Gamma-Ray Observations of COSMIC Accelerators

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Literature (phenomenologist’s menu):

Schönfelder, V.: The Universe in Gamma Rays Springer 2001


+ lots of up-to-date topical reviews in arXiv!
Outline of Lectures

Gamma-rays as messengers of the energetic universe

*Better observations as result of progress in instrumentation*
→ the chronological perspective (not yet with 1st GLAST results)

*Observables in gamma-ray astronomy – what do we actually measure?*
→ the observers perspective
→ three regimes: 511 keV ↔ ~30 MeV ↔ ~50 GeV ↔ 100 TeV

*Cosmic accelerators observed through γ-rays – the global picture*
→ the perspective involving primary particles/nuclei: Cosmic Rays

*Taxonomy: The zoo of cosmic gamma-ray sources*
→ identifying γ-ray sources with astronomical objects
→ periodic variable γ-ray sources
→ stochastic variable & transient γ-ray sources
→ steady γ-ray emitter & our anticipation of new source classes
Unlike many branches of physics founded on elaboration and analysis of experiments, particle astrophysics is a science of observation, based on the detection and study of messengers sent by celestial bodies.

**Messengers of the energetic universe**
- Electromagnetic radiation (from radio waves to gamma rays)
- Particles (protons & nuclei, electrons, neutrons, neutrinos, …)
- Gravitational waves

**Observables in gamma astronomy**
- Direction of arrival
- Energy
- Time of arrival
- Flux

*That’s it! Nothing else!*
1st Observable: Photon arrival direction

Locate celestial sources: astrometry

Unfortunately, source localization in HE astrophysics not good

(→ source confusion, ambiguity in source identifications, diffuse processes vs. unresolved sources)

products: celestial images / skymaps / source catalogs

Study morphologies: diffuse, extended, point-like

Allows us to study spatial multiwaveband associations

→ signatures of non-thermal emission mechanisms

(synchrotron features? expanding shocks? jets? … )

→ decisive clue to its identification
**1st Observable: Photon arrival direction**

*Point sources*
Angular size smaller than the instrument point spread function (PSF)
Background is a severe issue (except for focusing instruments)

*Extended sources*
Angular size > PSF, the source is resolved into many pixels
The statistics per image element is usually rather low
Background is a much more severe issue, instrumental sensitivity loss

*Main sources of background*
Charged particles within the detector
Actual messengers produced in the close environment
Actual messengers produced in the atmosphere
Actual messengers produced in the Galaxy
Actual messengers produced in the universe (cosmic background)
The Point Spread Function

Point Spread Function (PSF)

2D Point Source Image at 275 MeV

PSF Characterized by 68% & 95% Containment

Crab viewed with EGRET

Crab viewed with HEGRA-IACT

... and yes, they are in scale!
2nd Observable: Photon energy

Lines spectra: basis of astrophysics
Atomic physics of emitting (absorbing) media, Doppler shift, redshifts (cosmological, gravitational), …
HE domain: cyclotron features, nuclear lines (nuclear astrophysics), Annihilation lines

Continuum spectra: basis of HE astrophysics
Signature of non-thermal emission mechanisms
Signature of absorption processes

Responses of HE telescopes
HE telescopes generally answer in a rather complex manner to the photons (particles) released by cosmic sources
In particular, the count energy spectra differ markedly from the incident photon (particle) spectra

products: photon or energy spectrum, width in γ-ray lines
Two observables used: arrival direction & energy

- Gamma rays ($E_\gamma > 100$ MeV)
- Radio waves (408 MHz)
- Gamma rays ($E_\gamma = 1.8$ MeV)
- Gamma rays ($E_\gamma = 511$ keV)
3rd Observable: Arrival Time

An extremely powerful observable

Source size upper limit

Periodic behavior (binaries, pulsars, …)

Pseudo periodic behavior (QPO)

Source identification (light curve similarities)

Source identification (transient emission in coincidence)

Timing is well adapted to HE astrophysics

Many phenomena in $\gamma$-ray sources are highly variable

HE telescopes operate in an event by event manner*

Long observation time, survey capabilities

products: rate changes, light curves, phase-folded signals
In single photon counting experiments: Just count and keep time!

