The Stellar Population in the Galactic Center: 
Insights from the Spitzer Space Telescope

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Abstract. The Spitzer IRAC observations (Stolovy et al., these proceedings) of the central 265 pc × 210 pc provide an opportunity to study the relationships between massive stars, gas, and dust in the Galactic Center at unprecedented resolution. The observations are inclusive of the three known extremely dense clusters of massive hot young stars which ionize the unusual thermal filaments seen at both radio wavelengths and in PAH emission in the IRAC images. Here we explore the effects of the massive stars, particularly in regions including the Quintuplet and Arches clusters, on the nearby diffuse ISM emission (see also Simpson et al. these proceedings). We discuss the diagnostics available using the IRAC colors, and what these show us in regards to known massive stars. Finally, we discuss the 1-8 µm SEDs which are currently under construction, and the preliminary results using a novel SED fitting program to determine the stellar type and extinction to all available point sources in the survey region.

1. Introduction
The formation of stars in the Galactic center has posed a problem since the presence of young stars in the central parsec was first suggested [1, 2]. The canonical view has been that as a result of the high gas temperatures and pressures, large internal cloud velocity dispersions, and strong pervasive magnetic fields, star formation by the standard method of self-gravitational collapse is significantly suppressed. This is thought to be particularly true within a radius of ∼100 pc, because of the additional complication of strong tidal forces from the strongly peaked mass within that radius. The identification of very young stars (<2 Myrs) scattered throughout the central 100 parsecs [3, 4, 5, 6, 7], however, contradicts this canonical view. The existence of a truncated initial mass function (IMF) has been suggested based on observations of the Arches Cluster [8, 9], at approximately 6-7 M⊙. A truncated IMF is, however, highly unusual, and often later shown to be the result of resolution or background limitations.

Recently, two more challenges to the canonical idea of the suppression of typical star formation in the GC have arisen: (a) the magnetic fields may not be that strong [10], (b) slow self-gravitational collapse as the preferred mode of star formation, exemplified by low mass stars in
the Taurus-Auriga cloud, may not be correct. Recently Lada & Lada [11] have suggested that 70-90% of star formation occurs in rich embedded clusters, most of which contain massive stars. Star formation which is triggered by massive stars, is a viable [12] mode of star formation and may predominate.

Our *Spitzer Space Telescope* IRAC observations of the GC (see Stolovy et al., these proceedings), in addition to providing a detailed map of the filamentary structure of the interstellar medium, provide an amazing opportunity to explore the stellar population throughout an approximate 140 pc radius of the Central Molecular Zone. When combined with observations at NIR wavelengths, the IRAC point source catalog will provide a much needed census of stellar sources throughout the entire region. The identification and distribution of stellar types will provide us with a better understanding of the star formation mechanisms throughout the GC.

2. Regions of known young massive stars
As a first step in enhancing our understanding of the younger stellar population throughout the GC, we turn to the regions of known young massive stars. The four IRAC bands, referred to as Channels 1-4 in Stolovy et al. (these proceedings), provide observations at 3.6, 4.5, 5.8 and 8.0 $\mu$m respectively. At 3.6 $\mu$m, the observed flux is dominated by emission from stellar atmospheres, whereas at 8.0 $\mu$m, photospheric emission is weaker and diffuse ISM emission from polycyclic aromatic hydrocarbons (PAHs), tracing photodissociation regions, becomes an important component of the emission. The combination of the four bands therefore provides an excellent map of the relationship between the stars and the ISM.

**Figure 1.** IRAC Ch 4 (8.0 $\mu$m) image of the Sickle HII region. The image is in galactic coordinates with a FOV of $4' \times 4'$. For $R_{GC}$ of 8.0 kpc, $4'$ corresponds to $\sim$9.3 pc. At this distance, the fingers are approximately 1–1.5 pc long and 0.5 pc wide. The ionizing source for both Figs. 1 and 2 are located to the lower right of the image.

