Very High Energy Gamma Rays and Origin of Galactic Cosmic Rays

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Origin of Cosmic Rays:

*a mystery since the discovery in 1912 by V.Hess ... but now we are quite close (hopefully) to the solution of the (galactic) component below the energy 1PeV ($10^{15}$eV)*

*thanks to the H.E.S.S. (first important probes) and*

- next generation TeV detectors (IACT Arrays and HAWC)
- GLAST
- km3 scale neutrino telescopes (IceCube, Km3NeT)
- next generation hard X-ray missions
Gamma-Ray Astronomy

*a branch of high energy astrophysics for study of the sky in MeV, GeV, TeV (and more energetic) photons*

*provides crucial window in the spectrum of cosmic E-M radiation for exploration of non-thermal phenomena in Universe in their most extreme and violent forms*

*“the last window” in the spectrum of cosmic E-M radiation*
**the last E-M window ... 15+ decades:**

<table>
<thead>
<tr>
<th>LE or MeV</th>
<th>HE or GeV</th>
<th>VHE or TeV</th>
<th>UHE or PeV</th>
<th>EHE or EeV</th>
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<tbody>
<tr>
<td>0.1 -100 MeV</td>
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(0.1 -10 + 10 -100) *(0.1 -10 + 10 -100)* *(0.1 -10 + 10 -100)* *(only hadronic)* *(unavoidable because of GZK cutoff)*

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

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

potentially  IACT arrays  can cover five decades

*from 10 GeV to 1 PeV*

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* presently poorly explored  but in future could become the most advanced energy band*
why TeV gamma-rays?

TeV gamma-rays - unique carriers of astrophysical and cosmological information about non-thermal VHE phenomena

✓ are effectively produced in E-M and hadronic interactions in many galactic and extragalactic sources
✓ penetrate freely through intergalactic and galactic B-fields
✓ are effectively detected by ground-based detectors (IACTs)
uniqueness of the (stereoscopic IACT) technique

- huge (1km² or larger) detection area
- good (few arcmin or better) angular resolution
- reasonable (15% or better) energy resolution
- very good CR background rejection capability
- very low galactic and extragalactic diffuse backgrounds

morphology, spectrometry, timing

multi-functional effectively tools operating over three energy decades (0.1-100 TeV) with a potential of extension of the energy range down to 10 GeV and up to 1 PeV

minimum detectable flux => $10^{-14}$ erg/cm² s (for < 1 arcmin sources)!
impact of HESS: over last 3 years HESS has revolutionized the field

before - “astronomy“ with several sources and advanced branch of Particle Astrophysics

now - a new astronomical discipline with all characteristic astronomical key words:
energy spectra, images, lightcurves, surveys...

major factors which make possible the HESS success?

(1) effective acceleration of particles almost everywhere in Universe to TeV energies
(2) full exploitation of potential of stereoscopic approach in the IACT technique
(3) nice technical performance

one can predict (with confidence) many new exciting results also from Northern Hemisphere with VERITAS and MAGIC-II (soon!)
Why Cherenkov telescopes?

- large detection area – typically 0.1 km², potentially up to 10 km²
- low energy threshold – typically 0.1-1 TeV, potentially down to a few GeV

first result: 3σ signal from Crab - 3 years observations with the Whipple non-imaging 10m telescope (1969)

but CTs are ... cosmic ray detectors rather than γ-ray telescopes...

CT = optical reflector with a PMT in focus + fast (ns) electronics
Why Imaging?

- (certain) information about arrival direction
- capability to separate $\gamma$- and proton induced showers
- larger FoV (larger collection areas)

*first result:* 9 sigma signal from Crab with the Whipple *imaging* 10 m telescope (1989)

*a single IACT* - good $\gamma$-ray detector but not yet *a telescope* ...
Detecting Very High Energy Gamma-Rays with Cherenkov Light

At 100 GeV ~ 10 Photons/m^2 (300 – 600 nm) ~ 120 m

Focal Plane

~ 10 km Particle Shower

5 nsec

Intensity Shower Energy

Image Shape Background rejection

Image Orientation Shower Direction
why stereoscopy?

- better separation of hadronic and E-M showers
  better sensitivity

- angular resolution of about 3 arcmin
  better sensitivity, source localization, morphology

- energy resolution 10 to 15 per cent
  better spectrometry

- rejection of local muons, better rejection of N.S.B.
  lower energy threshold, systematics under control

- quite large (up to 5 degree) FoV
  extended sources, surveys, huge collection areas

first results: HEGRA system of four small 8.5m2 area IACTs (La Palma, 1996-2002) demonstrated the power and advantages of the stereoscopic approach

Stereoscopic IACT arrays are perfect γ-ray-telescopes!
Stereoscopic IACT arrays as perfect γ-ray-telescopes!

Image of source is somewhere on the image axis ... need several views to get unambiguous shower direction.
History of the field

1960s, first Cherenkov telescopes, first upper limits (Jelley, Porter, Chudakov, ...)

