Constraining the layout of circumnuclear clouds with respect to the SMBH in the GC: outlook of X-ray polarimetry

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X-ray polarization in astrophysics: a window about to open? - Stockholm - 2014

Presentation outline

I. **The Galactic center (GC) and X-ray polarimetry**

II. **Modeling and discussion**

III. **Observational challenges**

IV. **Conclusions**

The Galactic center

Picture :

- FoV of the picture ~ 1.5 x 2.5 degrees
- Mid-IR image from the Midcourse Space Experiment satellite

Curiculum vitae :

- Coordinates first established by Harlow Shapley in 1918:
  RA 17h45m40.04s, Dec −29° 00' 28.1'' (J2000 epoch)
- 8.33 ± 0.35 kpc (~27 ± 1 kly) (distance)
- Invisible in optical, ultraviolet and very soft X-rays due to interstellar dust
- Collection of vast cosmic dust clouds, bright star clusters, swirling rings of gas, and even a supermassive black hole (Sgr A*)

The intriguing case of Sgr A*

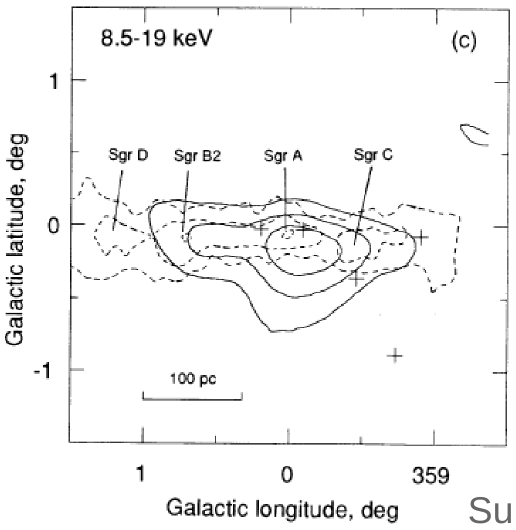
Sgr A* has a very low accretion rate:

About 10^{-8} $M_{sol}.y^{-1}$ near the event horizon (Baganoff et al. 2003)

resulting in X-ray luminosity of the order 2×10^{33} $erg.s^{-1}$ (Baganoff et al. 2001; Quataert 2002)

In comparison, 10^{7} - 10^{8} M_{sol} black holes in Seyfert 1 AGN accrete 0.01 - 0.2 $M_{sol}.y^{-1}$

(Meyer-Hofmeister & Meyer 2010)

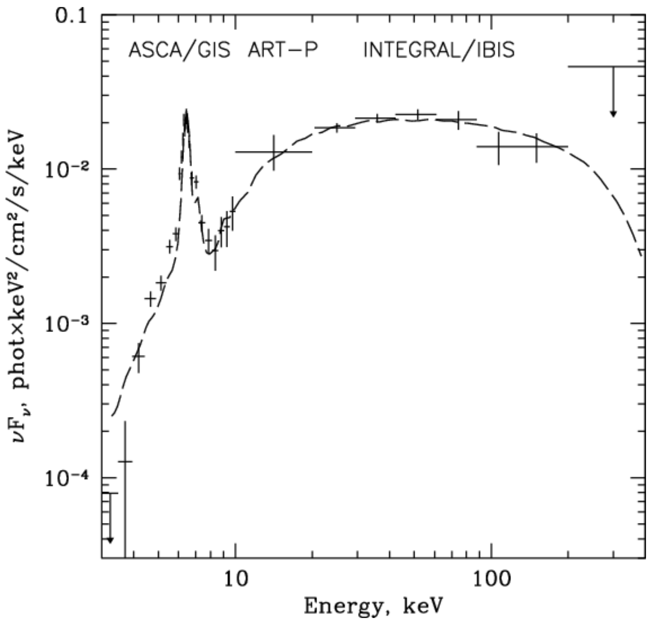


Sunyaev et al. (1993)

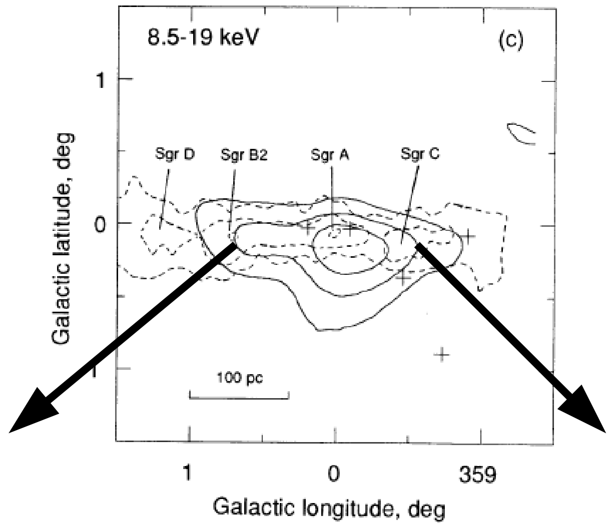
Such quiescence is in disagreement with several past X-ray observations of the Eastern and Western molecular clouds

(Sunyaev et al. 1993)
(Koyama et al. 1996)

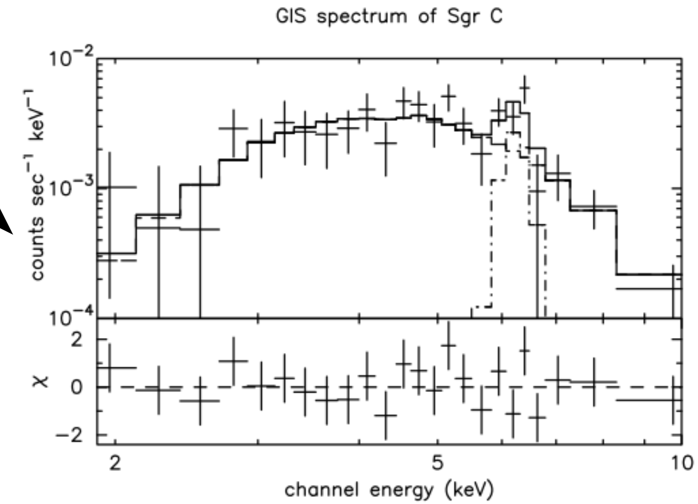
Past reflection?



