The Past High Activity of the Galactic Center and the 511 keV Annihilation Line Emission

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511 keV Positron line from GC/bulge

- extended spherical bulge with ~8 deg FWHM (~1.1 kpc)
- bulge / disk ratio = 3-9 (c.f. mass ratio 0.3-1.0, Robin+'03)
- positron production rate ~1.5×10^{43} s^{-1}
- No good explanations
  - bulge → not by young stars
  - SN Ia → not sufficient rate
  - MeV mass dark matter annihilation?

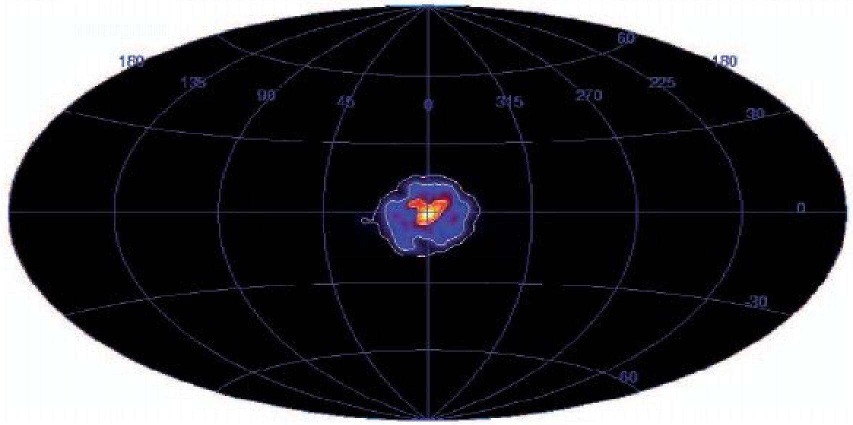


Fig. 4. Richardson-Lucy image of 511 keV gamma-ray line emi and 10^{-4} ph cm^{-2} s^{-1} sr^{-1} (from the centre outwards).

Knodlseder et al. 2005

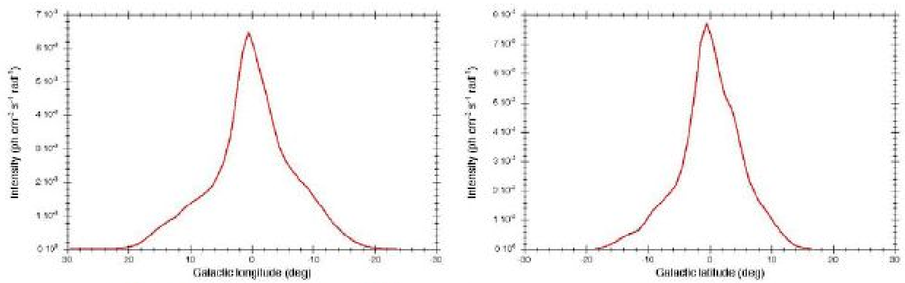


Fig. 5. Longitude and latitude profiles of the image shown in Fig. 4 (integration range $|l| \leq 30°$, $|b| \leq 30°$).

Outline

- Can Sgr A* be the origin of the 511 keV line?
  - Not by the currently observed accretion rate
  - Sgr A*'s accretion rate is extremely low

- However, there are some evidences for a much higher accretion rate in the past
  - X-ray reflection nebulae, mass outflow, …

- My bottom line:
  - Typical accretion rate of Sgr A* is much higher than observed now
    - 511 keV line can be explained by such a high rate
    - Such a high rate is theoretically reasonable
  - Sgr A* is currently in a special time with low accretion rate
    - Reason: SNR Sgr A East!

