Starburst Clusters in Galactic Nuclei

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Abstract. Galactic nuclei often harbor a disproportionately large amount of star formation activity with respect to their surrounding disks. Not coincidentally, the density of molecular material in galactic nuclei is often also much greater than that in disks (Table 1 in Kennicutt 1998). The interplay between rich populations of young stars and dense molecular environments is evident in our own Galactic center, which hosts over 10% of Galactic star formation activity within only 0.1% of the volume of the Galactic disk. Data obtained with the VLA and HST reveal a variety of star forming sites in the Galactic Center, including a substantial population of stars that are formed in very dense and massive clusters, while other stars are formed in somewhat sparsely populated associations of massive stars. Indeed, three of the stellar clusters are the most massive and densest in the Galaxy. In this paper, we discuss the Galactic center environment and its compact young star clusters, and compare them to their counterparts in star forming galactic nuclei, concluding that dense molecular environments and large velocity dispersions combine to alter star formation activity in both cases, particularly as regards massive young clusters.

1. Introduction

While occupying just a tiny fraction of the Galactic disk, the central molecular zone (CMZ, rGal < 500 pc) of our Galaxy harbors a plethora of astrophysical phenomena. Not only is about 10% of the star formation activity of the Galaxy inferred to be taking place there, but ~10% of the Galaxy’s molecular gas is present there, indicating that while the star formation rate per unit mass of gas is the same as in the disk (Güsten 1989), the star formation rate per unit volume is orders of magnitude higher than in the disk. The form that the star formation takes can apparently be dramatically different than in the disk. While the majority of newborn stars in the CMZ were perhaps formed in typical clusters or associations like those found in the disk, most of the young stars (τage < 10^7 yr) currently seen in the core of the CMZ (rGal < 50) were formed in three spectacular, dense clusters, the most massive such clusters in the Galaxy. Recently, the Hubble Space Telescope has identified similar, and even more
massive, young clusters in other galaxies. While not always confined to galactic nuclei, they are often found there. Evidently, such clusters represent the results of an important mode of star formation, for our Galaxy and others, and we hereafter refer to them as starburst clusters. In this paper, we describe recent results concerning the starburst cluster population in the Galactic center and discuss how these clusters compare to similar clusters in other Galactic nuclei.

2. Star Formation in the Galactic center – Theory

The gravitational collapse of a clump of material within a molecular cloud to form a star is slowed, or even counteracted, by a number of factors, including thermal gas pressure gradients, a magnetic field which permeates the molecular material, turbulence or other forms of macroscopic internal velocity dispersion, and the outward pressure of radiation from the heated clump. Most of these factors appear to be particularly important in the Galactic center, and we expect them to have a pronounced effect on both the rate of star formation there and on the initial mass function (IMF).

Indeed, Morris (1993) notes that the Jeans mass, $M_J$, in the GC is extraordinarily large ($\sim 10^5 \, M_\odot$), whether calculated by invoking turbulent velocities ($M_J \propto \Delta V_{turb}^3 n^{-1/2}$) or magnetic fields ($M_J \propto B^3 n^{-2}$) as the means of support against collapse, where $n$ is the particle density in the cloud. (Indeed, the kinetic and magnetic energies within clouds appear to be close to equipartition.) The physical meaning of such a large Jeans mass is unclear, except that it suggests a tendency for the medium to favor the formation of relatively massive stars, compared to clouds in the Galactic disk, which have a much smaller energy density. Furthermore, it is perhaps inappropriate to relate observed macroscopic quantities (turbulent velocities or magnetic field geometries) to processes such as compression and collapse, which are likely to be operating on smaller, unresolved scales.

A similar problem is found in the early Universe during the time of recombination, wherein the Jeans mass is also $\sim 10^5 \, M_\odot$. In this case, Peebles & Dicke (1968) note that this is about the mass of a typical globular cluster, so they suggest that the masses of globular clusters are defined by the original Jeans instability criterion. Subsequent compression, fragmentation, and cooling significantly alter the quantities which enter into the Jeans mass equation, giving ultimately the spectrum of stellar masses which form within the clusters. Perhaps a similar argument applies to the massive star clusters in the Galactic center, given that their masses (a few $10^4 \, M_\odot$) are not too different than the Jeans mass in the GC.