Koyama et al. (1996) / Terrier et al. (2010)



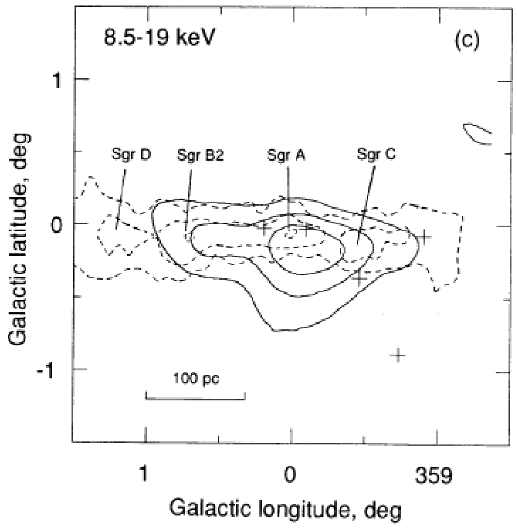
Sunyaev et al. (1993)



Murakami et al. (2001)

Pure reflection spectra ($L_X \sim 10^{35}$ erg.s^{-1}) … but no nearby sources bright enough!

Past reflection?



Sunyaev et al. (1993)

A geometrical solution:

Sgr B2 and Sgr C are reflection nebulae, shining the reprocessed emission from a past Sgr A* outburst ($L_X > 10^{39}$ erg.s^{-1})

Sunyaev & Churazov (1998)
Murakami et al. (2000)

→ past flaring period of Sgr A*
(Sgr A* would have been active ~400 years ago and again about 100 years ago)

Inui et al. (2009)
Ponti et al. (2010)

The estimated duration of the flare depends on the spatial location of the reflector
Cannot be properly constrained using X-ray spectroscopy or timing analyses

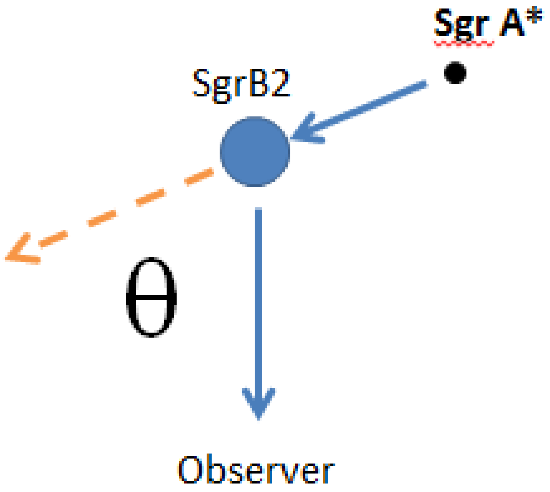
A solution: X-ray polarimetry

Reflection = scattering-induced polarization

X-ray polarization as a mechanism to:

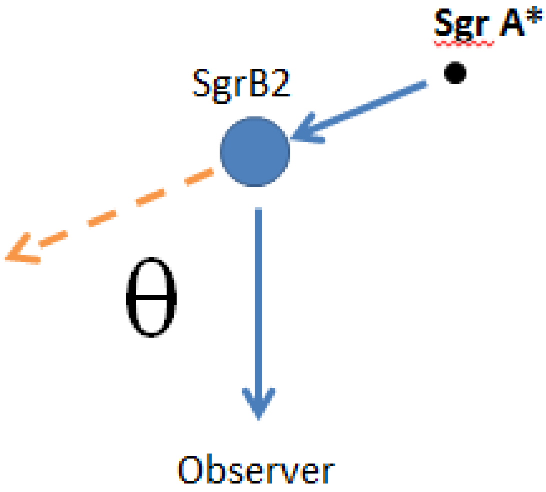
- prove / reject the hypothesis that the GC was active in the past
- estimate the 3D position of the clouds

Churazov, Sunyaev & Sazonov (2002)



