銀河系中心の過去の活動性
～フェルミバブルに関連して～

戸谷　友則 (CTA Japan X-PI)

（京大・理・宇宙物理）

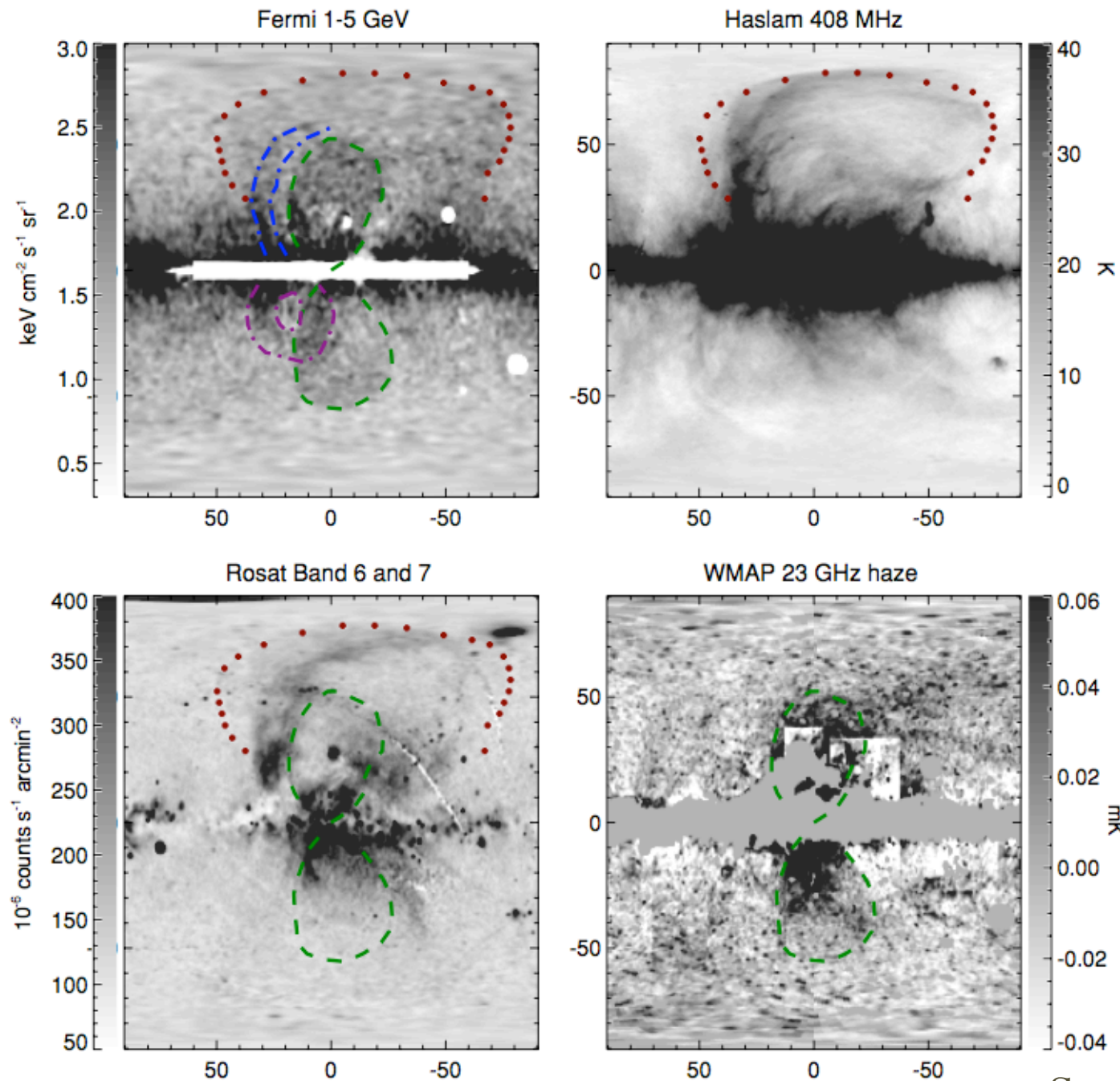CTA 国内研究会　平成２３年９月３０日　東大宇宙線研

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The Fermi Bubble

- Dobler+'10; Su+'10

- bipolar bubble around GC in Fermi gamma-ray map
  - sharp edge
  - uniform within the bubble

- features coincident with other wavelength
  - radio
  - X-ray
  - WMAP haze
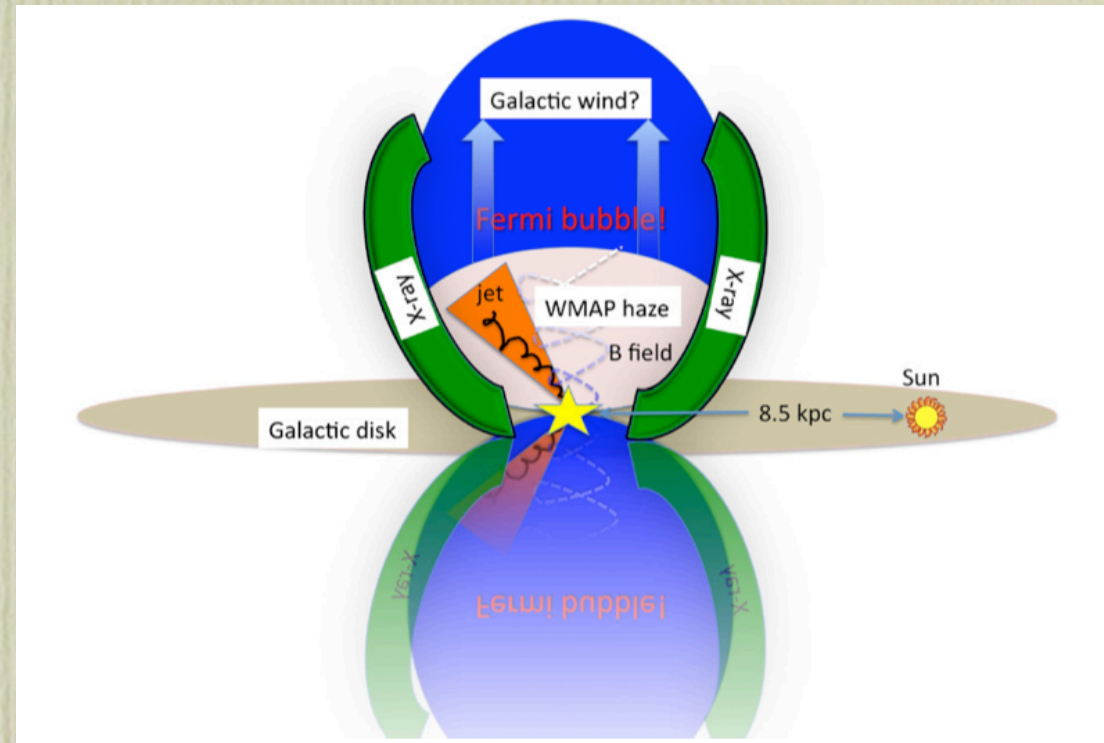
Su+'10

