Exploring Nature’s Extreme Particle Accelerators with Very High Energy Gamma Rays

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Gamma Ray Astronomy

a modern interdisciplinary research field at the interface of
astronomy, physics and cosmology

with the major objective: study of nonthermal phenomena
most energetic and violent forms in the Universe

many research topics are related, in one way or another, to
exploration of Nature’s perfectly designed machines:

Extreme Particle Accelerators
the last E-M window ... 15+ decades:

<table>
<thead>
<tr>
<th>Band</th>
<th>Symbol</th>
<th>Low Bound</th>
<th>High Bound</th>
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<tbody>
<tr>
<td>LE</td>
<td>MeV</td>
<td>0.1 -100</td>
<td>(0.1 -10 + 10 -100)</td>
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<tr>
<td>HE</td>
<td>GeV</td>
<td>0.1 -100</td>
<td>(0.1 -10 + 10 -100)</td>
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<tr>
<td>VHE</td>
<td>TeV</td>
<td>0.1 -100</td>
<td>(0.1 -10 + 10 -100)</td>
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<tr>
<td>UHE</td>
<td>PeV</td>
<td>0.1 -100</td>
<td>(only hadronic)</td>
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<tr>
<td>EHE</td>
<td>EeV</td>
<td>0.1 -100</td>
<td>(GZK-cutoff related)</td>
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low bound - nuclear gamma-rays, upper bound - highest energy cosmic rays

the window is opened in MeV, GeV, and TeV bands:

LE,HE  domain of space-based astronomy
VHE,.... domain of ground-based astronomy

1MeV=10^6 eV, 1GeV=10^9 eV, 1TeV=10^{12} eV, 1PeV=10^{15} eV, 1EeV=10^{18} eV
Gamma Ray Astronomy:  a part of multiwavelength astronomy  

but, at the same time, a discipline in its own right

- ‘Ground-based’: presently 3-decades from 0.1 to 100 TeV (TeV astronomy!)  
  potentially:  significant extension down to 10 GeV and up to 1 PeV (5 decades)

- Fermi/Agile: presently E: 3-decades: 0.1 to 100 GeV (GeV Astronomy!); t~10yr:  
  broader coverage but not significantly beyond 100 GeV and below 100 MeV

- 10-100 GeV - very interesting perspectives very-low-energy threshold  
  Chereknov Telescopes operating together with Fermi LAT as an all sky monitor

- MeV astronomy - hopeless or the next breakthrough ?
gamma-rays – unique carriers of information about high-energy processes in the Universe

- are effectively produced
  in electromagnetic and hadronic interactions

- penetrate freely throughout
  intergalactic and galactic magnetic and photon-fields

- are effectively detected
  by space-based and ground-based detectors
other astronomical messengers?

astronomical messengers should be neutral & stable:

*photons and neutrinos satisfy fully to these conditions*

but partly also ultra-high energy neutrons and protons ...

**neutrons:** \[ d < (E_n/m_n c^2) c \tau_0 \Rightarrow E_n > 10^{17} (d/1 \text{ kpc}) \text{ eV} \]

galactic astronomy with \( E > 10^{17} \) eV neutrons

**protons:** \[ \phi < 1^\circ \text{ if } E > 10^{20} \text{ for IGMF } B < 10^{-9} \text{ G} \text{ eV} \]

extragalactic astronomy with \( E > 10^{20} \) eV protons
carriers of information about Nature’s Particle Accelerators

neutral/stable secondary products of EM and hadronic interactions of electrons, protons and nuclei with plasma, radiation and B-fields

photons and neutrinos

**cosmic accelerator**

- **γ-rays** - produced in hadronic and E-M interactions
- **νμ, νe** - produced only in hadronic interactions
high energy cosmic gamma-rays

a few general remarks ...
extreme physical conditions...

generally the phenomena relevant to HEA generally proceed under extreme physical conditions in environments characterized with

- huge gravitational, magnetic and electric fields,
- very dense background radiation,
- relativistic bulk motions (black-hole jets and pulsar winds)
- shock waves, highly excited (turbulent) media, etc.

any coherent description and interpretation of phenomena related to high energy cosmic gamma-rays requires knowledge and deep understanding of many disciplines of experimental and theoretical physics, including

- nuclear and particle physics,
- quantum and classical electrodynamics,
- special and general relativity,
- plasma physics, (magneto) hydrodynamics, etc.

