ON THE ORIGIN OF THE CENTRAL 1″ HOLE IN THE STELLAR DISK OF SGR A* AND THE FERMI GAMMA-RAY BUBBLES

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ABSTRACT

The supermassive black hole Sgr A* at the center of the Galaxy is surrounded by two misaligned disks of young, massive stars extending from ~0.04 to 0.4 pc. The stellar surface density increases as ~r−2 toward Sgr A* but is truncated within 1″ (0.04 pc). We explore the origin of this annulus using a model in which star formation occurs in a disk of gas created through the partial capture of a gas cloud as it sweeps through the inner few parsecs of the galaxy and temporarily engulfs Sgr A*. We identify the locations within which star formation and/or accretion onto Sgr A* take place. Within 0.04 pc the disk is magnetically active and the associated heating and enhanced pressure prevents the disk from becoming self-gravitating. Instead, it forms a magneto-turbulent disk that drains onto Sgr A* in ≤3 × 10⁶ yr. Meanwhile, fragmentation of the gas beyond the central 0.04 pc hole creates the observed young stellar disk. The two large-scale bubbles of gamma-ray emission extending perpendicular to the Galactic plane may be created by a burst of accretion of ~1 × 10⁷ M☉ of gas lying between 0.01 and 0.03 pc. The observed stellar ages imply that this capture event occurred ~10⁶.5 yr ago, thus such events occurring over the lifetime of the Galaxy could have significantly contributed to the current mass of Sgr A* and to the inner few parsecs of the nuclear star cluster. We suggest that these events also occur in extragalactic systems.

Key words: accretion, accretion disks – galaxies: active – Galaxy: center – gamma rays: galaxies – magnetohydrodynamics (MHD) – stars: formation

Online-only material: color figures

1. INTRODUCTION

Two bubbles of gamma-ray emission with sharp edges extend symmetrically away from the Galactic plane up to Galactic latitudes b ~ ±50° (Dobler et al. 2010; Su et al. 2010). This gigantic structure is narrower near the Galactic plane and appears to emanate from the Galactic center. The gamma-ray luminosity, ~4 × 10³⁷ erg s⁻¹, requires a total energy input of 10³⁴–10³⁵ erg (Su et al. 2010). Two classes of model have been proposed to explain the origin of this emission. In one picture, the Fermi gamma-ray bubbles are a relic of past active galactic nucleus (AGN)-like activity stimulated by accretion of stars or gaseous material onto the central supermassive black hole (SMBH), Sgr A* (e.g., Zubovas et al. 2011; Cheng et al. 2011; Guo & Mathews 2012; Guo et al. 2012; Yang et al. 2012, 2013). In the other, a nuclear starburst drives a powerful wind from the inner region of the Galaxy that inflates the bubbles (e.g., Crocker & Aharonian 2011; Crocker 2012; Carretti et al. 2013).

The emission from Sgr A* is thought to arise from a radiatively inefficient accretion flow, with a possible contribution from outflows or jets (e.g., Blandford & Begelman 1999; Falcke & Markoff 2000; Yuan et al. 2002). However, the possible association of the Fermi gamma-ray bubbles with Sgr A* implies that periods of increased accretion onto Sgr A* may produce powerful outflow and jet driven activity (Zubovas & Nayakshin 2012). This activity requires high accretion rate and a reservoir of gaseous material feeding Sgr A*.

Indeed, there is evidence for an accretion event occurring a few million years ago in the form of one or perhaps two counter-rotating disks of young massive stars orbiting between 0.04 and 0.4 pc of Sgr A*. The stellar ages and total mass are estimated to be ~6 Myr and ~1.5 × 10⁴ M☉, respectively (Paumard et al. 2006; Lu et al. 2009; Yelda et al. 2014). The very high density (≥10¹⁶ cm⁻³ [r(pc)]⁻¹) required for self-gravity to overcome tidal shear in the vicinity of the black hole implies that the stars were formed by fragmentation of a self-gravitating disk (Levin & Beloborodov 2003), presumably from a captured molecular cloud (Nayakshin & Cuadra 2005; Nayakshin et al. 2007; Bonnell & Rice 2008; Wardle & Yusef-Zadeh 2008, 2012, hereafter WY08 and WY12; Alig et al. 2011; Mapelli et al. 2012; Lucas et al. 2013).

