the center contains at least 150 stars with $M_{\rm initial} > 20$ $M_\odot$. Figure 1 shows a collage of the three extraordinary clusters within the central 50 pc, each having $\gtrsim 10^4$ $M_\odot$ in stars and L $> 10^7$ $L_\odot$.

In addition to this large sample, the Galactic Center is an interesting region because the environmental factors which are thought to influence star formation and evolution are so extreme. The metallicity may be higher than anywhere else in the Galaxy, impacting both star formation and the evolution of massive stars with strong winds. The magnetic field strength is 300 times greater than the average in the Galactic disk, something which is expected to affect protostellar collapse. In addtion to these environmental factors, the clusters in the Galactic Center provide an opportunity to investigate star birth in dense clusters.

We review the latest results concerning massive stars near the Galactic Center, using the Pistol Star as a case study. We conclude that the massive stars in the Galactic Center provide an extraordinary opportunity to test stellar evolution and star formation models.

2. The Central Cluster

The past decade has seen major advances in our understanding of the stars in the Central Cluster. After Forrest et al. (1987) and Allen, Hyland, & Hillier (1990) detected a blue supergiant in the center (the "AF star"), Krabbe et al. (1991) discovered about a dozen HeI emission-line stars. These, and subsequent, discoveries eventually solved the question of heating and ionization in the central parsec, and gave impetus to other studies of the massive star clusters in the central 50 pc (Figer 1995, Cotera 1995, Blum, Sellgren & Depoy 1995, Tamblyn et al. 1996).

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). 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, but red supergiants are mainly concentrated outside of a $4''$ void at the very center.

Najarro et al. (1994) investigated the AF star using a detailed spectroscopic analysis. They found that the star is a helium-rich blue supergigant/Wolf-Rayet star, characterized by a strong stellar wind and a moderate amount of Lyman ionizing photons. Subsequent spectroscopic studies of the brightest He I emission-line stars by Najarro et al. (1997) confirmed the nature of these objects as "Ofpe/WN9" stars with extremely strong stellar 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 30×10^5 $L_\odot$. 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.

3. The Quintuplet Cluster

The Quintuplet Cluster was first noted, and named for, its five bright infrared sources (Okuda et al. 1990, Nagata et al. 1990, Glass et al. 1990). Since the discovery of these luminous sources, many other luminous stars in the region have been identified. The cluster contains, at least, 30 stars having $M_{\rm initial} >$ 20 $M_\odot$, including 4 WC types, 4 WN types, 2 LBVs, and many OBI stars; the Central Cluster is the only other Galactic cluster with so many bona fide WR stars. The two LBVs are added to the list of 6 LBVs in the Galaxy. They include the Pistol Star, one of the most luminous stars known (see below), and a newly identified LBV which is nearly as luminous as the Pistol Star (Figer, McLean, & Morris 1998b). Most of the luminous stars are thought to be 3−5 Myr old, but significant age differences remain, i.e., the Pistol Star is thought

