Exploring the Origin of Cosmic Rays with High Energy Gamma Rays

Felix Aharonian
DIAS/Dublin & MPIK/Heidelberg
three components of Cosmic Rays

- below knee around $10^{15}$ eV
  Galactic

- above ankle around $10^{18}$ eV
  ExtraGalactic

- between knee and ankle
  ???

HiRes/AUGER confirm the existence of a spectral break/cutoff around $10^{20}$ eV!

Is this the so-called GZK cutoff expected for the sources located beyond 100 Mpc?

Not necessarily - there is another fundamental reason to expect a cutoff around $10^{20}$ eV because of limited efficiency for particle acceleration in available astronomical objects.
Exploring the origin of Cosmic Rays with

- **Ground-based gamma-ray detectors**
  capability for deep spectrometric, morphological and temporal studies in the crucial energy band for GCRs: $< 1 \text{ PeV}$, also $1-100 \text{EeV}$?

- **FERMI/Agile**
  complementary information about the energy domain $1 \text{GeV}-1 \text{TeV}$

- **KM3 volume ν-detectors IceCube/Km3NeT**
  unambiguous information about hadronic component of galactic cosmic rays in the energy domain $0.1 - 10 \text{ PeV}$, also $>10 \text{EeV}$?

- **hard X-ray imagers NuStar/ASTRO-H**
  capability for high quality spectroscopic and morphological studies of highest energy protons through synchrotron radiation of secondary ($\pi^\pm$ decay) electrons: $100 \text{ TeV}-10 \text{ PeV}$
Power of IACT Arrays

$$F_{\text{min}} \Rightarrow 10^{-13} \text{ erg/cm}^2\text{s}$$ *coupled with* PSF$\approx 3$ arcmin & $\Delta E/E \approx 15\%$ + huge statistics

- **spectrometry**
  - RXJ 1713.7-3946
  - TeV image and energy spectrum of a SNR
  - variability of TeV flux of a blazar on minute timescales

- **morphology**
  - resolving GMCs in the Galactic Center 100pc region

- **timing**

---

**multi-functional tools:**  *spectrometry  temporal studies  morphology*

- extended sources: from SNRs to Clusters of Galaxies
- transient phenomena $\mu QSOs$, AGN, GRBs, ...

---

*Galactic Astronomy  |  Extragalactic Astronomy  |  Observational Cosmology*
Fermi LAT: very good sensitivity, reasonable angular resolution, very good energy resolution and large FoV - continuous watch of the sky!

thousands of sources - monitoring GeV flares -- very extended sources
RXJ1713.7-4639

hadronic vs leptonic

shell-type morphology of multi-TeV gamma-rays => acceleration of e or p to energies >100 TeV

phenomenological studies => main conclusions

- hadronic origin is most desirable with a number of good features - but it faces a serious problem - lack of thermal X-ray emission

- IC interpretation of gamma-rays is a viable option but it requires very small magnetic field
**X-rays:** acceleration in Bohm regime at presence of strong b-field

energy spectrum of synchrotron radiation of electrons in the framework of DSA; V. Zirakashvili & FA, 2007:

\[ J_\nu \propto \nu^{-1}[1+0.46(\nu/\nu_0)^{0.6}]^{11/4.8} \exp[-(\nu/\nu_0)^{1/2}] \]

\[ h\nu_0 \approx 1(\nu/3000 \text{ km/s})\nu_0^2 \eta \text{ keV}; \quad \eta=1: \text{Bohm diffusion} \]

strong support for Bohm diffusion, given the upper limit \( v_{\text{shock}} < 4000 \text{ km/s} \! \)

filamentary structure and especially time-variability of X-rays on year time-scales: witnessing particle acceleration in real time

\[ h\nu_0 = 0.67\pm 0.02 \text{ keV} \]

\[ h\nu_0 = (v/3000 \text{ km/s})\nu_0^2 \eta \text{ keV}; \quad \eta=1: \text{Bohm diffusion} \]

strong support for Bohm diffusion, given the upper limit \( v_{\text{shock}} < 4000 \text{ km/s} \! \)

filamentary structure and time variability on year timescales

\[ \Rightarrow B\text{-field as large as } 100\mu\text{G} \]
Strong B-field + Bohm diffusion

• key condition for proton acceleration to 1 PeV
• problem for leptonic origin of gamma-rays?
• support for hadronic origin of gamma-rays?