Fermi bubble physical parameters

- hard spectrum

  - consistent with IC emission by the same electrons responsible for WMAP haze

- total gamma-ray power:

  - 4.0×10^{37} erg/s (1-100 GeV)

  - 1.2×10^{52} erg for 10^7 yr

- kinetic energy of bubble

  - X-ray data: 10^{-2} cm^{-3}, ~2 keV

  - size ~ 10 kpc

  - E ~ 10^{55} erg

  - age ~ 10^7 yr for v~10^3 km/s
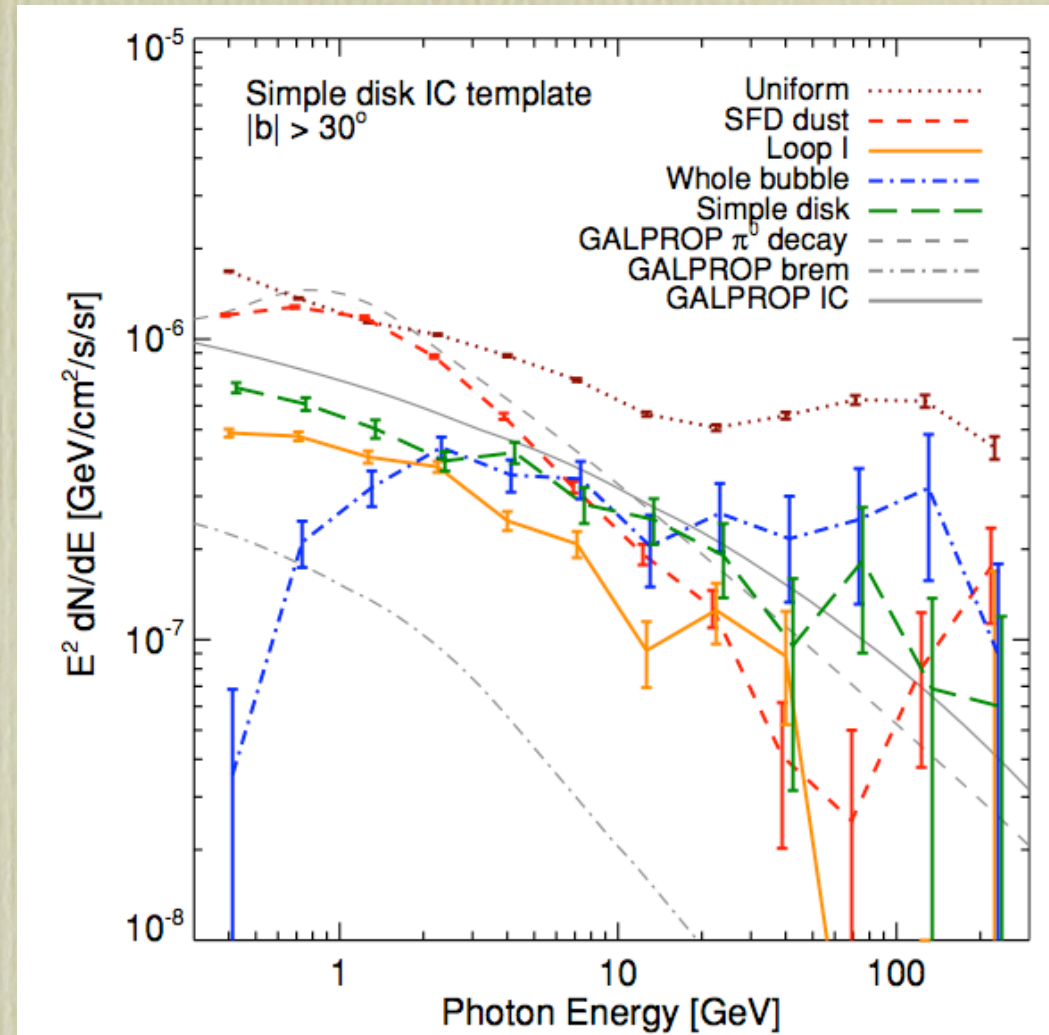
Su+'10

Fermi bubble: Interpretation?

- bubble energy source?
  - AGN (SMBH) ○?
    - evidence of past activities in other wavebands
  - nuclear starburst △?
    - no Hα emission
    - no ^{26}Al gamma-ray excess (Totani '06)
  - dark matter annihilation ×?
    - sharp edge
    - hot X-ray gas

Su+'10

銀河系中心の過去の活動性の兆候

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- Higher X-ray Luminosity

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- Outflows on various scales

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- 恐るべし　日本の貢献

Evidence for Brighter X-ray Luminosity of Sgr A*

- 巨大分子雲 Sgr B からの中性鉄輝線は、銀河中心からの放射の反射成分と考えられる

- 300 yr ほど前までは、Sgr A* の X線光度が ~3×10^{39} erg/s で輝いていたと考えると説明できる (Koyama+'96; Murakami+'00)

