Star formation within 0.5 pc of Sgr A*  

Mark Wardle  
Research Centre for Astronomy, Astrophysics & Astrophotonics  
Department of Physics & Astronomy  
Macquarie University  

Farhad Yusef-Zadeh  
Yoram Lithwick
Stellar disk formation

- Radii \( \sim 0.04 - 0.5 \) pc from Sgr A*
- \( r^{-2} \) surface density profile with central hole
- Kinematically warm
- Age several Myr, top-heavy IMF, stellar mass \( \sim 5 \times 10^4 \) M\(_{\text{sun}}\)
- Star formation via disk fragmentation
  - eccentric disk (Levin & Beloborodov 2003; Nayakshin, Cuadra & Springel 2007)
  - cf. inward migration and tidal disruption of stellar cluster
- Disk formation via cloud capture
  - circularisation of compact cloud (Bonnell & Rice 2008)
  - partial capture of extended cloud (Wardle & Yusef-Zadeh 2008; Alig+2011)
    - cf. multiple disks (Alig et al 2013; Alig, Burkert & Dolag P34; Lucas et al 2013, P44)
  - central hole ==> accretion onto Sgr A*, but expected rate is too low (Alexander et al 2012)
  - magnetic fields suppress fragmentation and drive strong accretion (Gaburov, Johanssen & Levin 2012)
encodes the relative numbers of stars as a function of the stars' masses. The higher-mass cloud (Fig. 4) produced a bimodal mass function: a population of very massive stars with masses between \( \sim 10 \) and \( \sim 100 \) \( M_\odot \), and a population of lower-mass stars. The higher-mass stars formed in the inner ring (\( a \sim 0.02 \) pc) while the lower-mass stars formed farther out (\( a \sim 0.05 \) to 0.1 pc) because of the different gas temperatures produced \((20)\). As additional gas remained bound at larger radii, it is possible that more lower-mass stars would eventually form if the simulation were followed further in time.

In addition to forming the stars, 10 to 30% of the infalling gas clouds were accreted onto the black hole. This accretion implies only that the material is bound within the size of the sink-particles' accretion radius of 4000 AU, and in fact this material had sufficient angular momentum to form a disk at radii of 1000 to 4000 AU around the black hole.

The actual size and evolution of this inner disk were not determined by our simulations and could not be accurately shown in the images provided.

Fig. 1. The evolution of a 10\(^4\) \( M_\odot \) molecular cloud falling toward a 10\(^6\) \( M_\odot \) supermassive black hole. (A) There is no region within 1.5 pc of the black hole, which is shown at 32,000 years after start of evolution; colors denote the column density on a logarithmic scale from 0.01 g cm\(^{-2}\) to 100 g cm\(^{-2}\). (B) Image at 42,000 years, showing the region within 1 pc of the black hole; color scale is from 0.025 g cm\(^{-2}\) to 250 g cm\(^{-2}\). (C and D) Images at 47,000 and 51,000 years, showing the region within 0.5 pc of the black hole; color scale is from 0.1 g cm\(^{-2}\) to 1000 g cm\(^{-2}\). Although the cloud is tidally disrupted by the black hole, some of the material is captured by the black hole to form an eccentric disk that quickly fragments to form stars. These are illustrated by the white dots and have eccentricities between \( e = 0.6 \) and \( e = 0.76 \) and semimajor axes between \( a = 0.11 \) pc and \( a = 0.19 \) pc. A small population of stars also forms quite early, becoming visible in (B) and being ejected from the system in (D).

Fig. 2. The final state of the simulation of a 10\(^5\) \( M_\odot \) molecular cloud falling toward a 3 \( \times \) 10\(^6\) \( M_\odot \) supermassive black hole. The image shows the region within 0.25 pc of the black hole located at the center; colors denote column densities from 0.75 g cm\(^{-2}\) to 7500 g cm\(^{-2}\). A portion of the cloud has formed a disk around the black hole, while— at the stage shown here— most of the mass is still outside the region shown. The disk fragments very quickly, producing 198 stars with semimajor axes between \( a = 0.04 \) pc and \( a = 0.13 \) pc and eccentricities between \( e = 0 \) and \( e = 0.53 \).
Figure 1. Snapshots of density structure in the XY plane at different times for the V01 model. The times are shown in units of 0.047 million years, which correspond to 0.0, 0.047, 0.096, and 0.240 million years for the top left, top right, bottom left, and bottom right panels, respectively. The unit of length is a parsec, and the unit of density is $4.1 \times 10^6 \text{ cm}^{-3}$.