Lack of thermal X-ray emission

• against hadronic origin of gamma-rays?
• support for nonlinear shock acceleration?

depth theoretical studies needed before any strong claim concerning the origin of TeV gamma-rays from SNRs
**Hadronic model**

Good spectral fit, reasonable radial, profile, but
(i) very low thermal efficiency
(ii) uncomfortable e/p ratio \((10^4)\)

**Leptonic model**

Not perfect, but still acceptable spectral fits for spectral and spatial distribution of IC \(\gamma\)-rays, very low magnetic field, but no problem with thermal x-ray emission, and comfortable e/p ratio \((10^2)\)

**Composite model**

Dominated by leptonic except for dense regions of the shell

Zirakashvili and FA 2009
highest energy particles, $E > 100$ TeV, are confined in the shell only during a few 100 years => most promising search for PeVatrons?

**multi-TeV $\gamma$-rays from dense gas clouds in the near neighborhood**

expected gamma-ray emission from interactions of protons which escaped the shell of SNR and interact with dense gas surrounding RXJ1713.7-3946

---

**Fig. 1.** The gas distribution in the region which spans Galactic longitude $340^\circ < l < 350^\circ$, Galactic latitude $-5^\circ < b < 5^\circ$ and heliocentric distance $50$ pc $< l_d < 30$ kpc, as observed by the NANTEN and LAB surveys, expressed in protons cm$^{-3}$. The distance axis is logarithmic in base 10. A value for the gas density is given every 50 pc in distance, which is reflected in the apparent slidy structure for distances below 100 pc. For sake of clarity only densities above 1 protons cm$^{-3}$ are shown. Also indicated the position of the historical SNR, RX J1713.7-3946.

surrounding gas density:

*NANTEN* data

**age:**

1600 yr

**escape of protons:**

model of Zirakashvili&Ptuskin 2008

**diffusion coefficient outside SNR:**

$D=10^{26} \ (E/10\text{GeV})^{0.5} \ \text{cm}^2/\text{s}$
Fermi Bubbles as reservoirs of cosmic rays produced in the central 100 pc region of our Galaxy: unique information about cosmic rays produced in the GC and accumulated in F-Bubbles over >5 Billion years.

Fig. 2.— All-sky residual maps after subtracting the Fermi diffuse Galactic model from the LAT 1.6 year maps in 4 energy bins (see §3.1.1). Two bubble structures extending to $b \pm 50^\circ$ appear above and below the GC, symmetric about the Galactic plane.
Fermi Bubbles as reservoirs of cosmic rays produced in the central 100 pc region of our Galaxy: unique information about cosmic rays produced in the GC and accumulated in F-Bubbles over >5 Billion years.

Fig. 2.— All-sky residual maps after subtracting the Fermi diffuse Galactic model from the LAT 1.6 year maps in 4 energy bins (see §3.1.1). Two bubble structures extending to $b \pm 50^\circ$ appear above and below the GC, symmetric about the Galactic plane.
suspected sites of acceleration of $10^{20}$ eV CRs based on the condition: size > Larmor radius:

$$(R/1\text{pc}) \times (B/1\text{G}) > 0.1(E/10^{20}\text{ eV})$$

size > Larmor radius:

\[(R/1\text{pc}) \times (B/1\text{G}) > 0.1(E/10^{20} \text{ eV})\]

a necessary but not sufficient condition: it implies

(1) minimum acceleration time \(t_{\text{acc}} = R_L/c = E/eBc\) and
(2) no energy losses