The RIAF Model for Sgr A*

- Radiatively Inefficient Accretion Flow (RIAF):
  - A generalized concept from ADAF
  - successfully applied to many low Eddington ratio BH systems

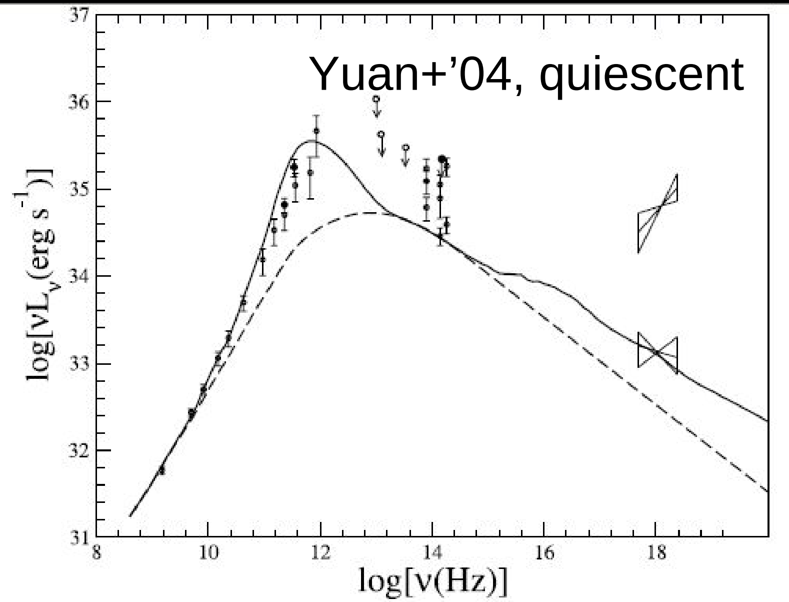


FIG. 1.—RIAF model for the quiescent state of Sgr A*. The IR data with error bars are from Ghez et al. (2004) and Genzel et al. (2003), the radio data with error bars from Falcke et al. (1998, *open circles*) and Zhao et al. (2003, *filled circles*), the IR data with upper limits from Serabyn et al. (1997, *open circles*) and Hornstein et al. (2002, *filled circles*), and the two "bow ties" in the X-ray for the quiescent (*lower*) and flaring (*higher*) states from Baganoff et al. (2003, 2001). The dashed line shows the synchrotron emission by power-law electrons with $p = 3$. The solid line shows the total quiescent emission, including that from thermal electrons. The slight difference in the value of p compared with that in YQN03 ($p = 3.5$) is to fit the quiescent IR data better.

