M82 starburst galaxy:
possible origin of the northern hot spot

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Toshiki Tajima (UC Irvine)
1. Star burst galaxy M82 and North hot spot
2. Bow wake acceleration
3. Bending by cosmological filaments
4. Future Observations
5. Conclusion
M82 galaxy
M82: Nearest Star Burst Galaxy

Just after the collision with M81

Composite of X-ray, IR, and optical emissions

M82 X-1: 100-10000 Ms BH

NASA / CXC / JHU / D. Strickland; optical: NASA / ESA / STScI / AURA/ Hubble Heritage Team; IR: NASA / JPL-Caltech /Univ. of AZ / C. Engelbracht; inset – NASA / CXC / Tsinghua University / H. Feng et al.
Ground Based Observatories

Auger
- 1600 surface detectors
- 3000 km²

TA
- 507 surface detectors
- 700 km²
One hemisphere by one instrument

Some (5%) disuniformity due to clouds, continents and moon phase
Arrival Direction Map (Auger/TA)
TA Hot Spot: UHECRs from M82?

He, Kusenko, Nagataki + PRD 2016.

The most likely Source Position As a Result of Our Analysis.

Purple Lines are Source Positions With 1,2,3-sigma Errors.

M82 is very Close from the most likely Source Position!

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Source Type</th>
<th>Distance (Mpc)</th>
<th>$A_1$ ($^\circ$)</th>
<th>$A_2$ ($^\circ$)</th>
<th>$P/P_{\text{best-fit}}$ (%)</th>
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</thead>
<tbody>
<tr>
<td>best fit</td>
<td></td>
<td></td>
<td>17.4</td>
<td>11.6</td>
<td>9.6</td>
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<td>M82</td>
<td>starburst galaxy</td>
<td>3.4</td>
<td>17.6</td>
<td>9.6</td>
<td>100</td>
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<tr>
<td>UGC 05101</td>
<td>star-forming galaxy</td>
<td>160.2</td>
<td>11.6</td>
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<td>96.9</td>
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<td>Mrk 180</td>
<td>blazar</td>
<td>185</td>
<td>19.9</td>
<td>9.3</td>
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<td>UGC 03957</td>
<td>galaxy cluster</td>
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<td>Mrk 421</td>
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<td>134</td>
<td>11.2</td>
<td>9.9</td>
<td>35.6</td>
</tr>
</tbody>
</table>
contents

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Formation of extragalactic jets from black hole accretion disk

Wake at the bow of the Alfven Pulse
Eruption of magnetic field in an accretion disk

A Burst of Torsional Alfven Waves

Accretion Disk around a BH

Accretion disk emits intense Alfven bursts
3-D relativistic MHD simulation
Formation of extragalactic jets from black hole accretion disk

Extragalactic jet

Burst of Alfven Waves

Magnetic field lines

Wake at the bow of the Alfven Pulse

Linear Bow Wake Acceleration

\[ \Gamma = 10 \sim 30 \]
Bow wake acceleration

One of the wake field acceleration, which takes place when $a_0 >> 1$
Laser Wakefield

$E_W \sim \text{GeV/cm}$

Particle acceleration

T. Tajima and J. M. Dawson (1979)

FIG. 2. (Color) Plasma density perturbation excited by Gaussian laser pulse with $a_0=1.5$, $k_0/k_p=20$, $k_pL_{\text{rms}}=1$, and $k_p r_0=8$. Laser pulse is traveling to the left.
Electron bunch by a single shot of laser beam

1D Particle-in-Cell simulation

with the code by Nagata2008

\[ a_0 = 0.4 \]

\[ a_0 = 2 \]

\[ a_0 = 60 \]

Lau et al. 2015, Phys. Rev. 18, 024401
Acceleration by pondermotive force at “bow wake”

\[ W_{\text{max}} = z \int_{0}^{D_3} F_{\text{pm}} \, dD \]

\[ F_{\text{pm}} = \Gamma m_e c a_0 \omega_A \]
cosmic ray acceleration and gamma-ray emission

\[ L_{\text{tot}} = 1.3 \times 10^{38} m \dot{m} \text{ erg s}^{-1} \]
Energy Flow and Spectra