and (of course) Astronomy/Astrophysics
conventional radiation/absorption processes

any interpretation of an astronomical observation requires

✓ unambiguous identification of radiation mechanisms and
✓ good knowledge of radiation and absorption processes

in any wavelength band, especially in gamma-ray domain

therefore deep understanding of physics of radiation and absorption mechanisms is a key issue in astrophysics

gamma-ray production and absorption processes: several but well studied
**gamma-ray production:** particle accelerator + target

existence of a powerful particle accelerator by itself is not sufficient for $\gamma$-radiation; an additional component – a dense target - is required

any gamma-ray emitter coincides with the target, but not necessarily with the “primary” source/particle-accelerator
a few examples
TeV γ-ray image - shell type morphology:
shock acceleration of $p$ or $e$ in the shell
To energies exceeding 100TeV

even we ignore the IC contribution, the proton spectrum should have a cutoff around 100 TeV - *no PeV protons?*

$\gamma$-rays from $pp \rightarrow \pi^0 \rightarrow 2\gamma$?
$\alpha_p \sim 2$ and $E_0 \sim 100$ TeV
Gamma-rays and neutrinos inside and outside of SNRs

1 - 400yr, 2 - 2000yr, 3 - 8000yr, 4 - 32,000 yr

**Gamma-rays**

**SNR**: $W_{51} = n_1 = u_9 = 1$

**ISM**: $D(E) = 3 \times 10^{28} (E/10\text{TeV})^{1/2} \text{ cm}^2/\text{s}$

**GMC**: $M = 10^4 \ M_\odot$  $d = 100\text{ pc}$

[S. Gabici, FA 2007]
highest energy particles, $E > 100$ TeV, are confined in the shell only during a few 100 years $\Rightarrow$ most promising search for PeVatrons? multi-TeV $\gamma$-rays from dense gas clouds in the near neighborhood

**surrounding gas density:**

*NANTEN* data

**age:**

1600 yr

**escape of protons:**

model of Zirakashvili&Ptuskin 2008

**diffusion coefficient outside SNR:**

$D=10^{26} \left(\frac{E}{10\text{GeV}}\right)^{0.5} \text{ cm}^2/\text{s}$
2.7 K CMBR and VHE gamma-rays

HESS J0835-456 (Vela X): a PWN

gamma-rays are produced due to IC scattering of multi-TeV electrons on 2.7 K, X-rays - due to synchrotron radiation of same electrons

since 2.7 K MBR is the main target field, TeV images reflect spatial distributions of electrons \( Ne(E,x,y) \); coupled with synchrotron X-rays, TeV images allow measurements of \( B(x,y) \)
$p + 2.7K \Rightarrow \pi^- \Rightarrow e, \gamma, \nu$ and “prompt” synchrotron radiation of secondary electrons!

see Anton Prosekin’s talk
TeV gamma-rays from GC

**GC** — a unique site that harbors many interesting sources packed with unusually high density around the most remarkable object $3 \times 10^6$ Mo SBH – Sgr A* many of them are potential γ-ray emitters - **Shell Type SNRs, Plerions, Giant Molecular Clouds Sgr A * itself, Dark Matter ...**

all of them are in the FoV an IACT, and can be simultaneously probed down to a flux level $10^{-13}$ erg/cm$^2$/s and localized within $<< 1$ arcmin
**Galactic Center**

γ-ray emitting clouds

90 cm VLA radio image

- Sgr A* or the central diffuse < 10pc region or a plerion? [no indication for variation]

Energy spectrum:

\[
dN/dE = AE^{-\Gamma} \exp\left[-\left(E/E_0\right)^\beta\right]
\]

- \(\beta=1\) \(\Gamma=2.1\); \(E_0=15.7\) TeV
- \(\beta=1/2\) \(\Gamma=1.9\) \(E_0=4.0\) TeV

γ-rays from GMCs in GC: a result of an active phase in Sgr A* with acceleration of CRs some \(10^4\) yr ago?
0.3-3 GeV
3-30 GeV
30-300 GeV

\[ L_p \approx 10^{39} \text{ erg/s} \]
Fermi Bubbles!

Finkbeiner and collaborators  2010
"direct" detection of LE/HE gamma-rays - possible from space, but can be effective below 10 (100?) GeV

"indirect" detection of VHE gamma-rays - possible from ground, but is effective above 100 (10?) GeV

presently 10-100 GeV - a fully unexplored gap in the γ-ray spectrum, but in future likely to become one of most promising energy domains in γ-ray astronomy available both with space- and ground-based detectors
Fermi LAT
- limited (1 m²) detection area
- reasonable angular resolution
- very good (10-205%) energy resolution
- flux sensitivity => 10⁻¹³ erg/cm² s
- domain: 0.1 - 100 GeV with a potential of extension down to 20 MeV and up to 1 TeV?