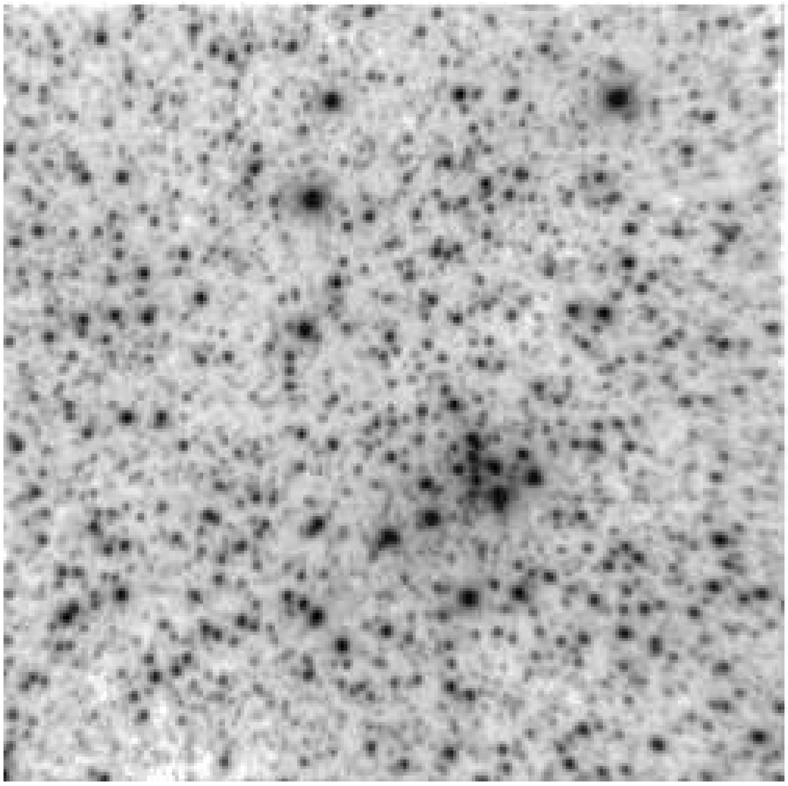

Figure 2. Alternate greyscale stretch of the K′-band image of Quintuplet Cluster in Figure 1.

to be ≈ 2 Myrs old. See Figer, McLean, & Morris (1998b) for a review of the massive stars in the cluster.

Figure 2 shows a *K*-band image of the cluster. Most of the stars in the image do not belong to the cluster, but are simply part of the dense Galactic Center stellar population. Figure 3 shows a map of massive stars in the cluster, symbolized by subtype.

The Quintuplet proper members (QPMs) represent a rare phenomenon, having analogs only in the Central Cluster. The QPMs have very red intrinsic spectral energy distributions which can be fit by cool blackbodies, $T_{\rm eff} \approx 800$ to 1,300 K. Being spectroscopically featureless at all observed wavelengths, their true nature has been elusive. Figer, McLean, & Morris (1998b) have summarized the hypotheses for the nature of these stars, and favor the "DWCL" hypothesis. DWCL stars (dusty Wolf-Rayet late-type carbon stars) are in a short-lived stage of evolution marked by massive circumstellar dust production (Williams, van der Hucht & The 1987). The classical WR emission-line spectrum has yet to be observed for these stars, so this hypothesis remains unproven.

Figure 4 shows isochrones from the Geneva models (Meynet et al. 1994) with data points for the B supergiants in the cluster overplotted. The stars span a large range in luminosity; however, the most luminous points could represent binary systems. If that is the case, then the plot suggests that the cluster is 2 Myr old. This age is in contrast to the expected age for a coeval cluster having equal numbers of WN and WC types, ≈ 4 Myrs assuming the models

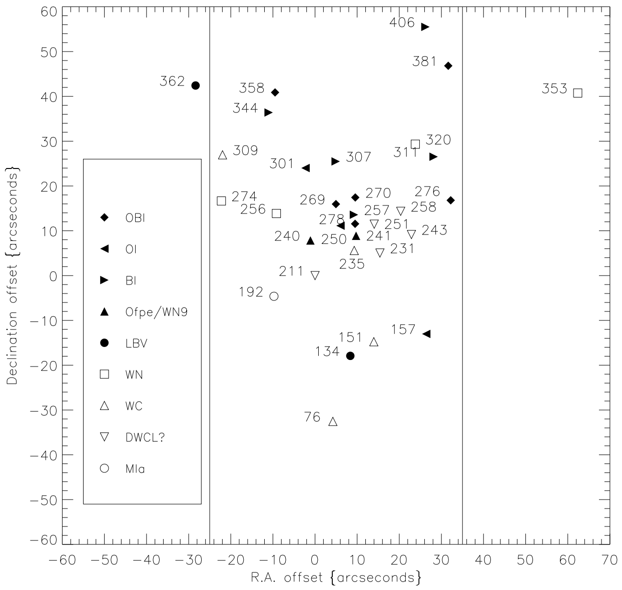

Figure 3. Massive stars in the Quintuplet Cluster, symbolized by subtype. The rectangular box indicates the region observed in a K-band slit scan. See Figer, McLean, & Morris (1998b) for details.