Problem: celestial and instrumental backgrounds

Calibrations (ground, Monte-Carlo, sky, relative vs. absolute)

Different responses to different phenomena (e.g. coded mask ↔ source extension)

Monitoring of activity states → flux/time domain: alerts, campaigns

Intensity ↔ distance estimates from astronomical tools

Interstellar absorption

Galactic rotation

products: fluxes (and flux uncertainties) → spectral energy distribution
Cosmic source of calibration

\[ \nu F_\nu (W) \]

Frequency \( \nu \) (Hz)

radio

visible

X rays

soft

hard

gamma rays

from space

from ground

Crab Nebula

10 GeV

300 GeV

10 TeV

100 TeV

10^{26}

10^{27}

10^{28}

10^{29}

10^{30}

10^{31}

10^{10}

10^{15}

10^{20}

10^{25}

10^{30}
Cosmic Rays and particle acceleration in our Universe

“...The results of my observations are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above.”
Victor Franz Hess (1912)

But we still fail to settle on the sources & acceleration of Cosmic Rays!

[adapted from Gaisser’05]
Cosmic Rays and particle acceleration in our Universe

Energy density \( \text{erg cm}^{-3} \)
- Cosmic Rays: \(~1.0 \times 10^{-12}\)
- Starlight: \(~0.7 \times 10^{-12}\)
- ISM pressure: \(~0.4 \times 10^{-12}\)
- \(B:\) \(~1.0 \times 10^{-12}\)

Galactic luminosity:
- Stars: \(~10^{44}\) erg/s
- CR sources: \(~10^{41}\) erg/s

CRs seem to be blend of many galactic / extragalactic accelerators!

\[ 10^{20} \text{ eV} = 16 \text{ J (lift 1 kg by 1.5m!)}\]
Cosmic-ray origin?

observables

- Arrival direction
- Intensity
- Energy spectrum
- Composition

- energy density: $\rho_{\text{CR}} \sim 1.8 \text{ eV/cm}^3$
  
  $\rho_{\text{CR}} \sim \rho_{\text{B}} \sim \rho_{\text{P}}$

- galactic CR energy content:
  
  $\rho \times (15 \text{ kpc} \times 15 \text{ kpc} \times 3 \text{ kpc})$, renewed every $10^7$ years

  $\Rightarrow 2 \times 10^{41} \text{ erg/s}$

  1 SN of $10^{51} \text{ erg}$ every 30 years $\Rightarrow 10^{42} \text{ erg/s}$

$\Rightarrow 20\%$ of the SN energy could energize galactic cosmic-rays
How to approach the enigmatic cosmic accelerators?

Theoretical: processes and conditions for particle acceleration

Experimental:
build an accelerator and study how it works

visit a 'natural' accelerator and measure the energetic particles directly:
• lightning flashes
• earth magnetosphere – bow shock
• interplanetary shock waves
• solar flares

look at secondary emission:
• electromagnetic spectrum (from radio to gamma-rays)
• neutrinos (tough!)

look at our most pristine primaries:
• UHECRs (tough!)
• gravitational waves (toughest!)
Basic Cosmic Accelerator Schemes

- **Fermi – I:** momentum convection
- **Fermi – II:** momentum diffusion
- **EM Accelerator**
Cosmic Acceleration environments

– Electrostatic Fields
  • Pulsars

– Magnetic Fields
  • Near Compact Stars \( \rightarrow \ldots \sim 10^{13} \text{G} \)
  • Stellar Environments & SNe \( \rightarrow \ldots \sim \text{G} \)
  • Galactic and Intergalactic Space \( \rightarrow \ldots \sim \text{mG} \)
  • Turbulent Magnetic Fields in Shocked Gas
    – Jets (AGN, \( \mu \text{QSOs} \), GRB, …)
    – SNR, stellar wind blown bubbles, superbubbles?