- wakefield
  - protons
  - electrons
- cosmic rays
  - 1:1
- gamma rays
  - 0.1:1
- UHECRs

\[ F(W) \propto W^{-2} \]
# Nine nearby Fermi AGNs

<table>
<thead>
<tr>
<th>Counterpart name</th>
<th>LII</th>
<th>BII</th>
<th>Class</th>
<th>Redshift</th>
<th>Flux 1 GeV-100 GeV (erg cm(^{-2}) s(^{-1}))</th>
<th>Spectral index</th>
<th>Radio flux (mJy)</th>
<th>X Flux (erg cm(^{-2}) s(^{-1}))</th>
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<tbody>
<tr>
<td>NGC 0253</td>
<td>97.39</td>
<td>-87.97</td>
<td>Starburst galaxy</td>
<td>0.001</td>
<td>(6.2 +/- 1.2 ) \times 10^{-10}</td>
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<td>NGC 1068</td>
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<td>-51.94</td>
<td>Seyfert galaxy</td>
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<td>(5.1 +/- 1.1 ) \times 10^{-10}</td>
<td>2.146</td>
<td>4849</td>
<td>4.55E-11</td>
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<td>For A</td>
<td>240.15</td>
<td>-56.7</td>
<td>Radio Galaxy</td>
<td>0.005</td>
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<td>2.158</td>
<td>255</td>
<td>2.38E-12</td>
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<td>M 82</td>
<td>141.41</td>
<td>40.56</td>
<td>Starburst galaxy</td>
<td>0.001236</td>
<td>(10.2 +/- 1.3 ) \times 10^{-10}</td>
<td>2.28</td>
<td>6205</td>
<td>2.29E-11</td>
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<td>M 87</td>
<td>283.78</td>
<td>74.48</td>
<td>Radio Galaxy</td>
<td>0.0036</td>
<td>(17.3 +/- 1.8 ) \times 10^{-10}</td>
<td>2.174</td>
<td>138488</td>
<td>6.30E-11</td>
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<tr>
<td>Cen A Core</td>
<td>309.51</td>
<td>19.41</td>
<td>Radio Galaxy</td>
<td>0.00183</td>
<td>(30.3 +/- 2.4 ) \times 10^{-10}</td>
<td>2.763</td>
<td>42000</td>
<td>9.00E-12</td>
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<td>NGC 4945</td>
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<td>13.33</td>
<td>Seyfert galaxy</td>
<td>0.002</td>
<td>(7.5 +/- 1.7 ) \times 10^{-10}</td>
<td>2.103</td>
<td>5776</td>
<td>2.36E-12</td>
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<td>Cen B</td>
<td>309.72</td>
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<td>Radio Galaxy</td>
<td>0.012916</td>
<td>(18.6 +/- 3.5 ) \times 10^{-10}</td>
<td>2.325</td>
<td>8890</td>
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<td>NGC 6814</td>
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<td>(6.8 +/- 1.6 ) \times 10^{-10}</td>
<td>2.544</td>
<td>52</td>
<td>1.56E-11</td>
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</table>

UCIrvine November 16, 2017
Nine nearby Fermi AGNs (Sky Map)

2MASS galaxy distribution

M82 X-1 is promising

- \( F_{\gamma M82} = 10.2 \times 10^{-10} \text{erg s}^{-1} \text{cm}^{-2} \rightarrow \)
  \[ L_{\gamma M82} = 1.3 \times 10^{42} \text{erg s}^{-1} \]
- 1% of M82 total \( \leftarrow \) M82 X-1
  \[ L_{\text{UHECR M82X-1}} = 1.3 \times 10^{39} \text{erg s}^{-1} \]
  \[ \frac{L_{\text{UHECR}}}{L_{\gamma}} = 0.1 \]
  \[ F_{\text{UHECR M82X-1}} \sim 3 \text{ UHECRs}/100\text{km}^2/\text{yr} \]
  \[ \sim F_{\text{HotSpot}} \]
Light Curves

![Graphs showing light curves for M82, NGC 253, NGC 1068, and NGC 4945.](image-url)
Energy Spectra

![Graphs showing energy spectra for different celestial objects.](image-url)
An AGN-like Jet in M87?