1972 first tentative detection of a TeV γ-ray signal (Whipple)

1989: first reliable detection of a TeV γ-ray signal (Whipple)

1990s: several exciting discoveries (HEGRA, Whipple, CAT, CANGAROO), but not yet a breakthrough; VHE gamma-ray astronomy is not yet accepted as a nominal astronomical discipline

2000s: gamma-ray astronomy emerged as a truly observational/astronomical discipline (HESS/MAGIC/VERITAS) with viable detection technique – stereoscopic IACT arrays high quality spectrometric, morphological and temporal studies of more than 50 sources representing several galactic and extragalactic source populations

2010+ next generation of IACT arrays
the pioneer of the field

1972 - first claim of detection of 3σ signal (G. Fazio)

1989 - detection of a signal at 9σ level (T. Weekes)

from the Crab Nebula
the pioneer of the current concept: stereoscopic array of large FoV IACTs

HEGRA, La Palma, 1996-2002

c. 100 m
**lessons from HEGRA:** stereoscopic approach does work and provides

excellent angular resolution - good energy resolution - very good CR background rejection - reduction of the energy threshold - broad dynamical energy range - reliable control of systematics - high detection rate (TeV photon statistics) ....

**but** no many TeV sources at the level of < $10^{-11}$ erg/cm$^2$ s

Recommendations?: *reduce energy threshold down to 100 GeV with*

(i) a significant (a factor of 5 or so) improvement of sensitivity around 1 TeV (because of large collection area and better CR rejection factor)

(ii) increase the chances of detection of sources with steep energy spectra or with sub-TeV cutoffs

solution?: *10m diameter class IACT array equipped with 5 deg FoV cameras*

formula: “HEGRA concept with several Whipple type telescopes”
First Unidentified TeV source TeV J2032+4130

found by HEGRA serendipitously (6 sigma signal accumulated 100h from the Cygnus region and confirmed in 2002 by pointing observations (130 h)

Basic features - hard power-law spectrum (photon index 1.9), constant flux and slightly extended (about 5 arcmin) source

if this object is a representative of a large source population, the planned survey of the Galactic Disk by H.E.S.S. will reveal (many ?) more new hot spots

HongKong 2004
H.E.S.S. (Namibia)

4 x 107 m² dish
H.E.S.S. - *High Energy Stereoscopic System*

- 13m diameter dish
- 920 pixel, 5 deg FoV camera

the first representative of the new generation of IACT arrays
VERITAS

South Arizona
La Palma  240 m² dish
current major instruments
Performance and Potential of HESS

- **Energy range**
  100 GeV - 100 TeV

- **Energy resolution**
  15 - 20%

- **Angular resolution**
  3 - 6 arcmin

- **Sensitivity:**
  1 Crab   30 sec
  0.1 Crab 20 min
  0.01 Crab 25 hours
  10 Crab  1 sec

- **Field of View**  5°

**HESS** - effective multi-functional tool in broad energy range (2+ decades) for probing VHE sources at the level

\[ L_\gamma (>100 \text{ GeV}) = 2.5 \times 10^{32} \left( \frac{d}{1 \text{kpc}} \right)^{-2} \left( \frac{f_\gamma}{10^{-12} \text{ erg/s}} \right) \]

✓ spectrometry
✓ morphology
✓ timing
✓ surveys

- extended sources: SNRs, PWNes, GMCs, etc.
- compact variable (periodic) sources:
  - binary pulsars, μQSOs, blazars

**contributions in several topical areas:**

- **GCRs**
- **Pulsars**
- **Blazars, μQSOs**
- **M87**

SNRs, strong shocks, DSA, ...
Pulsar Winds, Plerions
High Energy Processes in Jet
nonthermal processes close
to the event horizon of BH
Morphology

Shell-type SNRs

Plerions
Spectrometry

RXJ1713.7-3946
Detection of Giant Molecular Clouds in GC

HESS collaboration: Nature  Feb 9, 2006
LS 5039 as a TeV clock with $T = 3.9078 \pm 0.0015 \text{day}$

[Chance probability $< 10^{-15}$]

Period of the system (via Doppler shifted optical lines) $T = 3.90603 \pm 0.00017 \text{d}$

close to inferior conjunction - maximum close to superior conjunction – minimum absorption a prime reason for modulation?
preliminary

1 minute binning lightcurve

July 27, 2006 variability on < 200 s timescales!
on average 150 γ/min rate ⇒ more than 10,000 γ-rays for 1.5 h
TeV and CO data: narrow distributions in the Galactic Plane: because of GMCs? Star Formation Regions? or (most likely) both?
Detected TeV gamma-ray Source Populations

Extended Galactic Objects

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

Compact Galactic Sources

- Binary pulsar PRB 1259-63
- LS5039, LSI 61 303 - Microquasars?

