X-Ray Surveys reveal the past activity of the Galactic Center Super-Massive Black Hole and of the nuclear region

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Session parallèle: Les diverses facettes du centre galactique : des abords du trou noir à son environnement plus lointain
Outline

TOPICS:
• Introduction: Galactic Center SuperMassive Black Hole Sgr A*
• Search for past activity of Sgr A*
• Reflection from CMZ Clouds
• Hot gaz in the GC
• Gamma-ray Fermi Bubbles
• Summary

Collaborators:
R. Terrier, D. Chuard (APC Paris, CEA Saclay)
M. Clavel (IPAG Grenoble)
G. Ponti (MPE Garching D, INAF Merate I)
M. Morris (UCLA, US)
M. Chernyakova, M. Walls (DCU, Dublin, Ir)
and others

Data (2000 – 2017):
INTEGRAL, XMM-Newton (> 1.5 Ms GC surveys / obs.), Chandra

Black Holes

- BH are space time regions delimited by an event horizon
- When a given mass \( M \) is within a radius < its Schwarzschild radius \( (M_\odot = \text{Solar mass}) \)

\[
R \leq R_S = \frac{2GM}{c^2} \approx 3 \frac{M}{M_\odot} \text{ (km)}
\]

- Not even light can escape: BH are invisible
- Extreme distortion of space-time: probe for General Relativity in strong field
- Important Astrophysical objects but also for new physics at the frontier of Classical-Quantum theories (Quantum Gravity, String, ..)
- Two types of BH observed:
  - Stellar size \((3 - 100 \ M_\odot)\)
  - SMBH in GN \((10^6 - 10^{10} \ M_\odot)\)
- Historically studied through X-rays and now Multi-wave-messenger Astronomy (GW)
Huge radiative luminosities and powerful particles ejections

Maximal (Eddington) Luminosity

\[ L_E = 1.26 \times 10^{38} \left( \frac{M}{M_\odot} \right) \text{ erg/s} \]

Mainly in (UV) X and gamma rays
The Galaxy
Galactic Bulge in Visible Light
Infrared View of the Galactic Center

Spitzer/ IRAC 3.6 - 8 μm

Scale: 1.9° × 1.4° ≈ 274 pc × 202 pc (8 kpc)
AO Infrared Observations of the Nuclear Star Cluster

12″ = 0.5 pc
Enclosed Mass $M_{\text{enc}} = 4 \times 10^6 \, M_\odot$ within a radius of 124 AU (1500 $R_\odot$)

$=>$ A Super Massive Black Hole

$M_\bullet = 4 \times 10^6 \, M_\odot$

$R_\odot = 1.2 \times 10^{12} \, \text{cm}$

$= 0.08 \, \text{AU} = 10 \, \mu\text{as} (8 \, \text{kpc})$
Central Molecular Zone in Radio
The Sgr A Radio Complex

Circumnuclear Disk & Sgr A West

Sgr A West Minispiral
Sagittarius A*: electromagnetic counterpart of the SMBH of the Galaxy
X-Ray Obs.: 1 keV - 1000 keV

- X-ray Observatories used in the surveys of the Central Molecular Zone from 2000 – 2017
- Energy bands: 0. keV – 3 MeV
- Angular Res :1” – 12’
- Other: Suzaku (1-10 keV) and NuSTAR (3-80 keV)
12 yr XMM Galactic Center Survey

0.5 – 12 keV Image

Ponti et al. 2015
Sgr A*: GC SuperMassive Black Hole

- Bright compact non-thermal variable R-source Sgr A*
- Focus of central cluster star orbits $\Rightarrow M_* = 4 \times 10^6 \, M_\odot$
- Very weak in X-rays: $L_X \sim 10^{33} \, \text{erg s}^{-1} < 10^{-11} L_E (M=\text{M}_*)$
- Sgr A* Bright Flares in X-rays and NIR $\Rightarrow L_{\text{max}} \sim 10^{35} \, \text{erg s}^{-1}$
Open questions

Sgr A* Super-Massive BH at the GC

• Very quite today: was it active before? Did it have an AGN-like phase? When how why?
• Activity linked to mass accretion (galactic environment
• The SMBH and Galaxy (bulge) relations indicates co-evolution: feedback of BH to Gal?
• Which power SMBH has injected in Galaxy?
• Are there traces of large past activity from GC?
Co-evolution of SMBH and Host-G

Kormendy & Lo 2013

A. Goldwurm  SFP, Nantes, 8/7/19: Galactic Center Super-Massive Black Hole
Plasma kT \sim 7 \text{ keV}
Fe XXV Fluorescence 6.7 keV Line

