On the effects of Cosmic rays on Galactic center molecular clouds

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Outline

• Cosmic Ray Dominated Regions (CRDRs)
• Galactic center. Central Molecular Zone –CMZ- 
• Tracers of CRDRs
• CMZ thermal balance (cooling lines and dust)
• CMZ ionization
• Summary
• Future prospects
Cosmic Ray Dominated Regions (CRDRs)

Arp 220 Merger: $2 \times 10^{12} \text{Lo}$

- Forming stars a rate of $>10^3$ Msun/year
- Time scale is a short time of $10^5$ years
- Shows an extremely high SN rate: 4/years
- Very obscured Av $> 10^3$ magnitudes
- Large ionization rates ($>10^3$) from high density

- Resembles the star formation at high redshift (z>2)

A scale version of local starbursts like M82
Cosmic Ray Domained Regions (CRDRs)

CRs are expected to play an important role in dense regions (Av>5 mag) creating a CRDR and regulating:

• Thermal state (10 MeV≤E(CR)≤100 MeV)
• Ionization (chemistry and ambipolar diffusion)
• CRs feedback (talk by P. Girichidis)
• Initial conditions for star formation setting the IMF
  - Top heavy (less stars < 8 Msun)

Galactic center allows to study the importance of CRDRs in setting the initial conditions for star formation in the environment of galactic nuclei
The Central Molecular Zone

The CMZ covering the inner 300 pc shows:
• Strong emission in all tracers of high energy activity
• Strong nonthermal (synchrotron) emission associated with SNRs
• Gamma ray emission: interaction of energetic Cosmic rays with molecular clouds –CRDRs-

BUT ALSO:


Dense Molecular Clouds ~10^8 M☉
Tsuboi et al.(1999)
The Central Molecular Zone

Strong emission of X-rays (Fe 6.4 keV)

Huge kinematic activity:
- Bar potential
- Cloud collisions
- Turbulence..

Star formation

Large PDRs illuminated by clusters of massive stars.

Fe 6.4 kev line Chandra

XDRs

MDRs

Shocks

Sgr B

Sgr A

Sgr C

SiO J=1-0

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Cosmic rays, Florence
The Central Molecular Zone

• Strong emission of X-rays (Fe 6.4 keV) (XDRs)
• Large PDRs illuminated by clusters of massive stars
• Star formation throughout the region (clusters & protoclusters)
• Huge kinematic activity: Bar potential, disk-halo interactions, large turbulent motions (Mechanical Dominated Regions (MDRs))
• A massive black hole with past activity

The GC dense molecular clouds provides a unique laboratory for understanding the relevance of enhanced Cosmic rays in star formation in the nuclei of galaxies
The initial conditions of star formation: cosmic rays as fundamental regulators.

In order to solve the gas thermal balance equation in principle, we also must solve for \( T_{\text{dust}} \) in CR-dominated regions (CRDRs). For the purposes of computing \( T_{\text{min}} \), we set \( T_{\text{dust}} = 8 \text{ K} \), which is typical for CR-dominated cores in the Galaxy. Any stronger radiation field leaking inside such cores (as expected in starbursts) or remnant turbulent gas heating can only raise the gas temperatures computed here. In Fig. 1.3, the \( T_{\text{min}} \) values show that CR-heated dense gas (\( >10^4 \text{ cm}^{-3} \)) remains cold (\( \sim (10^{-15}) \text{ K} \)) for \( U_{\text{CR}} \) within \( \sim (0.2-10) \times U_{\text{CR}}^{\text{Gal}} \), rising decisively only when \( U_{\text{CR}} \sim (\text{few}) \times 10^3 U_{\text{CR}}^{\text{Gal}} \), where the thermal balance equation yields \( T_{\text{min}} \sim (40-100) \text{ K} \).

Solving for the coupled chemical and thermal states of dense gas in CRDRs does not change much of the aforementioned picture while it makes clear another important aspect that of CR-controlled thermal states of the gas, namely that high CR energy densities will induce a strong gas-dust thermal decoupling, with \( T_{\text{min}} \) remaining significantly higher than \( T_{\text{dust}} \), even at high densities (Fig. 1.4).

**Tracers of CRDRs**

**Thermal balance:**

Heating (\( \Gamma \)) = Cooling (\( \Lambda \))

\( \Gamma(\text{CR}) = \Lambda(\text{Lines}) + \Lambda(g-d) \)

- **Gas kinetic temperature \( T_g \)**
- **Strong dust-gas thermal decoupling**

**\( \Lambda(\text{lines}) \):**

- Fine structure lines:
  - OI, C+, ..
- \( H_2 \)
- CO

\( \zeta(\text{CR}) = 5 \times 10^{-17} \text{ s}^{-1} \)

\( n_H = 10^5 \text{ cm}^{-3} \)

\( A_v \) Papadopoulos et al (2012)
Tracers of CRDRs

Ionization rates:
\[ x(e) \propto (\zeta(CR)/n(H_2))^{-1/2} \]
\[ n(H_2) = 10^5 \text{ cm}^{-3}: \quad x(e)_{\text{Gal}} \sim 2.4 \times 10^{-8}. \quad \zeta(CR) = 100: \quad x(e) = 8.4 \times 10^{-7} \]

Chemistry:

