Massive Star Formation Near Sgr A* and Bimodal Star Formation in the Nuclear Disk

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Abstract.
The history of star formation in the strong gravitational potential of the Galactic center has been of much interest, recently. We propose that the sub-parsec-scale disk of massive stars orbiting the massive black hole at the Galactic center can be interpreted in terms of partial accretion of extended Galactic center clouds, such as the 50 km s\textsuperscript{-1} molecular cloud, as these clouds envelop Sgr A* on their passage through the inner Galactic center. The loss of angular momentum of the captured cloud material by self-interaction subsequent to gravitationally focusing by Sgr A* naturally creates a compact gaseous disk of material close to Sgr A* in which star formation takes place. On a larger scale the formation of massive clusters such as the Arches and Quintuplet clusters or on-going massive star formation such as Sgr B2 could also be triggered by cloud-cloud collisions due to gravitational focusing in the deep potential of the central bulge.

Unlike the violent and high-pressure environment of clustered star formation triggered by cloud-cloud collision, there are also isolated pockets of star formation and quiescent dense clouds. These sites suggest an inefficient, slow mode of star formation. We propose enhanced cosmic rays in the nuclear disk may be responsible for inhibiting the process of star formation in this region. In particular, we argue that the enhanced ionization rate due to the impact of cosmic-ray particles is responsible for lowering the efficiency of on-going star formation in the nuclear disk of our Galaxy. The higher ionization fraction and higher thermal energy due to the impact of these electrons may also reduce MHD wave damping which contributes to the persistence of the high velocity dispersion of the molecular gas in the nuclear disk.

1. Introduction

Radio and infrared observations of the central region of our Galaxy have come a long way since two major discoveries were reported more than 20 years ago, namely, the central stellar cluster at the Galactic center (Becklin & Neugebauer 1968) and the compact radio source Sgr A* (Brown and Balick 1974). After all these years, one wonders who would have predicted that the stars of the young central cluster at the Galactic center are on Keplerian orbits about Sgr A*. We now know from near-IR measurements of Sgr A* combined with proper motion measurements of Sgr A* (Reid & Brunthaler 2004; Ghez et al. 2005; Eisenhauer
et al. 2005) that a massive black hole of $3-4 \times 10^6 \, M_\odot$ is coincident with Sgr A*.

Again, who would have realized that most of the cluster members are distributed in one or perhaps two stellar disks orbiting Sgr A* (Paumard et al. 2006; Lu et al. 2006)? Again, who would have thought that in the hostile environment of the nucleus of our Galaxy, two additional young clusters (i.e. the Arches and Quintuplet clusters) lie within a projected distance of 30 pc from Sgr A* (e.g., Cotera et al. 1996; Figer et al. 1999). Lastly, on a larger scale, who would have predicted the co-existence of two star forming sites with extreme differences in star formation rates; namely Sgr B2 and a ridge of infrared dark clouds with quiescent star formation (Lis & Carlstrom 1994).

There are many challenges to understanding the star formation history in the nucleus of our Galaxy. Here we attempt to elucidate the environmental factors affecting star formation in the complex and rich region of our Galactic center. We argue that enhanced cloud-cloud collisions and cosmic rays, are likely to be important in on-going and past star formation activity in this region. In particular, we discuss two modes of star formation in the nuclear disk of our Galaxy. One mode is induced by cloud-cloud collision in the nuclear disk which we claim to be responsible for cluster star formation. The other mode is analogous to that of low-mass star formation in which gravitationally unstable cores within a cloud contract to the point that they overwhelm their magnetic support and form isolated stars.