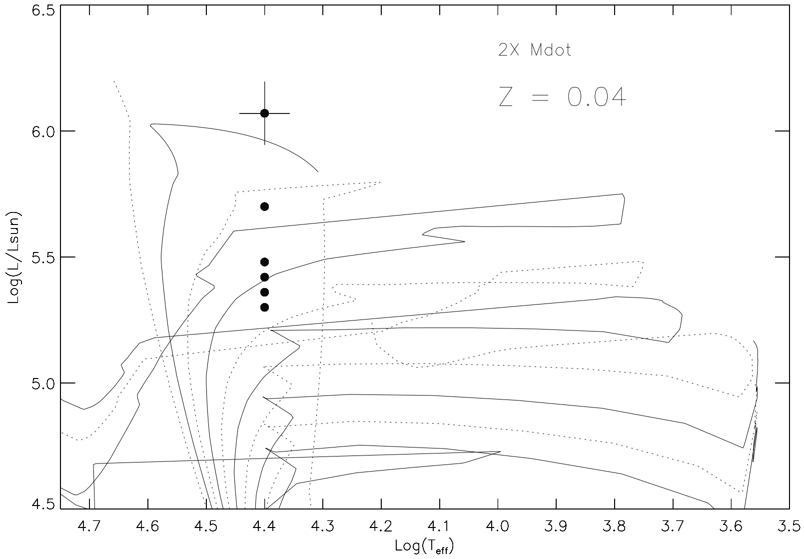

Figure 4. Model isochrones from the Geneva models for Z = $2Z_\odot$ with "2×" $\dot{M}$. Isochrones begin at 0.5 Myr and are spaced by 0.5 Myr. Data for early B supergiants in the Quintuplet Cluster are overplotted.

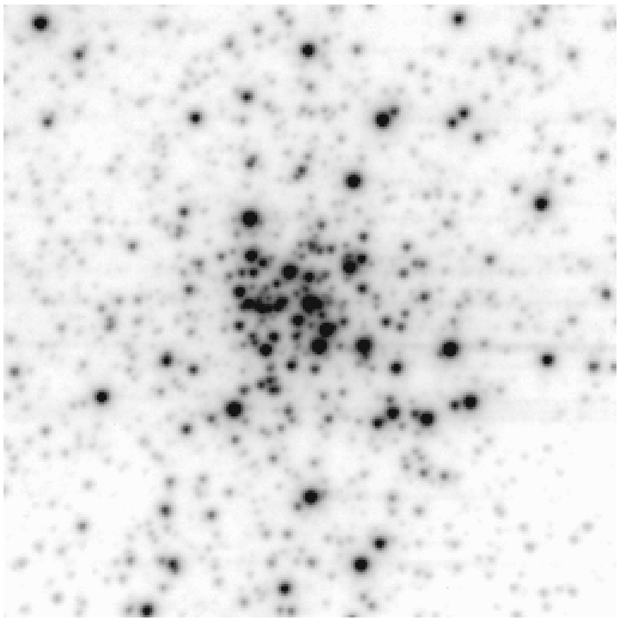

Figure 5. K′-band image of the Arches Cluster obtained with NIRC on Keck I. See Serabyn, Shupe, & Figer (1998) for details.

used for the tracks in the figure. It is also quite young compared to the youngest possible age for the red supergiant in the cluster, $\approx$ 4 Myrs. It does agree with our determination of the age of the Pistol Star (see below).

4. The Arches Cluster

The Arches Cluster (Figure 5) is, perhaps, the most massive cluster in the Galaxy (Serabyn, Shupe, & Figer 1998). It certainly appears to be the most dense, $\rho_{stars,ave} \sim 3 \times 10^5\ M_\odot\ \mathrm{pc}^{-3}$, substantially exceeding the core density in R136 and dwarfing any other massive cluster in the Galaxy, i.e., NGC 3603. Figure 6 shows a color-magnitude diagram of the brightest cluster members; the average apparent color ensures a location at a distance of the Galactic Center. Figure 7 shows the K-band luminosity function for the cluster with spectral types indicated. Cotera et al. (1996) presented H- and K-band spectroscopy of the brightest dozen or so members of the cluster, showing that they are similar to WN types. Unfortunately, it is difficult to dinstinguish between WNL stars and OI^+ stars solely on the basis of K-band spectra (Conti et al. 1995, Figer et al. 1997).