This suggests a picture in which a byproduct of this process was the accretion of gas by Sgr A*, and that the associated outburst provides the needed energetics to produce the Fermi bubbles (Zubovas et al. 2011; Zubovas & Nayakshin 2012). These models assume that roughly half of the captured gas is accreted by Sgr A*. However, the estimated timescale for accretion far exceeded the ~10⁶–10⁷ yr time frame required by the age of the stars and the timescale to power the Fermi bubbles.

Here we re-examine this issue in the context of the compact disks formed by partial cloud capture when an extended cloud temporarily engulfs Sgr A* while on a passage through the central few parsec of the Galaxy. Previous simple analytic estimates show that ~10⁴–10⁵ M☉ of gas settles into a sub-parsec disk (WY08, WY12). Here we show that this capture process produces surface density profiles that are steeper than \( \Sigma \propto r^{-3/2} \). Magnetic activity prevents fragmentation within the inner regions, driving accretion at rates ~0.01 M⊙ yr⁻¹.
The fate of the disk is determined by the competition between heating and radiative cooling. Heating by starlight or dissipation of magnetically driven turbulence may keep the disk warm enough that self-gravity is not important. Should the temperature drop to the point that Toomre’s parameter,

\[ Q = \frac{c_s \Omega}{\pi G \Sigma} < Q_{\text{crit}} \approx 1, \]

where \( \Omega \) is the orbital frequency and \( c_s \) is the sound speed, the disk will fragment if it can quickly radiate away the thermal energy liberated during gravitational collapse, i.e.,

\[ Q_{\text{cool}} < \beta_{\text{crit}}. \]

where \( t_{\text{cool}} \) is the local cooling timescale (Gammie 2001) and we adopt \( \beta_{\text{crit}} = 3 \), as suggested by simulations of self-gravitating disks (see the review by Lodato 2012, and references therein).\(^3\) However, if cooling is inefficient the disk enters a “gravitoturbulent” state in which self-gravity continually perturbs the density and velocity field, and heating via dissipation of weak turbulence maintains \( Q \approx Q_{\text{crit}} \) (Paczyński 1978; Gammie 2001; Rafikov 2009).

2. DISK MODEL

We begin our analysis by estimating the surface density profile of the cloud material as it circularizes, cools, and settles into a disk. We envisage, following WY08, that a disk of gas surrounding Sgr A* is formed via partial capture of a gas cloud that sweeps across the black hole with speed \( v \). Cloud material with impact parameter less than the critical value \( b_0 = 2GM/v^2 \) is captured, where we adopt \( M = 4 \times 10^6 M_\odot \) for the mass of Sgr A*. Partial Hoyle–Lyttleton-like angular momentum cancellation between material passing on opposite sides of Sgr A* leading to the formation of a sub-parsec disk with mass \( \sim 10^{-6} - 10^{-5} M_\odot \) (WY08). During the process of circularization, the components of angular momentum perpendicular to the eventual disk’s rotation axis are eliminated. We assume that on average each fluid element ends up with a fraction \( \lambda \) of its original specific angular momentum parallel to the final rotation axis. Thus a fluid element with initial impact parameter \( b \) perpendicular to the eventual rotation axis ends up on a Keplerian orbit with specific angular momentum \( \sqrt{GM/r} \lambda b v \). W08 adopted a nominal value \( \lambda_0 = 0.3 \), yielding disk masses \( M_d = \lambda_0 b_0^2 \Sigma_{\text{cloud}} \) and radii \( r_d = 2\lambda_0 b_0^2 \), that were later found to be consistent with those arising in simulations of cloud capture by this mechanism (Mapelli et al. 2012).

