Molecular Gas Accretion in the Galactic Center

Jürgen Ott
(NRAO)

D. Meier,
S. Gramze,
T. Candelaria,
& the SWAG team

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Molecular gas in the Central Molecular Zone (CMZ), the inner ~500pc
- abundant: 10% of all MW gas in 0.1% of the volume
- wide lines: ~20 km/s vs few km/s in the disk
- higher gas temperatures (~60K) than the disk (~10K)
- substantial diffuse component
- appears to move on a 100pc nuclear ring
- appears to be inefficient in forming stars

- How does the gas get there?
- Where is the gas energized?
- Does the energy input happen as a sequence of single events or is it a continuous energy input?

Energy injection sources: Bar potential dynamical forces, shocks from cloud-cloud collisions, embedded in high pressure regions, feedback from compact objects, (HII regions, AGB stars, SNRs, BHs, XRBs, NSs, …), magnetic fields, cosmic rays, large photon field (PDR, XDR), winds, … the CMZ hosts a plethora of energized components

For this talk, the focus will be on the inflowing gas
Gas Flows in Bar Potentials

Bar potential $x_1$ orbits, start self-intersecting $\rightarrow$ cloud-cloud collisions $\rightarrow$ loss of angular momentum $\rightarrow$ infall of gas $\rightarrow$ formation of dust lanes (‘bar shocks’) $\rightarrow$ instabilities form inner 100pc radius ring close to $x_2$ orbits (Sormani+ 2018)

Observed in nearby face-on barred galaxies; difficult to confirm and detail this scenario in the edge-on Milky Way
Gas flows from disk to CMZ: Based on CO, $\sim 2.7\text{M}_\odot/\text{yr}$, fairly symmetric from both sides, but episodic (Sormani & Barnes 2018) – dynamical approach.
HOPS data: Mopra Single dish survey in H$_2$O, NH$_3$ and other molecular lines (Walsh et al. 2011)

H$_2$O: relatively uniform distribution, YSOs and AGB stars in the CMZ but also across the entire MW disk

NH$_3$ (1,1): accumulation of (dense) molecular gas in the CMZ
**Gas Flows from the disk to the CMZ**

**NH₃ (1,1):** accumulation of (dense) molecular gas in the CMZ

What gas is in the flow and what gas is in the MW disk across the line of sight? → “missing link”

**NH₃ (3,3):** tracer of warm gas; (3,3) line also almost perfect correlation with large line widths: → gas properties similar to the CMZ, likely energized clouds in the gas flow
**B1 and G5**

**NH$_3$ (3,3):** tracer of warm gas; (3,3) line also almost perfect correlation with large line widths: → gas properties similar to the CMZ, likely energized clouds in the gas flow

Most prominent gas that is likely in the flow: G5, B2, B1

G5 (+5.5, -0.2) and B1 (-5.5, +0.2) are perfectly symmetric in position!

Are these specific spots in the Bar potential?

Other mechanisms possible, like outflow from CMZ/Sgr B2, molecular loops, etc. … → ALMA ACA Band 6 multi-line data on G5 and B1 to check for similarities other than position, like temperature, optical depth, shocks, … (Savannah Gramze REU)
**NH_3 (3,3):** tracer of warm gas; (3,3) line also almost perfect correlation with large line widths: \( \rightarrow \) gas properties similar to the CMZ, likely gas in the flow

** Velocity Field**
(not symmetric around 0, all positive)

** Velocity Dispersion**
(25 – 15 – 8 km/s)
G5 larger \( \Delta v \)
**NH$_3$ (3,3):** tracer of warm gas; (3,3) line also almost perfect correlation with large line widths: $\rightarrow$ gas properties similar to the CMZ, likely gas in the flow

SiO(5-4)/$^{13}$CO(2-1)

G5 shows brighter strong shock tracers

CH$_3$OH/$^{13}$CO(2-1)

...and G5 also brighter in weak shock tracers
NH₃ (3,3): tracer of warm gas; (3,3) line also almost perfect correlation with large line widths: \( \rightarrow \) gas properties similar to the CMZ, likely gas in the flow

\[ \text{^{12}CO(2-1)/^{13}CO(2-1)} \]

Higher optical depth in G5

H₂CO temperature

Warm gas overall, similar to CMZ
Bar Dynamics/Dust lane models

G5: more turbulent, more shocks, higher optical depth than B1
→ Sormani models show very different locations along G5 and B1:

\[ x \text{ [kpc]} \]

\[ l \text{ [deg]} \]