Soft X-ray polarimetry

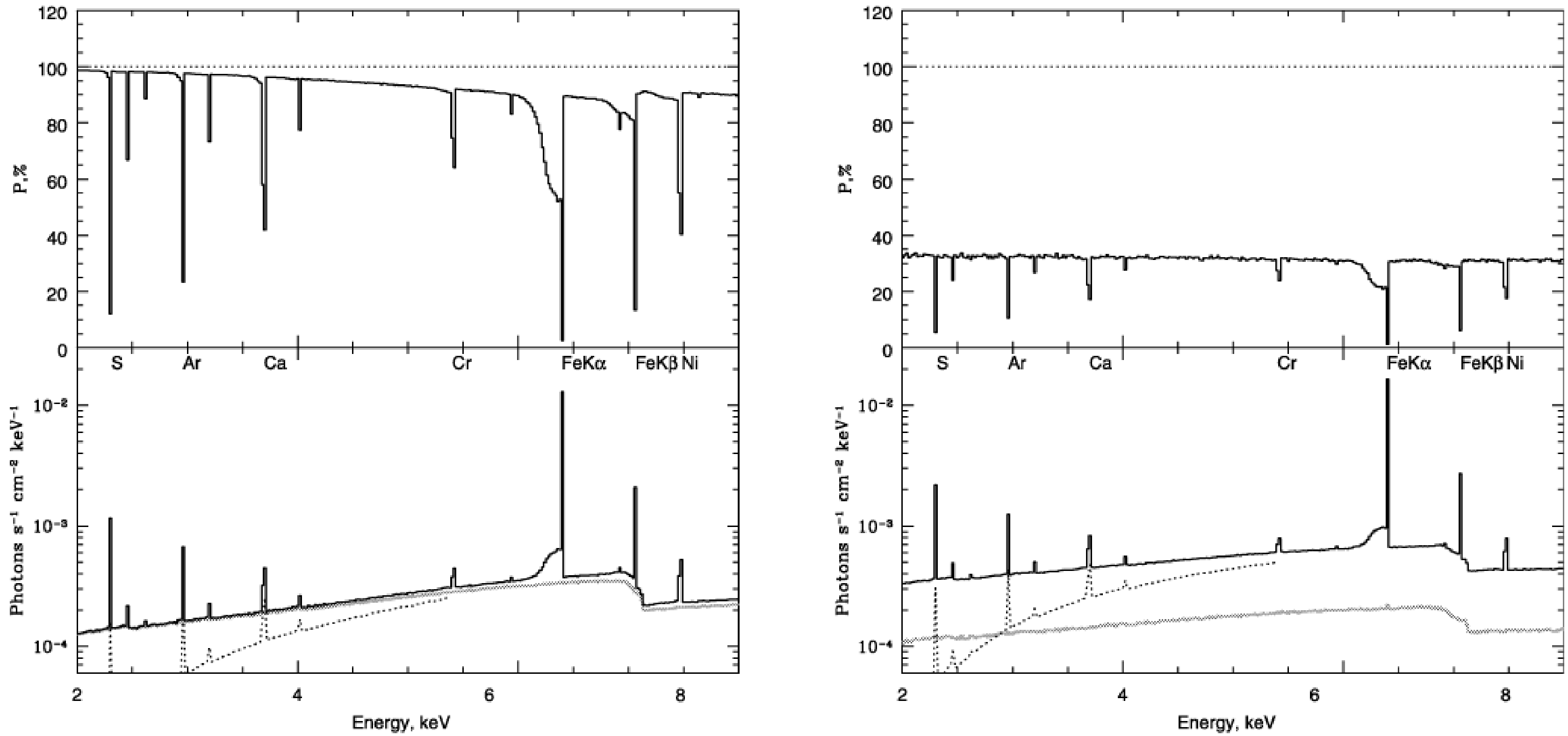
First estimation of $P_{Sgr\ B2}$ (linear pol. deg) and ψ (pol. ang.) at soft X-ray energies   Churazov, Sunyaev & Sazonov (2002)



Model:

- single cloud (radius 10 pc), Thomson optical depth 0.5, filled with neutral, solar abundance matter
- photoelectric absorption, fluorescent emission and Compton scattering by *bound* electrons
- 2 – 8 keV
- cloud situated at 100 pc from the unpolarized continuum
- 2 positions with respect to the Galactic plane (0 and 100 pc further away)

Soft X-ray polarimetry



Churazov, Sunyaev & Sazonov (2002)

GC plasma emission

If Sgr B2 is echoing a past flare of Sgr A*, the resulting soft X-ray polarization is expected to be high with its electric vector perpendicular to the line connecting the two sources

However ...

- Presence of a diffuse plasma emission towards the GC (SNR ?)
  Sidoli & Mereghetti (1999)

- Dilution of the polarized flux below 7 keV
  Mewe (1999)
  Liedahl (1999)

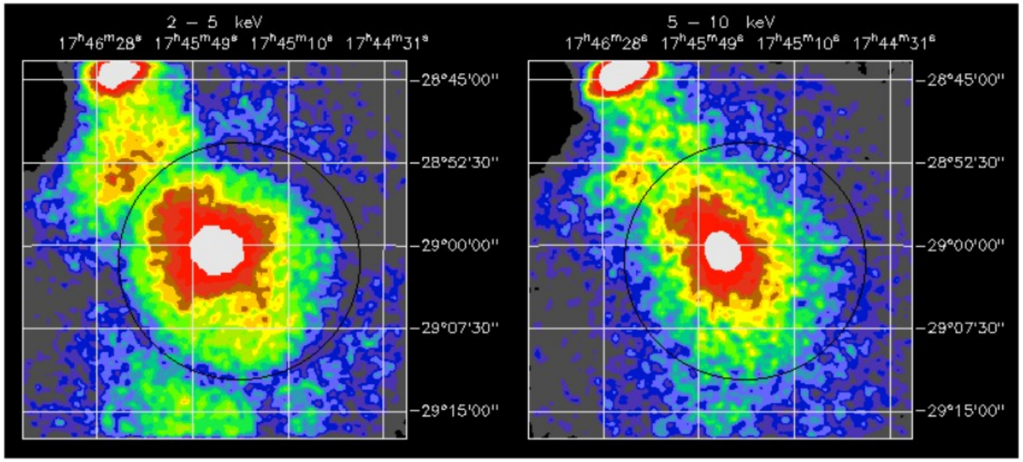


Fig. 3. 2–5 keV (left) and 5–10 keV (right) emission from the SgrA Complex. Both images have been smoothed with a gaussian with FWHM=1 arcmin. The strong source in the NE corner is 1E1743.1–2843 (Cremonesi et al. 1999). The low surface brightness in correspondence of the circle is an instrumental effect due to the absorption in the detector window support structure.