Here we generalize the W08 model by setting \( \lambda = \lambda_0 (b/b_0)^p \) for some \( p > 0 \). The physical motivation for this prescription is that cancellation should become less effective for material with larger impact parameters because of the cloud’s internal structure. We can then estimate the disk’s surface density profile \( \Sigma(r) \) by equating the mass of captured gas with impact parameters in the range \( [b, b + db] \), i.e., \( 4 \Sigma_{\text{cloud}} \sqrt{b_0^2 - b^2} \) \( db \), to the mass of disk material at radii \( [r, r + dr] \), i.e., \( 2\pi r \Sigma(r) dr \), with the prescription for angular momentum loss yielding \( r = (\lambda b v)^2/GM \). Then

\[ \Sigma(r) = \frac{q M_d}{\pi^2 r_d^2 \left( \frac{r}{r_d} \right)^{1+q-2}} \sqrt{1 - \left( \frac{r}{r_d} \right)^q}, \]

where \( q = 1/(1+p) \). We choose \( \lambda_0 = 0.3 \) for consistency with the simulated disk masses and radii, and adopt \( p = 1 \), noting that the profile is insensitive to \( p \). Note that the mass, radius, and profile are broadly consistent with the inferred \( \sim r^{-2} \) stellar profile, for reasonable parameters of the incoming cloud. For example, a cloud column density \( 1 \times 10^4 \) \( \text{cm}^{-2} \) and velocity \( 120 \) km s\(^{-1} \) yields \( M_d \approx 2 \times 10^5 M_\odot \) and \( r_d \approx 0.4 \) pc.

Figure 1. Schematic diagram of a gaseous disk orbiting Sgr A* (black dot). If the surface density profile is steeper than \( \sim r^{-1.5} \), self-gravity is unimportant in the outer radii. Fragmentation occurs at intermediate radii, but is suppressed by inefficient cooling at the innermost radii where the disk becomes very optically thick and magnetic activity drives accretion (see text).

3 Recent simulations suggest \( \beta_{\text{crit}} \sim 10 \), and it may even be that fragmentation happens stochastically for any value of \( \beta_{\text{crit}} \) (Paardekooper 2012; Rice et al. 2012; Meru & Bate 2012; Rice et al. 2014). Fortunately our results turn out to be insensitive to this uncertainty: the limited gravitoturbulent region in Figure 3 shrinks as \( \beta_{\text{crit}} \) is increased, vanishing when \( \beta_{\text{crit}} \gtrsim 30 \).
Alternatively, accretion will be driven by magnetic stresses if the level of ionization is sufficient. As in protostellar disks (e.g., Gammie 1996; Wardle 2007), external ionizing sources such as cosmic rays, X-rays, and UV are ineffective, and coupling can only be sustained by thermal ionization of potassium, magnesium, and sodium which becomes effective above \( \approx 900 \) K (e.g., Umebayashi 1983). When this is the case, shear in the disk maintains a strong azimuthal magnetic field developed from the incoming cloud’s pre-existing field, and this efficiently transports angular momentum, yielding \( M = 3\pi \dot{\Omega} h^2 \Sigma \), where \( 2\hbar \) is the disk thickness and \( \dot{\alpha} \approx 0.1-0.2 \) (Gaburov et al. 2012; Bai & Stone 2013). Crucially, the magnetic pressure in the disk is about an order of magnitude larger than the gas pressure, inflating the disk so that \( h \approx 3c_s/\Omega \). In addition, for a given temperature and column density, the volume density and hence the effective value of \( Q_{\text{crit}} \) are all reduced by a factor of three. Thus, when the temperature exceeds 900 K, we set

\[
\alpha = 1, \quad \text{and} \quad Q_{\text{crit}} = 0.3. \quad (9)
\]