  - 現在のX線光度の $10^{5\text{-}6}$ 倍
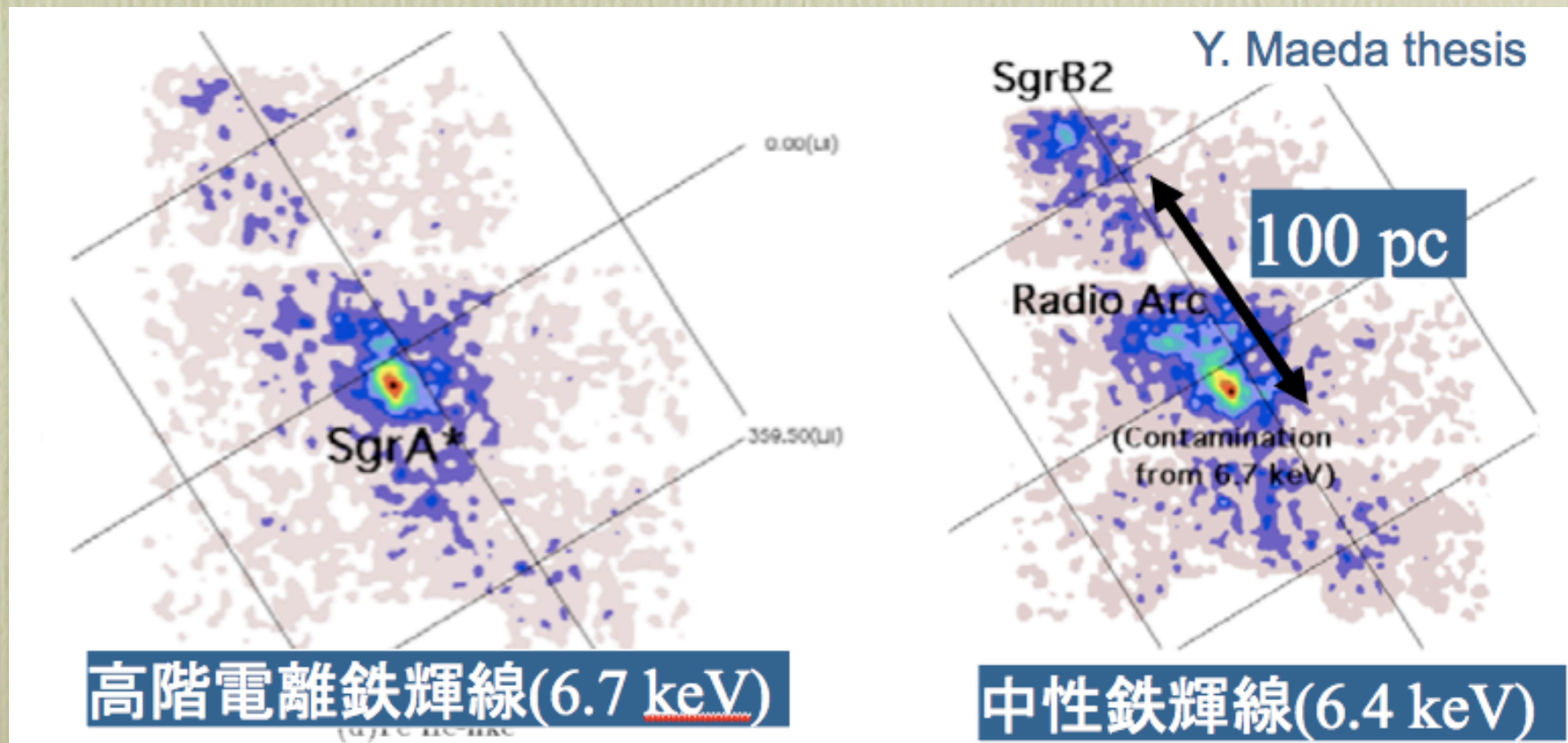
Evidence for Brighter X-ray Luminosity of Sgr A*
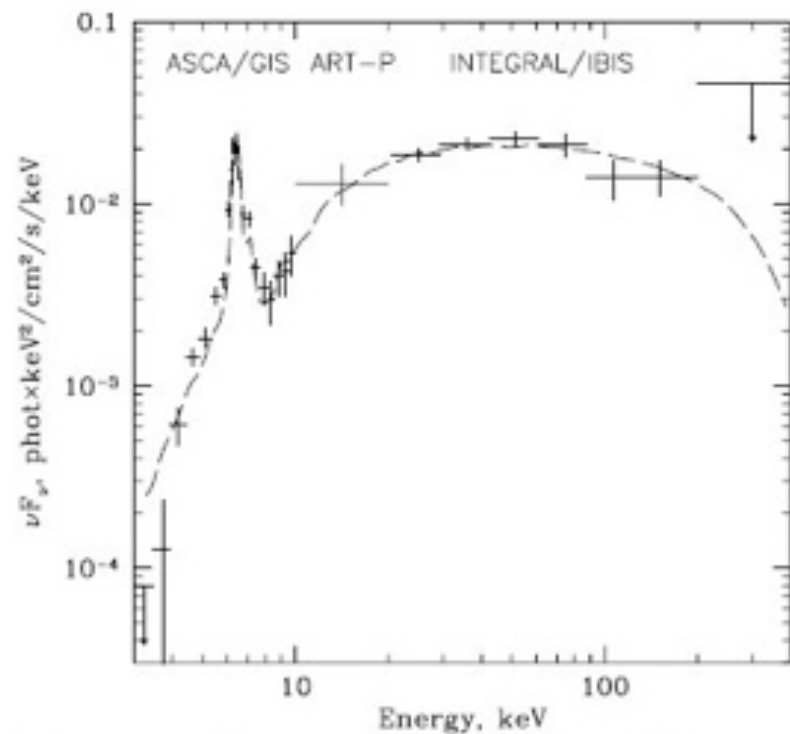
- INTEGRAL でも確認 (Revnivtsev+'04)
- すざくでもより精密に検証

Fig. 2. Broad band X-ray spectrum of the source IGR J17475–2822 associated with the Sgr B2 cloud. Data of ASCA/GIS (3–10 keV), GRANAT/ART-P (10–20 keV) and INTEGRAL/IBIS (20–400 keV) are presented. 1σ error bars and 2σ upper limits are shown. The dashed line is the best-fit model (see main text) convolved with the resolution of ASCA/GIS ($\sigma \approx 230$ eV).
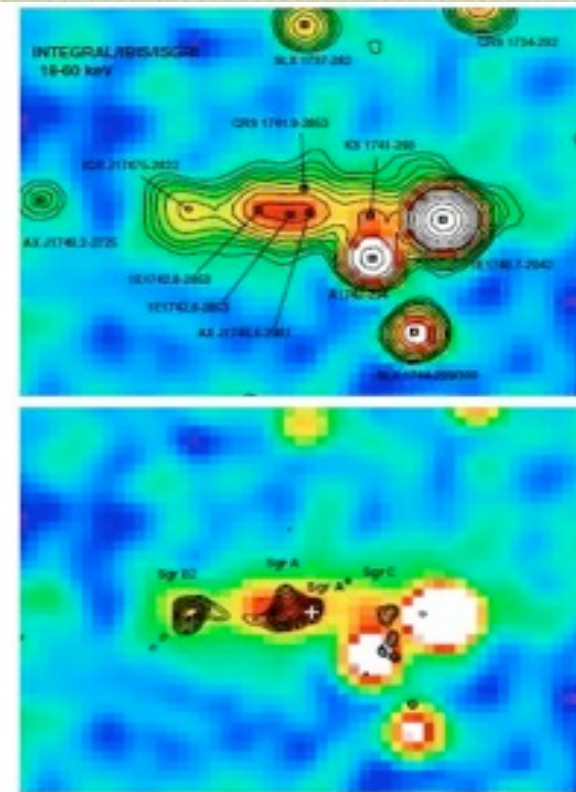

Fig. 1. Upper panel: $3.5° \times 2.5°$ hard X-ray (18–60 keV) image of the GC region obtained with INTEGRAL/IBIS. Contours denote levels of the signal to noise ratio, which start from S/N = 5.0 and increase with a multiplicative factor of 1.4. Detected known X-ray sources are indicated (see Revnivtsev et al. 2004a for details). Lower panel: The same IBIS color image, with overplotted contours of brightness distribution in the 6.4 keV line as measured by ASCA/GIS. Largest molecular clouds are indicated and the position of the Sgr A* source is marked with a cross.