2. Cluster Star Formation

2.1. The Central Cluster near Sgr A*

Proper motion and spectral line studies of stars within 0.5 pc of Sgr A* have recently shown that a cluster of about 80 massive stars in the inner pc of the Galaxy reside in one, and possibly a second, rotating disk (Paumard et al. 2006; Lu et al. 2006). These disks, inferred to have masses about $10^4 \, M_\odot$, have well-defined inner edges and are counter-rotating at large angles from each other with typical stellar ages of $6 \pm 2$ million years (Paumard et al. 2006). They are somewhat disordered with $h/r \sim 0.1$ and stellar orbit eccentricities ranging roughly between 0.2 and 0.8. Two scenarios have been proposed to explain the origin of these young stars, in-situ star formation within a disk (Nayakshin et al. 2007), or dynamical migration of stars formed at a large distance (Gerhard 2001). The latter requires a high mass concentration for dynamical friction to be effective on a time scale of a few million years (Hansen & Milosavljević 2003; Kim, Figer & Morris 2004; Gürkan & Rasio 2005), perhaps provided by an IMBH associated with the initial cluster of stars. Alternatively, in the in-situ picture, the young stars are formed by the fragmentation of gaseous disk that has been captured by the strong gravitational potential of Sgr A* (Nayakshin 2006). Nayakshin et al. (2007) model the fragmentation of a gravitational unstable gaseous disk to form massive stars. This scenario needs to address the issue of the observed high eccentricity of stars in a relatively thick accretion disk, as it is difficult to develop high eccentricity from an initially circular orbits in a thin accretion disk. Furthermore, this scenario leaves the question of how the orbiting gaseous disk got there in the first place unanswered. Capturing a cloud passing to one side of Sgr A* turns out to run into difficulty because the cloud has no
way of getting rid of its angular momentum, requiring an unlikely situation in which a dense and very compact cloud is on a trajectory towards Sgr A* with essentially zero impact parameter (Wardle and Yusef-Zadeh 2007).

These issues can be circumvented by considering a more common event: the near-radial passage of an extended cloud that sweeps through the strong gravitational potential of the Galactic center and temporarily engulfs Sgr A*. Sgr A* and the evolved stellar cluster with $r^{-2}$ density profile dominate the gravitational potential within and beyond the inner pc, respectively. In this picture, the gravitational potential more strongly deflects the inner regions of the cloud, affecting a collision between fluid elements that pass on either side of Sgr A* and oppositely directed angular momenta. This is a messy version of Hoyle-Lyttleton accretion (Edgar 2004) because of the pronounced inhomogeneity in the approaching molecular cloud. The resulting dissipation permits this gas to become bound to Sgr A*. Furthermore, the captured material is brought in from a capture radius of $\sim 3$ to $\sim 0.3$ pcs. The loss of angular momentum forms a compact disk and creates a large disk surface density which becomes gravitationally unstable as the gas settles down and cools. The details of the inhomogeneities in the cloud and its initial trajectory determine the direction of the disk’s angular momentum which as a result is largely unrelated to orientation of Galactic rotation. Simple estimates (Wardle & Yusef-Zadeh 2007) show that the disk becomes gravitationally unstable before settling down and cooling to the point of becoming thin, thus the stars that are formed should have a range of eccentricities. Both the clockwise and counter-clockwise stellar disks can also be explained in the context of this model by either the inhomogeneous nature of a

Figure 1. A schematic diagram of a cloud impacting the Sgr A*. The panel to the left shows the effect of gravitational focusing in capturing a colliding gaseous material. The panel to the right shows the carved out inner region of the cloud is captured first before brought in closer to Sgr A*. The outer region of the cloud continues its motion in the direction away from Sgr A*.
single giant molecular cloud or by the passages of two different clouds separated by $\sim 10^6$ years. These events may also coincide with the growth of the black hole as well as with an increase in the luminosity due to the accretion of gas directly onto Sgr A*, two subjects that are not discussed here.

While the inner region of the cloud interacts with Sgr A*, the outer regions continue their journey along the original radial orbit. Figure 1 illustrates the shape of the cloud before and after the cloud sweeps the Galactic center. The well-known 50 km s$^{-1}$ cloud at the Galactic center may be related to the formation of the current stellar disk: there is strong evidence that it is interacting with the Sgr A East supernova remnant which itself lies behind Sgr A*. Sgr A East and the 50 km s$^{-1}$ cloud are thought to lie within roughly ten parsecs of Sgr A* (e.g., Melia et al. 2001; Yusef-Zadeh et al. 2001). If this cloud extends for $\sim 25$–50 pcs, it would take $\sim 0.5 - 1 \times 10^6$ years before a inner portion of the cloud is completely carved out. This time scale is consistent with that needed to form one or two disks of stars. A more detailed account of this scenario can be found elsewhere (Wardle & Yusef-Zadeh 2007).

