Discovery of non-equilibrium ionization plasma around the Fermi Bubble
; new evidence of past activity of the Galactic Center

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Abstract

Fermi bubbles are giant gamma-ray structure toward the Galactic center (GC) with symmetrical north-south extension perpendicular to the galactic plane. Such giant structures toward the GC are also observed in various wavelengths from radio to X-rays, such as WMAP haze, North Polar Spur (NPS), and most recently, eROSITA bubbles. We investigated the detailed plasma condition of the NPS/Loop I around Fermi bubble using archival *Suzaku* data. In previous research collisional ionization equilibrium (CIE) have been assumed for plasma state, but we also assume non-equilibrium ionization (NEI) to check the plasma condition in more detail. We found that most of the plasma in the NPS/Loop I favors the state of NEI, and has the density-weighted ionization timescale of $net \sim 10^{11\text{-}12}$ s cm^{-3} and the electron number density $n_e \sim$ a few $\times$ 10^{-3} cm^{-3}. The plasma shock age, t, or the time elapsed after the shock front passed through the plasma, is estimated to be on the order of a few Myr for the NPS/Loop I, which puts a strict lower limit to the age of the whole NPS/Loop I structure. We found that NEI results in significantly higher temperature and lower emission measure than those currently derived under CIE assumption. The electron temperature under NEI is estimated to be as high as 0.5~keV toward the brightest X-ray NPS ridge at $\Delta\theta$=−20∘, which decreases to 0.3 keV at −10∘, and again increases to ~0.6 keV towards the outer edge of Loop I at $\Delta\theta$~0∘, about twice the currently estimated temperatures. Here, $\Delta\theta$ is the angular distance from the outer edge of Loop I. We discuss the implication of introducing NEI for the research in plasma states in astrophysical phenomena.

1. Introduction

▶ NPS (North Polar Spur) / Loop I structure

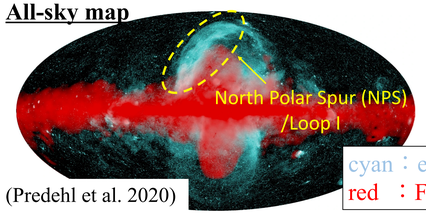
- ◆ Large structure towards GC (Galactic Center)
- ◆ Observation with various wavelengths
  - ex) microwave：**WMAP haze** (Finkbeiner 2004)
    numerous **loop structure**
  - X-ray：**NPS**, **e-Rosita Bubble**
  - γ-ray：**Fermi Bubble** (Su et al. 2010)

▶ Hypotheses on 2 prevailing & opposing origins

GC explosion @ ~ 10 kpc VS nearby SNR @ ~ 100 pc

⇨ The origin of these structures is under discussion

All-sky map



(Predehl et al. 2020)

cyan：eROSITA 0.6-1.0 keV
red ：Fermi bubbles

Previous research

- ◆ Plasma is assumed to be in ionization equilibrium (CIE)

$T_i(proton\ temp) = T_e(electron\ temp) = T_z(ionization\ temp)$

In this research

- ◆ Consider ionization non-equilibrium (NEI)
  - ⇨ionization timescale $n_e t$：**electron density** × **shock age**

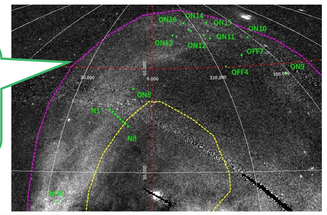
Investigate the origin by estimating plasma temperature, density, and time scale

2. observation region & spectrum analysis

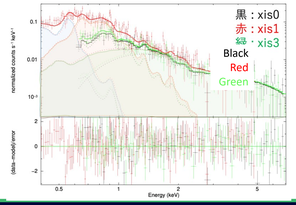
▶ Observation region

◆ Archive data from Suzaku XIS detector

Low-latitude ($b < 50°$) : 9 regions
High-latitude ($b > 50°$) : 11 regions



▶ Spectrum fitting model



Apec + wabs*(Apec/Nei + Powerlaw)