Emission thermique associée au plasma chaud

Non-thermal
Fe I Fluorescence 6.4 keV Line

Emission non thermique à 6.4 keV
Neutral Fe fluorescence line – Molecular Clouds
Fluorescent Iron line and reflected continuum from X-ray irradiation

\[ F_{6.4\, \text{keV}} \propto \left( \frac{N_{\text{H}}^c}{d^2} \right) L_X \left( \frac{R_c^2}{D_{\text{s-c}}^2} \right) \]

\[ F_{\text{sc}} \propto \left( \frac{\tau_T}{d^2} \right) L_X \left( \frac{R_c^2}{D_{\text{s-c}}^2} \right) \]

\[ \text{EW} \sim F_{6.4\, \text{keV}} / F_{\text{sc}}(6.4) > 1\, \text{keV} \]

with \( \tau_T \propto (1 + \cos^2 \theta) \)

\( D = \text{distance Source - Cloud} \)

\( N_{\text{H}}^c = \text{cloud col. dens.} \)

\( R_c = \text{cloud radius} \)

\( d = \text{distance cloud-observer} \)

\( \theta = \text{angle S – C – O} \)

Fluorescence Iron line at 6.4 keV

Scattered X-rays

Molecular Cloud

Source of X-rays (\( E > 7.1\, \text{keV} \))

\( \Gamma = 2 \)

\( Z = 2 \times Z_{\text{sol}} \)

\( \text{Irradiating X-ray Source (} L_X \) \)

\( \text{Thompson} \)

\( \text{Compton} \)
INTEGRAL (20-200 keV) Sgr B2 spectrum compared to ASCA & ART-P data at low energy

Broadband spectrum: Fe I fluorescence + Compton scattering of a $10^{39}$ erg/s luminosity outburst of Sgr A* ~300 yr back lasted > 10 yr (Revnivtsev et al 2004)

However hypothesis of particle induced non-thermal emission not completely excluded
• Points of equal time delay seen by an observer at infinity lie on an parabolic surface with focus on the illuminating source
• Light echoes easily produce variability in the reflected emission, even apparent superluminal motion (Sunyaev Churazov 98, Crampton Sunyaev 02)
• First variability of 6.4 keV line from Sgr B2 observed w/t different instruments (ASCA, Chandra, XMM, Suzaku) (Koyama+ 06 07 08, Inui+ 07)

Time delay of the reflection component and parabola of equal time-delay points
Propagation seen from above the Galactic plane

Reflected emission on the plan of the sky (as observed)

Simulation of reflection from a putative distribution of molecular clouds in the CMZ of a short (1 yr) X-ray outburst from Sgr A* at different delays (< 1000 yr). Complicated pattern of morphological changes related to the matter distribution.

Courtesy of Maïca Clavel (PhD Thesis, 2014)
INTEGRAL GC survey: Discovery of gamma-ray variability of Sgr B2

- Decrease of Sgr B2 20-60 keV flux over 7 yrs (cloud core size ~ 8 ly)
- Variation up to 40%, compatible with the 6.4 keV decrease observed by Suzaku (compared to XMM)
- Consistent with hypothesis of reflection of hard X-ray emission: end of outburst => decrease
- Not with particle interpretation (Terrier et al. 2010)
XMM monitoring of 6.4 keV line from MC around Sgr A*: discovery of superluminal motion

(Ponti et al. 2010)
Fe Kα + β: $E = 6.409 \pm 0.002$ keV, $\sigma = 28 \pm 4$ eV, norm=$4.7 \pm 0.3 \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$, EW=750 eV; $\Gamma_{PL}=1 \pm 0.4$; $n_H \sim 4 \pm 3 \times 10^{22}$ cm$^{-3}$, $\tau = 0.26 \pm 0.12$.
One 300 yr Outburst at $L \sim 10^{39}$ erg/s?
Chandra CMZ Obs.: multiple Echo events

Chandra Survey 1999–2011: 6.4 keV Iron K line rapid variability from Sgr A molecular cloud. **MC1 MC2 not constant, Br1 rapid event** => reflection of 2 bright events ($10^{39}$ erg/s), 1 short (< 2 yr) and 1 longer (~ 10 yr) produced by Sgr A* in the past few 100 yrs. **Not possible to determine the delays because unknown location of clouds. Need for spectral modelling.** (Clavel et al. 2013, Clavel PhD 2014)

NOT A SINGLE 300 YR OUTBURST !!
Monte Carlo Modeling of Reflection Spectrum

- Illumination (parallel beam) by external source, Power Law spectrum 1-300 keV and Ph. Index $\alpha$
- Spherical cloud diameter $D$
  - Uniform, Variable (Gaussian, Expo) Density
  - Solar composition
- Effects:
  - Absorption and Fluorescence (Fe)
  - Multiple Scattering
  - Bound-electrons

$N_H = 5 \times 10^{24}$ cm$^{-2}$

$N_H = 5 \times 10^{22}$ cm$^{-2}$

$\theta = 120^\circ$

$D_C = 2$ pc

Walls et al. 2016
Chuard PhD 2018
Reflection Spectrum as a function of scattering angle

- Strong dependence of low energy spectrum on Scattering angle $\theta$
- Determination of $\theta$ allows the location of the reflecting clump line-of-sight position
- Applied first to Sgr B (XXM + Chandra + INTEGRAL) (Walls+ 2016)
- Then to Sgr C (Chuard+ 2018)
- Improved code of simulation and simultaneous fit of several MC clumps (XMM) data confirm with increased accuracy the previous estimations.