### 2.2. The Orbiting Molecular Ring

On a scale greater than 0.5 pc, we find a disordered molecular ring that orbits Sgr A* at a distance of 2–10 pc with a velocity of 110 km/s (e.g. Genzel & Townes 1987; Jackson et al. 1993). This circumnuclear molecular ring or disk (CND) surrounds a cavity of ionized gas, known as Sgr A West. The ring is quite messy, incomplete, partially collisionally excited (e.g., Yusef-Zadeh et al. 2001) and is tilted with respect to the Galactic plane. This ring of gas may be a relic from a passage of a cloud similar to that envisioned in the previous section (see the illustration in Fig. 1), see also (Sanders 1998), but with, for example, a lower cloud speed resulting in the capture of a larger region of the incoming cloud. The lack or the presence of star formation can be understood in the context of inhomogeneity of the radially moving cloud toward Sgr A*.

It is not clear whether there is any signature of on-going massive star-forming activity in the molecular ring. The lack of on-going star formation implies that the molecular surface density is not sufficiently high for the gravitational instability to take place. On the other hand, recent high resolution molecular observations of the CND show dense molecular gas with H$_2$ density $10^7$ cm$^{-3}$ (Christopher et al. 2005). This highly clumped molecular material can withstand the strong tidal effects of the Galactic center if $n_{H_2} > 10^7 \times (1.6 pc/r)^{1.8}$ cm$^{-3}$ and could potentially collapse and form a new generation of massive stars. It is puzzling, therefore, that no sites of on-going star formation have been identified in the molecular ring.

### 2.3. The Arches and Quintuplet Clusters & Sgr B2

One of the questions that we’d like to examine is whether cloud-cloud collisions are relevant to the formation of other clusters in the Galactic center. The Arches and Quintuplet clusters are located at a projected distance of about 30 pc. It is not clear exactly the location of the parent cloud from which these clusters are formed from. However, it is clear that these clusters are not formed from a disk of gaseous material. This is because the orbital time scale is long at large distances from Sgr A* when compared to the free-fall time scale.
Although the production of a disk of gas is not effective beyond the inner several parsecs of Sgr A*, radially moving clouds can be focused by the gravitational potential of the evolved stellar cluster and enhance the cross-section for cloud-cloud collision. There is mounting evidence that the population of molecular clouds in the nuclear disk show forbidden and high velocities. This unusual kinematics can be explained by the tidal torque of the barred potential of the nuclear bulge or by the tidal friction of the bulge stars on clouds (e.g., Bally et al. 1988; Stark et al. 1991; Morris and Serabyn 1996). These effects can lead to rapid inward motion of clouds toward the Galactic center on highly elliptical orbits. The well-known -30 km s\(^{-1}\) cloud with its forbidden velocity on the positive longitude side is thought to be associated with a star forming region (e.g. Zhao et al. 1993).

The compression associated with violent collisions of clouds creates a high pressure environment suitable for cluster star formation (Tan and McKee 2002) provided that gravity is stronger than the tidal shear associated with the Galactic center potential. This implies that cluster star formation through this process will be inefficient within a few tens of parsec of Sgr A*, but may be effective beyond that. Indeed, there are several dense and massive ammonia clumps associated with the 45 km s\(^{-1}\)molecular cloud in the Sgr A complex (e.g., Serabyn & Güsten 1987) that show no signs of on-going stars formation. On the other hand, there is spectacular massive star formation with a dense cluster of ultra-compact HII regions associated with Sgr B2 at a projected distance of \(\sim 75\) pc. In fact, previous analysis of molecular clouds from several studied suggest that massive star formation in Sgr B2 is triggered by the collision between the 65 and 80 km s\(^{-1}\)molecular clouds. (Mehringer et al. 1993; Hasagawa et al. 1994).