The Arches appears to be much more compact than the other GC clusters, something which is likely to be due to its relative youth. The absence of WC stars in the cluster argues for an age less than $\approx$ 3 Myr. The presence of stars with WN-like spectra would normally indicate an age $>$ 2 Myr; however, the emission-line stars are much younger if they are O supergiants still on the main sequence. The cluster is probably 1−2 Myrs old, i.e., the Arches Cluster and R136 are probably closer in content and age than any other two clusters in the

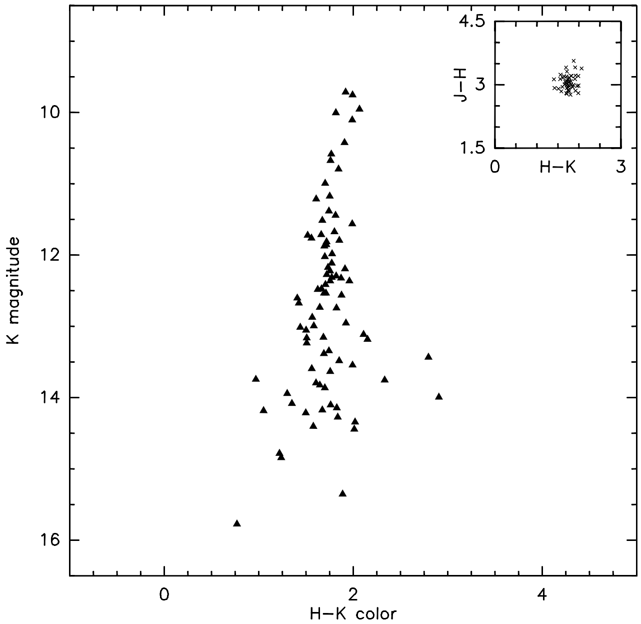

Figure 6. Color-magnitude diagram of the Arches Cluster. See Serabyn, Shupe, & Figer (1998) for details.

Galaxy or Magellanic Clouds. See Massey & Hunter (1998) for a discussion of the massive star content of R136.

5. The Pistol Star: a case study in stellar evolution

The Pistol Star poses an intriguing puzzle to the theory of stellar evolution (see Figure 8). Its position in the Hertzsprung-Russell diagram, i.e., very high luminosity but rather cool surface temperature, is seemingly in conflict with present ideas of massive star evolution. This can be seen in Figure 9, where the position of the Pistol Star is compared to two sets of stellar evolution tracks in the Hertzsprung-Russell diagram. The thin drawn tracks of Schaller et al. (1992) for 60, 85, and 120 $M_{\odot}$ avoid the upper right corner of the diagram, which is in agreement with the idea that "normal" massive stars do not cross the so called Humphreys-Davidson (1979) limit in the HR diagram or at least become unstable when they do so (cf., Langer 1997). The reason the tracks of very massive stars avoid the cool side of the HR diagram and quickly turn towards hotter surface temperatures is the enrichment of the envelope and surface with helium. This can, in principle, be achieved by two ways, either mass loss or internal mixing. The more massive a star is, the more efficient both of these processes become. E.g., a 120 $M_{\odot}$ zero age main sequence star contains more than 100 $M_{\odot}$ in its convective core, so only 20 $M_{\odot}$ need to be lost in a stellar wind for helium to be enriched at the surface of the star. Moreover, rotational mixing is thought to be important in massive stars (Langer et al. 1997, Maeder 1997), and more so with larger initial mass. Even though considerable uncertainties in the treatment of rotational mixing persist, it appears likely that this mixing will turn stars with $M_{\rm initial} \gtrsim 60\ M_{\odot}$ and average rotation rates into Wolf-Rayet stars while still in their core hydrogen burning evolution, so that they may not