Ion-neutral gas phase reactions:
- Hydrogen: H3+ (ionization of H2 by CR/X-rays)
  (Geballe & Oka 1996)
- Oxygen: OH+, H2O+ and H3O+
  (Ossenkopf et al. 2010; Gerin et al. 2010)

Icy mantle grain chemistry
Talks in session 2-a, 2-b and by S. Zeng

CRDR: 1, 10, 10^2, 10^3, 10^4
PDR: Go = 10^5
CMZ thermal balance

Decoupling Tk and Td: CR heating


Tk = 50-120 K
Tdust = 20-30 K

Heating by CRs

ζ(CR) ~ 10^{-15} s^{-1}

Consistent with the Gamma ray emission

Fig. 3. The distribution of the rotation temperatures $T_{41}$, $T_{42}$, and $T_{21}$ over the galactic center clouds
CMZ thermal balance

Decoupling $T_k$ and $T_d$: Mechanical heating
Martin-Pintado et al. (1997), (2000) and Hüttemeister et al. (1998)

SiO is one of the best tracers of shocks

In the CMZ, **large SiO widespread abundance** $>10^{-8}$
Widespread shocks with supersonic velocities ($T_d < T_k$)

**Origin of shocks?**
Bar potential dynamics (cloud-cloud collisions, turbulence, expanding shells:
300 shells in the CO survey by Hasegawa et al. (1998), Oka et al. (1997),...
CMZ thermal balance

Fine structure lines and H$_2$: PDRs


ISO + Spitzer

H$_2$: Gas temperature of $\sim$150-500 K (>30% total)

Fine structure lines
Large PDR consistent with ionization

PDR/ C-shocks can explain the temperatures
PDRs: ($n\sim10^3$ cm$^{-3}$, FUV$\sim10^3$ Go)

But not the intensities
Several PDRs and/or C-shocks and/or CRs?

Quintuplet and Arches ionization

C-Shock from Draine et al. (1983)
CMZ thermal balance

Large scale temperature variations

Ginsburg et al: APEX CMZ H$_2$CO


Multiline analysis of H$_2$CO to derive the temperature over the CMZ:
• Large temperature gradients from 60 to 120 K
• Modeling indicates that CRs are not the dominant heating in the CMZ
• Limits for ionization rates $<10^{-14}$ s$^{-1}$
• Preferred mechanical heating

Heating by UV photons and X-rays were neglected.
CMZ thermal balance

CO Spectral Line Energy Distributions

Requena-Torres (2012), Goicoechea et al. (2013), Etxaluze (2013)

**Herschel+SOFIA (CO J up to 24)**

**Sgr A* and Sgr B2 complexes:**
Tk >300 K

**Sgr B2:**
PDRs+shocks in cores

**Sgr A*:**
High-J CO lines can only be excited by shocks
Goicoechea et al. (2013) ruled out CR heating
CMZ ionization

\[ \text{H}_3^+ \]

Oka et al. (2005); Goto et al. (2008); Goto et al. (2014)

Diffuse foreground components

Density of 100 cm\(^{-3}\)

Temperature \( T \sim 250 \text{ K} \)

Ionization rate, \( \zeta(\text{CR}) \sim 10^{-14} - 10^{-15} \text{ s}^{-1} \)

Large filling factors

Small H\(_2\) fractions

Dense clouds

CND

Diffuse clouds
CMZ ionization

**OH⁺, H₂O⁺, H₃O⁺, H₂O**

**Herschel (OH⁺, H₂O⁺, H₃O⁺):** Indriolo et al. (2015) **Sgr A* and Sgr B2 complexes:** Very complex line profiles. Foreground absorption. Two type of clouds: Diffuse and dense clouds

**Diffuse:**
Large ionization rates of $\sim 10^{-14}$ s⁻¹

**Dense clouds:**
Similar ionization rates to those in the disk, $\sim 10^{-16}$ s⁻¹.

**APEX:** Van der Tak et al. (2006)
Confirm from H₃O⁺/H₂O ratio the $\zeta$(CR) $\sim 4 \times 10^{-16}$ s⁻¹.

The difference in the ionization rates between diffuse and dense cores is due to the propagation/spectrum of low energy CRs (Padovani et al. 2009). This will also have a strong impact in the thermal balance.
Summary

• CRs does not seem to dominate the global heating of the bulk of molecular clouds in the CMZ at scales >0.5 pc.
• Mechanical heating seems to be the global dominant mechanism. PDR/XDRs also play an important role locally. So far, it is unclear the contribution of CRs heating.
• The diffuse component shows enhanced $\zeta$(CR) by factors of $10-10^3$ with respect to that in the disk.
• The dense component, however, only show a moderate enhancement (factor of < 10) of the $\zeta$(CR) with respect to the disk.
Future prospects

• The high angular resolution provided by ALMA and JWST will allow to look at the thermal balance with enough spatial resolution to disentangle the dominant heating mechanism at the relevant scales for star formation.

• Herschel, ALMA, APEX, SOFIA would allow to look at key species like H₂O, OH⁺ and H₃O⁺ to better establish the ionization rates, and its dependence on the H₂ column density of the clouds in the GC.

• The thermal balance and the ionization rates in the molecular clouds in the GC need to be properly modeled by considering the propagation of low energy CRs from the diffuse envelopes to the dense cores. Prediction of line fluxes of the main cooling lines is crucial to compare with observations.