Galactic Center

Extragalactic objects

- M87 - a radiogalaxy
- TeV Blazars - with redshift from 0.03 to 0.18

- and a large number of yet unidentified TeV sources ...
TeV Galactic Sources

plus four identified molecular clouds in the Galactic Center
Potential of IACT Arrays

- **sensitivity:** $10^{-13} (10^{-14})$ erg/cm$^2$s
- **dynamical range:** 100 (3) GeV to 30 (1000) TeV
- **angular resolution:** 3 (1-2) arcmin
- **energy resolution:** 10 to 15%
- **detection area:** $10^8$ to $10^{10}$ ($10^{11}$) cm$^2$
- **photon statistics:** typically $>>100$

**Detector sensitivities compared to the Crab Nebula**

**IACTs - very effective multi-functional tools**
- spectrometry
- temporal studies
- morphology
- surveys

- extended sources: from SNRs to Clusters of Galaxies
- transient phenomena: mQSOs, AGN, GRBs, ...

Galactic Astronomy, Extragalactic Astronomy, Observational Cosmology
Major Objectives of TeV $\gamma$-ray Astronomy

- **Origin of Galactic Cosmic Rays**
  - SNRs, Molecular clouds, Diffuse radiation of the Galactic Disk, ...

- **Galactic and Extragalactic Sources with relativistic flows**
  - Pulsar Winds, $\mu$QSOs, Small and Large Scale jets of AGN, GRBs...

- **Observational Gamma Ray Cosmology**
  - Large Scale Structures (Clusters of Galaxies), Dark Matter Halos,
    Diffuse Extragalactic Background radiation, Pair Halos

  ....

  ....
Galactic Cosmic Rays and Gamma Rays
Solution of the Problem of Origin of Galactic Cosmic Rays

*the major (historical) motivation of gamma-ray astronomy*

and remains one of highest priorities of TeV/PeV gamma-ray astronomy tightly connected with many research areas related to

*shell type SNRs, Star Formation Regions/Giant Molecular Clouds, Interstellar Medium, as well as Plerions, Microquasars, GRBs ....*
Cosmic Ray Studies with Cosmic Rays  

or what do we know about Cosmic Rays?

- flux is dominated by hadronic component
- energy spectrum \( \frac{dN}{dE} = kE^{-2.6-2.7} \) up to the “knee”
- content of secondaries: \( \lambda = 5 \ (E/10\text{GeV})^{-0.6} \) g/cm\(^2\)

source spectrum close to \( E^{-2.0-2.1} \)

particle production rate \( (0.3-1) \times 10^{41} \) erg/s

but because of deflections in ambient random magnetic fields the information about the production sites is lost ...
$\gamma$-rays as tracers of CRs

*what we do not know about Galactic Cosmic Rays?*

acceleration sites, source populations, acceleration mechanisms

reason? *deflection (diffusion) of CRs in interstellar B-fields*

solution? *probing CRs with high energy gamma-rays:*

  - discrete $\gamma$-ray sources - productions sites of CRs
  - diffuse $\gamma$-ray emission - propagation of CRs in ISM
Galactic TeVatrons and PeVatrons – particle accelerators responsible for CRs up to $10^{15}$ eV

* the source population responsible for the bulk of GCRs are PeVatrons?

SNRs?
Pulsars/Plerions?
OB, W-R Stars?
Microquasars?
Galactic Center?
SNRs – the most probable factories of GCRs?

(almost) a common belief based on two arguments:

- necessary amount of available energy – \(10^{51}\) erg
- Diffusive Shock Acceleration – \(>10\%\) efficiency and \(E^{-2}\) type spectrum up to at least \(10^{15}\) eV

straightforward proof: detection of gamma-rays and neutrinos from pp interactions (as products of decays of secondary pions)

objective: to probe the content of nucleonic component of CRs in SNRs at \(d < 10\) kpc at the level \(10^{49} - 10^{50}\) erg

realization: sensitivity of detectors - down to \(10^{-13}\) erg/cm\(^2\) s

- crucial energy domain - up to \(100\) TeV
Visibility of SNRs in high energy gamma-rays

for CR spectrum with $\alpha=2$

$F_\gamma(>E) = 10^{-11} \frac{A}{(E/1\text{TeV})^{-1}} \text{ ph/cm}^2\text{s}$

$A = \left(\frac{W_{cr}}{10^{50}\text{erg}}\right) \left(\frac{n}{1\text{cm}^{-3}}\right) \left(\frac{d}{1\text{kpc}}\right)^{-2}$

1000 yr old SNRs (in Sedov phase)

Detectability? compromise between angle $\theta (r/d)$ and flux $F_\gamma(1/d^2)$

typically $A$: 0.1-0.01 $\theta$: 0.1° - 1°

TeV $\gamma$-rays – detectable if $A > 0.1$

$\pi^0$ component dominates if $A > 0.1 \left(\frac{S_x}{10 \mu\text{J}}\right) \left(\frac{B}{10 \mu\text{G}}\right)^{-2}$

nucleonic component of CRs - “visible” through TeV (and GeV) gamma-rays!
Cosmic Ray Accelerators?

SNRs in our Galaxy: 231 (Green et al. 2001) with nonthermal X-ray emission - 10 or so

Best candidates - young SNRs with nonthermal synchrotron X-rays

SN1006

Tycho Kepler CasA

30 arcmin

TeV emission

H.E.S.S. PSF
SN 1006 - a good candidate for particle source acceleration

H.E.S.S. upper limits - an order of magnitude below the flux reported by CANGAROO

a trouble? not at all ...