Spectral shapes and evolution are coupled to the size, temporal evolution and geometry of the accelerating sources!
Cosmic Particle Accelerators?

Size ~ Gyro-Radius

$E_{\text{max}} \propto \beta \cdot Z e \cdot B \cdot L$

[Diagram showing magnetic field versus size with various cosmic particle sources labeled.]
Where and what are the CR sources?

- Deflection of charged particles in interstellar magnetic fields

- For a given interstellar or intergalactic magnetic field and a given energy:
  → expect anisotropies at highest energies (AUGER results!)
  → however: arrival direction of particles isotropized (10^{-3} at 1 TeV)

- Turn to neutral messengers:
  - Photons
    - Radio
    - X-rays
    - γ-rays
  - or … Neutrinos
CR origin and propagation

γ-rays from secondary interactions:

p: $\pi^0$ production and decay

e: Inverse Compton scattering and bremsstrahlung

→ trace beam density x target density
The main photon production processes

- **Proton** accelerator:
  - Hadronic interaction, $\pi_0$-decay
  
  \[ p + p \rightarrow \pi^0 + X + \ldots \pi^\pm \]
  
  \[ \gamma + \gamma \rightarrow \nu_\mu + \nu_e \ldots \]

- **Electron** accelerator:
  - Synchrotron emission in magnetic field at radio to X-ray energies
  - Inverse Compton scattering off photon fields (CMB, ...) at $\gamma$-ray energies

[From W. Hofmann]
The technical challenges in observational gamma-ray astronomy

\[ \gamma \text{-ray detector} \]

No Optics: Detector Area = Collection Area
How to catch a $\gamma$-ray?

$\gamma$ - radiation

*focusing through Bragg diffraction

$2d_{hkl} \sin \theta = n\lambda$
Gamma rays cannot be detected directly on the ground

Atmosphere $\approx 1 \text{ m solid lead}$

No celestial photons* reach the ground.
Solutions to problem of Atmosphere

γ-rays

low E    high E

γ-ray detector

Move detectors up!
...but even Mt. Everest is below
half an atmosphere
One solution to problem of Atmosphere

γ-rays
low E  high E

γ-ray satellite

Move detectors up!
..but even Mt. Everest is below half an atmosphere

Artificial mountain!
Mountain of money := space-based γ-ray astronomy*

*quote by Trevor Weekes
Another solution to problem of Atmosphere

γ-rays

high E / ultra-high E / very high E

γ-ray detector

Use atmosphere!
Detect secondaries (Cherenkov light) from the secondaries (photon messenger) of our cosmic particle accelerators! ...and thereby gaining a huge collection area...
A misleading name – and a controversy

1912
Discovery of Cosmic Rays by Victor Franz Hess « Ultragamma-Strahlung »

1929
Bothe and Kolhörster proof charged particle nature of Cosmic Rays

1932
The dispute on the nature of Cosmic Rays erupts again
Radio astronomy leads the way

- **1933**: Jansky discovers radio emission from our own Galaxy.
- **1944**: Reber produces first radio sky maps.
- **1948**: P.M.S. Blackett: Cherenkov radiation constitutes small fraction of night sky light.
- **1950**: Kiepenheuer suggests CR $e^-$ as common source of radio emission.
An astronomical discipline?

Hutchinson: Prediction of diffuse $\gamma$-ray emission from CR via bremsstrahlung

Hayakawa: Prediction of diffuse $\gamma$-ray emission from $\pi_0$ decay in Galaxy

Galbraith & Jelley 1953: “Light Pulses from the Night Sky associated with Cosmic Rays”

Morrison: « On Gamma-Ray Astronomy »

1952

1953

1958

A trashcan setup made it into Nature!