IACT Arrays
- huge (>1km² or larger) detection area
- good (≥ 1arcmin) angular resolution
- good (10-205%) energy resolution
- flux sensitivity => 10⁻¹² erg/cm² s
- domain: 0.1 - 100 TeV with a potential of extension down to 10 GeV and up to 1 PeV?
neutrino telescopes

effective area: 0.3m$^2$ at 1 TeV
10m$^2$ at 10 TeV

\[ \Rightarrow \text{several events from a “1Crab” source per 1 year} \]

detection areas of neutrino telescopes \(<<\) detection areas of \(\gamma\)-ray detectors!

this fact should not be ignored, but should not be exaggerated either
probing hadrons with secondary hard X-rays with NASA-JAXA ASTRO-H

the JAXA-NASA mission ASTRO-H will provide X-ray imaging and spectroscopy in the hard X-ray band with angular resolution as good as few arcmin and minimum detectable energy flux down to $10^{-14}$ erg/cm$^2$s!

complementary to gamma-ray and neutrino telescopes

advantage - (a) comparable or better performance
           (b) compensates lack of neutrinos and gamma-rays at “right energies”

disadvantage - ambiguity of origin of X-rays
3 channels of information about cosmic PeVatrons:

- 10-100 TeV gamma-rays
- 10-1000 TeV neutrinos
- 10 -100 keV hard X-rays

- $\gamma$-rays: difficult, but possible with future “10km$^2$“ area multi-TeV IACT arrays

- neutrinos: detectable by a “several km3” neutrino telescope - don’t expect spectrometry, morphology; uniqueness - unambiguous signature!

- “prompt“ synchrotron X-rays: smooth spectrum $\propto \epsilon^{-(\alpha/2+1)} \exp[-(\epsilon/\epsilon_0)^{1/5}]$ a very promising channel - quality! ASTRO-H
GeV Sky:

The Fermi LAT 1FGL Source Catalog

Credit: Fermi Large Area Telescope Collaboration
July 2010:
113 TeV sources
72 Gal. / 41 EG

TeV Sky

J. Hinton
TeV gamma-ray astronomy - *a success story*

discovery of more than 100 TeV gamma-ray sources representing 10 (or so) Galactic and Extragalactic sources populations - a remarkable achievement

=> significant impact on several areas of modern Astrophysics

main factors which make possible this success? several factors...
but basically thanks to the lucky combination of two:

- effective acceleration of TeV/PeV particles on all astronomical scales coupled with favourable conditions for production of gamma-rays
- great potential of the detection technique
the major factors which make possible this success?

several factors... but basically thanks to the lucky combination of two:

- great potential of the detection techniques/high quality data
- effective acceleration of TeV/PeV particles on all astronomical scales coupled with favourable conditions for production of gamma-rays
good performance => high quality data => solid basis for theoretical studies

RXJ 1713.7-3946

Galactic Center

PKS 2155-309

multi-functional tools: spectrometry temporal studies morphology

extended sources: from SNRs to Clusters of Galaxies

transient phenomena \( \mu QSOs, AGN, GRBs, \ldots \)

Galactic Astronomy / Extragalactic Astronomy / Observational Cosmology
VHE gamma-ray observations:

“Universe is full of extreme accelerators on all astronomical scales”

Extended Galactic Objects

- Shell Type SNRs
- Giant Molecular Clouds
- Star formation regions
- Pulsar Wind Nebulae

Compact Galactic Sources

- Binary pulsar PRB 1259-63
- LS5039, LSI 61 303 - microquasars?
- Cyg X-1 ? (a BH candidate)

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Extragalactic objects

- M87, Cen A - radiogalaxy
- TeV Blazars - with redshift from 0.03 to 0.18
- NGC 253 and M82 - starburst galaxies
- GRBs (Fermi LAT; photons of tens of GeVs at z > 1)

and a large number of yet unidentified TeV sources ...
Potential Gamma Ray Sources

**Galactic Sources**

- ISM
- SFRs
- SNRs
- Pulsars
- Binaries

**Extragalactic Sources**

- GRBs
- AGN
- GLX
- CLUST
- IGM

**Major Scientific Topics**

- G-CRs
- Relativistic Outflows
- Compact Objects
- EXG-CRs
- Cosmology

**GeV**

- GMCs
- Magnetosphere
- Cold Wind
- Pulser Nebula
- Microquasars
- Binary Pulsars

**EBL**

**GeV**

- Blazars
- Radiogalaxies
- Normal
- Starburst

**GeV**

- Normal
- Starburst

**GeV**

- Normal
- Starburst
first lesson from recent observations: Universe is full of Extreme Accelerators - TeVatrons and PeVatrons

machines where acceleration proceeds with efficiency close to 100% efficiency?