HESS upper limits imply

IC : $B > 25 \, \mu G$
$
\pi^0 : W_p < (0.2 - 2) \times 10^{50} \text{ erg}$

no problem for the hypothesis of SNR origin of Galactic CRs ...
**Cas A – a proton accelerator**

Cas A is well designed to operate as a PeVatron? with a “right” combination of B-field, shock speed and age to accelerate and confine particles up to 1 PeV - a source of >10 TeV γ-rays and neutrinos?

- very important target for VERITAS and MAGIC
- GLAST should detect GeV gamma-ray emission in any case
- no way to detect TeV neutrinos even with km³ scale detectors
TeV images of two young “1Crab” strength shell type SNRs

Vela Junior

RXJ1713.7-3946

flux and spectrum - similar, morphology - somewhat different
RX 1713.7-3946:

the key issue - identification of γ-ray emission mechanisms: – π^0 or IC?

energy spectra 150GeV-30 TeV
from different parts - NW, S W, E, C

coordinate-independent from 0.2 to 10 TeV
difficult to explain by IC (?)

implications?

if π^0 - the hadronic component is detected!
estimate of W_p (with an uncertainty related to the uncertainty in n/d^2)

if IC - model independent estimate of W_e (multi-TeV electrons) \( L_e = L_x \) and
model independent map of B-field
Origin of radiation?

- **hadronic origin** preferable, given the high density environment:

  \[ W_p \text{ (above 10 TeV)} = 3 \times 10^{49} \text{ (n/1 cm}^{-3}\text{)}^{-1} \text{ erg} \]

- **IC origin** is not (yet) excluded, but this model requires B-field less than 10 \( \mu \)G

more complex scenarios? e.g. \( \gamma \)-rays from NW+SW are contributed by protons while gamma-rays from remaining parts are due to IC \( \gamma \)-rays...

HESS observations with 4 telescope in 2004 and 2005 provide higher quality data and... certain answers?
IC model: B-field cannot exceed 10 \( \mu \)G and does not provide good spectral fit.

IC origin? – very small B-field, \( B < 10 \mu \)G, and very large \( E_{\text{max}} > 100 \text{ TeV} \). Two assumptions hardly can co-exists within standard DSA models.
pp → π° → γγ – perfect spectral fits, reasonable energetics!

protons:

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

γ-rays:

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

\[ \Gamma = \alpha + \delta\alpha, \delta\alpha = 0.1, \beta_{\gamma} = \beta/2, \ E_0 = E_{\text{cut}}/20 \]

\[ W_p(>1 \text{ TeV}) = 0.5 \times 10^{50} (n/1 \text{ cm}^{-3})^{-1} (d/1 \text{kpc})^{-2} \]
spectrum of protons?

\[ W_p = 10^{50} \left( \frac{n}{1 \text{ cm}^{-3}} \right)^{-1} \text{ erg} \; ; \; n \text{ close to } 1 \text{ cm}^{-3} ? \; \text{ preferable - prefer}\]

\[ \text{can explain the production rate of GCRs by SNRs}\]

\[ E_0 \text{ significantly smaller than } 1000 \text{ TeV} ? , \; \text{ yes, although}\]

\[ \text{that could be connected with the fast escape of protons from}\]
\[ \text{accelerator, so RXJ 1713 still could be treated as a PeVatron}\]
RXJ1713: more HESS data in 2005

>40 TeV gamma-rays and sharper shell type morphology: acceleration of p or e in the shell to energies exceeding 100 TeV

Almost constant photon index!

Can be explained by γ-rays from pp→π⁰→2γ

\[ \alpha_p \sim 2 \text{ and } E_0 \sim 100 \text{ TeV} \]

Problems with IC because of KN effect
new developments in theory - e.g., nonliner shocks with amplification of B-field
calculations of the energy spectra of electrons, etc.

the energy spectrum of electrons at the shock front *)

\[ N(E) \propto E^{-2}[1 + 0.523(E/E_0)^{9/4}]^2 \exp[-(E/E_0)^2] \]

\[ E_0 \text{ almost coincides with the value derived from } t_{acc} = t_{synch} \]

the spectrum of synchrotron radiation at the shock front

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

\[ h\nu_0 \approx 1(\nu/3000\text{km/s})^2\text{keV} \]

*Synchrotron cutoff energy approximately 10 times \( h\nu_0 \)!

*) in the Bohm diffusion regime

V.Zirakashvili, FA 2006
Electron and synch. rad. spectra at shock front

\[ N(p)p^4, J(\omega)\omega \]

\[ \sigma=4, \ B_1= B_2 \]

\[ \frac{p}{p_0}, \ \frac{\omega}{\omega_0} \]

\[ \text{synch. rad.} \]

\[ \text{electrons} \]

\[ \text{upstream} \]

\[ \text{downstream} \]

\[ \text{B}_1/\text{B}_2 = \sqrt{11} \]

\[ J_1(\omega)\omega, J_2(\omega)\omega \]

\[ \text{Sy} \]

\[ \text{upstream} \]

\[ \text{downstream} \]

\[ \omega/\omega_0 \]

\[ \text{IC on 2.7 MBR Thompson!} \]

\[ \text{V.Zirakashvili, FA 2006} \]
Gamma-rays above 20 TeV - difficult to explain by IC

\[ \Gamma = 2, \ E_0 = 150 \ TeV \]

hadronic

leptonic

electrons to fit X-ray data
SNRs as Cosmic PeVatrons?