★ the acceleration in fact is slower: \(t_{\text{acc}} = (1-10)\eta R_L/c (c/\nu)^2\)
with \(\eta > 1\) and shock/bulk-motion speed \(\nu < c\) (\(\eta = 1\) - Bohm diffusion)

for this reason galaxy clusters cannot accelerate particles beyond \(10^{19} \text{ eV}\)

★ energy losses due to the proton synchrotron or curvature radiation in compact objects become severe limiting factor

even so, the AGN jets and GRBs are the most likely sources responsible for acceleration of \(10^{20} \text{ eV}\) protons and nuclei
Particle acceleration in Galaxy Clusters

all ingredients for effective acceleration of cosmic rays

✓ formation of strong accretion shocks
✓ magnetic field of order 0.1–1 μG
✓ shock velocity – few 1000 km/s
✓ acceleration time ~ Hubble time

but protons cannot be accelerated to $10^{20}$ eV
pair production losses shape the proton spectrum around the cut-off:
- small bump,
- non-exponential cut-off

**Fig. 1.** Acceleration and energy loss time scales as a function of the proton energy. The acceleration time scales are obtained for the values of the upstream magnetic field $B_1$ reported in figure and a downstream magnetic field $B_2 = 4B_1$. The thick lines correspond to a shock velocity of 2000 km/s, the thin lines to a velocity of 3000 km/s. As an horizontal dotted line we report the estimated age of the Universe, for comparison.

**Fig. 2.** Proton spectra at the shock location for an acceleration time of 10 Gyr (solid line) and 5 Gyr (dashed) for a shock velocity of 2000 km/s, a magnetic field upstream $B_1 = 0.3 \mu$G and a magnetic field downstream $B_1 = 4B_1$. 

Vannoni, FA, Gabici 2009
Self-consistent calculation: broader and less steep cut-off than exponential

**Synchrotron:** \( \sim \text{factor } 10 \) enhancement downstream due to higher \( B \); peak energy \( \sim 100 \text{ keV} \).

**Inverse Compton:** the same emission level up and downstream peak between 10 and 100 TeV but the intergalactic photon-photon absorption strongly reduces gamma-ray flux above 10 TeV.

\[
W_p = 10^{62} \text{ erg}
\]

in the case of non-linear shocks \( \Rightarrow \) 100% effective synchrotron source for \( d = 100 \text{ Mpc} \)

\[ f_E = 10^{-12} \text{ erg/cm}^2 \text{ s} \]

detectable by ASTRO-H at hard X-rays CTA at TeV gamma-rays

Self-consistent calculation: broader and less steep cut-off than exponential

**Synchrotron:** \( \sim \text{factor } 10 \) enhancement downstream due to higher \( B \); peak energy \( \sim 100 \text{ keV} \).

**Inverse Compton:** the same emission level up and downstream peak between 10 and 100 TeV but the intergalactic photon-photon absorption strongly reduces gamma-ray flux above 10 TeV.

![Graph of Broadband SED induced by UHE protons](image)
acceleration sites of $10^{20}$ eV CRs

$$t_{\text{acc}} = \frac{R_L}{c} \eta^{-1}$$

signatures of extreme accelerators?

✓ synchrotron self-regulated cutoff:

$$\hbar \nu_{\text{cut}} = \frac{9}{4} \alpha_f^{-1} mc^2 \eta :$$

$\simeq 300$GeV proton synchrotron

$\simeq 150$MeV electron synchrotron

✓ neutrinos (through “converter” mechanism)
production of neutrons (through p interactions) which travel without losses and at large distances convert again to protons $\Rightarrow 2$ energy gain!

Derishev, FA et al. 2003, Phys Rev D 68 043003

✓ observable off-axis radiation
radiation pattern can be much broader than 1/

acceleration sites of $10^{20}$ eV CRs

$$t_{acc} = \frac{R_L}{c} \eta^{-1}$$

signatures of extreme accelerators?