Evidence for a Large Scale Outflow from GC

- estimated massive outflow energy: 10^{55} erg in ~10^6 yrs on the scale of the Galactic center lobe (GCL)

  - ~100 km/s

  - a few degree ~ 300 pc

  - Bland-Hawthorn & Cohen '04

- Kinetic luminosity ~ $10^{41\text{-}42}$ erg/s
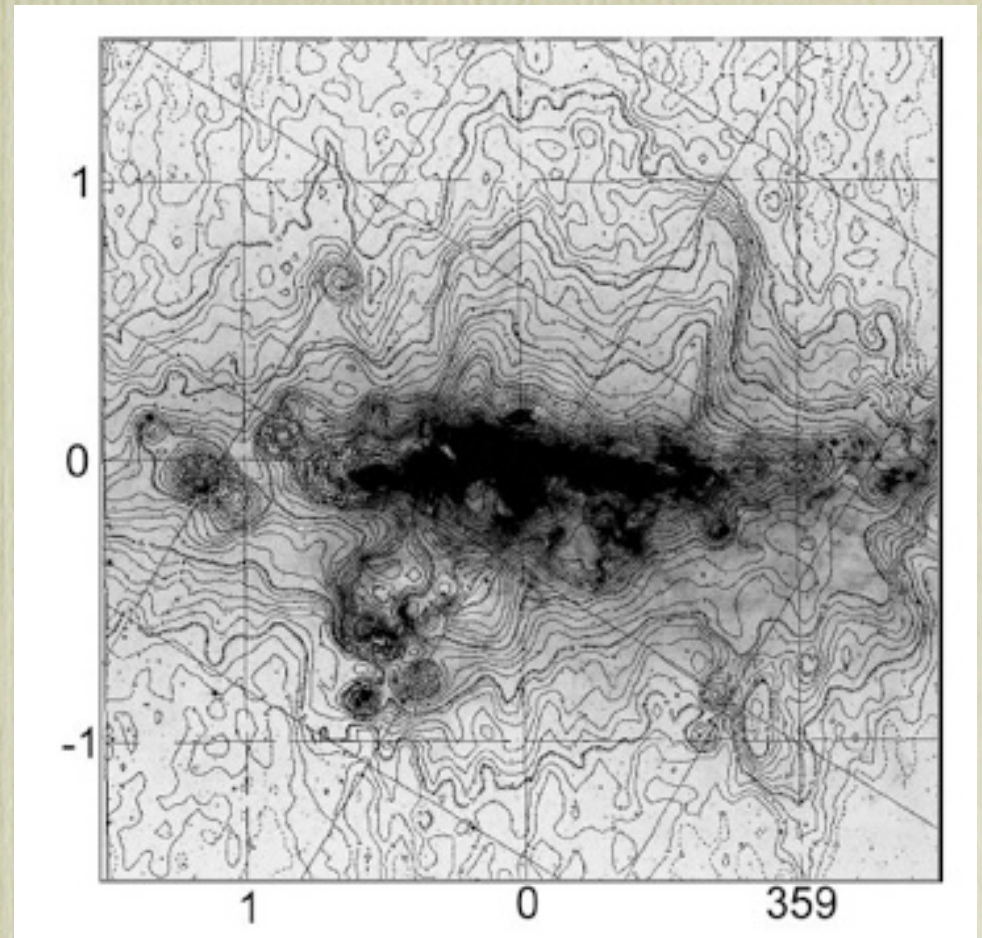
Bland-Hawthorn & Cohen '03
Image: MSX 8.3 um (dust)
Contour: 3 cm (thermal)

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

- expanding molecular clouds (Kaifu et al. '72; Scoville '72;...)
  - $E \sim 2 \times 10^{55}$ erg
  - $V \sim 100$ km/s
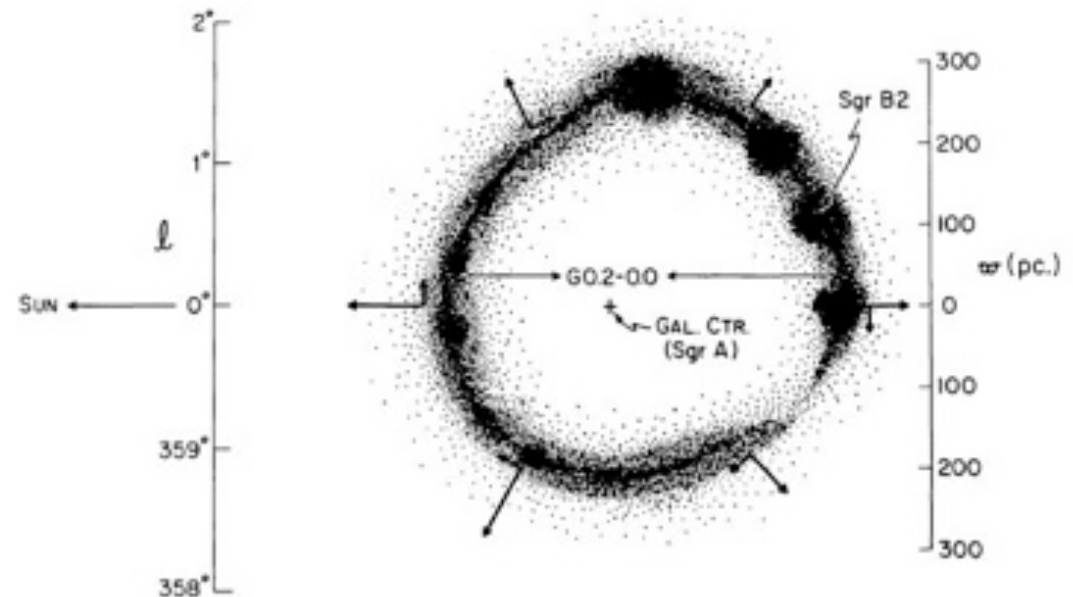 - $R \sim 300$ pc
  - time scale $\sim 10^6$ yrs

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 $l = 0°0$, $b = -0°0$.

Scoville 1972

Evidence for Mass Outflow from GC:
III. North Polar Spur (NPS) and/or Bulge X-Ray

- NPS (Loop I) / Bulge X-ray emission can be interpreted as mass outflow from GC: (Sofue '00; Bland-Hawthorn & Cohen '03)