3 channels of information about cosmic PeVatrons:

- 10-100 TeV gamma-rays
- 10-100 TeV \( \mu \)-neutrinos
- 10-100 keV hard X-rays

**sensitivities?**
better than \( 10^{-12} \text{ erg/cm}^2\text{s} \)

- \( \gamma \)-rays: difficult, but possible with future “10km\(^2\)” area multi-TeV IACT arrays
- neutrinos: difficult, but KM3NeT should be able to see (marginal) signals from SNRs RX 1713.7-3946 and Vela Jr
- “prompt“ synchrotron X-rays: a very promising channel (but presently we do not have sensitive hard X-ray detectors)
energy spectra of secondary gamma-rays, electrons and neutrinos

\[ x^2 F_j(x, E_p) \]

- \( E_p = 0.1 \text{ TeV} \)
- \( E_p = 1000 \text{ TeV} \)

\[ x = E_j/E_p \]
total inelastic pp cross-section and production rates of g and $\nu_\mu$ for power-law spectrum of protons:
$n_H = 1 \text{ cm}^{-3}$, $w_p = 1 \text{ erg/cm}^3$

$$\sigma_{\text{inel}} = (34.3 + 1.88 L + 0.25 L^2) \times \left[ 1 - \left( \frac{E_{th}}{E_p} \right)^3 \right]^2, \text{ mb}$$
Probing PeV protons with X-rays

SNRs shocks can accelerate CRs to <100 TeV (e.g. Cesarsky & Lagage 1984) unless magnetic field significantly exceeds 10 μG

Recent theoretical developments: application of the B-field up to >100 μG is possible through plasma waves generated by CRs (Bell and Lucek 2000)

>10^{15} eV protons $\rightarrow$ >10^{14} eV gamma-rays and electrons “prompt” synchrotron X-rays

cooling time: $t(\varepsilon) = 1.5 \left(\varepsilon/1\text{keV}\right)^{-1/2} \left(B/1\text{mG}\right)^{-3/2} \text{yr} << t_{\text{SNR}}$

energy range: typically between 1 and 100 keV with the ratio $L_x/L_\gamma$ larger than 20% (for $E^{-2}$ type spectra)

“hadronic” hard X-rays and (multi)TeV γ-rays – similar morphologies!
acceleration spectrum of protons: \[ \frac{dN}{dE} = AE^{-\alpha} \exp\left(-\frac{E}{E_o}\right)^{\beta} \]

production spectra of $\gamma$-rays, electrons, $\nu_\mu$:

\[ Q_i(E_i) = Q_0 E_i^{-\alpha+\delta\alpha} \exp\left(-\frac{E}{E_{i,o}}\right)^{\delta} \]

(i) $\Delta\alpha = 0.05-0.1$; (ii) $\delta = \beta/2$; (iii) $E_{i,o} = (1/20-1/100)E_o$

**good news!** cutoffs in the $\gamma$-ray ($e$, $\nu$) spectra are smoother; (relatively) easy to detect, but for spectrometry one needs good photon statistics up to 100 TeV

**detect gamma-rays in the energy band 10-100 TeV band**

**and** hard synchrotron X-rays of secondary electrons in 10-100 keV band
the index of the exponential cutoff in the production spectra of γ-rays ($\delta_\gamma$) and electrons ($\delta_e$) versus the power-law spectral index of protons $\alpha$ for 3 different $\beta$ (0.5, 1, 2) and two $E_0$ (10 TeV – dashed, $10^3$ TeV – solid curves)
“hadronic” X-rays versus synchrotron radiation of primary electrons:

electron injection spectrum \( Q_e(E_e) = Q_o E_e^{-\alpha} \exp\left((-E_e/E_{e,0})^\sigma\right) \)
spectrum of synchrotron radiation of cooled electrons
\( \varepsilon^{-(\alpha/2+1)} \exp\left((-\varepsilon/\varepsilon_o)\lambda\right) \) \( \lambda = \sigma/\sigma+2; \beta=1 \) \( \sigma=0.5, \lambda=1/5 \)

synchrotron spectrum of primary electrons: \( \lambda=2/(2+2)=1/2 \)

\( \varepsilon_o \): characteristic synchrotron frequency proportional \( BE_0^2 \) (prop. to \( B^3 \))

for \( E_0 = 1 \) PeV, \( B=1 \) mG \( X\)-ray emission extends well beyond 10 keV

while the cutoff energy in the synchrotron spectrum from directly accelerated electrons is expected around 1 keV

simultaneous measurements of \( \pi^0 \)-decay \( \gamma \)-rays and associated synchrotron radiation provide unambiguous estimate of B-field

\[ \text{in the acceleration region!} \]
broad-band emision initiated by pp interactions: $W_p=10^{50}$ erg, $n=1\text{cm}^{-3}$
searching for galactic PeVatrons ...