### 3. Isolated Star Formation

Most of the discussion in previous sections focused on bursts of massive star formation in the Galactic center region. However, several cases of isolated massive star formation or of quiescent star formation have been noted in the Galactic center region. For example, on a scale of five to ten parsecs from Sgr A*, there is a well-known cluster of four compact HII regions that lie at the edge of the 50 km/s molecular cloud M-0.02-0.07. These HII regions are the closest known sites of on-going massive star formation in the Galactic center. The HII regions are excited by O8-9 stars (e.g., Goss et al. 1985). Mid-IR spectroscopic measurements of these HII regions have detected [NeII] line emission from all four components (A-D) at radial velocities around 40 km s\(^{-1}\) (Serabyn, Lacy & Achtermann 1992). Another star forming site, SgrA-E, F, and G, within 5 pc of Sgr A* is known to be associated with the 20 km s\(^{-1}\) molecular cloud M-0.13-0.08. SgrA-E and F are known to be nonthermal features. Interestingly, all three sources SgrA-E-F and the bright circular HII feature SgrA-G to the southwest corner coincide with the peak of molecular line emission. The HII feature is thought to be excited by a massive star (Ho et al. 1985). There is also a great deal of quiescent star formation in a ridge of molecular clouds (Lis & Carlstrom 1994). These clouds show no signs of active star formation despite being characterized as members of the population of Galactic center molecular clouds. The question that we’d like to raise is whether there exists another star
formation mechanism that can be applied to these sites. Unlike the efficient mode of star formation induced by cloud-cloud collisions, this mechanism which is the upscaled version of low-mass star formation in the disk (Shu, Adams & Lizano 1987) has to be slow and inefficient in generating quiescent and isolated massive star formation.

3.1. The Role of Cosmic Rays in Star Formation

The interstellar medium of the central kpc (the nuclear disk) is characterized by a strong concentration of molecular gas in the nuclear disk or the so-called “Central Molecular Zone” (CMZ) (Morris & Serabyn 1996). Physical conditions in this region are extreme, characterized by high velocity dispersion ($\sim 20$ km/s), high density ($\sim 10^4$ cm$^{-3}$) and high temperature molecular gas ($\sim 70$K) (Hüttemeister et al. 1993). These clouds must have high density in order to be gravitationally bound against the strong gravitational shear that they experience in the gravitational potential associated with the high stellar density in the central region of the Galaxy. The nature of on-going massive star formation in the nuclear region is puzzling.

What could be the cause of the non-uniform star formation rate in the Galactic center region? One possibility is a spatially variable enhanced flux of cosmic ray particles (Yusef-Zadeh, Wardle and Roy 2007). Recent radio, infrared and X-ray measurements all point to an enhanced cosmic-ray flux in the central region of the Galaxy. In one study, Oka et al. (2005) reported strong H$_3^+$ absorption lines toward several directions in the Galactic center region. They infer an unusually high column density of H$_3^+$ which implies that the ionization rate in the nuclear environment must be more than two orders of magnitude higher than that in the Galactic disk. Also, a study of H$_3$O$^+$ inferred an order of magnitude higher cosmic-ray ionization rate toward Sgr B2 than in the disk (van der Tak et al. 2006). In another study, the detection of low frequency 74 MHz radio emission from the central disk of the Galaxy indicates that the cosmic-ray electron density of the central 1.5$\times$0.5 degrees is $\sim 7$ eV cm$^{-3}$, about six times higher than that estimated toward the inner 6$\times$2 degrees (LaRosa et al. 2005). Lastly, the fluorescent 6.4 keV K$\alpha$ line emission throughout the Galactic center region can be accounted for by the impact of low-energy cosmic-ray particles with neutral gas (Yusef-Zadeh et al. 2007a).