Sidoli & Mereghetti (1999) - BeppoSAX

To higher energies and complexity

X-ray polarization from the GC must be explored at E > 7 keV

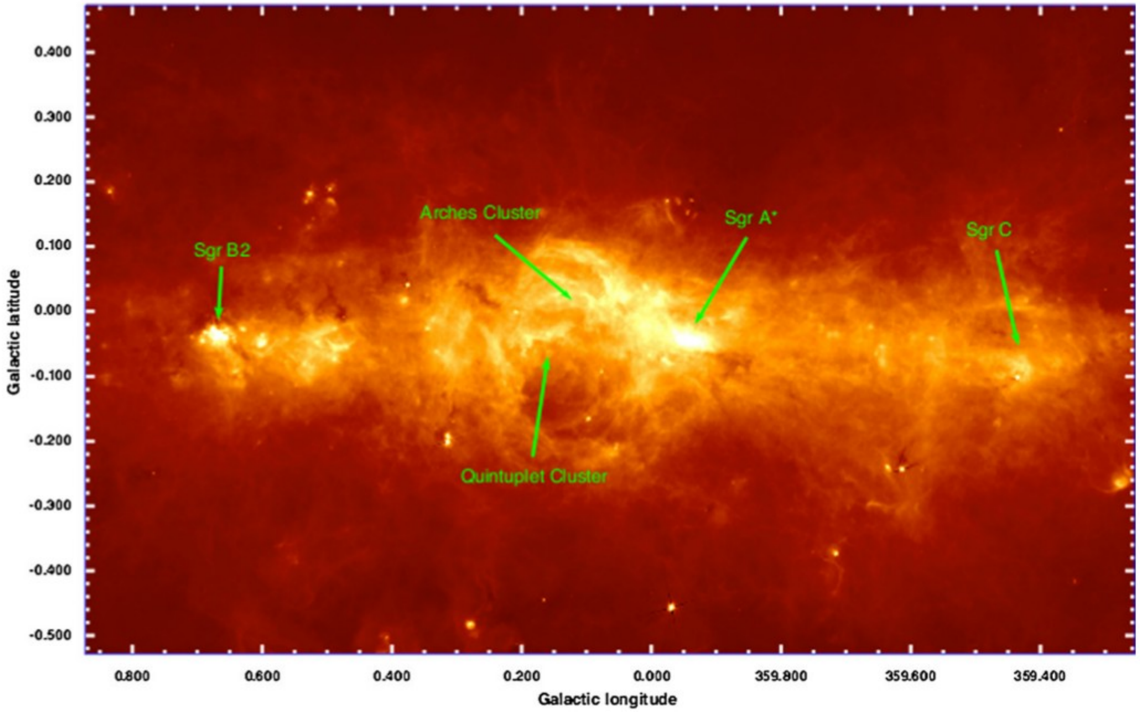


Figure 1. *Herschel* PACS 70 μm image of the Galactic center region. Labels identify known objects that are discussed in the text.

New model taking into account radiative coupling between different regions:

- Sgr B2
- Sgr C complex
- Circumnuclear disk (CND)

Molinari et al. (2011)

To higher energies and complexity

X-ray polarization from the GC must be explored at E > 7 keV

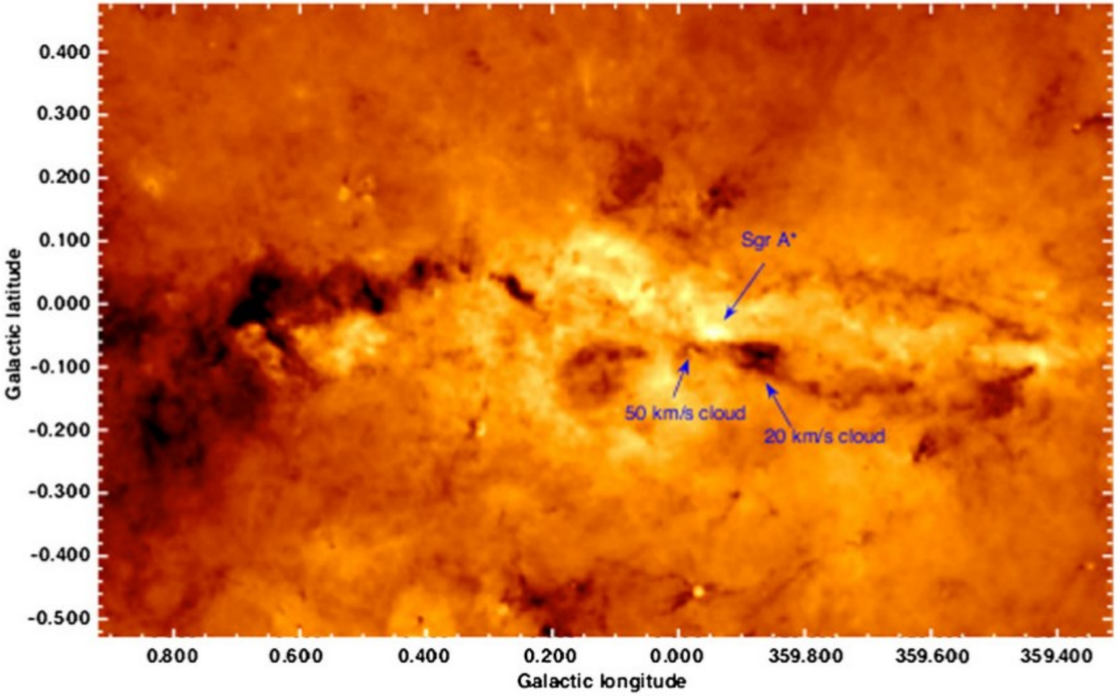


Figure 3. Temperature map of the Galactic center region. The log-color stretch extends from 15 K to 40 K on Sgr A*.

New model taking into account radiative coupling between different regions:

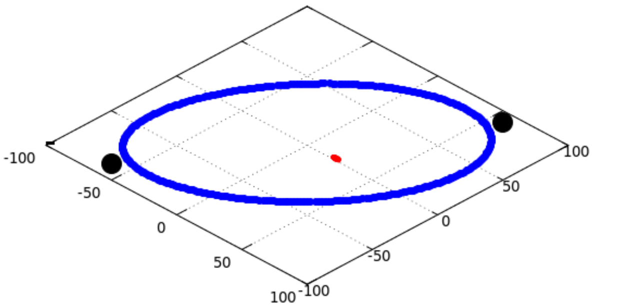
- Sgr B2
- Sgr C complex
- Circumnuclear disk (CND)
- Central molecular zone (CMZ, a 100 pc elliptical, twisted ring of cold, dense molecular clouds)

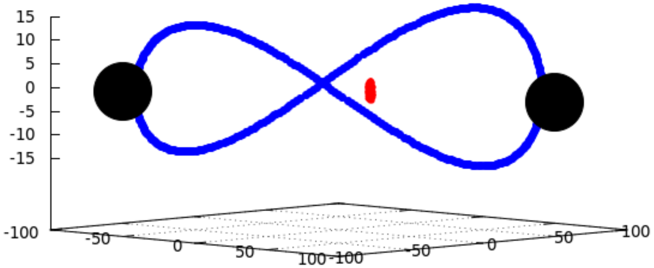
Molinari et al. (2011)