(i) fraction of available energy converted to nonthermal particles

in PWNe and perhaps also in SNRs, can be as large as 50%.

(ii) maximum (theoretically) possible energy achieved by individual particles

acceleration rate close to the maximum (theoretically) possible rate

sometimes efficiency can “exceed” 100% (!) e.g. at CR acceleration in SNRs in Bohm diffusion regime with amplification of B-field by CRs ($E_{\text{max}} \sim B (v/c)^2$) this effect provides the extension of the spectrum of Galactic CRs to at least 1 PeV

“> 100% efficiency” because of nonlinear effects:

acceleration of particles creates better conditions for their further acceleration
Galactic Cosmic Rays from $10^9$ to $10^{15}$ eV

up to $10^{15-16}$ (knee) - Galactic

most likely sources: Supernova Remnants
SNRs: $E_{\text{max}} \sim v_{\text{shock}} Z \times B \times R_{\text{shock}}$

“standard” DSA theory: $E_{p,\text{max}} \sim 10^{14}$ eV
solutions? amplification of $B$-field by CRs

$10^{16}$ eV to $10^{18}$ eV:
  a few special sources? Reacceleration?

above $10^{18}$ eV (ankle) - Extragalactic

$10^{20}$ eV particles? : two options
  “top-down” (non-acceleration) origin or Extreme Accelerators

T. Gaisser
Particles in CRs with energy $10^{20}$ eV

The very fact of existence of such particles implies existence of extragalactic extreme accelerators…

The “Hillas condition” - $l > R_L$ - an necessary but not sufficient condition…

(i) Maximum acceleration rate allowed by classical electrodynamics

$t^{-1} = \eta qBc$ or $c/R_L$ with $\eta \sim 1$ and $\sim (v/c)^2$ in shock acceleration scenarios

(ii) B-field cannot be arbitrarily increased - the synchrotron and curvature radiation losses become a serious limiting factor, unless we assume… perfect linear accelerators!

Only a few options survive from the original Hillas (“l-B”) plot:

$>10^9 M_\odot$ BH magnetospheres, small and large-scale AGN jets, GRBs
acceleration sites of $10^{20}$ eV CRs?

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

signatures of extreme accelerators?

- synchrotron self-regulated cutoff:
  $$\hbar \nu_{\text{cut}} = \frac{9}{4} \alpha_f^{-1} m c^2 \eta :$$

  $\simeq 300 \text{GeV}$ proton synchrotron
  $\simeq 150 \text{MeV}$ electron synchrotron

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

- observable off-axis radiation
  radiation pattern can be much broader than $1/\Gamma$

*) in nonrelativistic shocks
  $$\eta \approx 0.1 \left( \frac{v_{\text{shock}}}{c} \right)^2$$
Galactic TeVatrons and PeVatrons - particle accelerators responsible for cosmic rays up to the “knee” around 1 PeV

One of the highest priorities of TeV astronomy: experimental tests/demonstration that young SNRs operate as PeVatrons, and provide the bulk of the flux of Galactic CRs up to $10^{15}$ eV

Pulsars/Plerions?

OB, W-R Stars?

Microquasars?

Galactic Center?

* the source population responsible for the bulk of GCRs are PeVatrons?
Variability of X-rays on year timescales - witnessing particle acceleration in real time

flux increase - particle acceleration
flux decrease - synchrotron cooling *)

both require B-field of order 1 mG in hot spots and, most likely, 100 µG outside

strong support of the idea of amplification of B-field by in strong nonlinear shocks through non-resonant streaming instability of charged energetic particles (T. Bell 2001)

*) an alternative explanation: “variation of B-field”? should see variability also in radio band!
not likely, but cannot excluded in the case of RXJ1713.7-4639, however doesn’t work for Cassiopeia A - variation of X-ras in stable radio knots (Uchiyama & Aharonian 2008)
acceleration in Bohm diffusion regime at presence of strong B-field

energy spectrum of synchrotron radiation of electrons in the framework of DSA (Zirakashvili & FA 2007)

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

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

strong support for Bohm diffusion, given the upper limit on the shock speed of order of 4000 km/s!