We studied the vertical structure of the disk in the V01 simulation at $R \approx 0.1 \text{ pc}$, which are not far from the inner boundary and close enough that the disk performed approximately 100 orbital periods by the end of the simulation.

We compute scale height, $H$, at this radius by fitting an isothermal density profile in approximately two scale heights. The resulting scale height is $H \approx 0.01$, which gives $H/R \approx 0.1$ (top left panel in Figure 4). The radial temperature dependence is expected to produce disks with the scale height $H/R = 0.03 \sqrt{1 + \beta - 1}$, which, for $\beta - 1 = P_m/P_g \approx 10$ found at $R = 0.1 \text{ pc}$, gives $H/R \approx 0.1$, consistent with the simulation data (bottom right panel in Figure 4). We also studied the deviation of azimuthal velocity from the Keplerian velocity at $R = 0.1 \text{ pc}$, showing no function of height, and found that azimuthal velocity variations are less than a percent for $|z| < H$ (top right panel in Figure 4). It is therefore justifiable to assume that the disk angular velocity is constant on cylinders. Finally, in the bottom left panel of Figure 4, we show Maxwell stress $\alpha_M = -\langle B_r B_\phi \rangle / P_{\text{tot}}$ which is approximately 0.1 within the scale height.

In Figure 5 we show an azimuthally averaged magnetic field. This figure shows that the magnetic field is confined within a few scale heights of the mid-plane. The magnetic field is dominated by the azimuthal component that is an order of magnitude larger than the radial one. The vertical component, $B_z$, is much smaller compared to both $B_r$ and $B_\phi$ for $|z| \lesssim H/2$ (in this figure both $B_r$ and $B_z$ strength are magnified by a factor of 10).

All of our simulations show similar vertical confinement of the field, which can be interpreted as a result of the disk formation: a combination of isothermal shocks that amplify the magnetic field and Keplerian shear which generates a strong azimuthal field component. However, we would like to stress that the field confinement in our best-resolved model (V01) is in good agreement with Johansen & Levin (2008; hereafter JL) who find similar results in their shearing box models. In the JL shearing-box simulations, which were performed with a grid-based Pencil Code, the disk field was initially in equipartition with the gas pressure, but evolved by Parker and MRIs to a magnetic field configuration in the vertical direction similar to what we see in our disk which is formed via a collision of a magnetized gas cloud with the black hole. It is significant that the two simulations that are so different in their approach give vertical structure of $B_\phi$ that is in good agreement with each other. In particular, the azimuthal component is consistent with the other.
In a general case, the radial dependence of disk magnetization is specific to our simulations which we use to check for consistency. However, a similar dependence was found by Flock et al. (2011) in the case of weakly magnetized disks. In a realistic disk, however, we expect that the Maxwell stresses in Equation (4) are dominated by the mean thermal pressure. Since the radial dependence of disk magnetization depends on the thermal properties of the disk, we expect that a similar dependence will be seen in our numerical experiments from the first principles, we obtain it empirically. In our simulations (upper panel in Figure 1), whereas two bottom panels focus on the outer regions of the disk (5, 6), which will be the subject of subsequent research. This relationship predicts that the disk magnetization should decrease with radius, and in agreement with our simulations, this radial dependence is self-consistently computed by solving the radiative transfer equation in the vertical direction. Therefore, the magnetization depends on the thermal properties of the disk. Using the equations above, we derive the radial dependence of disk magnetization as

\[ \beta \propto \frac{\Omega}{\pi} \frac{1}{R} \frac{1}{\Sigma} \frac{\phi}{\alpha} \]

from which we have

\[ \frac{\phi}{\alpha} \approx \frac{\Omega}{\pi} \frac{1}{R} \frac{1}{\Sigma} \frac{\phi}{\alpha} \]

Using these equations and noting that

\[ 1 + \frac{\phi}{\alpha} \approx \frac{\Omega}{\pi} \frac{1}{R} \frac{1}{\Sigma} \frac{\phi}{\alpha} \]

we derive that for accretion viscosity\( \alpha = 0.03 \), the radial dependence of disk magnetization is

\[ \frac{\phi}{\alpha} \approx \frac{\Omega}{\pi} \frac{1}{R} \frac{1}{\Sigma} \frac{\phi}{\alpha} \]

The top two panels show magnetic field geometry in the central region of the disk (7), whereas two bottom panels focus on the outer regions of the disk (8), which gives

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Magnetic fields vs fragmentation....