Hard X-ray polarimetry

Modeling with STOKES : (Goosmann & Gaskell 2007; Marin et al. 2012)

- reflection nebulae (radii < 10 pc), Thomson optical depth 0.5, filled with neutral, solar abundance matter, *v*, T and n_H according to litterature
- photoelectric absorption, fluorescent emission and Compton scattering by *free* electrons
- 300 moving clouds for the CMZ
- inclined CND
- shifted SMBH / scattering nebulae
- 8 – 35 keV
- radiative coupling between all the regions
- imaging capability





Marin et al. (2014a,b)

Hard X-ray polarimetry

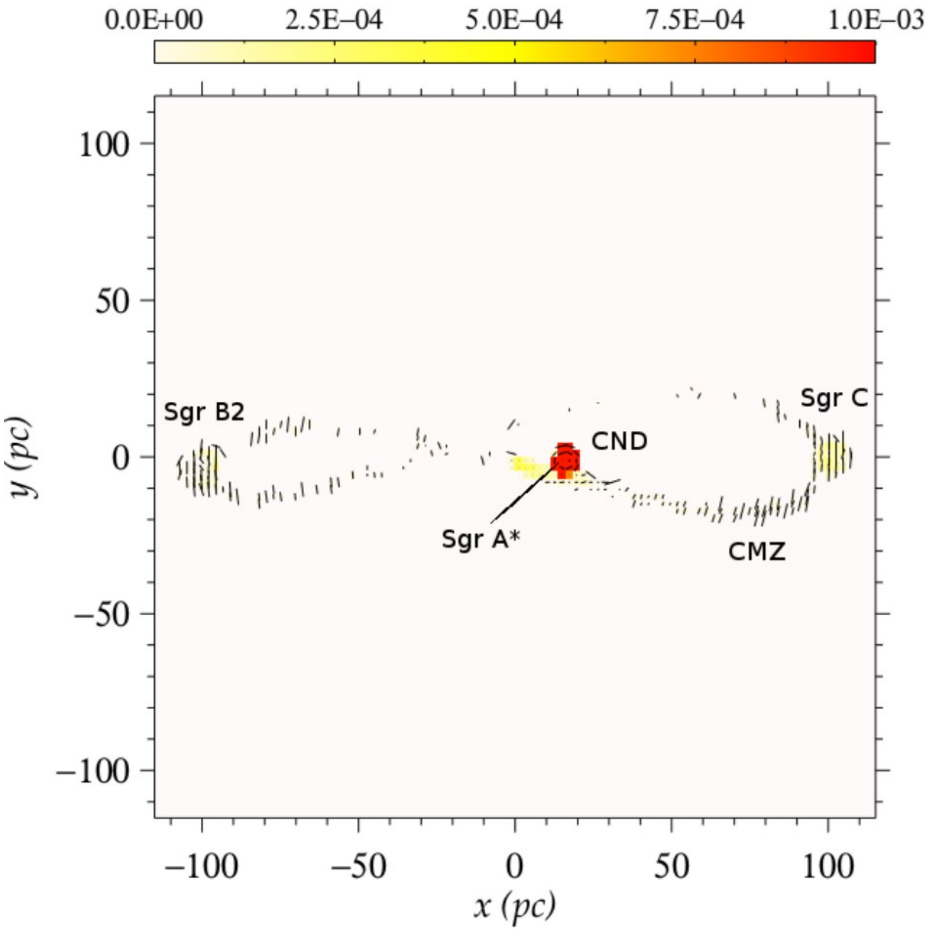
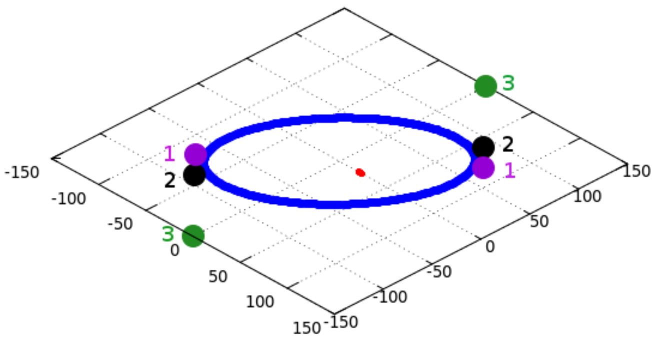


Table 1. Estimated 8–35 keV polarization degree P and polarization angle ψ of the $2^\circ \times 2^\circ$ GC and individual reprocessing regions. Polarization angles are defined with respect to the projected vertical axis of the system.

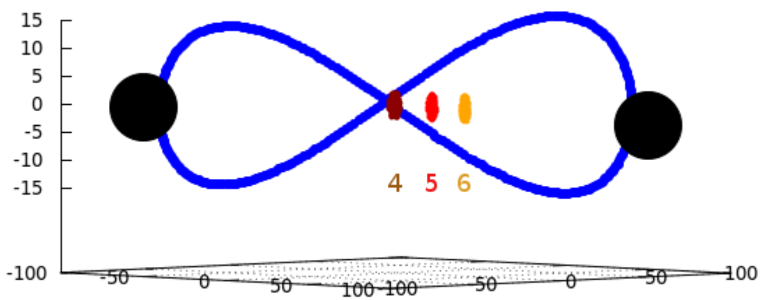
Region	P [per cent]	ψ [°]
GC (integrated)	0.9	− 22.8
CND	1.0	− 20.5
Sgr B2	66.5	88.1
Sgr C	47.8	89.5

Marin et al. (2014a)

Hard X-ray polarimetry



Region	P [per cent]			ψ [°]		
	M_1	M_2	M_3	M_1	M_2	M_3
GC	0.9	0.9	1.0	– 22.0	– 22.8	– 21.4
CND	1.0	1.0	1.0	– 18.7	– 20.5	– 19.9
Sgr B2	71.0	66.5	38.6	91.5	89.1	91.3
Sgr C	64.0	47.8	16.0	90.4	89.5	89.6



Region	P [per cent]			ψ [°]		
	M_4	M_5	M_6	M_4	M_5	M_6
GC	0.7	0.9	0.9	– 39.8	– 23.4	– 21.8
CND	0.7	1.0	0.9	– 36.0	– 21.3	– 20.3
Sgr B2	58.6	67.0	73.8	90.0	89.0	89.0
Sgr C	53.0	44.5	37.3	93.0	88.0	91.7

Marin et al. (2014a)

Detectability with a past project

From the soft to the hard X-ray band, Sgr B2 and Sgr C are the prime candidates

Are such levels of polarization detectable ?