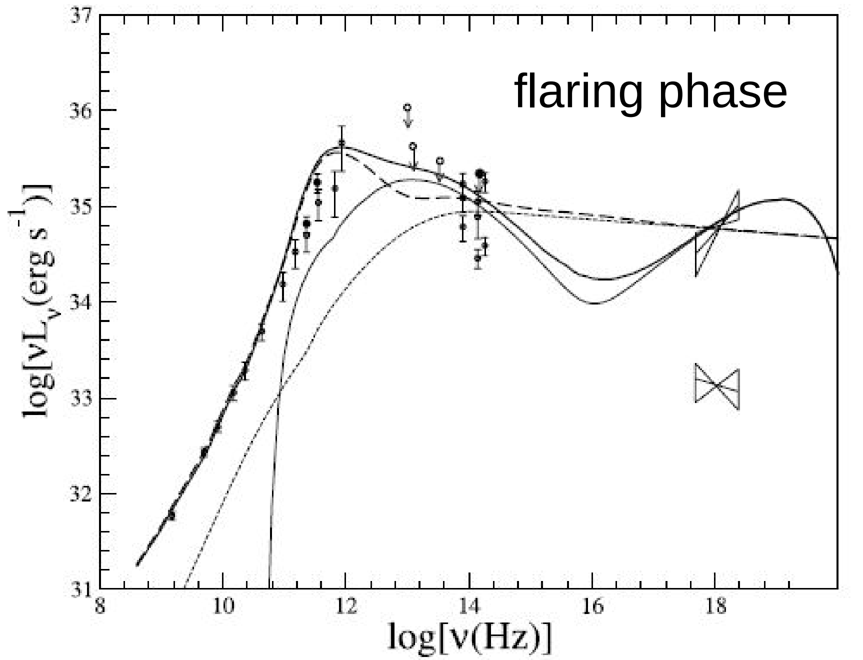


FIG. 3.—Pure synchrotron models for the IR and X-ray flares in Sgr A*. The two dashed lines are models in which the electrons are assumed to have $p = 2.1$. The solid lines are for the broken power-law model (eq. [1]), with $p_1 = 3$, $p_2 = 1$, $\eta = 7\%$, $\gamma_{max} \sim 10^6$, and $\eta_{IRX} = 1$. In each case, the thin lines correspond to the emission from only the power-law electrons, and the thick lines to the total emission, including the thermal electrons.

Properties of the RIAF Model for Sgr A*

- Outer boundary at Bondi radius from X-ray observation
  - quiescent X-ray emission spatially resolved by Chandra (~2"~0.03 pc)
  - Bondi accretion rate ~10^{-6} M_{sun} / yr

$$\dot{M} \propto r^s, \quad s = 0.27$$

$$n_e \propto r^{-3/2+s}$$

- Non-conserving mass accretion flow
  - necessary to evade the constraint from Faraday rotation observations

- It predicts outflow
  - non-conserving mass accretion rate → outflow
  - ADIOS (Blandford & Begelman '99)

Outflow from region around $r \sim r_s$

$$\text{mass outflow rate} : \sim \frac{d\dot{M}}{dr} r \sim 1.6\times10^{-8} M_{sun} / yr$$

$$\text{kinetic luminosity} : \sim \upsilon_{esc}^2 \frac{d\dot{M}}{dr} r \sim 3\times10^{38}\,\text{erg/s}$$

The RIAF Scaling Laws

X - ray luminosity :

$$L_X \propto \dot{m}^{\alpha}, \quad \alpha \sim 2$$

Mass outflow / kinetic luminosity

$$L_{\rm kin} \propto \dot{m}$$

- can we explain various evidences for past high activity of Sgr A* by this scaling?