The molecular gas temperature could be elevated by an enhanced cosmic-ray flux in the nuclear disk (e.g. Güsten & Downes 1981) with implications for star formation in this region. The higher cloud temperatures increase the Jeans mass, potentially changing the IMF in a high pressure environment. In addition a high cosmic-ray ionization rate increases magnetic coupling to the cloud material, suppressing ambipolar diffusion and increasing the time taken for gravitationally unstable cores to contract to the point that they overwhelm their magnetic support. This implies that star formation is slowed down in the nuclear region (Yusef-Zadeh, Wardle & Roy 2007). Although a low star formation rate and an enhanced cosmic ray flux may contradict each other, we believe the enhanced nonthermal particles arising from processes other than SN shock acceleration. For example, the production of excess nonthermal particles may be related to the origin of nonthermal radio filaments in the Galactic center (Nord et al. 2004; Yusef-Zadeh, Hewitt & Cotton 2004).
One additional consequence of an increased ionization fraction is that waves are damped less strongly. In a weakly ionized medium, waves with frequencies \( \omega \sim k \nu_A \) below the collision frequency of neutral particles with ions, \( \nu_{\text{ni}} = n_i < \langle \sigma v \rangle \), are damped on a time scale \( 2 \nu_{\text{ni}} / \omega^2 \) (Kulsrud & Pearce 1969; Zweibel & Josafatsson 1983), directly proportional to \( n_i \). The power input required to maintain wave motions on a given scale is reduced by the same factor. If the damping of MHD waves is reduced, then it may help to explain the observed high velocity dispersion of molecular clouds observed in the nuclear disk (e.g. Bally et al. 1988; Martin et al. 2004).

Another implication of the excess cosmic-ray particles is that cosmic-ray heating of molecular gas can be achieved without raising the dust temperature (Güsten et al. 1981). This could explain why warm gas is not often accompanied by hot dust. In the last two decades, studies of this region indicate that the molecular gas is warm, ranging between 75 to 200K (e.g., Hüttemeister et al. 1993). However, far-IR and sub-millimeter studies have shown a dust temperature ranging between \( \sim 13 \) to 40 K (Odenwald & Fazio 1984; Cox & Laureijs 1989; Pierce-Price et al. 2000). In typical clouds elsewhere in the disk of the Galaxy, the gas is heated by collisions with warm grains that are heated by massive stars. Thus, regions of high kinetic temperature in star forming regions are strongly correlated with clouds with high dust temperature.

A global heating mechanism such as cloud-cloud collisions has also been suggested to explain the significantly higher gas temperature in a large fraction of clouds in the nuclear disk (Hüttemeister et al. 1993). In fact there is evidence of shocked gas traced by the detection of SiO emission from Galactic center molecular clouds (Martin-Pintado et al. 1997) Although this is consistent with the cloud-cloud collision picture proposed here, shocked emission cannot heat molecular cloud in its entirety, because much of the shocked emission is distributed in a thin layer where clouds collide with each other. In contrast, low energy cosmic rays can penetrate deep into a cloud and heat the gas (Yusef-Zadeh, Wardle & Roy 2007).

In summary, in order to explain the paradoxical nature of highly efficiency cluster star formation co-existing with quiescent star formation, we have proposed a bimodal distribution of star formation in the nuclear region of our Galaxy. Two environmental factors become important in star formation processes in the nucleus of our Galaxy when compared to those of the disk. One is the enhanced rate of cloud-cloud collision due to the strong gravitational potential of the barred nuclear potential. This colliding picture of clouds very close to the peak of the potential is a special case which can explain the origin of stellar disks orbiting Sgr A*. The other is the enhanced cosmic rays permeated throughout this region. We believe these two factors play important roles in enhancing as well as suppressing massive star formation in this region of the Galaxy.