...predates birth of X-ray astronomy!
The 60ies: Photon counting

- **1958**: Peterson & Winckler. Solar flare $\gamma$-ray outburst by balloon experiment.
- **1962**: Arnold et al. $0.4 - 2$ MeV $\gamma$-ray spectra by Explorer 11.
- **1968**: Kraushaar & Clark. 22 high-energy photons by Explorer 11.
- **1972**: Crab nebula in TeV: Grindlay (1971, 1972) and Fazio et al. (1972).
1970 to 1990: Discoveries turn in

Nuclear lines

- e\(^+\) e\(^-\) annihilation line
  - Johnson et al. (1972)

- Radioactive \(^{26}\)Al
  - Mahoney et al. (1984)

Crab nebula > 700 GeV
- Weekes et al. (1989)

SMM
- OSO-7
- HEAO-1
- HEAO-3
- COS-B
- SAS-2

Mayer-Hasselwander et al. (1982)
The 90ies: An observatory in orbit, finally

April 5, 1991

CGRO

OSSE: keV to MeV spectroscopy

COMPTEL: mapping the sky in MeV

BATSE: locating 2704 γ-ray bursts

EGRET: mapping the sky above 100 MeV
**Three major branches**

511 keV … 30 MeV nucleosynthesis

30 MeV … 50 GeV satellite-based

50 GeV … 100 TeV ground-based

“γ-ray line observations”

“HE γ-ray observations”

“VHE γ-ray observations”

Coded mask & Compton

Principle realized in

INTEGRAL

SWIFT

HETE

(in orbit)
SPI aboard INTEGRAL
First detected, still puzzling: $e^+e^-$ annihilation at 511 keV

Either directly ($2\gamma$ of $E = 511$ keV each),
or, after formation of Positronium (Ps), with probability $f$

\[ T = 1.25 \times 10^{-10} \text{ s} \implies 2\gamma \text{ of } E = 511 \text{ keV} \]

\[ T = 1.4 \times 10^{-7} \text{ s} \implies 3\gamma \text{ of } E \leq 511 \text{ keV} \]

\[ F_{2\gamma} = 2(1-f) + \frac{3}{4} \times 2f \quad \text{direct, paraPs} \]
\[ F_{3\gamma} = \frac{3}{4} \times 3f \quad \text{orthoPs} \]

\[ f = \frac{2}{1.5 + 2.25(F_{2\gamma}/F_{3\gamma})} \]

[from Prantzos]
Impressive spectral signature...
This year's feature:

1997: OSSE

<table>
<thead>
<tr>
<th>Galactic latitude (degrees)</th>
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<tbody>
<tr>
<td>10</td>
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interstellar medium

Heinz and Sunyaev (2002)

But are the hard X-ray detected LMXBs dominated by leptonic jet emission?

...but imaging the 511 keV line is hard!
Three major branches

511 keV ... 30 MeV
nucleosynthesis

30 MeV ... 50 GeV
satellite-based

50 GeV...100 TeV
ground-based

“γ-ray line observations”

“HE γ-ray observations”

“VHE γ-ray observations”

Coded mask & Compton telescopes

COMPTEL (1991-2000)
Mapping the sky at 1,809 MeV

just weeks: COMPTEL

maximum entropy method (MEM)

2 years: COMPTEL

... 5 years
...but when using another imaging technique.

multi-resolution imaging (MREM)
The 1.809 MeV line emission of $^{26}$Al ($\tau_{1/2}\sim720000$ y):

**COMPTEL (~2001)**
- demonstrates that this radioactivity reflects an entire population of massive, young stars in the Galaxy
- massive stars reach the terminal phases of their evolution and finally explode as supernovae
- corresponds to a rate of supernovae from massive stars (i.e. "Types Ib/c and II") of two per century

**INTEGRAL (2006)**
- $^{26}$Al source regions co-rotate with the Galaxy → Galaxy-wide origin

→ confirm our understanding of nucleosynthesis, not CR acceleration up to the knee
Gamma-ray sources from 0.75 to 30 MeV
Three major branches

511 keV ... 30 MeV
nucleosynthesis
“γ-ray line observations”