TeV gamma-rays from Cas A and RX1713.7-3946, Vela Jr - a proof that SNRs are responsible for the bulk of GCRs ?- not yet the hunt for galactic PeVatrons continues

unbiased approach - deep survey of the Galactic Plane - not to miss any recent (or currently active) acceleration site:

SNRs, Pulsars/Plerions, Microquasars...

not only from accelerators, but also from nearby dense regions
Gamm-rays/X-rays from dense regions surrounding accelerators

The existence of a powerful accelerator by itself is not sufficient for gamma radiation; an additional component - a dense gas target - is required.

Gamma-rays from surrounding regions add much to our knowledge about highest energy protons which quickly escape the accelerator and therefore do not significantly contribute to gamma-ray production inside the proton accelerator-PeVatron.
older source – steeper $\gamma$-ray spectrum

\[ t_{esc} = 4 \times 10^5 \left( E/1 \text{ TeV} \right)^{-1} \kappa^{-1} \text{ yr} \ (R=1 \text{ pc}); \ \kappa=1 \text{ – Bohm Diffusion} \]

\[ Q_p / E^{-2.1} \exp(-E/1 \text{ PeV}) \]

\[ L_p = 10^{38} (1+t/1 \text{ kyr})^{-1} \text{ erg/s} \]
Giant Molecular Clouds (GMCs) as tracers of Galactic Coismic Rays

GMCs - 10³ to 10⁵ solar masses clouds physically connected with star formation regions - the likely sites of CR accelerators (with or without SNRs) - perfect objects to play the role of targets!

While travelling from the accelerator to the cloud the spectrum of CRs is a strong function of time $t$, distance to the source $R$, and the (energy-dependent) Diffusion Coefficient $D(E)$

depending on $t$, $R$, $D(E)$ one may expect any proton, and therefore gamma-ray spectrum - very hard, very soft, without TeV tail, without GeV counterpart ...
Propagation Effects on the spectrum of Gamma Rays

emissivities and fluxes \( \left( \frac{M_5}{d^2 \text{kpc}} \right) \) of gamma rays from a cloud at different times and distances from an impulsive accelerator with \( W=10^{50} \text{erg} \) \( D(E)=10^{26} (E/10\text{GeV})^{0.5} \text{ cm}^2/\text{s} \)
Gamma-rays and neutrinos inside and outside of SNRs

SNR: \( W_{51} = n_1 = u_9 = 1 \) \( d = 1 \) kpc

GMC: \( M = 10^4 M_\odot \) \( \Delta = 100 \) pc

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

[S. Gabici, FA 2007]
spectra of $\gamma$-rays and neutrinos from clouds with $M_4/d^2_{\text{kpc}}=1$

gamma- thick curves
neutrino -thin curves

CLOUD, 50 pc

CLOUD, 200 pc

$F(E) E^2 \text{ [TeV/cm}^2\text{s]}$
unidentified HESS sources
Origin of Extended HESS TeV sources

three basic mechanisms of $\gamma$-ray production in extended sources:

characteristic timescales:

\[ p+p \rightarrow \pi^0 \rightarrow \gamma \gamma \quad t_{pp} = 1 \times 10^{15} \frac{n}{1 \text{cm}^{-3}}^{-1} \text{ sec} \]
\[ e+2.7 \text{ K} \rightarrow e \gamma \quad t_{\text{IC}} = 4 \times 10^{12} \frac{E}{10 \text{ TeV}}^{-1} \text{ sec} \]
\[ \text{e-bremsstrahlung} \quad t_{\text{br}} = 3 \times 10^{14} \frac{n}{1 \text{cm}^{-3}}^{-1} \text{ sec} \]

- IC is very effective as long as magnetic field \( B < 10 \mu G \)
- Bremsstrahlung important in dense, \( n > 10^2 \text{ cm}^{-3} \), environments
- pp interactions dominate over Bremsstrahlung if the ratio of energy densities of protons to electrons \( w_p/w_e > 10 \), and Inverse Compton component if \( w_p/w_e > 500 \frac{n}{1 \text{cm}^{-3}}^{-1} \) (at energies above 10 TeV)
Morphology vs. Energy Spectrum

**morphology:**
- **pp:** depends on spatial distributions of CR and gas: \( n_H(r) \times N_p(r) \)
- **IC:** depends only on spatial distribution of electrons: \( N_e(r) \)

**energy spectra:**
- depends on acceleration spectrum \( Q(E) \), energy losses \( \frac{dE}{dt} \), age of accelerator \( t_o \), and character of propagation/diffusion coefficient \( D(E) \)

**pp:**
- generally energy spectrum independent of morphology, but for young objects energy spectrum could be harder at larger distances than near the accelerator → angular size increases with energy

**IC:**
- very important are synchrotrin energy losses;
- weak B-field (\(<10 \, \mu G\)) and/or fast diffusion → angular size increases with energy
- strong B-field (100 \( \mu G \)) and/or slow diffusion → angular size decreases with energy

**irregular shapes of γ-ray images:**
- because of inhomogeneous distribution of gas (pp) or unisotropic propagation of cosmic rays (pp or IC)
why the energy spectra of most of HESS sources are hard
(Γ=2.2-2.3 or even 2.5), but not very hard (Γ=2 or less)?
because of early cutoffs ...