B=100 \mu G + Bohm diffusion - acceleration to 1 PeV and… hadronic origin of gamma-rays! (?)
**RXJ 1713.7-3946**

**Protons:**

\[ \frac{dN}{dE} = K \ E^{-\alpha} \ \exp\left[-\left(\frac{E}{E_{\text{cut}}}\right)^\beta\right] \]

**γ-rays:**

\[ \frac{dN}{dE} \sim E^{-\Gamma} \ \exp\left[-\left(\frac{E}{E_0}\right)^{\beta\gamma}\right] \]

\[ \Gamma \approx \alpha + \delta\alpha, \ \delta\alpha \approx 0.1, \ \beta\gamma \approx \beta/2, \]

\[ E_0 \approx E_{\text{cut}}/20 \]

Neutrinos can be detected by KM3NeT (see talk by Piera Sapienza) but note large uncertainties in calculations of neutrino fluxes in the crucial energy band above 10 TeV (Villante & Vissani 2008)

\[ W_p(>1 \ \text{TeV}) \approx 0.5 \times 10^{50} \ (n/\text{cm}^{-3})^{-1} \ (d/1\text{kpc})^2 \]
**broad-band SEDs**

**hadronic model**

good spectral fit, reasonable radial profile, but …
(1) lack of thermal emission - possible explanation?
>70% energy is released in acceleration of protons!
(2) very high p/e ratio (10^4)

**leptonic model**

not perfect, but still acceptable, fits for spectral and spatial distributions of IC gamma-rays;
suppressed thermal emission, comfortable p/e ratio (~10^2); small large-scale B-field (~ 10 μG)

**“composite” model?**

gamma-rays detected by Fermi?
very important… but not decisive

Zirakashvili, FA 2010
the “composite” model

IC gamma-rays from (i) the entire shell with average small B-field and (ii) $\pi^0$-decay gamma-rays from dense clouds inside the shell not strong correlation is expected between GeV and with TeV gamma-ray image, but GeV and $E > 10$ TeV gamma-rays correlate with dense CO clouds detected by NANTEN recent reports from AGILE and Fermi LAT support spectral and morphological predictions of this scenario?

for decisive conclusions multi-messenger and multi-wavelength approach is needed

X-rays and neutrinos provide complementary information
Fermi Observations of Supernova Remnants

TeV $\gamma$-rays are produced in shells of young SNRs and in MCs close to mid-age SNRs. GeV $\gamma$-rays can be produced both in the shells of young and old SNRs and nearby GMCs. GeV $\gamma$-rays can be produced also through bremsstrahlung of electrons if $e/p > 0.1$.
Crab Nebula – a perfect PeVatron of electrons (and protons?)

Crab Nebula – a powerful $W_e = 1/5 \ L_{rot} \ \omega$ $10^{38}$ erg/s

and extreme accelerator: $E_e \gg 100 \ TeV$

$E_{max} = 60 \ (B/1G)^{-1/2} \ \eta^{-1/2} \ TeV$ and $h\nu_{cut} \sim 150 \ \eta^{-1} \ MeV$

- Cutoff at $h\nu_{cut} = 10-20 \ MeV$ ? $\eta \sim 10$ - acceleration at 10 % of the max. rate
- $\gamma$-rays: $E_\gamma > 50 \ TeV$ (HEGRA, HESS) $\Rightarrow E_e > 200 \ TeV$
  
  B-field $\sim 100 \ \mu G$ $\Rightarrow \eta \sim 10$ - independent and more robust estimate
  
  $1 \ mG$ $\Rightarrow \eta \sim 1$ ?

standard MHD theory (Kennel&Coroniti)

cold ultrarelativistic pulsar wind terminates by reverse shock resulting in acceleration of multi-TeV electrons

synchrotron radiation $\Rightarrow$ nonthermal optical/X-ray nebula
Inverse Compton $\Rightarrow$ high energy gamma-ray nebula
Crab Nebula - news from AGILEE and Fermi LAT:

IC emission consistent with average nebular B-field: $B \sim 100 \mu G - 150 \mu G$

seems to be in agreements with the standard PWN picture, but … MeV/GeV flares!!

although the reported flares perhaps can be explained within the standard picture - no simple answers to several principal questions - extension to GeV energies, $B > 1 mG$, etc.

observations of 100 TeV gamma-rays - IC photons produced by electrons responsible for synchrotron flares - a key towards understanding of the nature of MeV/GeV flares!
variability of >100 MeV emission from Crab (Agile & Fermi)

The possible sites of acceleration of the second electron population could be the peculiar compact regions such as wisps, knots, etc. Since the equipartition magnetic field in these regions is estimated to be as high as few mG (in that case $E_2$ is reduced to $\sim 10^{14}$ eV) the highest energy electrons could not escape the acceleration sites due to severe synchrotron losses. Although these variable structures, with typical size 0.2'' (Hester, 1995), are not resolvable by low-energy $\gamma$-ray instruments, the detection of variability of the 1-100 MeV emission would be direct proof for the synchrotron origin of the "MeV bump".