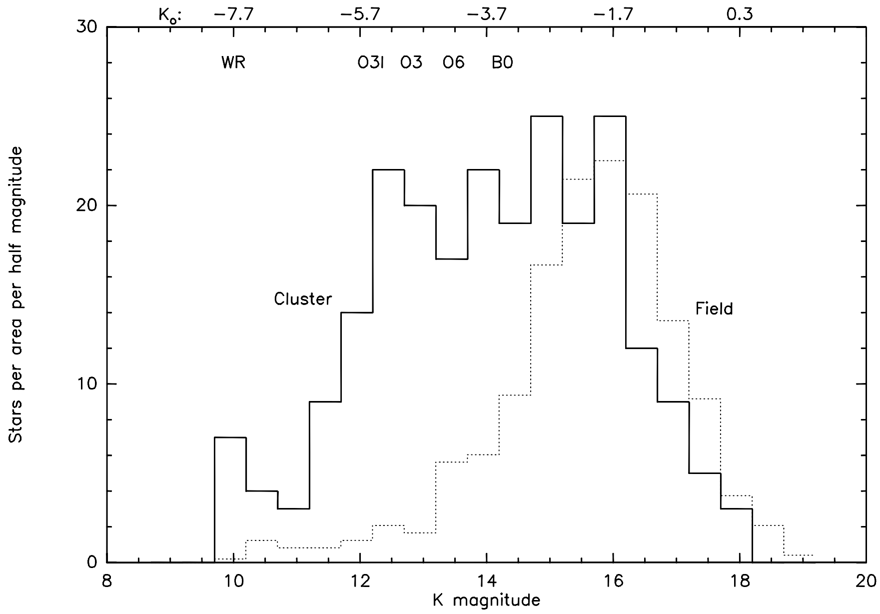

Figure 7. *K*-band luminosity function of the Arches Cluster. See Serabyn, Shupe, & Figer (1998) for details.

only avoid a red supergiant stage but perhaps even a Luminous Blue Variable stage (Maeder 1987, Langer 1992, Fliegner & Langer 1995, Meynet 1997).

How can a very luminous and cool star as the Pistol Star be understood? First, its high luminosity suggests a very high mass, but strong internal mixing can appreciably increase the luminosity of a star (cf., Fliegner et al. 1996). However, strong internal mixing appears to be excluded in the case of the Pistol Star from the arguments above. Second, the previous mass loss must not have been too large. E.g., the tracks of Schaller et al. (1992) shown in Figure 9, which include moderate convective core overshooting but no rotational mixing, and which use the empirical mass loss formula of de Jager et al. (1988), avoid the cool side of the HR diagram for $M_{\rm initial} \gtrsim 100\ M_\odot$.

There are basically no empirical mass loss rates for stars with masses $\gtrsim 100$ $M_\odot$, — i.e., the use of empirical mass loss rates always involves an extrapolation in those cases. We have calculated evolutionary tracks with a metallicity of 2% and initial masses in the range 60−300 $M_\odot$, applying the radiation driven wind theory of Kudritzki et al. (1989), with wind parameters $k = 0.085$, $\alpha = 0.657$, $\delta = 0.095$, and $\beta = 1$ according to Pauldrach et al. (1994). Our models lose less mass than those of Schaller et al. (1992); the 60, 100, and 150 $M_\odot$ sequences have, at core hydrogen exhaustion, 54, 84, and 110 $M_\odot$ respectively. The 200, 250, and 300 $M_\odot$ sequences are terminated at central hydrogen mass fractions of $X_c = 0.16$, 0.22, and 0.29 where the remaining masses are 158, 197, and 244 $M_\odot$ due to a hydrodynamic instability occurring at the stellar surface (see below).

We did not invoke any "convective core overshooting." This has been applied in many massive star calculations in the recent years in order to obtain a wider main sequence band (cf., Schaller et al. 1992). However, as rotationally induced mixing has a very similar effect (e.g., Langer 1992, Fliegner et al. 1996), we argue that any main sequence widening may be due to rotation and thus