boost factor

$$f_B \equiv \dot{M}_{past} / \dot{M}_{now}$$

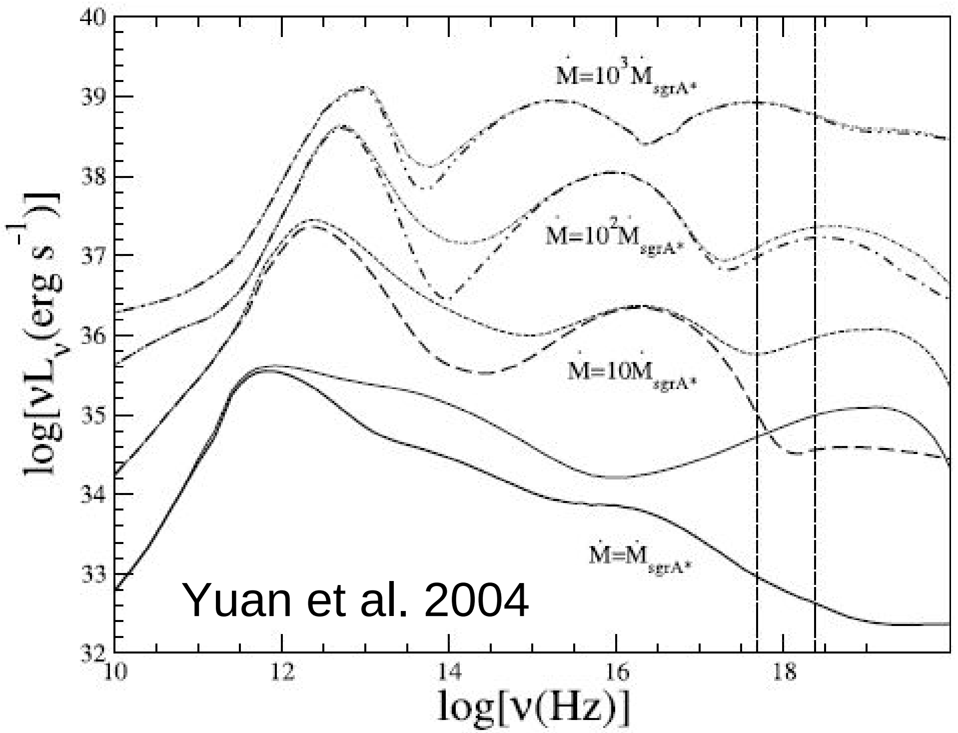
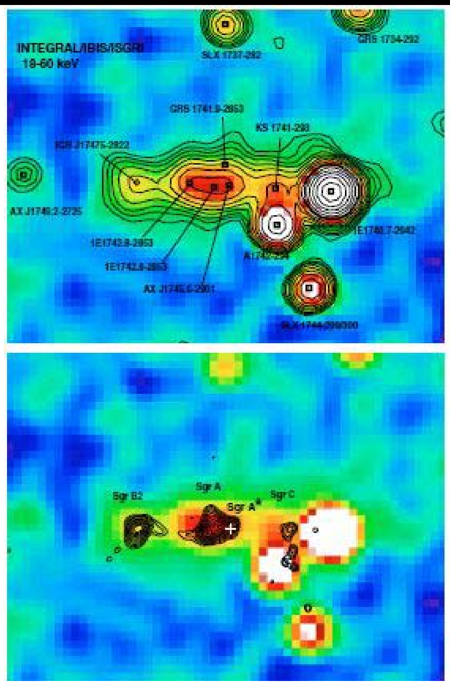
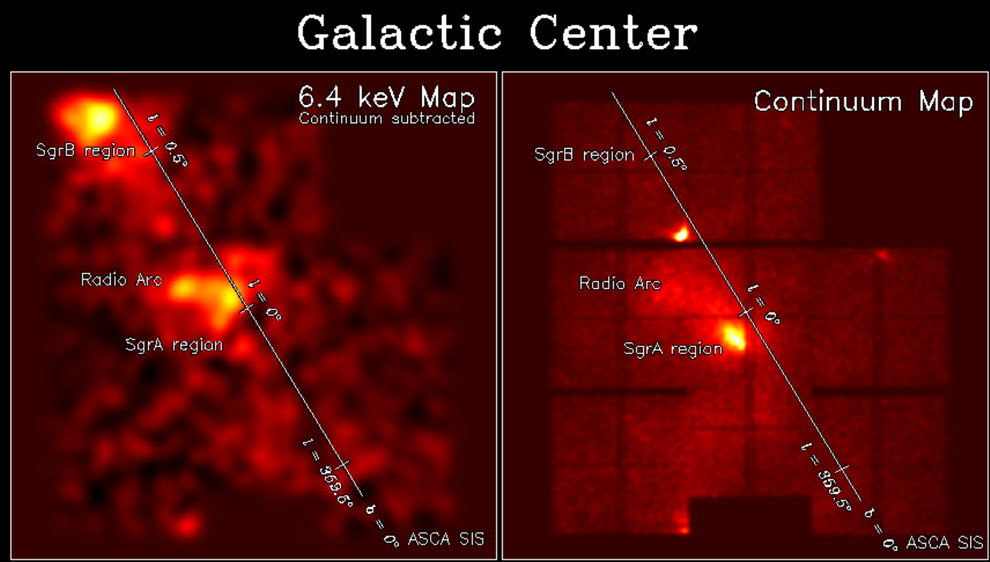


FIG. 5.—Quiescent (*thick lines*) and flaring (*thin lines*) spectra for different accretion rates. The solid lines correspond to the broken power-law synchrotron model of Sgr A* shown in Fig. 3. The dashed, dot-dashed, and double-dot–dashed lines are for systems with accretion rates of 10, 100, and 1000 times the rate in Sgr A*, respectively. For more luminous systems (higher $\dot{M}$), the SSC emission from thermal electrons increases substantially. As a result, the emission from flares would be much more difficult to detect.