Example with the New Hard X-ray Mission (NHXM)
- M-class satellite
- 2–10 keV low-energy polarimeter (LEP)
- 6–35 keVmedium-energy polarimeter (MEP)
- angular resolution ~ 20 arcsec: spatially resolving the two reflection nebulae

99% confidence level MDP + 500 ks observation

Region	P_{source}	MDP	$P_{detect.}$	Error on ψ
Sgr B2	66.5 per cent	7.7 per cent	66.7±1.8 per cent	0.63°
Sgr C	47.8 per cent	4.5 per cent	48.7±4.6 per cent	1.52°

Marin et al. (2014a)

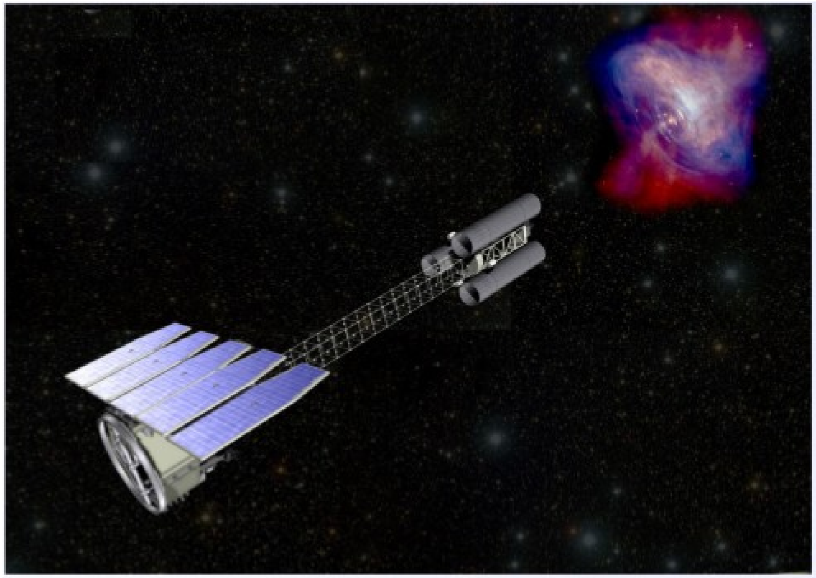
Detectability with a future project

Imaging X-ray Polarimeter Explorer (IXPE)

Weisskopf et al. (2008)

2 – 8 keV → re-run modeling taking into acount plasma emission acting like an unpolarized background

Telescope system	
Angular resolution	< 25" half-power diameter
Total mirror effective area	≈ 900 cm² up to 7 keV
Field-of-view	6.4' (detector-limited)
Imaging Gas Pixel electron-tracking detector	
Fill gas	He/DME (20/80) @ 1 atm
Read-out resolution	50 μm
Number of pixels	300 x 352
Absorption and drift depth	10 mm



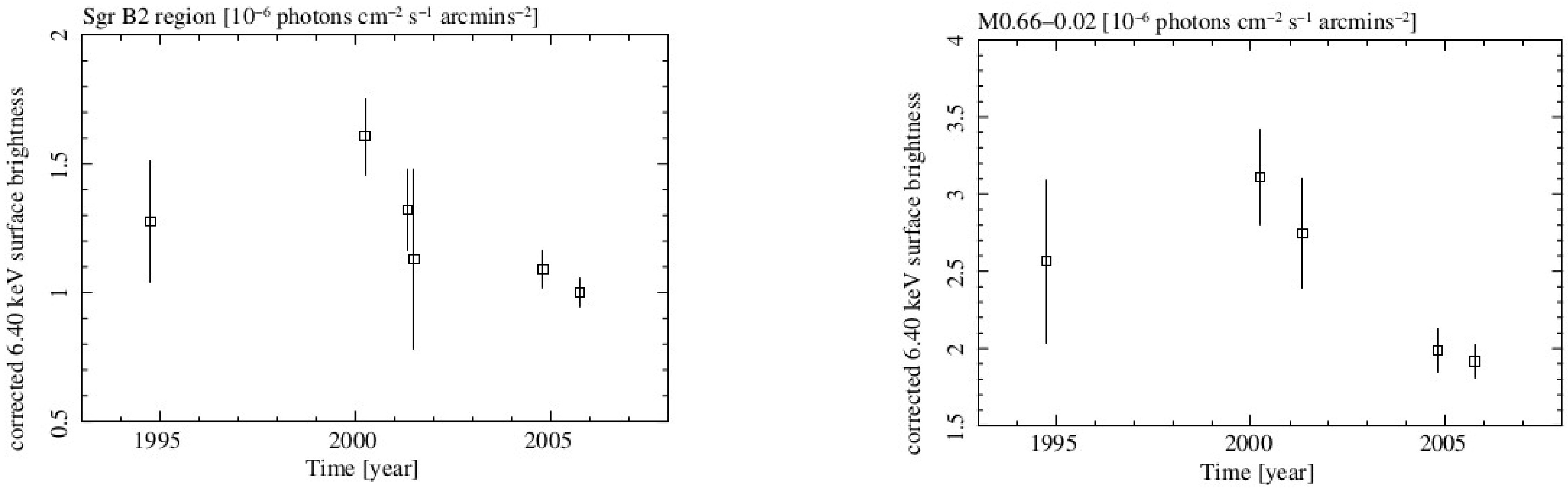
Weisskopf et al. (2008)

An observational challenge

Several molecular clouds present a temporal decay of their Fe Kα emission

Koyama et al. (2008), Inui et al. (2009), Terrier et al. (2010)

Flux diminution is consistent with the reflection mechanism … we have to hurry !