X-ray/Radio (flare in 1981)


Radio Flare 1981
Astrophysical Implication

• Hot spot component came from M82
  – too near for GZK (D=3.4 Mpc)
  – mainly proton

• How about magnetic deflection?
  – We need $B \sim 10 \text{ nG}$ for $D = 3.2 \text{ Mpc}$

  • $\theta = 0.5^\circ \left(\frac{D}{\text{Mpc}}\right) \left(\frac{B}{\text{nG}}\right) \sim 17.4^\circ$

  • $\Delta \theta = 0.36 \left(\frac{D}{\text{Mpc}}\right)^{1/2} \left(\frac{D_c}{\text{Mpc}}\right)^{1/2} \left(\frac{B_r}{\text{nG}}\right) \sim 9.4^\circ$
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We are living on a filament of the cosmological web!

UHECR propagation among cosmological magnetic web (2)

- Huge variation $\sim$1-100°
  - Strongly depends on the source location and the path
- Average $\sim$10° at 3 Mpc

$$\epsilon_B = \phi \left( \frac{t}{t_{eddy}} \right) \epsilon_{turb}$$

- $t_{eddy}$ and $\epsilon_{turb}$: simulation
- $\phi$: different simulations with fine meshes

How about Cen A and M87/Vir A?

• **Cen A**
  – $D = 4.3 \text{ Mpc} \geq D_{\text{M87}} = 3.4 \text{ Mpc}$
  – **In the filaments**
  – $\theta, \Delta \theta \sim 10 - 20 \text{ degree}$
  – CNO rich?
    = WR stars in the jets

• **M87/Vir A**
  – $D = 18 \text{ Mpc} \gg D_{\text{M87}} = 3.4 \text{ Mpc}$
  – **In the filaments**
    Virgo centric inflow
  – $\theta, \Delta \theta \sim 60 \text{ degree}$
  → diffuse source along SGP
全天Map (TA >57EeV, Auger > 57EeV)

近傍の銀河団との位置関係

Virgo Cluster (D=20Mpc)
Perseus-Pisces Supercluster (D=70Mpc)
Eridanus Cluster (D=30Mpc)
Fornax Cluster

Centaurus Supercluster (D=60Mpc)

◊ Dots: 2MASS catalog Heliocentric velocity <3000 km/s
◊ TA hotspot is found near the Ursa Major Cluster
◊ TA & Auger found no excess in the direction of Virgo.

UHECR emission: Isotropic or Beaming?

- Radio galaxies: Angle to Line of sight $\theta > 10$–20°
  - M87 43°
  - Cen A 50–80°
- Blazers: $\theta < 10°$
- No information for M82 X-1
  - Single jet?
- UHECR beam may suffer from the local magnetic field
Background Component:
Numerous number of Distant Sources
Ebisuzaki and Tajima 2014

• Distant Blazers
  – Local gamma-ray Luminosity of blazers:
    \[ l_\gamma = 10^{37} - 10^{38} \text{ erg s}^{-1} \text{ Mpc}^{-3} \]
    \[ \rightarrow \Phi_{\text{UHECR}} \sim 0.1 \text{ particles/(100 km}^2 \text{ yr sr)} \]
    GZK (if mainly protons)
    \[ \rightarrow \Phi_{\text{UHE}_\nu} \sim 5 \text{ particles/(100 km}^2 \text{ yr sr)} \]
    for \[ E_{\text{UHE}_\nu} > 10^{20} \text{ eV} \]
Figure 3 from Spectral Properties of Bright Fermi-Detected Blazars in the Gamma-Ray Band
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5. K-EUSO
K-EUSO

Russian Federal Space Program

- Passed the stage of preliminary design with Roscosmoc
- Technical requirements, accommodation, operations study performed by Energia space corporation
- Evolution of KLYPVE Russian detector (reflector)
- Mission of opportunity Launch in 2022
Science of K-EUSO

1. Study of UHECR flux from space with uniform response
2. Flux $E > 3 \times 10^{19}$ eV north & south
3. Anisotropy
4. Earth observations, bioluminescence
5. Debris tracking and removal
N-S spectral difference

1yr

$\# \text{ of events (>E)}$

Threshold energy [eV]

1 year

6 years
Uniform response over both hemispheres

Some (5%) disuniformity due to clouds, continents and moon phase
K-EUSO exposure
Double Donut Schmidt Camera (named by P. Mazzinghi)
How about neutrinos?

