Fermi-LAT and Suzaku observations of Radio Galaxy Centaurus B

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Cosmic-ray spectrum

Power-law distribution up to $10^{20}$ eV

Ultra-high energy cosmic rays ($E > 10^{19}$ eV)

Where is the source? How are UHECRs accelerated?
Candidates of UHECR source

Hillas condition

\[ E_{\text{max}} = Z \beta B L \]

- \( Z \): Charge number
- \( \beta \): Plasma velocity \((v/c)\)
- \( L \): System size

\((\beta B\): Electric field\)

Candidates are limited among various celestial objects (magnetars, AGN, radio galaxy lobes, GRBs etc)
• Diffusive shock acceleration (1st order Fermi)
• Turbulent (i.e., randomly-moving magnetic cloud) acceleration (2nd order Fermi)
• So far, it was believed that Shock acceleration was the most promising mechanism and turbulent acceleration was not emphasized well due to its inefficiency (takes much time for particles to be accelerated)
Fermi Gamma-ray Space Telescope

- Launched on 2008 June 11
- Large Area Telescope (LAT): 20 MeV--300 GeV
- Gamma-ray Burst Monitor (GBM): 8 keV--30 MeV
- All-sky is scanned every 3 hours

1873 sources
arXiv:1108.1435
Gamma-ray lobes of Centaurus A

Abdo+10, Science

B: Fermi/LAT (E>200 MeV)

C: WMAP (22 GHz)
Turbulent acceleration probably works within the lobe

\[ t_{\text{cool}} \sim 3 \times 10^5 \ (B/3 \mu G)(\gamma/10^7) \ [\text{yr}] \] for TeV electrons

\[ L/c \sim 3 \times 10^6 \ (L/1 \ Mpc) \ [\text{yr}] \]

Shocks are NOT seen within the lobe
Ultra High Energy Cosmic Rays

Pierre Auger Observatory detected 4 UHECR events from the direction of Cen A

- UHECRs are produced within the radio lobe through turbulent acceleration?
UHECR events from the direction of Cen B

Centaurus B is a nearby radio-loud active galaxy (D=56 Mpc)

Pierre Auger Observatory detected 1 UHECR event from the direction of Cen B

Moskalenko+09
Fermi-LAT and Suzaku observations of Radio Galaxy Centaurus B
Large Area Telescope (LAT) onboard Fermi

Pair-conversion telescope
Si-strip Tracker with tungsten foil converter:
  Measure the photon direction
CsI Calorimeter: Measure the photon energy,
  Image the shower
ACD (Plastic scintillator):
  Reject charged-particle background

- Large effective area 8000 cm² @ 1 GeV, normal incidence)
- Large field-of-view (2.4 str), which enables to observe the entire sky every ~3 hours
- Energy range: 20 MeV – 300 GeV
- Angular resolution (68% contaminant radius): 0.6 deg @ 1 GeV
3 slides regarding Fermi-LAT results are removed
Suzaku X-ray Observatory

- Launched on 2005 July 10
- XRS (X-ray micro-calorimeter) was lost just after the launch
- XIS (3 CCDs) and HXD (hard X-ray detector, $E > 10$ keV) are still working quite well without any severe problems
XIS is the best instrument for extended sources

- 3 FI CCDs and 1 BI CCD, but 1 FI CCD was lost
- Low Earth orbit: Steady and low background
- PSF is relatively large (~2’ HPD)

Mitsuda+07
Wide-band spectroscopy with XIS+HXD

- Non-imaging instrument. Should be careful for confusion.
- HXD consists of PIN (Silicon diode, 10 keV< E<~50 keV) and GSO (scintillator, E>~50 keV)
- Detection limit is ~1mCrab (~2x10^{-11} erg/cm^2/s, 10-50 keV)

See Suzaku Technical Description
### Suzaku/XIS observation

![Image](image_url)

**Taken from ISAS DARTS**

<table>
<thead>
<tr>
<th>Name</th>
<th>Observation ID</th>
<th>Start time (UT)</th>
<th>End time (UT)</th>
<th>Net Exposure† (ks)</th>
</tr>
</thead>
</table>

†After the event screenings.
XIS1 data were not used, because Cl was changed to 6 keV since 2011 June 1, and current standard ftool (xisnxbgen) does not does well reproduce the NXB level (especially critical for dim diffuse analysis).
Suzaku/XIS0+3 image
(2-10 keV, exposure and vignetting corrected)

Core

unrelated source

No extended lobe feature is present
Spectral analysis of X-ray BGD

Spectral parameters of X-ray background around CenB region is determined from blank sky data

- Non X-ray background was obtained by “xisnxbgen” (night Earth data)
- Contaminant of 4U 1344-60 was estimated by “xissim”
Derived parameters

X-ray background consists of 3 components: Local Hot Bubble, Galactic halo, and Cosmic X-ray background (e.g., Yuasa+07)

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Hot Bubble</td>
<td>$kT$ [keV]</td>
<td>$0.61^{+0.09}_{-0.16}$</td>
</tr>
<tr>
<td></td>
<td>$Z$</td>
<td>$1.0$ (fixed)</td>
</tr>
<tr>
<td></td>
<td>Normalization</td>
<td>$(7.0 \pm 3.3) \times 10^{-4}$</td>
</tr>
<tr>
<td>Galactic halo</td>
<td>$N_H [\times 10^{22} \text{ cm}^{-2}]$</td>
<td>$1.06$ (fixed)</td>
</tr>
<tr>
<td></td>
<td>$kT$ [keV]</td>
<td>$0.17^{+0.09}_{-0.06}$</td>
</tr>
<tr>
<td></td>
<td>$Z$</td>
<td>$1.0$ (fixed)</td>
</tr>
<tr>
<td></td>
<td>Normalization</td>
<td>$0.26^{+3.38}_{-0.24}$</td>
</tr>
<tr>
<td>CXB</td>
<td>$\Gamma_X$</td>
<td>$2.22^{+0.23}_{-0.22}$</td>
</tr>
<tr>
<td></td>
<td>Normalization</td>
<td>$(8.6^{+1.3}_{-1.0}) \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$\chi^2(\chi^2/d.o.f)$</td>
<td>$1.02 (63.41/62)$</td>
</tr>
</tbody>
</table>
X-ray upper limit of radio lobe

90% CL UL of total lobe flux = $8.7 \times 10^{-13}$ erg/cm$^2$/s

(2-10 keV, assumed power-law of $\Gamma = 1.7$)
• SED modeling suggest that gamma-rays would come from lobe
• More stringent UL disentangles the gamma-ray emission region
Future plan

- Deep X-ray observation with XMM-Newton might provide more stringent UL
- Determine the origin of gamma-rays, core or lobe?
- Magnetic-field dominated lobe? (very rare)
- So, we are now planning a long XMM proposal (say, 300 ksec)
Summary

- Fermi-LAT detected HE gamma-ray emission from Cen B
- Suzaku/XIS did not detect extended X-ray emission from radio lobe
- SED modeling suggest that gamma-rays would be produced by radio lobe
- More stringent UL or detection of the lobe will provide robust information of the gamma-ray emission site
Kanata Telescope

- Operated by Hiroshima Univ.
- Diameter=1.5 m, Optical/IR
- Quick follow-up of transient objects such as GRB, Blazar flare, Supernova etc
- Polarization measurement (Abdo+10)