The disk would also have been heated by hot stars lying within a few parsecs of Sgr A*, which at present have a net luminosity \( \approx 2 \times 10^7 L_\odot \) (Krabbe et al. 1995; Latvakoski et al. 1999). As many of these stars were presumably created by fragmentation of the disk we adopt half of the present-day value, i.e.,

\[
D_e = \frac{10^7 L_\odot}{4\pi(1 \text{ pc})^2} \quad (10)
\]

as a rough estimate of the heating rate per unit area, independent of distance from Sgr A*.4

3. RESULTS

We first consider how the disk’s fate at \( r = 0.04 \text{ pc} \) depends on the local column density, with the aim of determining the column that would place the inner boundary of the fragmentation region there (see Figure 2). If \( \Sigma \gtrsim 600 \text{ g cm}^{-2} \), the high optical depth allows magnetic heating to maintain the temperature above 900 K, and thermal ionization allows continued magnetic activity. Inflation by magnetic pressure then implies that \( Q_{\text{crit}} \approx 0.3 \) and as this corresponds to temperatures below 600 K we conclude that self-gravity is unimportant. On the other hand, when \( \Sigma \lesssim 600 \text{ g cm}^{-2} \) magnetic heating is unable to maintain the temperature above 900 K, thermal ionization is insufficient to couple the magnetic field to the gas, magnetic activity shuts down, and \( Q_{\text{crit}} = 1 \). For \( \Sigma \lesssim 250 \text{ g cm}^{-2} \) stellar radiation keeps the disk hot enough to avoid becoming self-gravitating, whereas at higher column densities the disk is able to cool to the point that self-gravity is important, and between \( \sim 300 \) and \( 600 \text{ g cm}^{-2} \) the disk cools rapidly enough to fragment.

Figure 3 shows how the disk behavior depends on column density and distance from Sgr A*. In general, high surface densities are unstable to fragmentation, while low surface densities are neither able to fragment nor to accrete because stellar heating maintains \( Q \gtrsim 1 \) but with \( T \lesssim 900 \text{ K} \) so that magnetic coupling is ineffective. Within about 0.05 pc of Sgr A* there is an intermediate range of column densities for which magnetic activity maintains \( T > 900 \text{ K} \) and prevents fragmentation. Note that disks are gravitoturbulent over a severely limited range of radii and surface densities.

The blue dashed curve shows the surface density profile (Equation (3)) for a disk mass \( M_d = 2 \times 10^5 M_\odot \), corresponding to \( \Sigma \approx 600 \text{ g cm}^{-2} \) at 0.04 pc, so that the inner boundary of the fragmentation region is at 0.04 pc, consistent with the hole in the stellar distribution around Sgr A*. In light of the very rapid cooling we expect that the gas will fragment well before settling into the well-ordered disk we implicitly assume here, producing a dynamically warm stellar distribution. Fragmentation very near the outer edge of the disk may be prevented by stellar heating, although the exact profile of the disk edge and the stellar heating rate are both rather uncertain. Such a disk would be magnetically active interior to 0.04 pc, with initial accretion

4 Although stellar heating at the time of disk formation may have been even lower, it has little effect on fragmentation within 0.5 pc of Sgr A* (see the upper panel of Figure 4).
rates 0.01–0.03 \( M_\odot \) yr\(^{-1}\), as indicated by the red contours in Figure 3.

Figure 4 shows the radial structure of this disk. The top panel compares the temperatures maintained by magnetic activity and stellar heating with those at which the disk becomes self-gravitating and the cooling timescale is \( 3 \Omega^{-1} \) or \( 10 \Omega^{-1} \). The lower panel of Figure 4 shows the radial profile of surface density and optical depth. The latter is calculated for the equilibrium temperature maintained by magnetic dissipation within 0.04 pc, or the temperature corresponding to \( Q = 1 \) at larger radii. The discontinuities in optical depth arise due to evaporation of ice mantles at 150 K, the sublimation of grains at \( \sim 1200 \) K, and collisional dissociation of water at \( \sim 1500 \) K. The fragmentation region contains about \( 6 \times 10^4 M_\odot \) of gas, consistent with estimates of the stellar mass in the disk (Lu et al. 2013). The characteristic initial fragment mass is \( (2\pi c_s/\Omega)^2 \Sigma \sim 2.5 M_\odot \), but this is expected to grow by about an order of magnitude by collisions (Levin & Beloborodov 2003). Meanwhile the disk within 0.04 pc exhibits accretion rates \( \sim 0.01–0.03 M_\odot \) yr\(^{-1}\), with accretion timescales \( \sim 1–3 \) Myr that are an order of magnitude shorter than previously estimated (Alexander et al. 2012) because of the enhancement by magnetic levitation.