  - $E \sim 10^{56}$ erg

  - Scale ~ 20 deg ~ 1 kpc

  - time scale $\sim 10^7$ yrs

  - Kinetic luminosity ~ $10^{41\text{-}42}$ erg/s

- But: many papers claiming that NPS is local nearby SNR
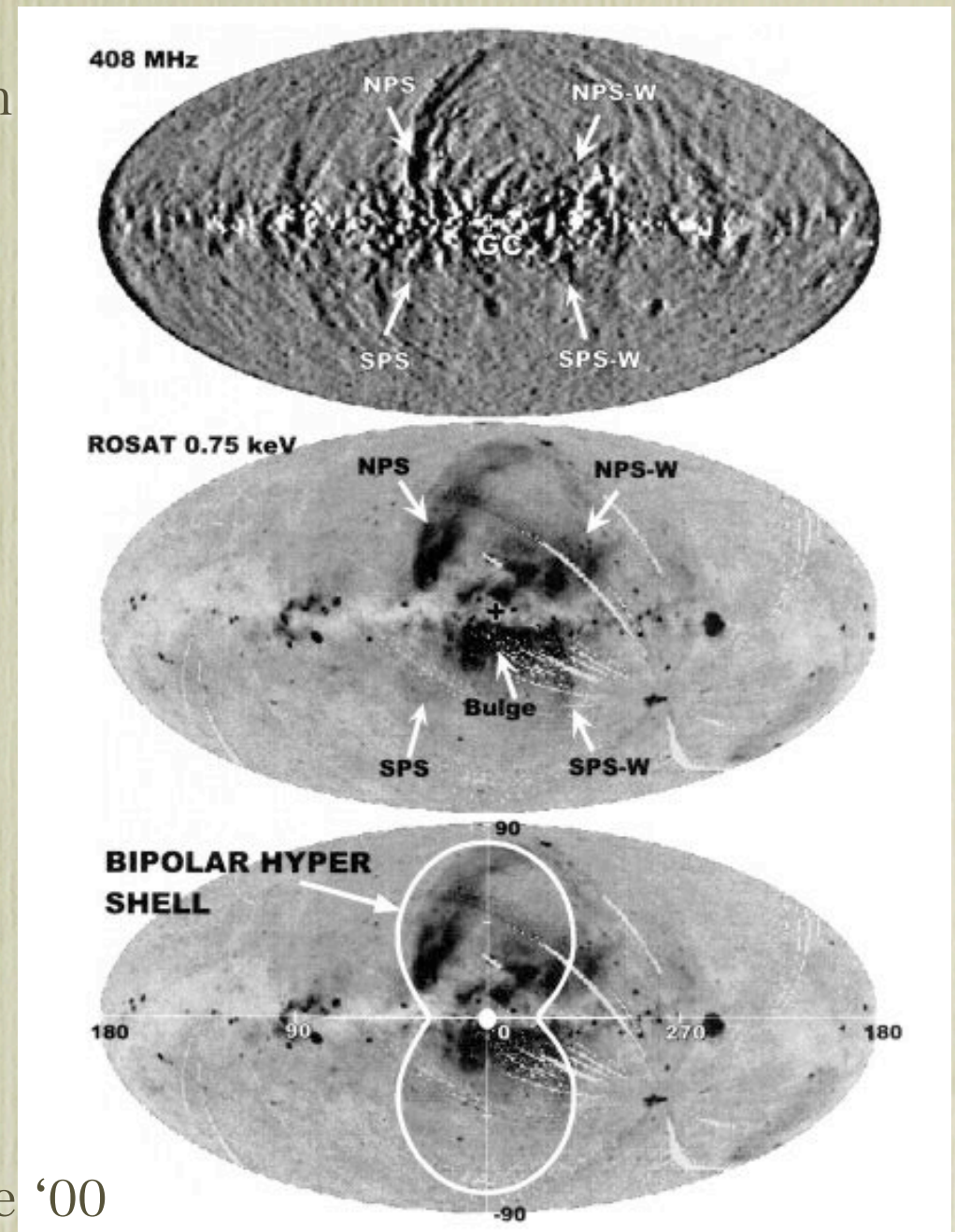
Sofue '00

The 511 keV Annihilation Line Emission from GC

- extended spherical bulge with ~8 deg FWHM (~1.1 kpc) + weak disk component (Knodlseder et al. 2005)

- bulge / disk flux ratio = 3-9 (c.f. mass ratio 0.3-1.0, Robin+'03)
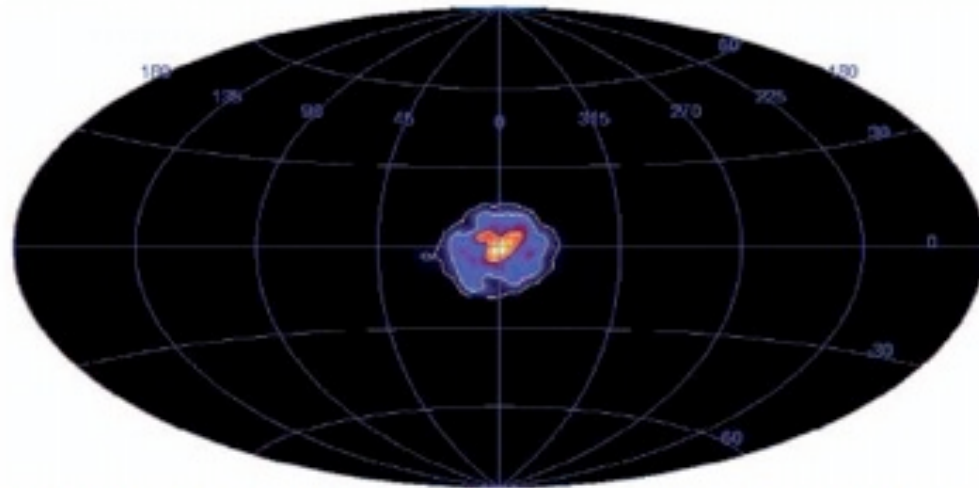
- positron production rate ~1.5×10^{43} s^{-1}