(i) not very effective acceleration mechanisms
(ii) in order to make a TeV source detectable, the accelerator
    should be relatively old, but from an old accelerator the
    highest energy particles are effectively left the source ...

Γ=2.2-2.3 a compromise in the TeV band?

Yes... if we are lucky - from a recent burst like powerful event, otherwise one should expect very hard spectra from weak sources - from young accelerators themselves or from dense clouds in the proximity of mid-age accelerators

targets for the next generation of IACT arrays
an important issue for the next generation detectors:

significant improvement of sensitivity of HESS at TeV energies especially above 10 TeV for several key measurements

- search for Cosmic PeVatrons via probing young accelerators or the <100 pc neighbourhood (GMCs) of relatively old accelerators
- detection of gamma-rays from passive several GMCs located around the cosmic accelerator => determination of the diffusion coefficient of Cosmic Rays D(E) - absolute value and energy dependence
- detection of passive GMCs we can act as barometers for measurements of the pressure of the “sea” of Galactic Cosmic Rays
- detection and resolution of the “diffuse” TeV background contributed by GMC (relatively compact/extended objects) and accelerators of TeV/PeV electrons (a few degree halos around the accelerators)
gamma-rays due to IC on 2.7 K

IC on 2.7 K MBR - direct information about the spatial and spectral distributions of electrons without any model assumptions!

no analog in astrophysics!

Le=10^{36} \text{ erg/s}, Q(E)=Q_0 E^{-2} \exp(-E/10^3 \text{ TeV}), \text{ age } T=10,000 \text{ yr}

D(E)=D_0 (E/10 \text{ GeV})^{\beta}, Do=10^{27} \text{ cm}^2/\text{s}, \beta=1/3, d=1 \text{kpc}, B=5 \mu\text{G}

R=[2D(E) t(E)]^{1/2} \quad t_r=a/E \quad \Rightarrow \quad R(E) = \text{const only when } \beta=1
Crab Nebula – a perfect PeVatron of electrons (and protons?)

Standard MHD theory

cold ultrarelativistic pulsar wind terminates by a reverse shock resulting in acceleration with an unprecedented rate: $t_{acc}=\eta r_L/c$, $\eta < 100$)

synchrotron radiation $\Rightarrow$ nonthermal optical/X-ray nebula
Inverse Compton $\Rightarrow$ high energy gamma-ray nebula

Crab Nebula – a very powerful $W=L_{rot}=5\times10^{38}$ erg/s

and extreme accelerator: $E_e > 1000$ TeV

$E_{\text{max}}=60 \ (B/1G)^{-1/2} \ \eta^{-1/2} \ \text{TeV}$ and $h \nu_{\text{cut}}=(0.7-2) \ \alpha_f^{-1}mc^2 \ \eta^{-1}=50-150 \ \eta^{-1} \ \text{MeV}$

$\eta=1$ – minimum value allowed by classical electrodynamics

Crab: $h \nu_{\text{cut}}=10\text{MeV}$: acceleration at 1 to 10 % of the maximum rate ( $\eta=10-100$)

maximum energy of electrons: $E_{\gamma}=100$ TeV $\Rightarrow$ $E_e > 100 (1000)$ TeV $\Rightarrow$ B=0.1-1 mG

– very close the value independently derived from the MHD treatment of the wind

* for comparison, in shell type SNRs DSA theory gives $\eta=10(c/v)^2=10^4-10^5$
TeV gamm-rays from other Plerions?

Crab Nebula is a very effective accelerator but not an effective IC γ-ray emitter.

We see TeV gamma-rays from the Crab Nebula because of very large spin-down flux $f_{\text{rot}} = L_{\text{rot}}/4\pi d^2$

but gamma-ray flux $<<$ “spin-down flux“ because of large magnetic field

$\dot{W}_e \approx L_{\text{rot}}$ but the strength of B-field also depends on $L_{\text{rot}}$

less powerful pulsar $\rightarrow$ weaker magnetic field

$\rightarrow$ higher gamma-ray efficiency

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

HESS confirms this prediction! (?) - several famous PWN already detected - MSH 15-52, PSR 1825, Vela X, ...

* Plerions – Pulsar Driven Nebulae
HESS J1825 (PSR J1826-1334)

Pulsar’s period: 110 ms, age: 21.4 kyr, distance: 3.9 +/- 0.4 kpc

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

The \( \gamma \)-ray luminosity is comparable to the TeV luminosity of the Crab Nebula, while the spindown luminosity is two orders of magnitude less!

Implications?

(a) Magnetic field should be significantly less than 10 \( \mu \text{G} \).

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 age of the source).

(b) The spin-down luminosity in the past was much higher.