~10-11kpc

6.5kpc

Models: Sormani+ 2019
Bar Dynamics/Dust lane models

G5: more turbulent, more shocks, higher optical depth than B1
→ Sormani models show very different locations along G5 and B1:
→ B1: line of sight along dust lane, on the far side
→ G5: dust lane overshooting CMZ accretion zone, collision with dust lane on other side

Sormani+ 2019  
Rodriguez-Fernandez+ 2006
Accretion Zone on the Molecular ring at about 100pc from the center, or \( \sim 0.1 \) degree radius.
Dust Lane – Nuclear Ring Interface: $l=1.4$ Cloud

Mopra 3mm & 12mm data (Jones et al. 2012; JO 2016)

Strong shocks

Weak shocks

Ammonia T map

Sgr B2

Sgr A*
Dust Lane – Nuclear Ring Interface: $l=1.4$ Cloud

- **Warm – weakly shocked**
- **Hot – strongly shocked & high $\Delta v$**
- **Warm – weakly shocked**
- **Accretion on CMZ ring**

**Strong shocks**

**Weak shocks**

**Ammonia T map**

**Sgr B2**

**Sgr A*”

**$l=1.4$ cloud**
Gas more turbulent
Where the shock is strong and the gas is hotter
Dust Lane – 100pc Ring Interface: l=1.4 Cloud

There are a sequence of shocks in the dust lane as the gas moves to the CMZ 100pc ring accretion point. Some of the shocks may be due to shear and cloud-cloud collision within the dust lane, other regions may be gas from the other side that overshoots.

High resolution: SWAG “Survey of Water and Ammonia in the Galactic center”
Tens of lines in radio K (1.3cm) band, Large Australia Telescope Compact Array project, ~30”/1pc resolution 6000 pointings across CMZ, 750h
$\text{NH}_3(3,3)$ Intensity (m0)

Velocity field (m1)

Velocity dispersion (m2)

Dust lane accretion zone

Nuclear ring

Many velocity components with large variation of linewidths

Many velocity components with large variation of linewidths
NH$_3$(3,3)

Intensity (m0)

Velocity field (m1)

Velocity dispersion (m2)

Dust lane accretion zone

Nuclear ring

Many velocity components with large variation of linewidths
$\text{NH}_3(3,3)$ Intensity $(m0)$

$\text{HNCO}$ Intensity $(m0)$

$\text{HNCO}/\text{NH}_3(3,3)$ weak shocks

Prominent, widespread shocks in $l=1.4$

HNCO weak, but also high noise in map

Localized HNCO

HNCO: weak shock tracer

Dust lane accretion zone

Nuclear ring

Dust lane accretion zone

Shocked clouds appear in HNC/CO line ratio
**NH₃(3,3) Intensity (m0)**

**NH₃(3,3)/NH₃(1,1) temperature**

**HNCO/NH₃ (3,3) weak shocks**

Cloud-cloud temperature variations

Ammonia thermometer

Shocked clouds appear in HNCO/CO line ratio
1.3cm SWAG radio continuum:

Few HII regions, most notably Sgr D; almost no star formation at $l>1.3\text{deg}$
Sgr D has little influence on the gas outside the immediate environment → gas arrives in clouds with their individual but overall energized properties.
Filaments!

30pc
Conclusions

- There is a sequence of warm, high velocity dispersion clouds on both sides of the CMZ, similar to CMZ gas properties
- The clouds are likely in the gas flow within the bar potential, along the dust lanes
- *(some)* inflowing gas is energized along dust lanes, it already arrives at the CMZ in this state, before it is accreted on the 100pc ring
- Gas is likely shocked by cloud-cloud interactions, the shocks can differ significantly between individual regions
- G5 and B1 may have very different causes despite their exact point symmetric locations: G5 may be the region where overshooting gas from western dust lane hits the eastern dust lane (similar to B2); B1 could be the line of sight aligned with the western dust lane,
- The l=1.4 cloud consists of a sequence of clouds at very different velocities, velocity dispersions, shock degrees, and temperatures
- SF increases close to accretion point
- The high resolution SWAG maps show very filamentary gas in l=1.4, independent of energy content or shock state

**Ongoing:** Accepted ALMA/ACA project to map all the incoming warm clouds in the dust lane that will likely be accreted on the CMZ