Fig. 4. Richardson-Lucy image of 511 keV gamma-ray line emission (iteration 17). Contour levels indicate intensity levels of 10^{-2}, 10 and 10^{-4} ph cm^{-2} s^{-1} sr^{-1} (from the centre outwards).
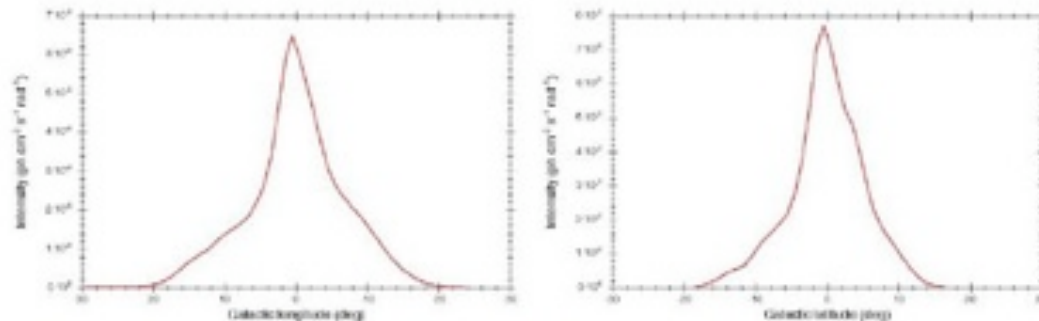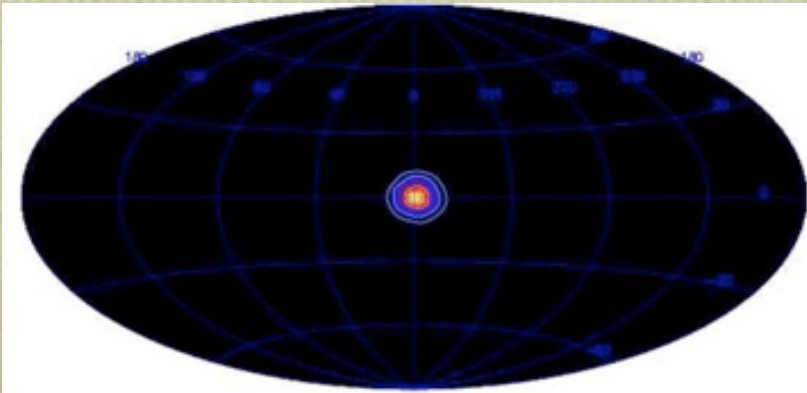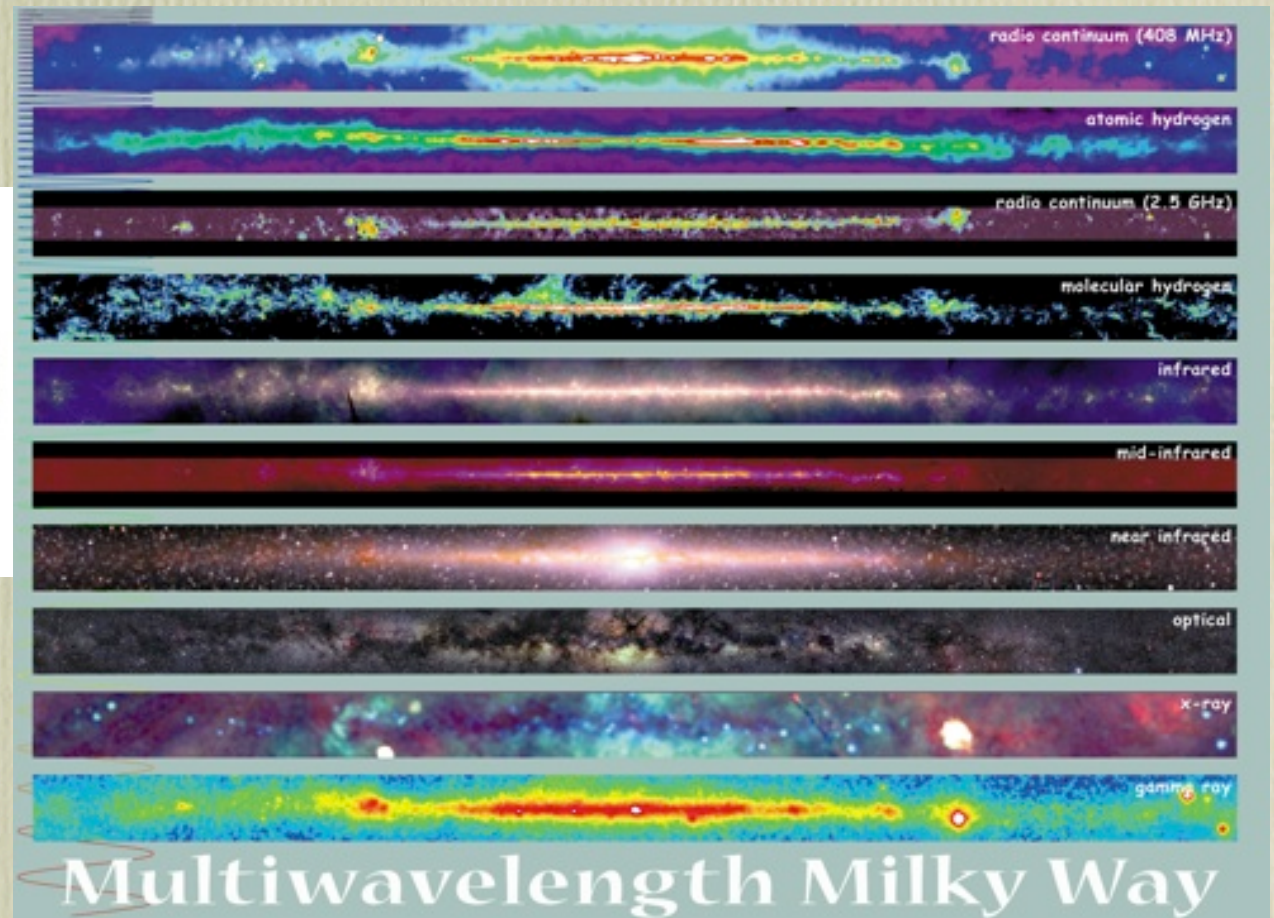
Fig. 5. Longitude and latitude profiles of the image shown in Fig. 4 (integration range $|l| \le 30°$, $|b| \le 30°$).

Knodlseder et al. 2005

A Unique Morphology!

Weidenspointner+ '06

the RIAF Model for Sgr A*

- radiatively inefficient accretion flow (RIAF)
  - Eddington ratio が小さいときのBH降着流の標準理論
- Application to Sgr A* (Yuan+ '03)
  - 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} Msun / yr
- Non-conserving mass accretion flow
  - Faraday rotation 観測からの制限を満たす上で必要

$$\dot{M} \propto r^s,\ s = 0.27$$
$$n_e \propto r^{-3/2+s}$$
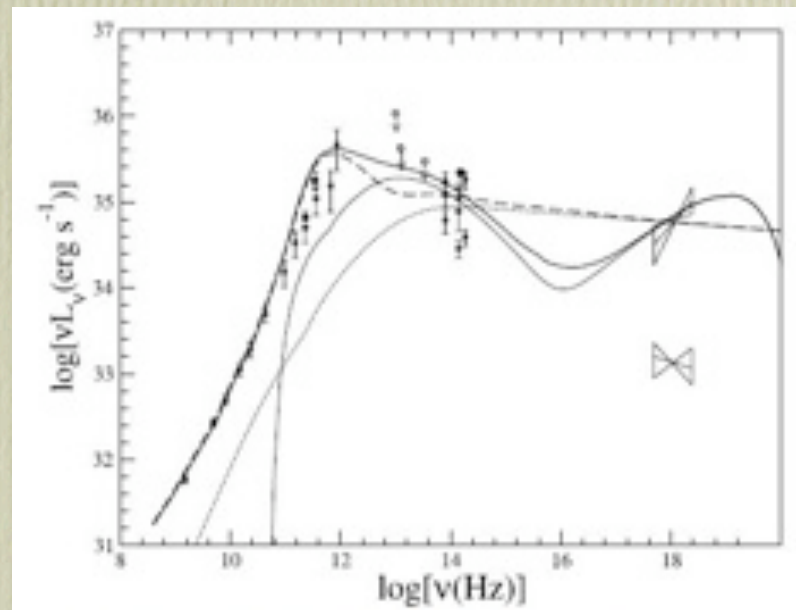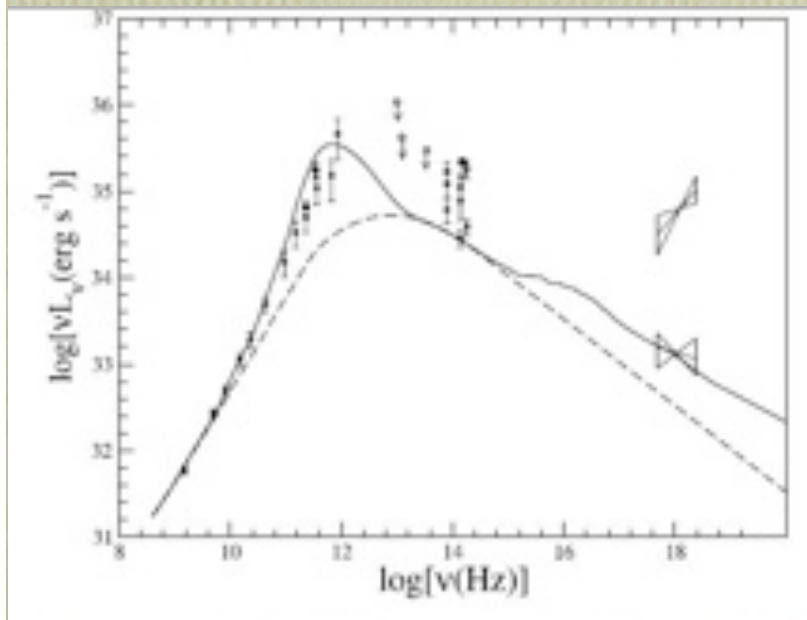
Yuan+ '04