3. Starburst Clusters in the Galactic center – Observations

A number of infrared studies in the past 30 years have revealed three starburst clusters in the Galactic center: 1) the Central cluster (Becklin & Neugebauer 1968; Forrest et al. 1987; Krabbe et al. 1991; Allen 1994; Libonate et al. 1995; Tamblyn et al. 1996; Najarro et al. 1997; Genzel et al. 1994; Paumard et al. 2000), 2) the Quintuplet cluster (Okuda et al. 1990; Nagata et al. 1990; Glass,
Figure 1. HST/NICMOS images of the Quintuplet (left) and Arches (right) clusters (Figer et al. 1999b). The images are plotted to the same scale, where the Arches cluster image spans $38'' \times 38''$, or 1.5 pc on a side at the distance of the GC (8000 pc).

Moneti, & Moorwood 1990; Figer, McLean, & Morris 1999a), and 3) the Arches cluster (Nagata et al. 1995; Cotera et al. 1996; Serabyn, Shupe, & Figer 1997; Figer et al. 1999b). Indeed, radio observations obtained over the same time period hinted at these clusters by revealing their associated ionizing radiation in the form of HII regions, i.e. the “mini-spiral,” the “Sickle”, and the “Thermal Arched Filaments.” Each cluster is thought to contain a few thousand stars and to have masses of at least $10^4 M_\odot$. The Arches and Quintuplet clusters have been probed down to a few solar masses (Figer et al. 1999b), while data for the Central cluster are only available for stars at the very upper tip of the main sequence (Genzel et al. 1997; Eckart, Ott, & Genzel 1999; Figer et al. 2000). The clusters are rather compact, with half-light radii between 1 pc (the Quintuplet) and 0.2 pc (the Arches cluster; Figer et al. 1999b). Note that this implies a central density of $> 5(10^5) M_\odot pc^{-3}$ for the Arches cluster, greater than that for most old globulars.

The presence of these extraordinary clusters makes it possible to measure the IMF via a direct count of coeval stars in the Galactic center. Recall that the IMF describes the relative number of stars produced in a star forming event as a function of initial stellar mass, and is often expressed as a single power law over mass ranges above $1 M_\odot$, with a form $d(Log N)/d(Log M_{\text{initial}}) = \Gamma$. The IMF for most young clusters can be described reasonably well by a power law
Figure 2. Mass function for Arches cluster as measured in the F160W image for stars within an annulus from 3" to 9" (reproduced from Figer et al. 1999b). Lines have been fit to the completeness-corrected data (dashed lines) over two mass ranges. The slopes of both are relatively flat. The dotted histogram shows the number of massive stars over the whole cluster, including the inner region; the counts have been terminated at the mass where incompleteness exceeds 50%.

with Salpeter index ($= -1.35$; Salpeter 1955), although significant variations are observed ($-0.7 > \Gamma > -2.1$) (Scalo 1998).

Figer et al. (1999b) targetted the Arches and Quintuplet clusters for just such a measurement, avoiding the prohibitively confused Central cluster. They describe Hubble Space Telescope (HST) Near-infrared Camera and Multi-object Spectrometer (NICMOS) observations which were used to identify main sequence stars in the Galactic Center with initial masses well below 10 $M_\odot$, leading to the first determination of the IMF for any population in the Galactic center. They found a slope which is significantly greater than $-1.0$ (see Figure 2), and so is one of the flattest mass functions ever observed for $M_{\text{initial}} > 10 M_\odot$, although note that Eisenhauer et al. (1998) found a similar result for the Galactic cluster NGC3603. These two results can be contrasted with the average IMF slope for 30 clusters in the Milky Way and LMC: $\approx -1.3$ for $\log(M_{\text{initial}}) > 1$, although $\Gamma_{\text{NGC6611}} = -0.7 \pm 0.2$ and $\Gamma_{\text{NGC2244}} = -0.8 \pm 0.3$ over this mass range (Scalo 1998). Some of these clusters discussed in Scalo (1998) suggest a flattening of the IMF at higher masses, although the IMF slopes reported for these comparison clusters are in general biased toward lower masses. Finally, we find that there are $\geq 10$ stars with $M_{\text{initial}} > 120 M_\odot$ in the Arches cluster. This number is consistent with the absence of any clear upper-mass cutoff to the IMF.
The rarity in our Galaxy of massive compact clusters, such as are found in the Galactic center, suggests that they form under circumstances which are quite unusual. Locally, their formation must have been under conditions which fall under the category of “starburst,” given the tremendous energy release accompanying the coeval formation of $\sim 10^4 M_\odot$ of predominantly massive stars. Furthermore, although the central density of the Arches cluster may have been enhanced somewhat by dynamical processes since its formation, its equivalent density of $10^7$ hydrogen molecules per cm$^3$ is as high as the density of only the densest of cloud cores, suggesting that the formation process must have been very efficient. One imagines the sudden and catastrophic transformation of an entire dense cloud into a massive, compact star cluster having an unusually flat IMF. While such clusters merit the name of “starburst cluster,” they would presumably appear as a starburst on a Galactic scale, and thus be an element of what we would regard as a starburst galaxy, only if a multitude ($\gtrsim 10 – 100$) of such clusters were to form all at once in a galactic nucleus.