Inui et al. (2008)

Conclusions

X-ray polarimetry can probe the complex environment of the GC
+ it can prove or reject the AGN history of Sgr A*

The 3D localisation of the reflection nebulae with respect to Sgr A* can be fixed by measuring the degree of polarization
+ help to define the correct light-curve of its flare

Hard X-ray polarimetry more suitable for polarization measurement
2 – 8 keV observation possible if the GC plasma emission is taken into account

Polarization imaging is the strength of a future mission such as IXPE

X-ray polarization may distinguish between the two scenarios explaining the power-law continuum and the 6.4 keV iron feature (flaring / low-energy CR electrons)

Supplementary material

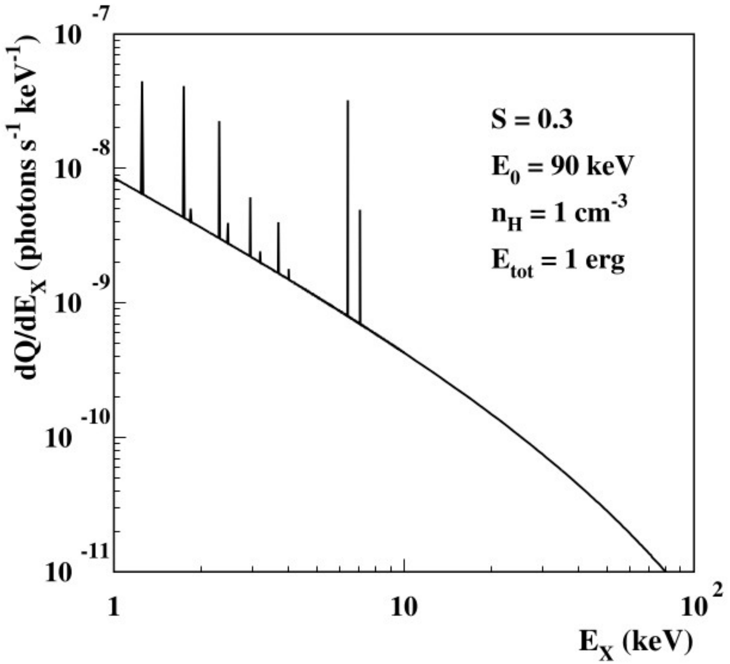


FIG. 1.—Nonthermal X-ray emission produced by LECRe with $S = 0.3$ and $E_0 = 90$ keV (eq. [3]) interacting in a neutral ambient medium of solar composition. The differential X-ray production rate is normalized to an average ambient H density of 1 atom cm^{-3} and a total electron kinetic energy of 1 erg.

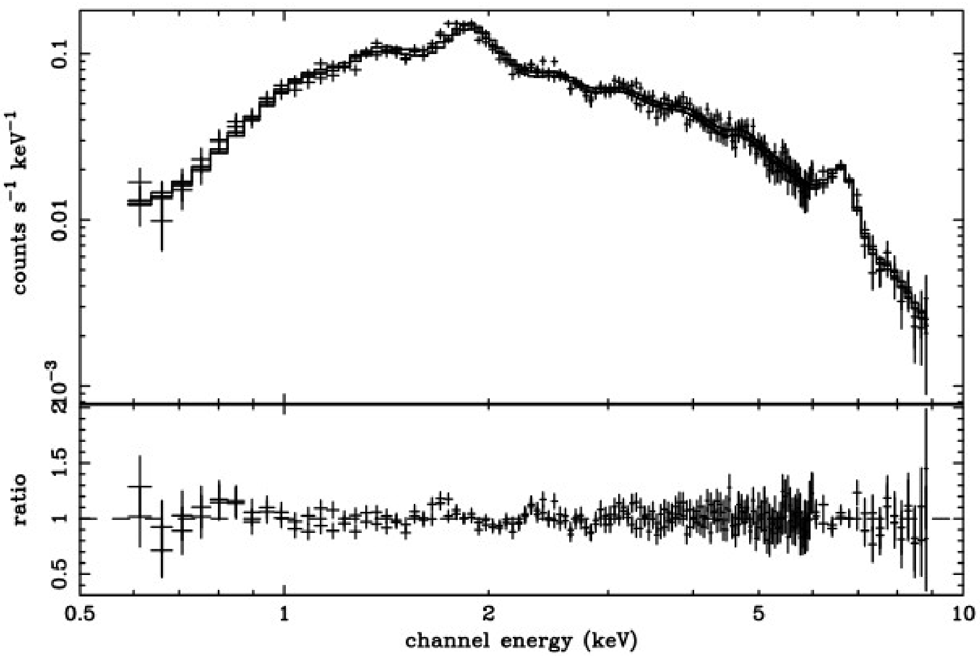


FIG. 3*a*

Valinia et al. (2000)