RIAF model は mass outflow を予言する

- non-conserving mass accretion rate $\propto$ outflow
  - ADIOS: Blandford & Begelman '99

$$\dot{M} \propto r^s, \ s = 0.27$$
$$n_e \propto r^{-3/2+s}$$

Outflow from region around $r \sim r_s$

mass outflow rate $: \sim \dfrac{d\dot{M}}{dr} r \sim 1.6 \times 10^{-8} M_{sun} / yr$
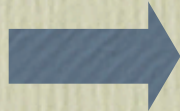
kinetic luminosity $: \sim \upsilon_{esc}^2 \dfrac{d\dot{M}}{dr} r \sim 3 \times 10^{38}$ erg/s

RIAF model for past higher activity of GC

- 現在の降着率より、10^3 倍程度高い降着率を考えると、過去の活動性の兆候が統一的に説明できる

  - X-ray reflection nebular (L_X が現在の10^6倍)

  - outflow on 0.3-3 kpc scale ($L_{kin} \sim 10^{41\text{-}42}$ erg/s)

  - （注：RIAF では、$L_X \propto (dM/dt)^2$, $L_{kin} \propto (dM/dt)^1$ ）

- さらに、RIAF 中の$e^\pm$生成（$e^-e^- \rightarrow 3e^-e^+$など）を考えると、511 keV 放射も無理なく説明できる

Why Sgr A* Currently So Dim?

- 現在の低降着率は Sgr A East との相互作用のため (Totani '06)
  - Sgr A East のシェル運動量はそれまでの降着流を破壊するに十分

- 現在より10^{3-4}倍高い降着率は、近傍の通常銀河では普通
  - むしろ現在の Sgr A* の降着率は異常に低い

- たまたま現在のように低い時期にあたる確率？
  - 銀河系中心付近の星形成率から類推すると、約１％程度

$n_e \sim 10^{2-3}$ cm^{-3}

Maeda+ '02

日本の貢献

of the central MBH. We highlight some of the evidence of previous activities toward the GC, which may relate to the production of the *Fermi* bubbles.

X-ray reflection nebulae in the GC. There are indications of previous GC activity from X-ray echoes and time variability of reflected X-ray lines from cold iron atoms in molecular clouds around Sgr A* including Sgr B1 and B2, Sgr C, and M0.11-0.11 (Sunyaev et al. 1993; Sunyaev & Churazov 1998). The changes in the intensity, spectrum, and morphology of the fluorescent iron nebulae near the GC, observed by *ASCA* and *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*) are likely due to reflected X-rays from previous activity of Sgr A* with high luminosity $\sim$300 yr ago. The luminosity is $\sim 1.5 \times 10^{39}$ erg s^{-1} in 2–200 keV with a power-law spectrum $dN/dE \propto E^{-\gamma}$ with $\gamma = 1.8 \pm 0.2$ (Ponti et al. 2010; Revnivtsev et al. 2004; Nobukawa et al. 2008). The changes in the intensities and morphologies of hard X-ray nebulosities on parsec scales have been discovered (Muno et al. 2007).

$n \approx 0.1$ cm^{-3} at 2 kpc above the plane (Bland-Hawthorn & Cohen 2003b). Free–free emission in the resulting high-temperature plasma produces the observed X-ray signals. The GCL on *degree* scale has estimated the total kinetic energy $\sim 10^{55}$ erg and a dynamical timescale of $\sim 10^{6}$ yr. The size, energy, and timescales are similar to those of the expanding molecular ring (EMR) around the GC (Kaifu et al. 1972; Scoville 1972; Totani 2006). Sofue (2000b) interpreted the North Polar Spur (NPS) with tens of degrees scale to be an outflow from the GC with an energy scale of $\sim 10^{55}$–10^{56} erg and a timescale of $\sim 10^{7}$ yr. Totani (2006) suggested that all these outflows can be attributed to the past high activity of Sgr A* of a duration of $\sim 10^{7}$ yr, comparable to the reasonable estimation of the lifetimes of AGNs.

Diffuse X-ray emission. Muno et al. (2004) studied the diffuse X-ray emission within ~ 20 pc of the GC in detail using *Chandra* observations. The hard component plasma with $kT \sim 8$ keV is spatially uniform and correlated with a softer component with

Su+'10 の一節

日本の貢献

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Su+'10 の一節

まとめ

- フェルミバブルは、他波長で知られている銀河系中心の過去の活動性の一つの現れと考えられる
  - 様々な波長、スケールで、過去の活動性の兆候有り
  - 普通の銀河の SMBH の活動性として不自然ではない
  - 日本の貢献大

- Question: origin of cosmic-rays? E_{CR} ~ 0.001-0.01 E_{bubble}
  - challenge for CR production/propagation?
    - sharp edge → CTA
    - uniform surface brightness
    - hard spectrum → CTA
  - origin of cosmic-rays beyond the knee?