Evidence for Brighter Past L_X of Sgr A*

- X-ray reflection nebulae indicate that Sgr A* was much brighter ($L_X \sim 10^{39-40}$ erg/s) ~300 yrs ago
  - Now: $L_X \sim 10^{33}$ (quiescent) to10^{34-35} erg (flaring)
  - Koyama et al. (1996), Murakami et al. (2000), Revnivtsev et al. 2004), Koyama et al. (2007)
- boost factor $f_B \sim 10^{3-4}$ required for Yuan+ '04 model
  - still in RIAF regime ($L_X \sim 4 \times 10^{39}$ erg/s ~ 10^{-5} L_{Edd})

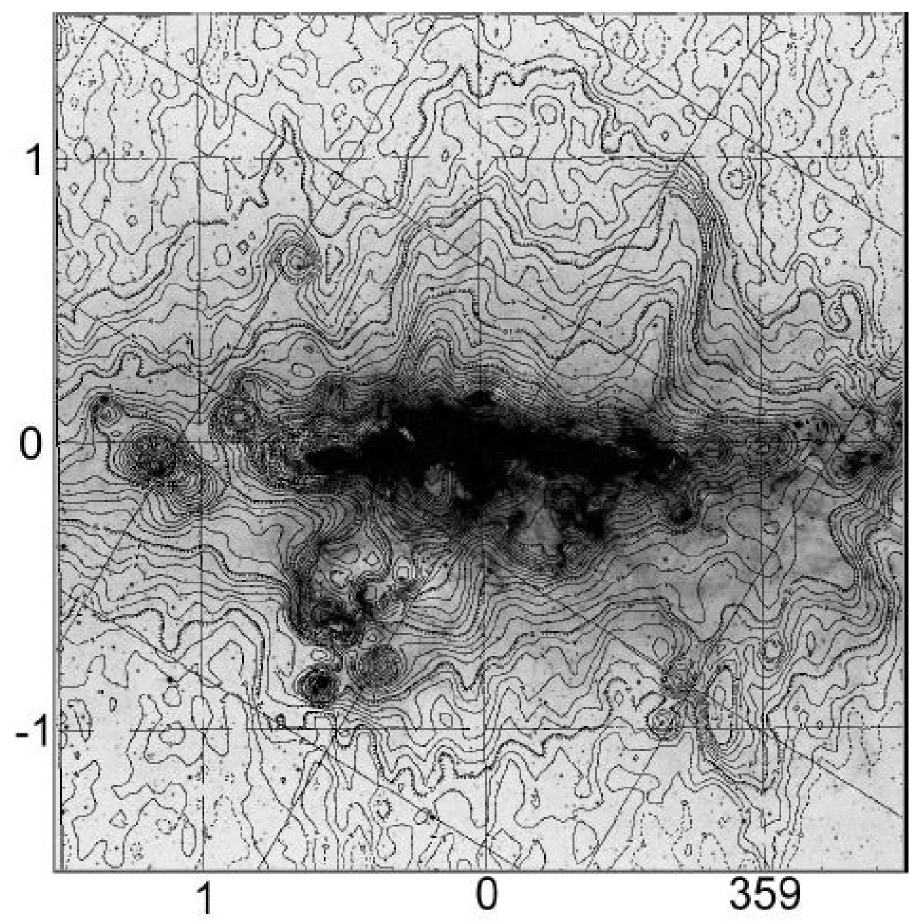




Evidence for Mass Outflow from GC:
I. Galactic Center Lobe (GCL)