4. DISCUSSION

We have examined in more detail the earlier proposal in which gas clouds engulfing SMBHs leave behind a captured disk (WY08; WY12). The angular momentum cancellation inherent in this scenario naturally produces steep (\( \sim r^{-1.75} \)) surface density profiles consistent with the observed stellar disk, with \( 10^2–10^3 M_\odot \) and size \( \sim 0.5 \) pc (W08). For reasonable parameters we found that such a captured disk would indeed be unstable to fragmentation between 0.04 and 0.4 pc, consistent with the sizes of the observed stellar disks. Between 0.04 and 0.04 pc dissipation of magnetically driven turbulence prevents the disk from becoming self-gravitating and enables accretion with \( M \approx 1–3 \times 10^{-2} M_\odot \) yr\(^{-1}\).

The magnetized accretion disk that arises in the central 0.04 pc explains the central 1" hole in the stellar distribution (cf. Alexander et al. 2012). Of significance here is that because magnetic pressure dominates gas pressure (Gaburov et al. 2012), thickening the disk and increasing the turbulent velocities by a factor of three, the accretion rate is an order of magnitude larger than in "standard" accretion disk models (e.g., Alexander et al. 2012). This increases the plausibility of accretion models for the origin of the Fermi bubbles, notably by reducing the accretion timescale to a few million years, enabling significant accretion to occur between formation of the stellar population and the Fermi bubbles. The energy released by such an event is uncertain. The current accretion rate onto Sgr A* is thought to be \( \sim 10^{-8} M_\odot \) yr\(^{-1}\) and the bolometric luminosity \( L \sim 150 L_\odot \) (see Genzel et al. 2010 and references therein), yielding an efficiency \( L/Mc^2 \sim 10^{-6} \). If the accretion of \( 10^{-8} M_\odot \) is to power the Fermi bubble then it must produce \( \sim 10^{55} \) erg; the corresponding efficiency is \( \sim 6 \times 10^{-5} \), indicating that the efficiency of this accretion mode must be significantly higher than at present.

The feeding of molecular gas into the central 100 pc of the Galaxy is thought to be ongoing and related to the presence of the Galactic bar (e.g., Morris & Serabyn 1996). Infall of molecular gas into the central few parsec of the Galaxy appears to be continual, and so partial capture of gas clouds by Sgr A* may be quite common. The cloud capture event responsible for the formation of the stellar disk, and potentially the Fermi bubble, occurred within the last few million years and added 1% to the mass of Sgr A* and a similar mass to the local stellar population; such events may have contributed significantly to the growth of Sgr A* and the surrounding stellar population over the life time of the Galaxy.

This scenario may also apply to gas accretion by SMBH in external galaxies, where it has been argued that the difficulties in fuelling AGN through an extended accretion disk imply that black holes are fed by a series of small gas capture events that create a sub-0.1 pc accretion disk (Goodman 2003; King & Pringle 2007). The partial cloud capture model predicts a quadratic dependence of the disk mass on black hole mass (WY12). Recent studies suggest a correlation between star formation rate and average black hole accretion rate in star-forming galaxies (e.g., Chen et al. 2013). In addition, there is evidence for gamma-ray emission from starburst galaxies such as M82 and NGC 253 (Abdo et al. 2010). This correlation and the energetic activity associated with starburst galaxies can be understood as arising through simultaneous star formation and accretion during a series of cloud capture events over the lifetime of the central black hole.

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