• Fragmentation requires high density and rapid cooling
  – disk is self gravitating when density exceeds roche density (i.e. $Q < 1$)
    $\Omega \ t_{\text{cool}} < 3 \implies$ fragmentation
    $\Omega \ t_{\text{cool}} > 3 \implies$ “gravitoturbulent” state

• Fragmentation is suppressed by magnetic fields
  – magnetic pressure = 10 x gas pressure
  – scale height $3 \times$ thermal
    $Q < 0.3$ for fragmentation
    $Q > 0.3 \implies$ alpha $\sim 1$ !

• Magnetisation is suppressed by ambipolar diffusion
  – need $T > 900K$ so that thermal ionisation $\implies$ neutral–ion collision frequency $> \Omega$

• Build a vertically-averaged disk model including these effects
  – surface density profile implied by cloud capture
  – heating by starlight, gravitoturbulence, magnetic activity
  – radiative cooling
Suppose then that an extended cloud with surface mass density $\Sigma_{\text{cloud}}$ is passing through the Galactic center with velocity $v$. Cloud material with impact parameters less than about $b_{\text{limit}}$ will be imperfect because of the inhomogeneities and finite spatial dimensions of the cloud.

The observed stellar disk has radius $r$ and density equivalent to a column density of hydrogen nuclei $N_\text{H}$. The disk material at this radius corresponds to the outer radius of the disk, $r$, which has specific angular momentum $l$. Thus, the ratio of the captured mass $M_{\text{captured}}$ to the disk mass $M_{\text{disk}}$ is

$$\frac{M_{\text{captured}}}{M_{\text{disk}}} \approx \frac{\Sigma_{\text{cloud}} r^2 v}{M_{\text{cloud}} r^\frac{3}{2}}$$

The outer radius of the disk, $r$, has specific angular momentum $l$. To estimate the gross features of the resulting disk of captured material, its mass and size are sufficient. These key parameters are retained by the captured material. These key parameters are inferred for the progenitor of the observed stellar disk without engulfing Sgr A* during the capture. The capture is enhanced by the gravitational focusing of incoming molecular cloud material (in-between encounter). Consider an incoming cloud with velocity $v$.

Now consider the partial capture of clouds that engulf Sgr A*. The outer radius of the disk, $r$, has specific angular momentum $l$. To avoid engulfing Sgr A* during the capture, the cloud's radius must be much less than $r_{\text{l}} \approx \frac{3}{2} H_{11407}^3 M_\odot$.

Fluid elements passing on opposite sides of Sgr A* have negligible velocity fluctuations because the velocity dispersion of the cloud is much lower than the velocity of the cloud. The elemental focusing of material passing by Sgr A* and the subsequent collision of the gas just beyond Sgr A* is analogous to Bondi-Hoyle-Lyttleton accretion (Bondi & Hoyle 1944). Simulations are needed to address the details of the circularization process. Tidal stretching and shocking of the disk material at the disk's outer radius are expected.

Density inhomogeneities in molecular clouds are large; however, their effect is mitigated because the collision-induced angular momentum conversion between the cloud and the gas is of order unity. Numerical simulations have confirmed that the cancellation in the departure from homogeneity (Davies & Pringle 1980). Nevertheless, the mean angular momentum per unit mass $j_{\text{cloud}}$ may still be larger than the angular momentum per unit mass $j_{\text{disk}}$ of the disk material. The outer radius of the disk, $r$, has specific angular momentum $l$. To avoid engulfing Sgr A* during the capture, the cloud’s radius must be much less than $r_{\text{l}} \approx \frac{3}{2} H_{11407}^3 M_\odot$. The observed stellar disk size, pc, then implies that the impact parameter is