Low-energy cosmic ray electrons scenario

Supplementary material

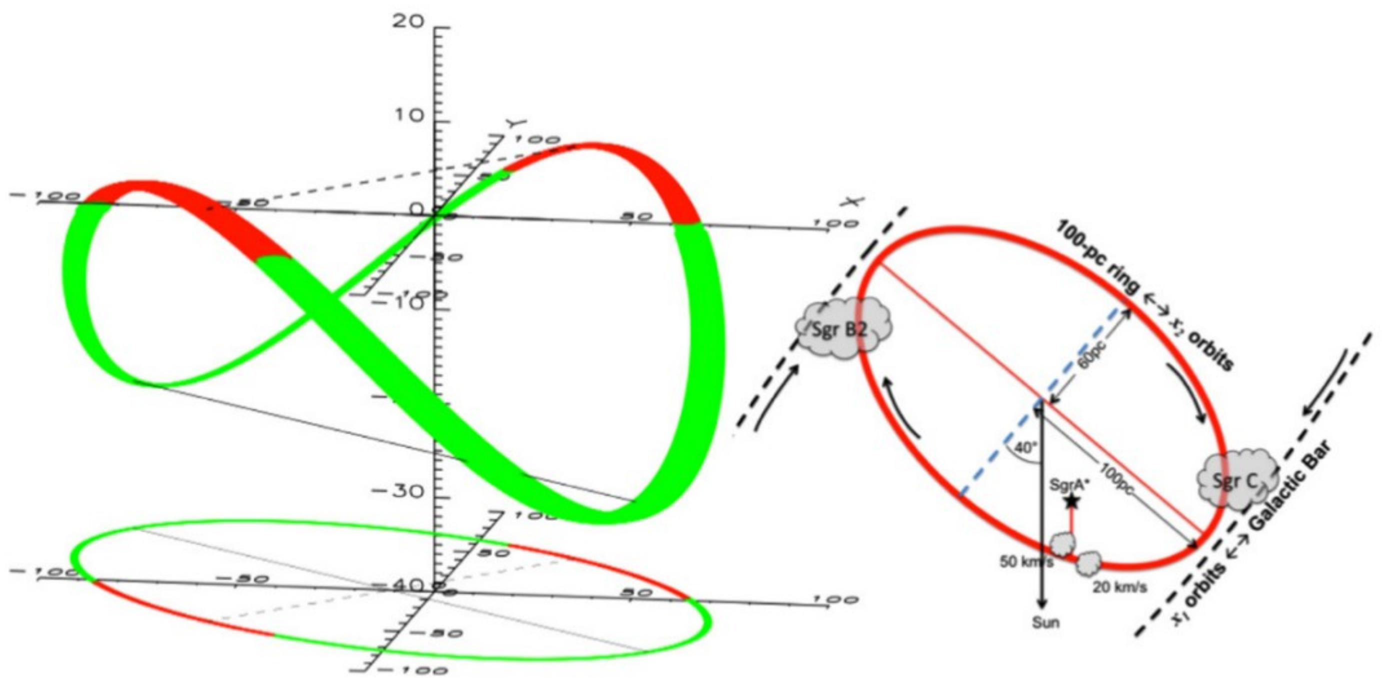
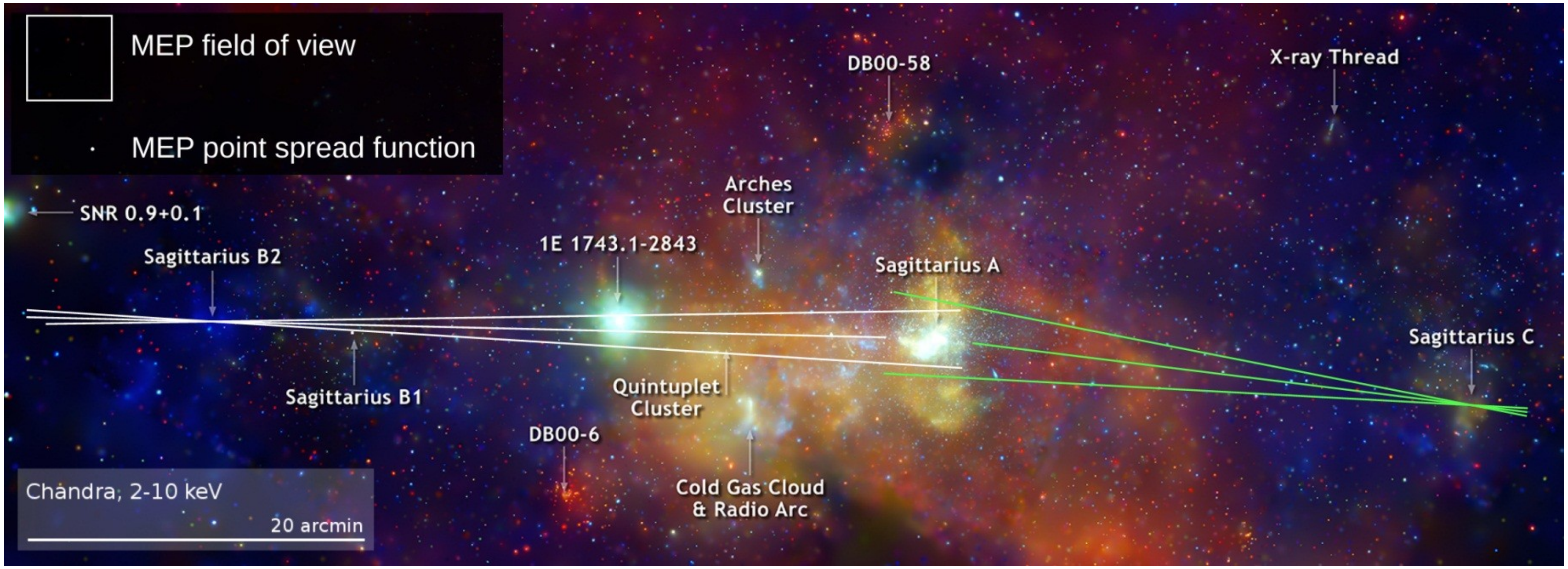


Figure 5. Sketch of the proposed three-dimensional structure and placement of the 100 pc ring. Left panel: the ring is represented by the thick color line (red and green mark positions above and below $b = 0°$). The line of sight to the Sun is along the *Y*-axes. The thin full and dashed lines represent the major and minor axes of the ellipse. Right panel: top view of the 100 pc ring with the proposed location of major clouds. The thick black dashed lines represent the innermost x_1 orbits. The position of Sgr A* along the line of sight is the one corresponding to the distance it should have from the front portion of the 100 pc ring to justify the velocity difference between the 20 and 50 km s^{-1} clouds if due to the gravitational pull of the mass concentration around Sgr A⋆ (see the text).

Molinari et al. (2011)

Supplementary material



The precision with which the measurement of the angle of polarization pinpoints the source of the primary emission

From P. Soffitta's 2013 talk at Granada meeting