**Figure 2.** IRAC Ch 4 image of the Pillars in M16. The image has been rotated to approximate the orientation of the Sickle. The FOV is $16' \times 16'$, which at the distance of M16, $\sim$2 kpc, corresponds to $\sim$9.3 pc. Thus, Figs. 1 and 2 have the same physical size. Overall, the features in the Sickle are remarkably similar to those in M16.
2.1. The Quintuplet, Sickle and Pistol region

One of the most intriguing early results of this survey is the possibility that we are seeing a photoevaporative region similar to those seen in the HST images of the “elephant trunks” (also known as the “Pillars of Creation”) in M16 [12]. In the GC, these features, which we call the “fingers”, are associated with the Sickle HII region and are presented in Fig. 1. IRAC observations were also made of M16 as part of the GLIMPSE Legacy program [13], and are shown for comparison in Fig. 2. In M16, the columns are thought to be regions of locally higher density than their surroundings, capable of retaining their natal molecular material despite the strong disruptive influences of the nearby OB association. Simpson et al. [14] demonstrated that the hot stars located within the Quintuplet cluster (e.g. [5]) are the most likely ionizing source for the Sickle. Our Spitzer images strongly suggest that the emission from the Sickle comes from fingers analogous to the columns in M16, and are the result of photoionization in a photoevaporative flow from the hot massive stars known to exist in the Quintuplet cluster. Analysis of the GLIMPSE IRAC data of M16 [15], clearly indicates the presence of low mass star formation throughout the M16 region, including the Pillars, despite the presence of the more evolved nearby OB stellar cluster. A detailed comparison of this region and the Sickle is in progress, and will address the uniqueness of the Sickle as a site of current star formation.

2.2. The Arched Filaments

The region of the Arched Filaments contains the Arches Cluster, which represents one of the densest known clusters of young massive stars, including ~15 WN stars [16]. The Arches Cluster has been shown to ionize the nearby thermal filaments [17, 18]. The IRAC Ch 4 image of the region surrounding the Arches Cluster is presented in Fig. 3. As discussed in Stolovy et al. (these proceedings) the diffuse emission seen in IRAC Ch 3 and 4 images is predominately from PAHs, and the ratio of the two bands is remarkably uniform throughout the entire region, with
Ch4/Ch3∼3 (Arendt et al. in preparation). Using this global ratio to normalize the Ch 3 to the Ch 4 data, and subtracting off the adjusted Ch 3 image, we are able to identify regions of 8 μm excess. The largest region displaying this excess consists of an elongated bubble centered on the Arches Cluster. The bubble extends to the west, ending parallel to the E2 filament, is bounded on the south by the G0.95+0.07 region, but crosses perpendicularly to the E1 filament. This elongated bubble has not been previously identified, but the underlying mechanism has not yet been determined.

2.3. The H1-H8 HII Regions

The H1-H8 regions are a group of compact HII regions located between the areas containing the Quintuplet and Arches Clusters, and the central few parsecs. At least one young massive star has been identified in this region, associated with H2 [6, 7]. Each of the regions also has strong, compact, 8 μm excess emission. Unlike the known massive stars in the Quintuplet and Arches, however, the stars located throughout this region appear to be forming singly. As such, they perhaps provide a template for a less spectacular, but perhaps more common region of ongoing star formation within the central few hundred parsecs.

3. Photometry

The morphology of the ISM and its juxtaposition with the stellar population, only scratches the surface of the ability of the GC IRAC data set to explore the stellar population throughout the entire 265 pc×200 pc of the galaxy. One of the goals of the project is to create a point source catalog of the entire region, and combine this with 2MASS observations at shorter wavelengths. In addition, we have recently obtained J band images of the central ~100 pc to significantly fainter magnitudes, and will use this data to enable inclusion of NIR stars to fainter magnitudes. The region is extremely crowded (see Stolovy et al.), and reliable point source extraction of the IRAC fluxes requires combining the results of aperture and PRF extraction which is discussed in more detail in Stolovy et al., and will be discussed fully by Ramirez et al. (in preparation).

One of the challenges in utilizing the IRAC observations to explore the stellar populations is the uniqueness of the filter set. A second consideration, particularly when combining the IRAC observations with both 2MASS and in the future with Spitzer MIPS 24 μm data (PI: Yusef-Zadeh), is the number of possible combinations of color-color (CCD) and color-magnitude diagrams (CMD). Fortunately, considerable work has already been done on the parameter space explored by the IRAC filters (e.g. [19, 20]). In Figs. 5 and 6, we present the [4.5] vs. [3.6]−[4.5] CMD, and the [3.6]−[4.5] vs. [5.8]−[8.0] CCD plots typically utilized to begin exploring the stellar populations with the IRAC observations. In Fig. 5 we have convolved Kurucz stellar atmosphere models [21] with the Li & Draine extinction curve [22], and the IRAC filter function available from the SSC website, to produce theoretical magnitudes for normal stars assuming (a) a distance of 2 kpc with no extinction, and (b) 8 kpc with A_ν=25. Using the approximate turnover in the number vs. magnitude plots (see Stolovy et al. these proceedings) to set a confidence limit, we find that we can probe the stellar population to approximately BV stars, including M-K giants and all supergiants. In the CCD, we find stars for which we are observing the stellar atmospheres are located at [3.6]−[4.5]=0.39±0.07, while [5.8]−[8.0]=−0.10±0.06, which is displaced from the origin primarily by extinction. We note that in the [3.6]−[4.5] vs. [5.8]−[8.0] CCD plot, this can be seen as an extinction vector which goes up and to the left.