Fig. 6.16 Synchrotron and IC radiation components produced by the first (solid) and second (dashed) populations of electrons (see text). The heavy solid line shows the total flux. The hatched region corresponds to $I(E) = (2.5 \pm 0.4) (E/1\text{ TeV})^{-2.5} \text{ cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$ which generally describes the reported fluxes from
TeV gamm-rays from other Plerions (PWNe) ?

Crab Nebula is a very effective accelerator
    but not an effective IC $\gamma$-ray emitter

we do see TeV $\gamma$-rays from the Crab Nebula because of very large spin-down flux: $f_{\text{rot}} = L_{\text{rot}}/4\pi d^2 = 3 \times 10^{-7}$ erg/cm$^2$ s

gamma-ray flux $\ll$ “spin-down flux“ because of large B-field

if the B-field is small (environments with small external gas pressure)

higher $\gamma$-ray efficiency $\rightarrow$ detectable $\gamma$-ray fluxes from other plerions

HESS confirms this prediction – many (20+) candidates associated with PWNe; firm detections - MSH 15-52, PSR 1825, Vela X, ...

only a few at GeV energies - good agreement with expectations?
Luminosities:

spin-down: \( L_{\text{rot}} = 3 \times 10^{36} \text{ erg/s} \)

X: 1-10 keV \( L_x = 3 \times 10^{33} \text{ erg/s} (< 5 \text{ arcmin}) \)

\( \gamma: 0.2-40 \text{ TeV} \) \( L_\gamma = 3 \times 10^{35} \text{ erg/s} (< 1 \text{ degree}) \)

the \( \gamma \)-ray luminosity is comparable to the TeV luminosity of the Crab Nebula, while the spin-down luminosity is two orders of magnitude less! Implications?

(i) magnetic field should be significantly less than 10 mG (<1 \( \mu \)G?)

**but… even for \( L_e = L_{\text{rot}} \) this condition alone is not sufficient to achieve 10% \( \gamma \)-ray production efficiency (Compton cooling time of electrons on 2.7K CMBR exceeds the source age)**

(ii) the spin-down luminosity in the past was much higher

Since 2.7 K MBR is the main target field, TeV images reflect spatial distributions of electrons \( \text{Ne(E,x,y)} \); coupled with synchrotron X-rays, TeV images allow measurements of \( B(x,y) \)!
\[ L_e = L_0 (1 + t/\tau)^{-2}, \quad \tau = 5300 \text{ yr} \]

\[ L_0 = 1.8 \times 10^{37} \text{ erg/s}; \quad R_s = 5 \times 10^{18} \text{ cm}; \quad \sigma = 10^{-3} \]

The ratio of \( \gamma \)-ray luminosity at energies between 0.1 TeV and 10 TeV to the current electron injection rate, \( L_e (>10 \text{ TeV}) \); if \( L_e \) is comparable to the pulsar spin-down luminosity \( L_{SD} \), the \( \gamma \)-ray "efficiency" could exceed 100%.

\[ R_s = 1.8 \text{ pc} \left( L_{SD}/10^{37} \text{ erg/s} \right)^{1/2} \left( p_{ext}/10^{-12} \text{ erg/cm}^3 \right)^{-1/2} \]

\[ B_s = 0.6 \mu \text{G} \left( L_{SD}/10^{37} \text{ erg/s} \right)^{1/2} \left( \sigma/3 \times 10^{-3} \right)^{1/2} \]
the first unidentified HESS source:  HESS J 13030-62

Dramatic reduction of the angular size with energy: strong argument in favor of the IC origin of the γ-ray nebula.

Very small average B-field; for d=12.6 kpc
L_γ/L_{SD} = 0.07; 3 arcmin ~ 10 pc
Vela X and MSH-15-52

both are of almost same age (10kyr), same power \( L_{\text{rot}} \sim 10^{37} \text{erg/s} \), and angular size, but very different luminosities, energy spectra, distances and … sizes!

because the small distance to Vela X, we see only a very small part of the nebula \( \Rightarrow \) very low luminosity, but also because of quick escape of electrons from this small area - we see IC spectrum of uncooled electrons

\[
L = 1.8 \times 10^{37} \text{ erg/s}, \ r_{\text{sh}} = 5 \times 10^{18} \text{s}, \ \sigma = 3 \times 10^{-3}, \ Q(E) = E^{-2.2} \exp(-E/300\text{TeV})
\]

Khangulyan, FA, Bogovalov 2010
PSR1259-63 - a unique high energy laboratory

**binary pulsars** - a special case with strong effects associated with the optical star on both the dynamics of the pulsar wind and the radiation before and after its termination

the same 3 components - *Pulsar/Pulsar Wind/Synch.Nebula* - as in PWNe*
both the electrons of the cold wind and shocke-accelerated electrons are illuminated by optical radiation from the companion star $\rightarrow$ detectable IC $\gamma$-ray emission