References

Balick, B. & Brown, R. L., 1974, ApJ, 194, 265
Bally, J., Stark, A.A., Wilson, R.W. & Henkel, C. 1988, ApJ, 324, 223
Becklin, E. E. & Neugebauer, G. 1968, ApJ, 151, 145
Cox, P., & Laureijs, R. 1989, The Center of the Galaxy, 136, 121
Cotera, A. S. et al. 1996, ApJ, 461, 750
Christopher et al. 2005, ApJ, 622, 346
Edgar, R. 2004, New Ast Rev, 48, 843
Eisenhauer, F. et al. 2005, ApJ, 628, 246
Figer et al. 1999, ApJ, 514, 202
Genzel, R. & Townes, C. H., 1987, ARA&A, 25, 377
Gerhard, O. 2001, ApJL, 546, L39
Ghez, A. M. et al. 2005, ApJ, 620, 744
Goss et al. 1985, MNRAS, 215, 69p
Gürkan, M. A. & Rasio, F. A. 2005, ApJ, 628
Güsten, R. & Downes, D. 1981, A&A, 99, 27
Hansen, B. M. S. & Milosavljević, S. ApJ, 593, L77
Hasegawa, T., Sato, F., Whiteoak, J. B. & Miyawaki, R. 1994, ApJ, 429, L77
Ho et al. 1985, ApJ 288, 575
Hüttemeister, S. et al. 1993, A&A 280, 255
Jackson et al. 1993, ApJ, 402, 173
Kim, S. S., Figer, D. F. & Morris, M. 2004, ApJ, 607, L123
Kulsrud, R. & Pearce, W. P. 1969, ApJ 156, 445
LaRosa, T. N. et al. 2005, ApJ 626, L23
Lis, D. C. & Carlstrom, J. E. 1994, ApJ 424, 189
Lis, D. C. & Menten, K. 1998, ApJ 507, 794
Lu, J. et al. 2006, JPhCS, 54, 79
Martin-Pintado, J., de Vicete, P., Fuente, A. & Planesas, P. 1997, ApJ, 482, L45
Mehringer, D. M., Palmer, P., Goss, W. M. & Yusef-Zadeh, F. 1993, ApJ, 412, 684
Melia, F., Yusef-Zadeh, F. & Fatuzzo, M. 1998, ApJ, 508, 676
Morris, M. & Serabyn, E. 1996, ARA&A 34, 645
Martin, C. L. et al. ApJS, 150, 239
Nayakshin, S. 2006, JPhCS, 54, 208
Nayakshin, S., Cuadra, J. & Springer, V. 2007, MNRAS, 379, 21
Nord, M. E. et al. 2004, AJ, 128, 1646
Odenwald, S. F. & Fazio, G. G. 1984, ApJ, 283, 601
Oka, T. et al. 2005, ApJ 632, 882
Paumard, T. et al. 2006, ApJ 643, 1011
Pierce-Price, D. et al. 2000, ApJ 545, L121
Reid, M. J. & Brunthaler, A. 2004, ApJ, 616, 872
Sanders, R. H. 1998, MNRAS, 294, 35
Serabyn, E. & Güsten, R. 1987, A&A, 184, 133
Serabyn, E., Lacy, J. M. & Achtermann, J. E. 1992, ApJ, 395, 166
Shu, F., Adams, F. C. & Lizano, S. 1987, AR&AA, 25, 23
Stark, A., Gerhard, O., Binney, J. & Bally, J. 1991, MNRAS, 248, 14
Tan, J. C. & McKee, C. F. 2002, in ASP Conference Proceedings, eds: P.A. Crowther, 267, 267
van der Tak, F.F.S. et al. 2006, A&A, 454, L99
Wardle, M. & Yusef-Zadeh, F. 2007, in preparation
Yusef-Zadeh, F., Hewitt, J. & Cotton, W. 2004, ApJS, 155, 421
Yusef-Zadeh, F., Munoz, M., Wardle, M. & Lis, D. C. 2007b, ApJ 656, 847
Yusef-Zadeh, F., Wardle, M. & Roy, S. 2007a, ApJ, 665, L123
Yusef-Zadeh, F. et al. 2001, ApJ, 560, 749
Zhao, Jun-Hui, Desai, K., Goss, W. M. & Yusef-Zadeh, F. 1993 ApJ, 418, 235
Zweibel, E. G. & Josafatsson, K. 1983, ApJ, 270, 511