4. Starburst Clusters in Other Galactic Nuclei

Populations of starburst clusters in galactic nuclei are seen in a variety of galaxies, some of which display general starburst or AGN properties. These galaxies include NGC 1275 (Carlson et al. 1998), Arp 220 (Scoville et al. 1998), NGC 253 (Watson et al. 1996), NGC 1365 (Lindblad 1999), NGC 2903 (Mulchaey & Regan 2001), among many others. Of course, many galactic nuclei, such as M31, have little or no star formation activity and certainly no starburst clusters. In galaxies where clusters have been produced in large numbers, their properties are similar to those inferred for clusters in our own Galactic globular cluster system in its infancy, i.e., both types of systems might share commonality in their formation histories (Whitmore 2000).

Recent evidence suggests that nuclear starbursts occur in the late stages of galactic interaction events, a beautiful example of which can be seen in the “Antennae” merger system (Whitmore et al. 1999). Indeed mergers or interactions produce starbursts in many cases, as is seen observationally (Borne et al. 2000) and anticipated theoretically (Mihos 1999). Mihos & Hernquist (1996) performed Smoothed Particle Hydrodynamics calculations and produced a simulation which reproduces many of the dynamical features thought to describe a galaxy merger event such as the one leading to the “Antennae” system. In this simulation, star formation starts in the arms and finishes in the centers of the galaxies after mass inflow. The predicted timeline produces a range of cluster ages and demonstrates the importance of galaxy interactions in producing a spectrum of cluster masses; however, such dramatic events as mergers are not requisite for the production of starburst clusters, at least on a small scale, as evidenced by our own Galactic center.

5. Conclusions

The starburst clusters in our Galactic center are similar to those found in the centers of some starburst galaxies, although they are much fewer in number than those found in galaxies culled for their starburst properties. Of course,
this is simply a selection effect, in that galaxies with the highest star formation rates are most prominent in the properties observed. Rather than comparing absolute numbers of starburst clusters in various environments, it is useful to compare star formation surface density ($M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$) to gas surface mass density ($M_\odot \text{ pc}^{-2}$). In doing so, one finds that IR-selected starburst nuclei tend to exhibit a linear relation between these two quantities with absolute values that imply very high star formation efficiencies, roughly an order of magnitude above those inferred for normal disks (see Figures 5 and 7 in Kennicutt 1998). Our own GC has a very high star formation rate, given its molecular density, implying a high star formation efficiency. Given the facts described in this paper, then, we suggest that starburst clusters tend to be produced by events which convert gas into stars at a very high efficiency, but the absolute numbers of starburst clusters formed in an environment is strongly constrained by the available amount of gas. In other words, our modest GC has recently formed 3 starburst clusters, whereas massive interacting systems, i.e. NGC 1275, have produced thousands (Carlson et al. 1998). A corollary to this suggestion is that our own GC does not have enough molecular mass to fully populate the initial mass spectrum of clusters seen in bona fide starburst galaxies, where “super-star clusters” having masses ranging above $10^5 M_\odot$ are readily observed (Ho & Filippenko 1996).

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