"on-line watch" of the MHD processes of creation and termination of the ultrarelativistic pulsar wind, as well as particle acceleration by relativistic shock waves, through spectral and temporal studies of $\gamma$-ray emission

(characteristic timescales 1 h or shorter !)

the target photon field is function of time, thus the only unknown parameter is B-field:

TeV electrons are cooled and and radiate in deep Klein-Nishina regime with very interesting effects on both synchrotron X-rays and IC $\gamma$-rays
explanation of the tendency of reduction of both X-ray and TeV gamma-ray fluxes towards the periastron: (1) adiabatic losses; (2) reduction of $E_{e,\text{max}}$

energy flux of starlight close to the periastron around $1 \text{ erg/cm}^3$

B-field is estimated between 0.1 to 1 G

predictable X and gamma-ray fluxes?

**HESS:** detection of TeV $\gamma$-rays from PSR1259-63 at $< 0.1\text{Crab}$ level several days before the periastron and 3 weeks after the periastron
the interpretation of the X-ray and TeV lightcurve by sub-TeV cutoffs is supported by the recent detection of GeV gamma-rays by Fermi LAT?

variation of the maximum energy of electrons due to IC losses

Bo=0.05 (Do/D) Gauss,
\[ t_{\text{acc}} = \eta r_L/c; \quad \eta = 4 \times 10^3 \]

nonrelativistic shocks?

minimum at periastron at high energies, but maximum - at low energies
probing the wind Lorentz factor with HESS and GLAST by the emission due to the Componization of the cold wind

probing the wind Lorentz factor with HESS and GLAST

reduction of the Lorentz factor of the wind ("deacceleration" of the wind) is not significant

\[ \Gamma > 10^6 \] are already excluded by HESS; the range of \( \Gamma = 10^3 \text{-} 10^5 \) can be probed by GLAST

Recent detection (by Fermi) +/- few weeks around periastron: \( 3 \times 10^3 < \Gamma < 10^5 \)

the gap between \( 10^5 \) to \( 10^6 \) can be probed with HESS-2!
LS 5039 - a binary system
works as a perfect TeV clock
and an extreme accelerator
close to inferior conjuction - maximum
close to superior conjuction – minimum

modulation of the gamma-ray signal? a quite natural reason (because of γ–γ absorption), but we see a different picture... anisotropic IC scattering? yes, but perhaps some additional factors (adiabatic losses, modest Doppler boosting) also play a non-negligible role
can electrons be accelerated to > 20 TeV in presence of radiation?

Yes, but accelerator should not be located deep inside binary system; even at the edge of the system $\eta < 10$

does this excludes the model of “binary pulsar”

Yes, unless the interaction of the pulsar and stellar winds create a relativistic bulk motion of the shocked material
Blazars - sub-class of AGN dominated by nonthermal/variable broad band (from R to γ) adiation produced in relativistic jets close to the line of sight, with massive Black Holes as central engines

before 2004:
detection of 6 TeV Blazars, extraordinary outbursts of Mkn 501 in 1999, variations on <1h timescales;
=> initiated huge interest in AGN and EBL communities

today:
more than three dozens TeV blazars; quite unexpectedly TeV γ-rays from distant blazars;

=> strong impact on both blazar physics and on the Diffuse Extragalactic Background (EBL) models

most exciting results - variability on 2-3 min timescales
unusually hard gamma-ray spectra
Mkn 501: $z=0.031$: an “infrared crisis”, but with a happy end…

reported EBL flux at FIR have not been confirmed

TeV blazars detected by HESS at $z>0.15$!

corrected for EBL absorption 
$\gamma$-ray spectrum not harder than $E^{-\Gamma}$ ($\Gamma=1.5$) $\Rightarrow$ u.l. EBL
HESS upper limits on EBL - good agreement with recent EBL studies

EBL (almost) resolved at NIR?