30 MeV ... 50 GeV
satellite-based
“HE γ-ray observations”

50 GeV...100 TeV
ground-based
“VHE γ-ray observations”
cross section for pair production dominant at $E_\gamma > 10$ MeV

cross section saturates at $\sim E_\gamma > 1$ GeV

Fig. 2: Photon cross-section $\sigma$ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where $x$ is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

→ $(e^+e^-)$ pair production telescopes
Past Gamma-Ray Satellites (size about in proportion)

- **1967-1968, OSO-3**
  - Detected Milky Way as an extended $\gamma$-ray source
  - 621 $\gamma$-rays

- **1972-1973, SAS-2**, ~8,000 $\gamma$-rays
  - + the Pulsars: Crab, Vela

- **1975-1982, COS-B**
  - Orbit resulted in a large and variable background of charged particles
  - + the 1st AGN: 3C273
  - ~200,000 $\gamma$-rays

- **1991-2000, EGRET**
  - Large effective area, good PSF, long mission life, excellent background rejection
  - >1.4 $\times$ 10$^6$ $\gamma$-rays
OSO-III 1967-1968

The begin of galactic $\gamma$-ray astronomy: Milkyway
The begin of extragalactic $\gamma$-ray astronomy: 3C273
• $\sim 1.4 \times 10^6 \gamma$, $\sim 60\%$ interstellar emission from the MW
• $\sim 10\%$ are cataloged (3EG) point sources
Different phenomena at $E > 100$ MeV
Present Gamma-Ray Satellites

- **2007-…, AGILE**
  
  30 kg instrument, small detector size compensated through precise track detector (Si-strip), larger incidence angle possible
  
  "-" mini-calorimeter
  
  "+" SUPER-AGILE

- **2008-…, GLAST**
  
  got it all (large collection area, precision tracker, deep calorimeter, modularity, wide field of view, default observation mode survey, high time resolution, wide spectral coverage GBM+LAT)

! Dedicated GLAST lecture Aug 14 !
Still simulated, but only days before entering the scene: GLAST 2008-2013...18...?

- Based on what we know so far, and anticipate from instrument performance
- Surprises ahead, it may look different, when looked at close
Three major branches

511 keV ... 30 MeV  
nucleosynthesis

30 MeV ... 50 GeV  
satellite-based

50 GeV...100 TeV  
ground-based

“γ-ray line observations”  
“HE γ-ray observations”  
“VHE γ-ray observations”
The VHE frontier

• First Generation Systems 1960 – 1985
  • Weak or no discrimination
  • Lebedev, Glencullen, Whipple, Narrabri, Crimea,..

• Second Generation Systems 1985 – 2003
  Atmospheric Cherenkov Imaging Telescopes
  • Whipple, Crimea, CAT, Durham, CANGAROO
  • Stereoscopy: HEGRA
  • A sideway: Celeste, Stacee, Cactus, Graal
  • Wavefront sensing shower arrays: Milagrito

New technology:

Zero $\sim 12$ TeV sources
Past sensitive ACT detectors

... i.e. those having discovered or made major contributions to field

7TA

Whipple

HEGRA

CAT

Durham Mk VI
The VHE frontier

- First Generation Systems 1960 – 1985
  - Weak or no discrimination
  - Lebedev, Glencullen, Whipple, Narrabri, Crimea,..

  - Atmospheric Cherenkov Imaging Telescopes
    - Whipple, Crimea, CAT, Durham, CANGAROO
    - Stereoscopy: HEGRA
    - A sideway: Celeste, Stacee, Cactus, Graal
    - Wavefront sensing shower arrays: Milagrito

- Third Generation Systems 2003 – 201x
  - CANGAROO-III, HESS-4, MAGIC, VERITAS-4
  - Extensions: MAGIC-2, HESS-5
  - overcome gamma/hadron separation problem: Milagro, Argo
Current VHE $\gamma$-ray world

VERITAS
MAGIC
VERITAS
H.E.S.S.
CANGAROO II
CANGAROO III
H.E.S.S.
CANGAROO-III
most sources extended; source positions measured at arc min. level, best to ∼10″