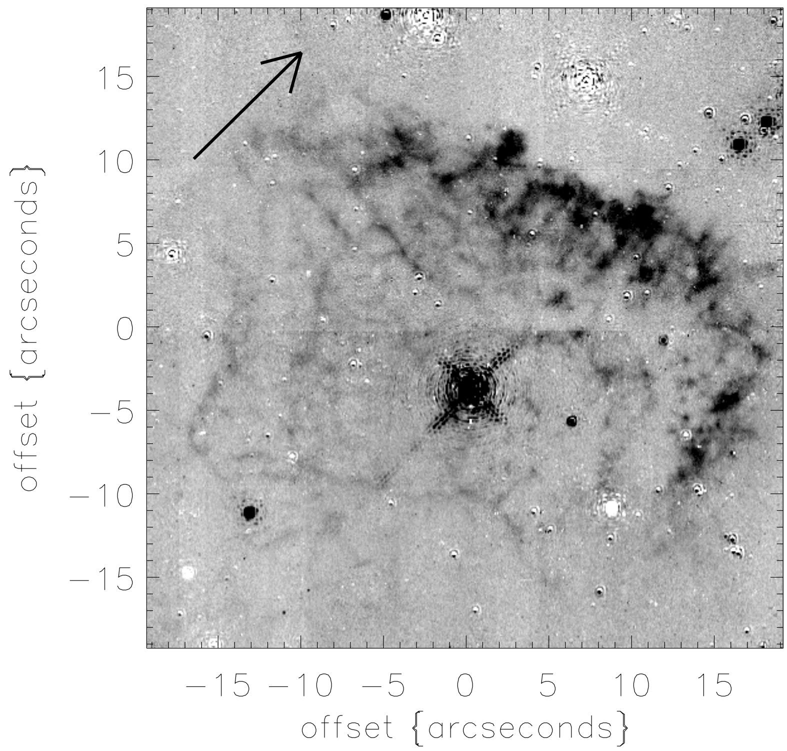

Figure 8. Negative greyscale Paschen-α minus continuum image of the Pistol Nebula obtained with NICMOS/HST. See Figer et al. (1998a) for details.

that the convective cores of non-rotating stars are not extended over their sizes predicted by the Schwarzschild criterion.

Our finding that the most massive stellar models computed here become unstable at around $T_{\rm eff} \simeq 20{,}000$ K and $\log(L/L_{\odot}) \gtrsim 6.5$ (cf., Stothers & Chin 1997), together with the coincidence of the position of the Pistol Star with these figures, leads us to propose the following scenario. The Pistol Star is unusually massive and may therefore have an unusual formation history. Apparently, it has obtained very little angular momentum, which perhaps allowed its mass to grow so much. Consequently, it evolved with 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. This is its present evolutionary stage. As it is still burning hydrogen in its core, the probability for the star to be found in this stage is not small. According to our models, its initial mass is $\sim 200\ M_{\odot}$, and its present age is in the range 1.7−2.1 Myrs. The amount of mass lost prior to the occurrence of the surface instability is 42−53 $M_{\odot}$ (see Figer et al. 1998a, for more details). Figure 10 places the Pistol Star in an HR diagram among its stellar "peer group."

6. Implications for Stellar Evolution and Star Formation Models

Stellar evolution and formation models make definite predictions of the content of starburst clusters as a function of time. These predictions can be tested by comparing their outputs to observations of the massive clusters in the Galactic Center. It is crucial that state of the art models predict the content of these