鹿児島天文学会で思ったこと

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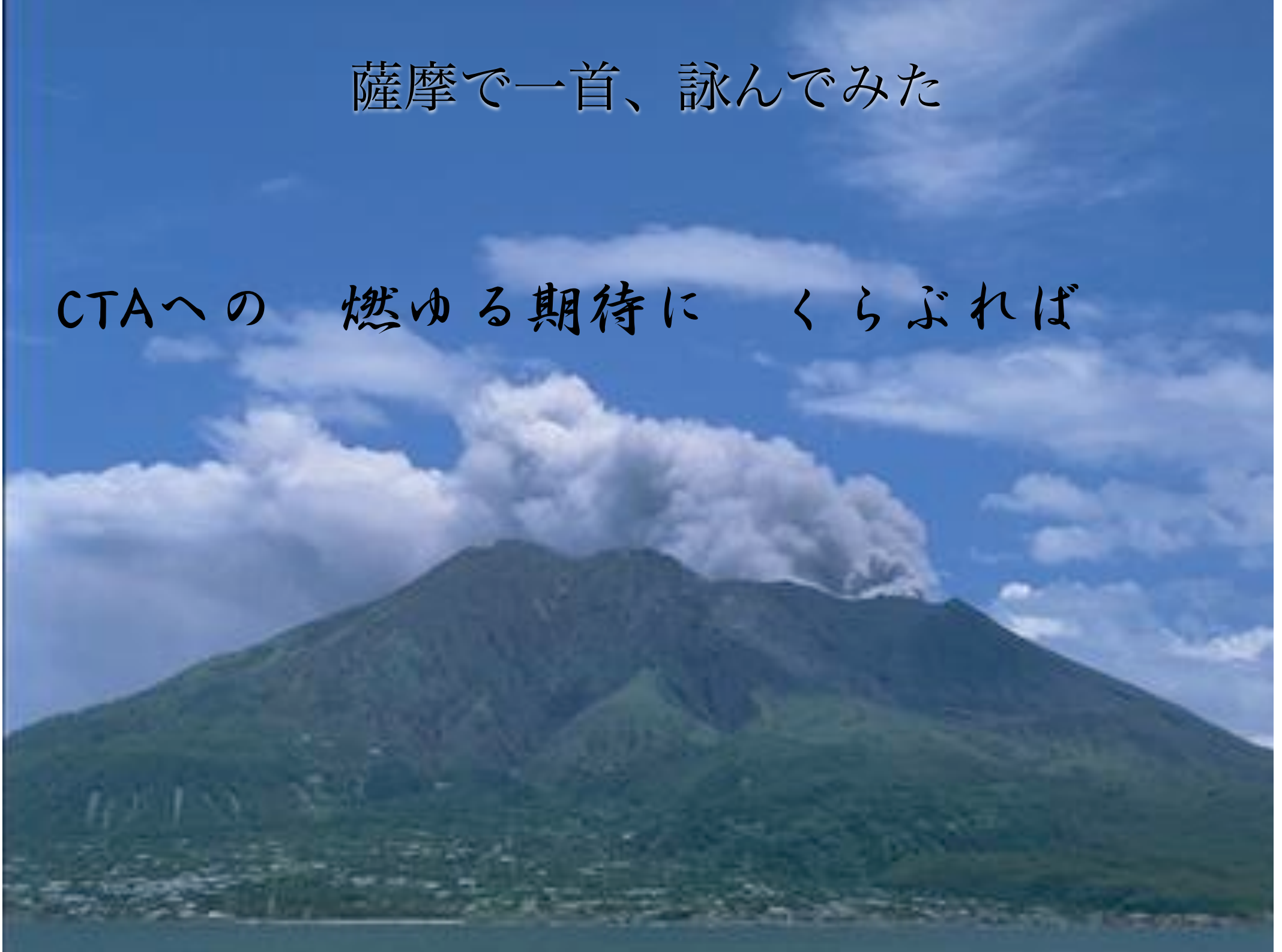- 斉彬から西郷、維新へ

Conclusion

Conclusion

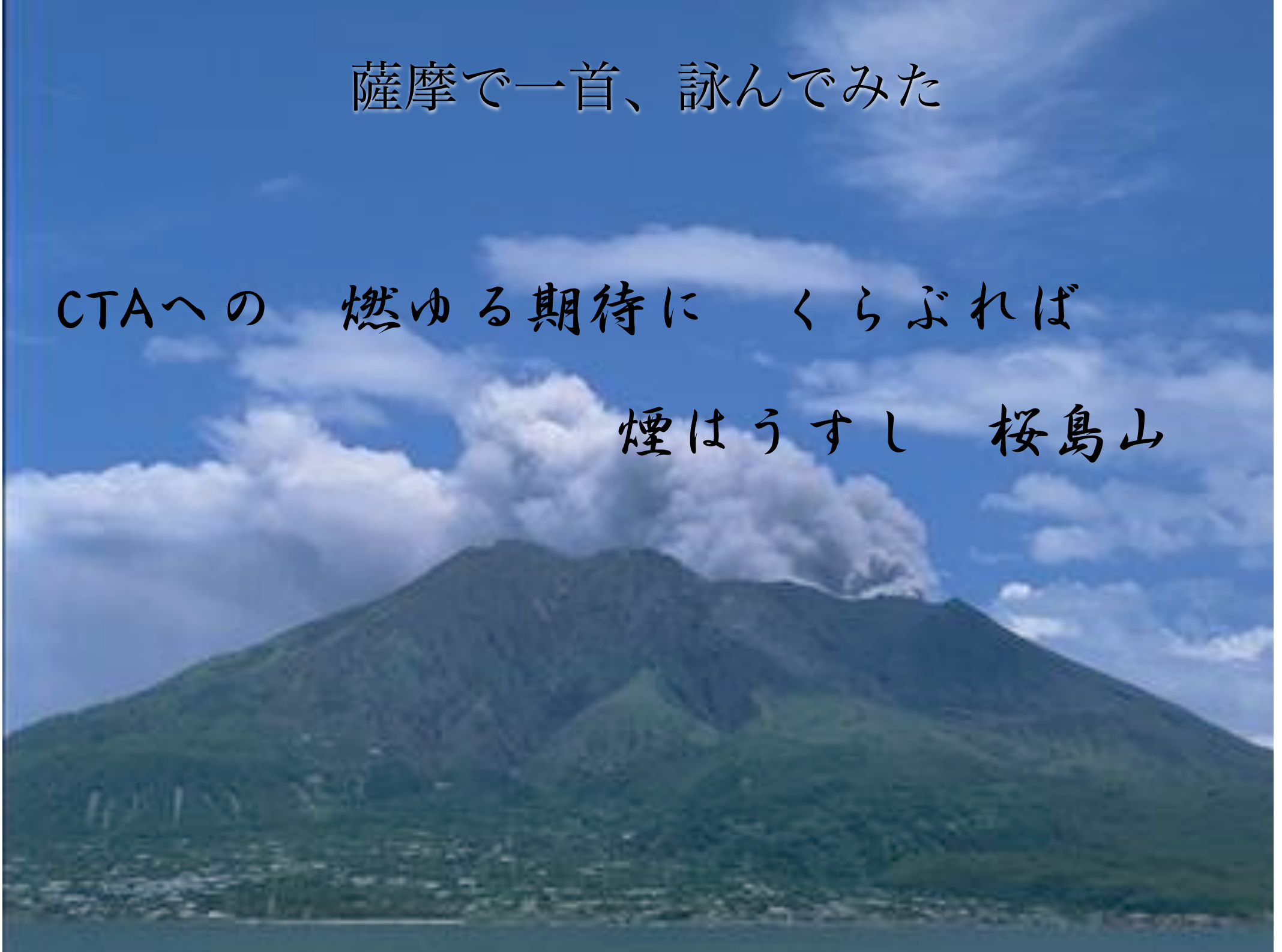- 明治維新は、天文学から始まった

薩摩で一首、詠んでみた

薩摩で一首、詠んでみた

CTAへの　燃ゆる期待に　くらぶれば

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CTAへの　燃ゆる期待に　くらぶれば

　　　　　　　煙はうすし　桜島山

薩摩で一首、詠んでみた

CTAへの　燃ゆる期待に　くらぶれば

　　　　　煙はうすし　桜島山

（ちなみに元ネタはこちら…）

我が胸の　燃ゆる思いに　くらぶれば　煙はうすし　桜島山

平野国臣　万延元年 (1860)