In Fig. 6, we reproduce Figs. 8 and 9 from Whitney et al. (2004). These figures were produced from theoretical models of YSOs (young stellar objects) of varying temperatures and circumstellar disk orientations, located at a distance of 2 kpc. As can be seen, unlike the case of the stellar atmosphere models, the objects are typically located at [3.6]−[4.5]>0.5 and [5.8]−[8.0]>1.0. In the GC, we would expect these numbers to be [3.6]−[4.5]>0.9 and [5.8]−[8.0]>0.9. At 2 kpc, our confidence limit translate to [4.5]∼8±0.5. Based on the theoretical models, we should be able to observe YSOs with a temperature of >8000 K for much of the survey. In the region of the CCD occupied by massive YSOs, however, we expect
significant contribution from AGB stars, and future work will address differentiating YSOs from AGB stars in our point source catalog.

In Figs. 7-8, we present the same CMD and CCD for the entire IRAC GC survey, and for an 8′ × 8′ FOV centered on the Quintuplet Cluster; previously known young massive stars are indicated by diamonds. Although the plots for the entire region apparently contain an abundance of sources, they in fact represent only the 284,676 sources which are common to all four IRAC bands. As such, the [4.5] vs. [3.6−[4.5] CMD presented only represents ~35% of the sources identified in the [4.5] band alone. The CMD clearly shows that the brightest sources are saturated at the shorter wavelength, therefore their colors are not always reliable. The known young massive stars which are not in this saturation region are located in the region expected for supergiant stars in Fig. 5. In the CCD, again the vast majority of the stars are located in the
region expected for supergiant stars in the GC, however, the known massive stars have slightly larger $[5.8]−[8.0]$ colors than theoretical predictions for supergiant stars. In addition, we find that only one of the known stars resides in the region with $[3.6]−[4.5]>0.9$ and $[5.8]−[8.0]>0.9$: this is in fact the Pistol Star, an LBV star. There are numerous other stars in this region of the CCD that have not been spectroscopically classified as yet, and theoretically may be either YSOs or AGB stars. The diagram provides a place to begin our search for additional young massive stars in the GC.

4. Future Work: SED fitting

The Spitzer Space Telescope legacy project GLIMPSE, utilized the IRAC camera to image much of the Galactic plane, producing a point source catalog which contains millions of sources. To help analyze this data, Robitaille et al. [25] have produced a grid of YSO models and a tool to fit these models rapidly. The grid also makes extensive use of stellar atmosphere models [21, 25], and will include AGB stars at a future date. The models utilize absolute luminosity, and therefore can fit for distance within a specified range. In addition, since they use at least four data points, typically from combined 2MASS and IRAC catalogs, they can simultaneously fit each source for extinction.

We have used this SED fitting program with a preliminary catalog of our IRAC data. We combined our data with the 2MASS catalog for the region. The version of the 2MASS catalog that we used had detections in all three NIR bands, and for the input to the SED fitting routine we required detections in at least two of the four IRAC bands. Of the 352,235 sources in our combined catalog, 204,035 were fit with stellar atmospheres. There were an additional 147,912 sources that were not well fit by the available stellar atmospheres, but are likely to be stars and their classifications will be improved in future refinements of the fits. There were an additional 1291 sources remaining, which are best fit by the YSO models. Planned future work on the SED fitting program are to include spectra from AGB, Carbon and OH/IR stars which will greatly improve our fits to the GC IRAC data set. The results of the final fitted data will enable us to create a present day mass function over the entire region of the survey, identify possible massive stars and YSO candidates, and create a detailed, extensive extinction map.

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Figure 7. CMD and CCD for the full band merged IRAC catalog. The diamonds indicate previously identified young massive stars. The vast majority of the stars are normal Class I-V stars.

Figure 8. Similar plots as Figs. 5-7 for a $8' \times 8'$ FOV centered on the Quintuplet cluster. The known star at [3.6]$-\times$[4.5]$\sim 1.4$ and [5.8]$-\times$[8.0]$\sim 0.8$ is the Pistol Star.

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