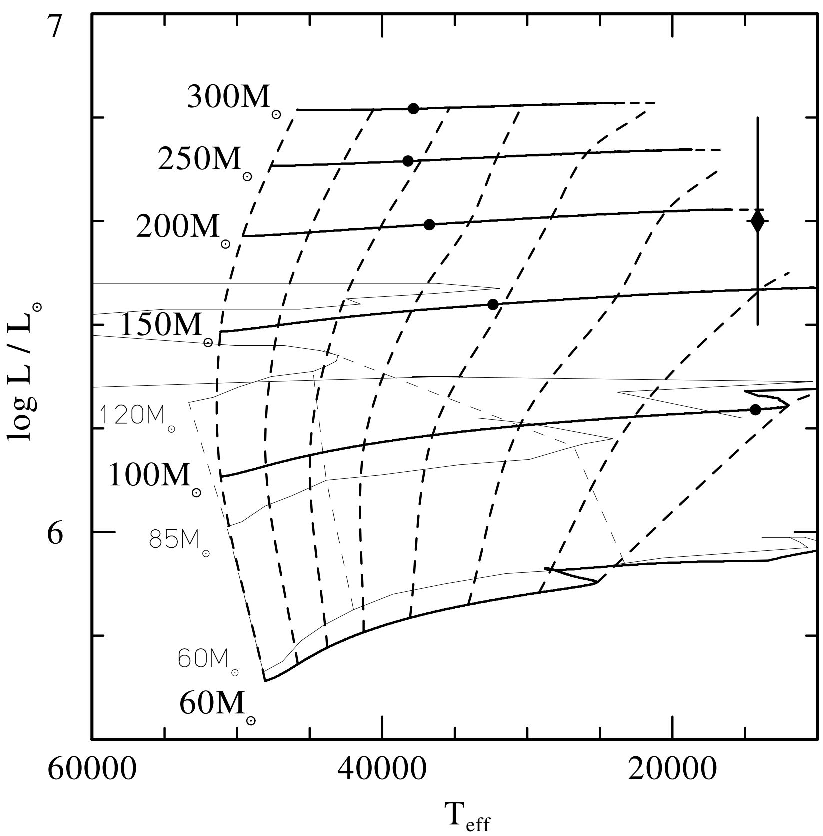

Figure 9. Stellar evolutionary tracks in the HR diagram for non-rotating stars in the initial mass range 60−300 $M_\odot$ and a metallicity Z of 2% (thick continuous lines). Thick dashed lines connect models with central helium mass fractions of 0.28 (leftmost track, ZAMS), 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 0.98. Black dots mark the first appearance of hydrogen burning products at the stellar surface. The tracks of the 200, 250, and 300 $M_\odot$ models end due to the occurrence of surface instabilities. Thin continuous lines show evolutionary tracks for 60, 85, and 120 $M_\odot$ and Z=0.02 obtained by Schaller et al. (1992) — without their effective temperature correction — with thin dashed lines connecting models with central helium concentrations of 0.30, 0.60, and 0.90. The position of the Pistol Star is marked by a diamond, together with the error bar.