$N_H = 2.5 \times 10^{23}$ cm$^{-2}$

D. Chuard, PhD 2018
Fitting Reflection spectra of several MCs

The two-events (\(L_X \sim 10^{39}\) erg/s) model is significant at 5 sigma c. l.

Delays of 2 events derived from all MCs data fit:

\[ \Delta t_1 = 84 \pm 16/-9\text{ yr} \quad \text{Short Event} \]

\[ \Delta t_2 = 238 \pm 19/-20\text{ yr} \quad \text{Long Event} \]

(Chuard PhD Nov 2018, Chuard et al. 2019 in prep.)
CMZ Soft X-ray Line Emission as mapped by XMM-Newton
CMZ Soft X-ray Line Emission: the structures

- GC LOBES
- SUPERBUBBLES
- LARGE SCALE OUTFLOW
2000-2012: Large GC X-ray surveys (b ≈ +/- 0.5°)
Large project to explore GCL-N Approved and performed in 2016 -2017
Total of 46 XMM obs (25 ks) => 1.15 Ms ≈ 320 hr expo
Images reveal structures of thermal gas extending towards Gal poles
Discovery of Galactic Center X-ray Chimneys of Hot Gas

From XMM GCL Survey + Archival data we detected and characterized:

- 2 long (1° ≈ 160 pc) thermal (T ≈ 7 × 10^6 K) structures extending N & S of GC (d=8 kpc), width: ±0.4° ≈ 50 pc
- Similar parameters and origin N / S
- N-Ch co-spatial with R/IR GCLN
- N-S Differences: galactic weather (ISM density)
- Origin within 50 pc from Sgr A*
- 15pc-lobes (L≈8 × 10^{38} erg/s, t_s ≈ 3 × 10^4 yr) nested but not clearly related
- Total power: L_{X-chi} ≈ 4 × 10^{39} erg/s
  Time scale: t_s ≈ 3 × 10^5 yr

- Reach the Fermi Bubbles Bases !!

XMM-Newton Soft X-ray GC 300 pc x 500 pc image:
Red 1.5-2.6 Green 2.35-256 SXV line Blue 2.7-2.97 keV (continuum, no SXV ArXVII). Point Sources+dsh removed. Sgr A*, Base Fermi-B (Extrapolated Rosat)
FERMI All-Sky Image > 1 GeV – Six years


NASA
Fermi data reveal giant gamma-ray bubbles
The Galactic Center Chimneys

- Scheme of Chimneys and other X-ray structures of the GC region
- The Chimneys link the GC region to the Fermi Bubbles
- No clear connection to the bipolar lobes (not excluded either)
- Originated in the nuclear region (like the lobes) or over more extended region (50 pc in long.)

- Origin:
  - Large Star Formation Episodes
  - AGN-like activity of the Super-Massive Black Hole
The Galactic Center Chimneys

Gamma-ray bubbles
~ 15 000 light years

X-ray emission

Milky Way stellar disc
~ 50 000 light years

Gamma-ray bubble

Northern chimney
X-ray/radio lobe
Supermassive black hole
X-ray lobe
Southern chimney

Credit: ESA – XMM-Newton
Summary

• Variable Neutral Iron fluorescence line and X-ray continuum from molecular clouds (MC) in the Galactic Center (GC) are due to reflection of past X-ray outbursts ($> 10^6$ increase in Luminosity) from supermassive Black Hole Sgr A*  
  - The emission of all main MC varies => no single century long outburst  
  - At least 2 events of different time scales (2 yr, 10 yr) propagate in CMZ (as proposed by Clavel+ 2013)  
  - Monte Carlo spectral modelling on XMM/Chandra data of several MC allowed us to locate the clumps and to determine the time of the 2 events  
  - Work is in progress to establish X-ray emission of Sgr A* in the last millennium

• Discovery of 150-pc Chimneys of hot gas North and South of the GC  
• Connect the GC region to the Fermi Bubbles: channel of energy injection  
  - Power $10^{39}$ erg/s , $t \approx 10^5$ yr => modest, compatible with the lower estimations of Fermi Bubbles power  
  - Origin: Star formation episodes or SMBH active phase ?

• Future observations: XMM, Chandra, Nu-STAR, ...  
• Future observatories : eROSITA, XRISM, XIPE, Athena ...
Thank you

Merci

Chernyakova 2019 March, Nature, N&V