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\[
\frac{1}{2}v^2 = \frac{GM}{b_0} \quad \implies \quad b_0 = \frac{2GM}{v^2} = 2.4 \, \text{pc}
\]

for \( v = 120 \, \text{km s}^{-1} \)

\( b < b_0 \) escapes

\( b > b_0 \) captured
$M_{\text{disk}} = \pi b_0^2 \Sigma_{\text{cloud}} = 2.0 \times 10^5 \text{M}_\odot$

for $N_H = 10^{24} \text{cm}^{-2}$
Disc profile: angular momentum

\[ r_d \sqrt{\frac{GM}{r_d}} = \lambda b_0 v \quad \implies \quad r_d = 0.43 \text{ pc} \quad \text{for} \quad \lambda = 0.3 \]

\[ \Sigma(r) = \frac{M_{\text{disk}}}{2\pi^2 r_d^2} \left( \frac{r}{r_d} \right)^{-7/4} \sqrt{1 - \left( \frac{r}{r_d} \right)^{1/2}} \]
Cooling

Thermal energy / unit area = \( \frac{5}{2} \sum c_s^2 \)

Power radiated / unit area = \( 2\sigma T_{\text{eff}}^4 = \frac{2\sigma T^4}{\tau} = \frac{4\sigma T^4}{\kappa \Sigma} \)

Cooling time scale \( t_{\text{cool}} = \frac{7}{8} \frac{\kappa \Sigma^2 c_s^2}{\sigma T^4} \)
Heating by starlight / unit area = $\frac{10^7 L_\odot}{4\pi (1 \text{ pc})^2}$

Heating by accretion / unit area = $\frac{3}{4\pi} \dot{M} \Omega^2$
Accretion rate

\[ \dot{M} = 3\pi \alpha \frac{c_s^2}{\Omega} \Sigma \]

Gravitoturbulence: \[ Q \equiv \frac{c_s \Omega}{\pi G \Sigma} = 1 \quad \Omega t_{\text{cool}} > 3 \]

\[ \alpha = \frac{14}{9} \frac{1}{\Omega t_{\text{cool}}} \]

Magnetic turbulence: \[ T > 900 \text{ K} \]

\[ \alpha = 1 \]
Temperature (K) vs. Surface Density (g cm\(^{-2}\))

- Starlight
- Magnetic activity
- \(Q = 1\)
- \(Q = 0.3\)
- \(\Omega t_{\text{cool}}\) for different values

Wardle & Yusef-Zadeh in prep
\[ \Sigma \ (g \ cm^{-2}) \]

Distance from Sgr A* (pc)

- magnetically active
- gravitoturbulent
- unstable to fragmentation

Wardle & Yusef-Zadeh in prep
\[ \Sigma (g \text{ cm}^{-2}) \]

- Distance from Sgr A* (pc)
- Unstable to fragmentation
- Gravitoturbulent
- Magnetically active
- \( M_{\text{disk}} = 2 \times 10^5 M_{\odot} \)

Wardle & Yusef-Zadeh in prep
\[ \Sigma(r) = \frac{M_{\text{disk}}}{2\pi^2 r_d^2} \left( \frac{r}{r_d} \right)^{-7/4} \sqrt{1 - \left( \frac{r}{r_d} \right)^{1/2}} \]
Summary

• Disk formation and evolution model
  – disk mass and size, steep surface density profile
  – fragmentation outside of 0.04 pc (kinematics?)
  – rapid accretion of bulk of material inside 0.04 pc (0.01-0.03 $M_{\text{sun}}$ yr$^{-1}$ for 1–3 Myr)

• Formation of S stars?
  – dynamical evolution

• History of accretion events onto Sgr A*?
  – high accretion rate ==> Fermi bubble?
  – $10^4 M_{\text{sun}}$ every 10 Myr => $10^6 M_{\text{sun}}$ per Gyr

• Simulations needed!
  – magnetic fields: either direct or via prescription for magnetic activity
  – sensible prescriptions for heating/cooling/magnetic decoupling/fragmentation
Opacity

$P \ (\text{dyn cm}^{-2})$

$T \ (\text{K})$

- electron scattering
- H scattering
- molecules / H scattering
- water dissociation
- water
- grain evaporation
- grains
- icy grains

$10^{-12}$  $10^{-8}$  $10^{-4}$  $10^0$  $10^4$