Gamma = 1.5

favored EBL – before HESS

HESS upper limits

lower limits from galaxy counts

"direct measurements"

upper limits

HESS upper limits

Gamma = 1.5

P1.0

P0.55

P0.45
1ES 0229+200 - a new "trouble-maker"

\( z = 0.14 \), but spectrum extends to \( >5 \) TeV! Even slight deviation from the "standard" EBL \( \Rightarrow \) extremely hard spectrum with \( \Gamma < 1 \).
Explanation 1: **SSC model with a power-law spectrum of electrons with high “low-energy” cutoff - no cooling**  =>  low magnetic field, $B<10^{-3}$ G

<table>
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<th></th>
<th>$\gamma_{\text{min}}$</th>
<th>$\gamma_b$</th>
<th>$\gamma_{\text{max}}$</th>
<th>$n$</th>
<th>$n_2$</th>
<th>$B$ (G)</th>
<th>$K$ (cm$^{-3}$)</th>
<th>$R$ (cm)</th>
<th>$\delta$</th>
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<td>$4 \times 10^7$</td>
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<td>3</td>
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<td>50</td>
</tr>
</tbody>
</table>

$B \sim 10^{-3}$ G: deviation from equipartition by many orders of magnitude!

Tavecchio et al. 2009

1ES 0229+200

$z=0.1396$
Explanation 1: *internal absorption* - can provide an arbitrary hardness, but generally requires very large field, $B \sim 100\ G$, to avoid cascading

range of parameters: $R \sim 10^{15}-10^{16}\ cm$, $B \sim 10-100G$; $L_r \sim 10^{41}\ erg/s$, $T \sim 10^4\ K$, $\delta \sim 10-30$

synchrotron radiation of protons with internal $\gamma-\gamma$ absorption (Zacharopoulou et al. 2010)
B-field: very large or very small?

in powerful blazars at subparsec scales B-field cannot be smaller than 1G, a serious constraint for the simplified one-zone “leptonic models,
risetime: \( 173 \pm 28 \) s

Crab Flux

HESS

28th July 2006

several min (200s) variability timescale \( \Rightarrow R = c \Delta t_{\text{var}} \delta_j = 10^{14}\delta_{10} \) cm for a \( 10^9 \) Mo BH with \( 3R_g = 10^{15} \) cm \( \Rightarrow \delta_j > 100 \), i.e. close to the accretion disk (the base of the jet), the bulk motion \( \Gamma > 100 \)

\[
\delta_j > 100, \text{ i.e. close to the accretion disk (the base of the jet), the bulk motion } \Gamma > 100
\]
on the Doppler boosting and mass of BH in PKS2155-309

- several min (200s) variability timescale $\Rightarrow R = c \Delta t_{\text{var}} \delta_j = 6 \times 10^{12} \delta_{10}$ cm for a $10^9 M_\odot$ BH with $3R_g \sim 10^{15}$ cm $\Rightarrow \delta_j > 150$, i.e. close to the accretion disk (the base of the jet), the Lorenz factor of the jet $\Gamma > 75$ - this is his is not the case!

- the (internal) shock scenario: shock would develop at $R = R_g \Gamma^2$, i.e. minimum gamma-ray variability would be $R_g/c = 10^4 (M/10^9 M_\odot)$ sec, although the gamma-ray production region is located at $R_g \sim c \Delta t_{\text{var}} \Gamma^2$ (e.g. Chelotti, Fabian, Rees 1998) - this is true for any other signal-perturbation originating from the central BH

thus for the observed $t_{\text{var}} < 200$ s, the mass of BH cannot significantly exceed $10^7 M_\odot$. On the other hand the “BH mass-host galaxy bulge luminosity” relation for PKS2155-304 gives $M > 10^9 M_\odot$.

Solution? Perturbations are cased by external sources, e.g. by magnetized condensations (“blobs”) that do not have direct links to the central BH; do we deal with the scenario “star crosses the jet” (Barkov et al. 2010)?
M 87 – evidence for production of TeV gamma-rays close to BH?

Distance: \( \sim 16 \) Mpc

central BH: \( 3 \times 10^9 \, M_\odot \) *)
Jet angle: \( \sim 30^\circ \)
\[ \Rightarrow \text{not a blazar!} \]
discovery \( (>4\sigma) \) of TeV \( \gamma \)-rays
by HEGRA (1998) and confirmed recently by HESS/VERITAS, MAGIC
*) recently \( 6.4 \times 10^9 \, M_\odot \)
M87: light curve and variability

short-term variability on 1-2 day scales => emission region \( R \approx 5 \times 10^{15} \delta \) cm
=> production of gamma-rays very close to the ‘event horizon’ of BH?

because of very low luminosity of the core in O/IR: TeV gamma-rays can escape the production region

\( L_{IR} \approx 10^{-8} L_{Edd} \)
Simultaneous TeV and radio observations allow localization of gamma-ray production region within 50 $R_s$

monitoring of the M87 inner jet with VLBA at 43 GHz (ang. res. 0.21x0.43 mas) revealed increase of the radio flux by 30 to 50% correlated with the increase in TeV gamma-ray flux in Feb 2008

conclusion? TeV gamma-rays are produced in the jet collimation region within 50 $R_s$ around BH