✓ synchrotron self-regulated cutoff:

$$h\nu_{cut} = \frac{9}{4} \alpha_f^{-1} m c^2 \eta :$$

≈ 300 GeV proton synchrotron

≈ 150 MeV electron synchrotron

compact/magnetized objects!

✓ neutrinos (through “converter” mechanism) production of neutrons (through p interactions) which travel without losses and at large distances convert again to protons => $^2$ energy gain!

Derishev, FA et al. 2003, Phys Rev D 68, 043003

acceleration and radiation of UHE protons in kpc-scale structures of AGN jets

\[(R/1\text{kpc}) \times (B/100\mu\text{G}) > 1(E/10^{20}\text{ eV}) : \text{protons can be accelerated to } 10^{20}\text{ eV e.g. by relativistic shocks}\]
acceleration/radiation of $>10^{19}$eV protons in sub-parsec AGN jets

\[ E_{\text{cut}} = 90 \left( \frac{B}{100 \text{G}} \right) \left( \frac{E_p}{10^{19} \text{ eV}} \right)^2 \text{ GeV} \]

\[ t_{\text{synch}} = 4.5 \times 10^4 \left( \frac{B}{100 \text{G}} \right)^{-2} \left( \frac{E}{10^{19} \text{ eV}} \right)^{-1} \text{ s} \]

\[ t_{\text{acc}} = 1.1 \times 10^4 \left( \frac{E}{10^{19} \text{ eV}} \right) \left( \frac{B}{100 \text{G}} \right)^{-1} \text{ s} \]

\[ E_{\text{max}} = 300 \eta^{-1} \delta \text{ eV} \]

requires extreme accelerators: $\eta \sim 1$
internal absorption can help to make very hard spectra, but B-field should be large to avoid the cascading in the radiation field.
because of interstellar and intergalactic magnetic fields, the information about the original directions of cosmic rays pointing to their production sites is lost.

The flux of cosmic rays is contributed, most likely, by a large number of galactic and extragalactic sources; these objects represent different source populations characterized by essentially different physical parameters – age, distance, energy budget, etc., as well as by different particle acceleration scenarios.

\[ \Rightarrow \] extremely difficult the identification of sources of the isotropic flux of cosmic rays based on two measurables – the chemical composition and energy spectra of particles – characterizing the "soup" cooked over cosmological timescales.

but ... at extremely high energies, \( E \sim 10^{20}\) eV, the impact of galactic and extragalactic magnetic fields on the propagation of cosmic rays becomes less dramatic, which might result in large and small scale anisotropies of CR flux depending on the strength and structure of the (highly unknown) intergalactic magnetic field, the highest energy domain of CRs may offer us a new astronomical discipline – "cosmic ray astronomy", provided that \( B_{\text{IGM}} < 10^{-9} \) G.
extension of studies to energies $10^{20}$eV and beyond enhances chances of localization of particle accelerators for three independent reasons:

- with an increase of energy, the probability that a proton of $10^{20}$eV would penetrate through IGM without significant deflections in chaotic magnetic fields increases; for IGMF $\ll 10^{-9}$G, the deflection angle can be quite small also for lower energies, but $10^{20}$ eV is a special energy because

- deflection of protons with energy less than $10^{20}$ eV in galactic magnetic fields exceeds 1 degree (angular resolution of UHE cosmic ray detectors)

- particles of such high energies can arrive only from relatively nearby accelerators located within 100 Mpc. this dramatically (by orders of magnitude) decreases the number of relevant sources of $\geq 10^{20}$eV protons contributing to the observed cosmic ray flux, and correspondingly reduces the level of the diffuse background, i.e. the (quasi) isotropic flux due to superposition of contributions by unresolved discrete sources.
Angular, spectral, and time distributions of highest energy protons and associated secondary gamma-rays and neutrinos propagating through extragalactic magnetic and radiation fields

F.A. Aharonian, S.R. Kelner, and A.Y. Prosekin
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-6917 Heidelberg, Germany
(Dated: June 8, 2010)

The angular, spectral and temporal features of the highest energy protons and accompanying them secondary neutrinos and synchrotron gamma-rays propagating through the intergalactic magnetic and radiation fields are studied using the analytical solutions of the Boltzmann transport equation obtained in the limit of the small-angle and continuous-energy-loss approximation.