- mass outflow inferred from radio and infrared obs.:
  - a few degree ~ 300 pc
  - ~100 km/s
  - $\sim 10^{55}$ erg
  - time scale: $\sim 10^{6}$ yrs

  - Sofue & Handa1984
  - Sofue 1985
  - Bland-Hawthorn & Cohen ’04



Bland-Hawthorn & Cohen ’03
Image: MSX 8.3 um (dust)
Contour: 3 cm (thermal)

Evidence for Mass Outflow from GC: II. Expanding Molecular Ring (EMR)

- expanding molecular clouds (Kaifu et al. ‘72; Scoville ’72;...)
  - R~300 km/s
  - V~100 km/s
  - E ~ 2x10^{55} erg
  - time scale ~10^6 yrs

Scoville 1972

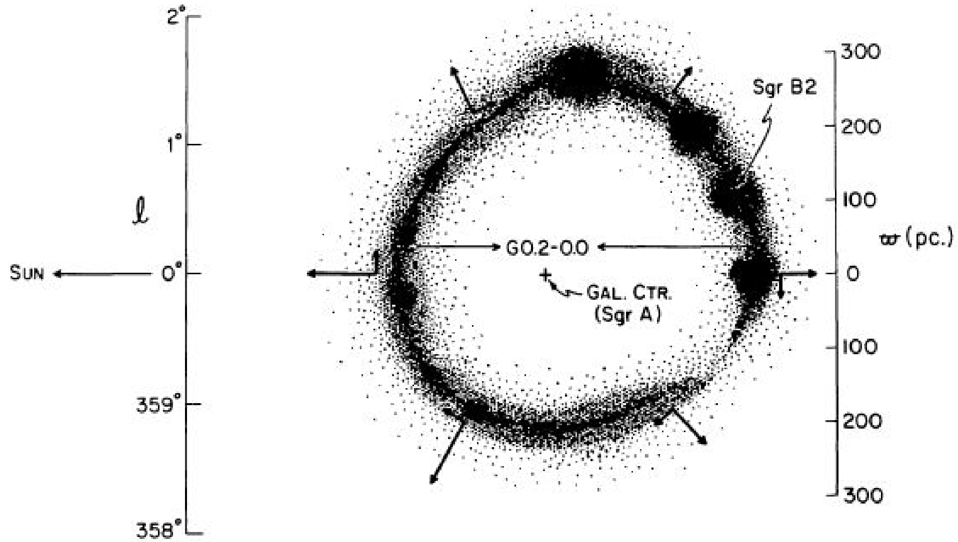


FIG. 2.—Sketch of rotating molecular ring near the galactic center as seen from above the galactic plane. Here the ring is taken to be expanding, although as discussed in the text, contraction cannot be ruled out. The suggested locations of continuum sources relative to ring are included; the label Sgr A refers only to the nonthermal component at $l = 0^\circ.0$, $b = -0^\circ.0$.

Outflow and the RIAF Model of Sgr A*

- All evidences indicate L_{kin} ~ 10^{42} erg/s
  - corresponding to f_B ~ $10^{3\text{-}4}$, consistent with what required for X-ray reflection nebulae
  - time scale of the high activity >~ $10^{6\text{-}7}$ yr

- starburst activity rather than SMBH?
  - ~0.01 SN / yr assuming 10^{51} erg per one SN
  - almost comparable with the total Galactic SN rate 0.019±0.011 /yr (Diehl et al. '06)
  - No evidence for such nuclear starburst from ^{26}Al gamma-ray observation

Positron Production from the RIAF model of Sgr A*

- production processes in accretion flow:
  - $e^- e^- \rightarrow e^- e^- e^- e^+$
  - $e^- \gamma \rightarrow e^- e^- e^+$
  - $\gamma \gamma \rightarrow e^- e^+$
- ejection by outflow
- predicted positron production rate is close to what required from observations (~10^{43} /s) when $f_B \sim 10^{3\text{-}4}$
- high bulge/disk ratio naturally explained
- injection positron energy and propagation distance consistent with observations
- time scale of the high activity must be >~10^7 yr
  - from positron annihilation time scale in ISM

A Good Hypothesis

- typical (mean) accretion rate of Sgr A* in the past ~10^7 yrs has been 10^{3-4} times higher than the currently observed rate

  - X-ray reflection nebulae
  - Outflow evidence
  - 511 keV line emission

Why Sgr A* Currently So Dim?

