Star Formation in the Galactic Center Region
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- Overview
  1. Small Scale ~ 0.5pc - few pc
     - The stellar disk orbiting Sgr A* + the molecular ring
     - Partial accretion of passing molecular cloud
     - $\tau_{\text{dynamic}} < \tau_{\text{shear}}$
  2. On-going Star Formation in the Molecular Ring
     - Methanol masers
     - Infancy of the molecular ring + in situ star formation
  3. Large Scale ~ 200pc: Highlights of Spitzer Observations
     - A population of YSOs
     - Star Formation Rate
     - $\tau_{\text{dynamic}} > \tau_{\text{shear}}$

- Conclusions

Collaborators
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Stellar Disk 0.03–0.3 pc

- Majority of early type stars in one or two disks < 0.5pc

- Disks have moderate thickness (h/r~0.1)

- Stars have low-to-high eccentricities

- Coeval disks t=(6+/−2)x10⁶ yrs

- Disk mass < 10⁴ solar mass

Levin and Beloborodov 2003; Genzel et al. 2003; Lu et al. 2008; Paumard et al. 2006
Young stars so close to Sgr A*? (The paradox of youth)
Why formed in counter-rotating disks?

Two scenarios of star formation:
1. **Migration**: massive clusters will undergo dynamical friction (Gerhard 2001)
   - dynamical friction is too long
   - no massive stars beyond 0.5pc
   - disordered stellar orbits

2. **In-situ**: massive disk becomes Jeans unstable (preferred)
Stellar Disk Formation

- In-situ star formation
- Simulation of star formation in an accretion disk: efficient
- Snapshot of disk column density
- Red spots: stars $> 3$ solar mass

Questions:
- How do these disks get in there in the first place?
- What about eccentric orbits?
- The trajectory of a compact cloud less than 1pc at 100 km/s: highly rare
- Compact cloud has no way of shedding its angular momentum

Nayakshin, Cuadra and Springel 2007
Molecular Cloud Engulfs Sgr A*  

- Bondi-Hoyle: Inhomogeneous, extended cloud gravitationally focused  
- Capture radius: 3pc  
- 70% of angular momentum cancels out as $r=3$pc circularizes to 0.3pc  
- $Q<1$ as the disk self-gravitates  
- Cloud-cloud collisions: The circumnuclear ring (few pcs)  

Wardle and FYZ (2008)
Mass-Radius Relationship

\[ Q = \frac{c_s \Omega}{\pi G \Sigma_d} = 0.11 \frac{T_{100}^{1/2} \lambda v_{100}^3}{\kappa N_{24}} \]

\( Q = \frac{\tau_{\text{dynamical}}}{\tau_{\text{shear}}} \)

\( \lambda: \) Fraction of angular momentum retained by the captured cloud \( \sim 0.3 \)

\( \kappa: \) Ratio of captured mass to accreted mass \( \sim 1 \)

- Stars circularize with a range of eccentricities

Wardle and FYZ (2008)
SPH Simulations: Formation of an Eccentric Disk

- Plunging of a $10^4$ solar mass molecular cloud onto a $10^6$ BH
- A: size 1.5 pc, $t=3.2 \times 10^4$ yrs
- B: size 1 pc, $t=4.2 \times 10^4$ yrs
- C: size 0.5 pc, $t=4.7 \times 10^4$ yrs
- D: size 0.5 pc, $t=5.1 \times 10^4$ yrs
- Eccentric orbits

Bonnell and Rice (2008)
Molecular Ring Orbiting Sgr A*

- Kinematics: rotation with $v \approx 110$ km/s
- Velocity dispersion $\approx 27$ km/s; Disturbed motion
- 26 dense cores
- size $\approx 0.3 \times 0.2$ pc
- Velocity dispersion $\approx 27$ km/s
- Mass $\approx 1.6 \times 10^4$ Msolar
- Evidence for star formation?

- Molecular Ring
  - HCN(1-0) line

- Sgr A West
  - Free-free emission at 1.3cm

\[ \text{~ few pcs} \]
Molecular Ring: H$_2$O and CH$_3$OH Emission

Detection of methanol and water maser emission with GBT

- Methanol Masers: signposts of on-going massive star formation

- Interstellar water masers: collisionally pumped at high densities
Molecular Ring: \( \text{CH}_3\text{OH}, \text{HCN}, \text{SiO}, \text{H}_2 \)

- \( \text{CH}_3\text{OH} \):
  - Clump \( d_{\text{projected}} \sim 0.6 \) pc
- Narrow line:
  - \( \text{V} \sim 44 \) km/s & FWHM \sim 0.35 km/s
  - Collisionally excited
- Broad line:
  - FWHM \sim 25 \) km/s

- HCN:
  - A red-shifted broad wing
- SiO:
  - Broad line emission
Protostellar Outflow in the Molecular Ring

\[ \dot{M}_J \rightarrow \dot{M}_r \rightarrow M \approx 100-200M_\odot \]

\[ v \approx 20 \text{ km/s} \]

\[ L \approx 0.8 \text{ pc} \]

Momentum deposited into a cloud:

\[ \frac{M_{\nu}}{N} \]

Momentum deposited by the jet:

\[ \frac{M_{\nu}}{\nu} \]

\[ \tau = \frac{L}{NJ} \]

\[ \dot{M}_J = \frac{M_{\nu}}{L} \times 4 \times 10^3 M_\odot \]
Star Formation in the Nuclear Disk

- Jeans Mass

\[ M_J \approx 0.53 \left( \frac{T}{10^4 \text{K}} \right)^{3/2} \left( \frac{n_H}{10^6 \text{cm}^{-3}} \right)^{-1/2} M_\odot \]

- \( M_J \sim 11 M_{\text{solar}} \) when \( T \sim 75 \text{K} \): consistent with massive stellar clusters

- Ambipolar diffusion time scale

\[ t_{AD} = \frac{R}{v_d} \approx 8 \left( \frac{x_e}{10^{-8}} \right) \text{ Myr} \]

- High ionization fraction: \( x_e \) \( \rightarrow \) Suppression of star formation

- Cosmic ray ionization rate in the nuclear disk is high by 1-2 orders of magnitude

\( \text{H}^+_{3} \) and \( \text{H}_3\text{O}^+ \) measurements (Oka et al. 2005; van der Tak et al. 2006)

6.4 KeV \( \text{K}_\alpha \) line emission from neutral Fe (FYZ et al. 2006)
ALMA opportunities

- Great uv coverage: wide range of angular scales in the GC
- Spectral imaging and mosaics for extended sources
- Chemistry of gas: PDR vs XDR \( \rightarrow \) star formation
- Zeeman measurements: High B vs. Low B
- low-mass star formation: HH objects
- Band 1 is a must: ionized stellar winds+synchrotron

Conclusions

- Star Formation in the Nuclear Disk: \( Q < 1 \) and \( Q > 1 \)
  - Stellar Disks and the molecular Ring:
    - In-situ star formation
    - Clouds passing through a strong potential
    - The ring is young
    - Star formation is being fed by clouds
  - A young population of YSO candidates
  - SFR \( \sim 0.08 \) M\(_{\text{solar}}\)/yr