PACS numbers: 96.50.sb, 13.85.Tp, 98.70.Sa, 98.70.Rz

I. INTRODUCTION

Because of deflections in the interstellar and intergalactic magnetic fields, the information about the original protons \( \theta \propto B/E \). However at energies significantly below \( 10^{20} \) eV, the deflection in galactic magnetic fields becomes the dominant factor leading to the loss of information about the original directions of particles (see, e.g., Ref. [1]).

5 Jun 2010
mean free path of protons in IGM due to interactions with CMBR at $z \ll 1$

mean deflection angle of protons for fixed final (observed) energy $E_f$ for IGM $B=1$ nG; $\lambda=1$ Mpc. Numbers at curves are energies of protons at distance $r$ from the observer.
mean free path of protons in IGM due to interactions with CMBR at \(z<<1\)

mean deflection angle of protons for fixed final (observed) energy \(E_f\) for IGM \(B=1\) nG; \(\lambda=1\) Mpc. Numbers at curves are energies of protons at distance \(r\) from the observer.

detection of \(10^{21}\) eV protons very important!
energy spectra of protons within different solid angles

\[
dN/dE = AE^{-\alpha} \exp(-E/E_0); \alpha = 2, \ E_0 = 3 \times 10^{20} \text{eV}; \\
L_p = 10^{44} \text{ erg/s}; B = 1 \text{nG}; \lambda = 1 \text{Mpc}
\]

“bump” (just before the cutoff) - due to interactions with CMBR
“sharp maximum” - due to the magnetic “filter”
for $B$ between $10^{-9}$ to $10^{-7}$ G electrons are produced within 10 Mpc and radiate predominantly through synchrotron radiation before any significant deflection => point-like GeV/TeV gamma-rays and EeV neutrinos (FA 2002; Gabici&FA 2005)

**FIG. 4:** Energy loss rates of electrons due to inverse Compton scattering on CMBR photons (solid line) and synchrotron radiation in random magnetic field for $B=1$ nG, 10 nG, and 100 nG. For electrons of energy $E \gtrsim 10^{19}$ eV the inverse Compton scattering on the radiowaves of CRB becomes comparable or even can exceed the contribution of the Compton scattering on CMBR, however for IGMF $B \gtrsim 1$ nG the synchrotron radiation remains the main cooling channel.

**FIG. 5:** Number of electrons of energy $E_e$ located inside a sphere of the radius $r$. 
distributions of secondary photons, electrons, neutrinos from photomeson interactions

second generation of electrons from (B-H) pair production of γ-rays more important than the contribution from the first generation of electrons
secondary electrons

\[ E^2 \frac{dN}{dE} \text{, eV s}^{-1} \]

1: \( E_p = 6.4 \times 10^{19} \text{ eV} \)
2: \( E_p = 10^{20} \text{ eV} \)
3: \( E_p = 3 \times 10^{20} \text{ eV} \)

“photomeson electrons”

B-H pairs

Kelner&FA 2008
energy spectra of synchrotron radiation of secondary (pion-decay) electrons within different angles

\[ E^2 F(E), \text{erg cm}^{-2} \text{s}^{-1} \]

\[ E, \text{eV} \]

\[ r=100 \text{ Mpc} \]
\[ B=1 \text{ nG} \]

\[ 1 - 0.05^\circ \]
\[ 2 - 0.16^\circ \]
\[ 3 - 0.5^\circ \]
\[ 4 - 1.6^\circ \]
\[ 5 - 5^\circ \]

\[ E_0=1 \times 10^{21} \text{eV} \]
\[ E_0=3 \times 10^{20} \text{eV} \]
\[ E_0=1 \times 10^{20} \text{eV} \]

\[ dN/dE=AE^{-\alpha} \exp(-E/E_0) \] with \( \alpha=2, L_p=10^{44} \text{ erg/s}; B=1\text{nG}; \lambda=1\text{Mpc} \]
Energy spectra of synchrotron radiation of secondary (pion-decay) electrons within different angles

\[ \frac{dN}{dE} = AE^{-\alpha} \exp\left(-\frac{E}{E_0}\right) \]

with \( \alpha = 2 \), \( E_0 = 3 \times 10^{20} \) eV; \( L_p = 10^{44} \) erg/s