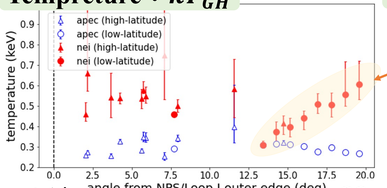
※Apec model：CIE, Nei model：NEI

① LHB / SWCX
② GH (Galactic Halo)
⇨CIE (Apec model) or NEI (NEI model)
③ CXB (Cosmic X-ray Background)

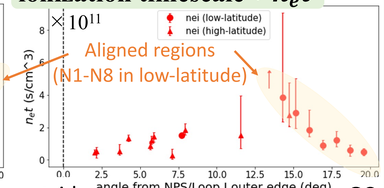
3. Results

▶ Comparison of fitting results of GH component

Tempreture：kT_{GH}



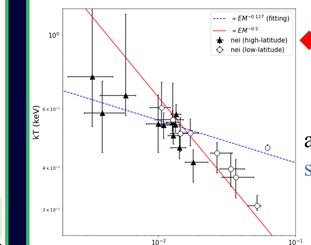
ionization timescale：$n_e t$



- ◆ Plasma temperature is $kT_e \sim 0.6$ keV assuming NEI (hotter than CIE)
- ◆ Ionization timescale is $n_e t \sim 10^{11}$ s/cm^3 ⇨ plasma is in state of NEI
- ◆ NEI model is favored than CIE with more than 95% confidence level

4. Discussion

▶ Correlation between EM & kT



◆ negative correlation
in NEI : -0.858
(than CIE : -0.484)

according to self-similar solution,

$kT \propto EM^{-0.5}$

(red line in the Figure)

▶ Origin of the NPS/Loop I

GC explosion (@ ~ few kpc)

- ◆ shock age : $t \sim 1$ Myr
- ◆ electron density : $n_e \sim (2-5)\times 10^{-3}$cm^{-3}
- ◆ energy : $E_g \sim 10^{54\text{-}55}$ erg

VS

nearby SNR (@ ~100 pc)

- ◆ shock age : $t \sim 300$ kyr
- ◆ electron density : $n_e \sim 2\times 10^{-2}$cm^{-3}
- ◆ energy : $E_g \sim 10^{52}$ erg

Considering the shock front temperature as kT~0.6keV,
$v_{sh} \geq 460 - 530 km/s$

but ◆ Older than typical SNR ◆ Thinner than ISM(n_e~1.0 cm^{-3})
◆ Equivalent energy of several dozen type-II SNRs

∴ NPS/Loop I is interpreted as a structure from GC

▶ Plasma State

timescale to reach equilibrium of the plasma

◆ **Collision equilibrium**

Difference in temperature between electrons and protons due to shock wave heating (m_p/m_e~1836)

$$t_{ep} \sim 1.1\times 10^6 \left(\frac{n_e}{3\times 10^{-3} cm^{-3}}\right)^{-1} \left(\frac{kT_e}{0.3\ keV}\right)^{\frac{3}{2}} yr$$

◆ **Ionization equilibrium**

Ionization timescale $n_e t \geq 10^{12}$, it is in CIE state

$$t_{CIE} \sim 10^7 \times 10^6 \left(\frac{n_e}{3\times 10^{-3} cm^{-3}}\right)^{-1} yr$$

✓ If NPS/Loop I is Myr-scale event…
plasma is almost collision equilibrium, but non-ionization equilibrium $T_i \sim T_e \neq T_z$

5. Conclusion & Future work

▶ Conclusion

- ◆ NPS/Loop I plasma is **NEI** status, close to CIE.
  - ⇨ ~Myr-scale event
- ◆ The origin of NPS/Loop I is more likely to be an explosion near the **GC**.

▶ Future work

- ◆ Systematic analysis with increased region
  - ex) use other satellite data, analyze south region

⇨Unified understanding of the giant structure
Understanding the **origin** and **explosion model**