- SNR Sgr A East shell seems to have overrun Sgr A* about a few hundreds years ago (Maeda+ ’02)
- Sgr A East is energetic enough to destroy the former accretion flow with $f_B \sim 10^{3-4}$
  - suppress the current accretion rate
- The RIAF model with $f_B \sim 10^{3-4}$ is naturally connected to the ambient medium (ionized gas) at r ~ 1 pc (gravitationally effective radius of SMBH)
  - time scale of >~10^7 yr is possible
  - A natural time scale for AGN activity

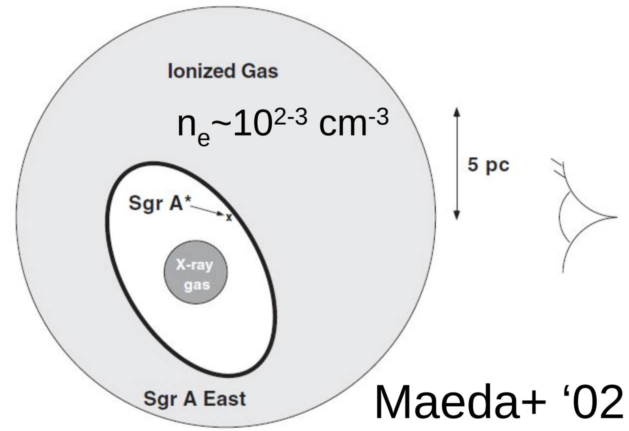


FIG. 9.—Schematic diagram of the relative positions and sizes of Sgr A*, Sgr A East, and the ionized gas halo along the line of sight from the Sun with the positive Galactic longitude (east) at the bottom. The ionized gas halo of 10^3 cm^{-3} is rotating around Sgr A* and is filling the non–solid-body rotation region. An SNR, Sgr A East, was expanding into the ionized gas halo, and the radio structure associated with the slow forward shock was sheared by the Galactic rotation. The hot ejecta plasma is centrally concentrated within the Sgr A East radio shell and is visible in X-rays. Sgr A* was hit by the front edge of the Sgr A East shell in the recent past and is currently in the hot cavity inside of the shell.

Is Sgr A* special as an AGN?

- Is the increased luminosity (L_X~10^{39} erg/s) especially bright?
  - No!
  - Nuclei of L_X~10^{39-40} erg/s are quite often found in nearby normal galaxies (e.g., Ho 2004)
    - Current Sgr A* accretion rate is rather surprisingly low!
- Are we living in a special time of low accretion?
  - Yes!
  - Sgr A* is on the edge of Sgr A East shell
  - ~100 OB stars in r<1pc (Paumard+ ’06) → SN rate ~1.7×10^{-5} /yr
    - chance probability of witnessing Sgr A* just 300 yrs after a SNR shell passage is ~1% ... not extraordinarily small

Conclusions

- The mean accretion rate of Sgr A* in the past 10^7 yr is likely to be higher than the current rate by a factor of $\sim 10^{3\text{-}4}$
  - past high X-ray luminosity (from X-ray reflection nebulae)
  - Mass outflow (from GCL, EMR, …)
  - bulge 511 keV line emission

- the high activity is physically natural in the GC environment

- the current low rate is due to the interaction with SNR Sgr A East

- See TT 2006, PASJ, 58, 965 (astro-ph/0607414) for details