- \( B = 100 \) nG
- \( B = 10 \) nG
- \( B = 1 \) nG

\( r = 100 \) Mpc

\( E_0 = 3 \times 10^{20} \) eV

1 - 0.05°
2 - 0.16°
3 - 0.5°
4 - 1.6°
5 - 5°
6 - 15.8°
neutrinos

\[ \frac{dN}{dE} = A E^{-\alpha} \exp\left(-\frac{E}{E_0}\right) \] with \( \alpha = 2 \), \( L_p = 10^{44} \text{ erg/s} \); \( B = 1 \text{ nG} \)
spectral energy distribution of gamma rays, muon neutrinos and protons*

dN/dE=AE^{-\alpha} \exp(-E/E_0) \text{ with } \alpha=2, \ E_0=3 \times 10^{20} \text{ eV}; \ L_p=10^{44} \text{ erg/s}; \ B=1 \text{nG}

✓ if protons escape the source within a small angle towards the observer $\delta \Omega$, all fluxes are increased by a factor of $4\pi/\delta \Omega$

✓ if CR sources are located well beyond 100 Mpc - no chances to detect protons but synchrotron GeV-TeV $\gamma$-rays and EeV neutrinos can be yet observed
arrival time distribution of protons

\[ f_{A,B} \text{, arb. units} \]

A. detection of protons with arbitrary arrival angles;

B. protons arriving along the radius-vector at the registration point

\[ \lg y = \lg \tau - 2 \lg r - \lg \lambda - 2 \lg B + 2 \lg E + \text{const} \]

E=10^{20} \text{ eV; } L_p=10^{44} \text{ erg/s; } B=1 \text{ nG, } d=10 \text{ Mpc}
CR sources at high redshifts

\[ F(z, E, \theta) = \frac{2\pi}{(1 + z)^2} \left( \frac{r}{b} \right)^{b\theta/r} \int_0^r f_z(r, E(1 + z), x) x \, dx \]

The mean free path of protons in CMBR

Number of electrons of energy \( E \) located inside a sphere of the radius \( r \)
CR sources at high redshifts: gamma-ray detectability

- Narrow angles < PSF of LAT
- Increase of angular size for high \( z \)

\[ \theta_{\text{beam}} = 10^\circ \]

\[ L_p(E_p > 10^{19}\text{eV}) = 10^{45}\text{ erg/s} \]

Conclusions

there are all reasons to believe that future GeV/TeV gamma-ray observations will contribute (are already contributing!) to the solution of the long-standing problem of the origin of both Galactic and Extragalactic Cosmic Rays, in particular

1. Extragalactic Cosmic Rays:

GeV/TeV (i) demonstration of hadronic origin of gamma-rays from some sub-populations of AGN and GRBs; (ii) discovery of point like but not variable sources (with or without identifications); (iii) γ-rays from galaxy clusters and Pair Halos (iv) derivation of luminosity of entire Universe through correct measurement and interpretation of the diffuse extragalactic gamma-ray background
2. Galactic Cosmic Rays:

**GeV:** (i) low-energy CR accelerators; (ii) “relics” of powerful PeVatrons; (iii) “sea” of Galactic CRs; (iv) total CR acceleration power of the Universe

**TeV:** (i) SNRs as young proton TeVatrons; (ii) other proton TeVatrons/PeVatrons; (iii) search for old PeVatrons through “delayed” very hard emission from GMCs;

**GeV/TeV:** (i) external nearby (ordinary and starburst) Galaxies and (ii) Fermi-Bubbles