Greisen-Zatsepin-Kuz’mín Process

Greisen1966; Zatsepin and Kuz’mín1966

- Neutrino production in high-energy interactions

2.7K CMB γ

Proton: E = 10^{20} eV

Neutron: \gamma \rightarrow \Delta \rightarrow \pi^0 + p, \pi^+ + n

Microwave Cosmic Background Radiation

2.725 K

410 photons/cm^3

Gamma Beam Energy (GeV)

Cross Section (mb)

0.1

0.01

0.001

0.0001

Gamma Beam Energy (GeV)

Cross Section (mb)

0.1

0.01

0.001

0.0001

0.3 1 10
Neutrino and gamma ray flux

\[ \Phi_{\text{UHECR}} \propto E^{-2} \exp(-E/10^{21.5}\text{eV}) \]

Engel et al 2001 (GZK neutrino)

Conclusions

• **M82: the nearest starburst galaxy**
  – M82 X-1: Intermediate Mass Blackholes ($10^2$-$10^4$ Ms)
    = possible origin of northern hot spot

• **Bow Wake Acceleration**
  – Accreting BH+disk+jet
    = Astronomical Linear accelerator
  – Bursts of Intense Alfven waves $\leftarrow$ Laser
  – Jet $\leftarrow$ wave guide

• **Bending by magnetic field**
  – $B \sim 10nG$ in the cosmic filaments of local supercluster
  – Study of supercluster magnetic field

• **K-EUSO**
  – Confirmation of south-north anisotropy
  – Identification of M82 and other sources

• **Ultra High energy neutrinos** from distant blazers
  – Ice Cube and POEMMA
Back up
cosmic ray acceleration and gamma-ray emission

$L_{\text{tot}} = 1.3 \times 10^{38} \text{mm} \ erg \ s^{-1}$
GW150914

- Merging of Binary BH: 36Ms+29Ms
- Distance : 410 Mpc=0.410 Gpc (Z=0.09)
SNR=10, spin parameter averaged

Event Rate [1/yr]

BH mass (final BH) [M_☉]

Theoretical Upper limit of Fermi mech. $< 10^{20}$ eV
Fermi mechanism
requires bending \rightarrow \text{synchrotron loss}
Difficulties of Fermi acceleration in UHECR

1. Bending is inevitable
   → synchrotron loss

2. Confinement is difficult
   → no acceleration

3. Escape problem
   → magnetic field does not disappear without adiabatic loss

Wakefield acceleration
Difficulties of Fermi acceleration in UHECR

1. Bending is inevitable
   → synchrotron loss

2. Confinement is difficult
   → no acceleration
Radio/X-ray nots in Cen X-1 Jets

Wolf-Rayet Stars in the Jets?
effective CNO supply? ()

Fermi gamma-ray galaxies (Nearby)


- Radio Galaxy
- Seyfert Galaxy
- Starburst Galaxy
Cosmic-ray acceleration
Wake of a ship
Conditions for UHECRs

\[ L_{\text{tot}} = 1.3 \times 10^{38} \, m \dot{m} \, \text{erg s}^{-1} \]
Relativistic coherence

- Extremely relativistic
  → freezing-out

[Diagram showing electromagnetic wave pulse and related plots]
Origin of Cosmic rays

• 100 years enigma
  – Discovered in 1912 by Victor Hess

They lose original directions because of magnetic field

Isotropic distribution
\( \omega_A < \omega'_p \)  
Alfven wave  
\( \omega_A > \omega'_p \)  
EM wave  
Pondermotive Acc.
Jet

\[ \omega_A > \omega'_p \]
EM wave

\[ \omega_A < \omega'_p \]
Alfvén wave

Accretion Disk

D/R_g

R/R_g

Accretion Disk

BH