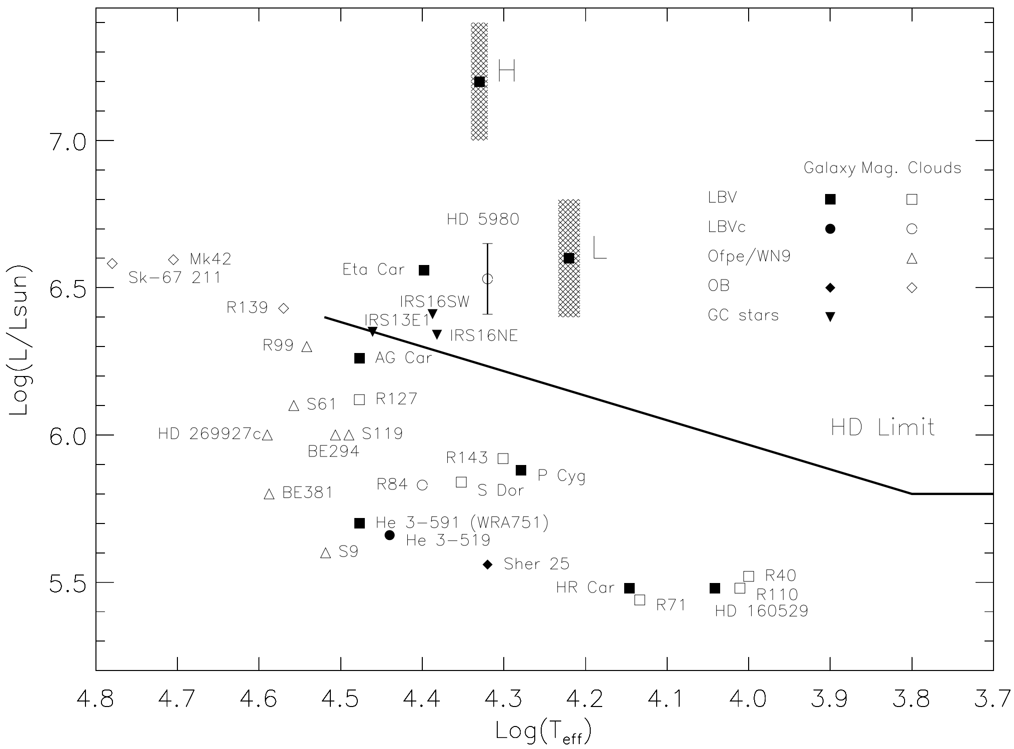

Figure 10. HR diagram reproduced from Figure 12 in Figer et al. (1998a). HR diagram of the Pistol Star and other hot, luminous stars in the Galaxy and Magellanic Clouds, in quiescence. The data were taken from Humphreys & Davidson (1994), unless otherwise noted. When possible, the LBV data are at quiescence. LBV's are shown as squares, LBVc's as circles, Ofpe/WN9 as triangles, and OB stars as diamonds. Filled symbols are for stars in the Galaxy, and open symbols are for stars in the Magellanic clouds. LBVs make redward excursions in this diagram during eruption. For example, η Car might have been as cool as 5,000 K during its last major eruption. See Humphreys & Davidson (1994) for more information concerning the locations of LBVs during eruption. Note that η Car may be a binary (Damineli, Conti, & Lopes 1997). Data for Sher 25 in NGC 3603 were taken from Moffat (1983). Data for HD 5980 are from Koenigsberger, Auer, & Guinan (1997); it is not certain which component of this binary system is the LBV, so the luminosity spans a large range. Data for He 3-591 (WRA 751) are from Hu et al. (1990). Data for He 3-519 are from Smith, Crowther, & Prinja (1994). Data for R71 and R84 were taken from Crowther, Hillier, & Smith (1995). Data for Sk $-67^\circ_.211$ and Mk42 were taken from Kudritzki et al. (1996). Data for the Ofpe/WN9 stars are from Pasquali (1997). Data for R139 (O7 Iafp) are from Walborn & Blades (1997). Data for the "GC stars" are from Najarro et al. 1997. Note that IRS16NE has some LBV-like spectral characteristics (Tamblyn et al. 1996).

clusters before they are used to predict the contents of more distant clusters, i.e., super-star clusters in other galaxies.

Morris (1993) has argued that the lower mass cutoff might be elevated in the Galactic Center. A Salpeter intitial mass function (Salpeter 1955) suggests a few $\times\ 10^5$ lower mass stars in the GC clusters, assuming a lower mass cutoff of 0.1 $M_\odot$. This cutoff should be directly obsevable in these clusters. Present observations are unable to detect lower mass stars in the clusters, but HST/NICMOS and adaptive optics observations will be able to detect them. Once these observations are in hand, the Arches Cluster will provide the best testpoint for determining whether the initial mass function depends upon metallicity, galactocentric radius, or stellar density. Current evidence suggests that there is little, if any, correlation between the IMF and these environmental factors, at least to within measurement errors (Scalo 1998).

Stellar evolution models predict that massive stars should evolve into Wolf-Rayet stars, perhaps via an LBV stage, and onward to supernovae. The exact mixture of various WR subtypes and O-stars is sensitive to assumed mass-loss rates and metallicity. A key challenge for these models is to reproduce the content in the Quintuplet Cluster. As discussed earlier, the observed subtypes cannot be fit for a unique age. Arguments against coevality are suspect because tidal shear and the strong winds from massive stars will tend to dissipate a natal cloud over short timescales. Note that the Quintuplet Cluster should have orbited the Galactic Center about 1.5 times since its birth. It will be more difficult to use the Central Cluster as a test point for stellar evolution models because it appears not to be coeval. In fact, star formation appears to be currently ongoing (Genzel et al. 1996).

The process of triggered star formation may be more prevalent in the Galactic Center than anywhere else in the Galaxy. In fact, the Jean's mass is so large, triggered star formation might be necessary to form stars in the Galactic Center (Morris 1993). Triggering could come from cloud-cloud collisions, or from supernova shocks. Meynet (1995) gives $\approx 5\ \times 10^{-7}\ \times\ \mathrm{N}_{\mathrm{O-stars}}$ supernovae per year during the peak supernovae period for a starburst cluster, where $\mathrm{N}_{\mathrm{O-stars}}$ is the number of O-stars in the cluster at $\tau_{\mathrm{age}} = 0$. These periods are expected to last a few Myrs, starting at $\tau_{\mathrm{age}} \approx 4$ Myrs. Using $\mathrm{N}_{O-stars} \approx 100$, we find a supernovae rate of 1 per 20,000 years. Stars in the Quintuplet and Central clusters are closest to the onset of supernovae production, and their massive stars probably number around 100 total. Once the Arches Cluster becomes old enough to participate in supernovae production, the massive stars in the Quintuplet and Central clusters should be gone, so that the total supernovae rate in the Galactic Center should remain fairly constant over the next 5 Myrs or so ($\mathrm{N}_{\mathrm{O-stars,\,Arches}} \approx 100$).

Finally, we note that some very interesting single objects in the Galactic Center are still unexplained. The Quintuplet proper members are unique, although fainter mid-infrared sources are located in the Central Cluster. Why are there so many such objects in the Galactic Center? Why don't we see QPM-like objects in other massive clusters?

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