Energy-dependent image:
- red – below 0.8 TeV
- yellow – 0.8 TeV - 2.5 TeV
- blue – above 2.5 TeV
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 $B(x,y)$

the energy spectrum - a perfect hard power-law with photon index $\Gamma=2.2-2.3$ over 2 decades!

- cannot be easily explained by IC… (unless intense IR sources around)
- hadronic ($\pi^0$-decay) origin of $\gamma$-rays?
HESS J0835-456 (Vela X) — do we see the Compton peak?

the image of TeV electrons ! (?)

- spectral index $\Gamma = 2$ with a
- break around 70 TeV
- total energy $W_e = 2 \times 10^{45}$ erg

questions:
- B-field – as weak as several $\mu$G or even less?
- energy in ultrarelativistic electrons only $2 \times 10^{45}$ erg?
- integrated energy over 11 kyr: $>2.5 \times 10^{48}$ erg – in which form the “dark energy” is released?

('inisible') low energy electrons or in ultrarelativistic protons? (!)
pulsar wind consisting of protons and nuclei?

\[
dN_p/DE = AE^2 \exp[-(E/80\text{TeV})^2]
\]

\[W_p = 1.3 \times 10^{49} \text{ (n/0.6cm}^{-3}) \text{ erg}
\]

Total spin down energy released over the last 11kyr: $5 \times 10^{48}$ – $5 \times 10^{51}$ erg depending on the braking index (time-history of $L_{\text{rot}}$)

\[B=10 \mu\text{G}
\]

\[W_e = 10^{45} (B/10\mu\text{G})^{-2} \text{ erg}
\]

for $B=100 \mu\text{G}$ – half of X-ray flux can be explained by secondary electrons

High $L_{\text{rot}} \text{ in the past}$
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 plerions*
both the electrons of the cold wind and shocke-accelerated electrons are illuminated by optical radiation from the companion star ➞ detectable IC γ-ray emission

**HESS**: detection of TeV gamma-rays from PSR1259-63 at < 0.1Crab level several days before the periastron and 3 weeks after the periastron

the photon field is a strong 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-ray and IC gamma-rays**

* but with characteristic timescales much shorter - less than 1 h!
time evolution of fluxes and energy spectra of X- and γ-rays contain unique information about the shock dynamics, electron acceleration, B(r), ...

energy flux of starlight close to the periastron around 1 erg/cm³

B-field is estimated between 0.1 to 1 G

predictable X and gamma-ray fluxes?
while the gamma-ray energy spectrum can be explained by IC mechanism

the lightcurve is still a puzzle

deep theoretical (in particular MHD) studies needed to understand the source

an improvement of the HESS sensitivity by a factor of >3 for comprehensive study of the lightcurve of this source
Explanation of the TeV lightcurve within the IC model

time (position) dependent adiabatic losses

energy losses of electrons versus separation distance $D$ between the pulsar and companion star: $B=0.05(Do/D)$ Gauss

minimum at periastron at all energies
Explanation of the TeV lightcurve within the IC model

variation of the maximum energy of electrons

Bo=0.05 (Do/D) Gauss,
\[ t_{\text{acc}} = \eta \frac{r_L}{c}; \quad \eta=4\times10^3 \]

minimum at periastron at high energies, but maximum - at low energies

Khangulyan et al 2006
Explanation of the TeV lightcurve by Comptonization of the wind

reduction of the Lorentz factor of the electron-positron wind

the effect is not negligible, but not sufficient to explain the lightcurve

Probing the unshocked wind Lorentz factor

Lorentz factors exceeding $10^6$ are excluded
TeV Gamma Rays From LS5039 and LSI+61 303

microquasars or binary pulsars?

independent of the answer – particle acceleration is linked to (sub) relativistic outflows
presence of two basic components for TeV γ-ray production!

- the compact object initiates (through a BH jet or a pulsar wind) acceleration of electrons (protons?) to energies at least 10 TeV
- $10^{39}$ erg/s companion star provides seed photons for IC or pγ or dense wind for pp interactions

scenario? γ-ray production region within (despite $\tau_{\gamma\gamma} \gg 1$)

and outside the binary system cannot be excluded

periodicity expected? yes - because of periodic variation of the geometry (interaction angle) and density of optical photons - as target photons for IC scattering and $\gamma\gamma$ absorption, as a regulator of the electron cutoff energy ($E_{\text{cut}} \propto w^{3.3}$); also because of variation of the B-field, density of the ambient plasma (stellar wind), ...
LS 5039 as a TeV clock with $T=3.9078 \pm 0.0015\text{day}$

close to inferior conjunction - maximum
close to superior conjunction – minimum

[...]

one needs a factor of 3 or better sensitivity compared to HESS to detect signals within different phase of width 0.1 and measure energy spectra (strongly phase dependent!)
LS5039 as a (detectable) neutrino source?

if TeV γ-rays are produced within the binary system (R < 10^{12} cm)

- **severe absorption of >100 GeV γs**
  - up to a factor of 10 to 100 higher initial luminosity

- **severe radiative losses**
  - difficult to accelerate electrons to multi-TeV energies

- pulsar wind rather than BH Jet (even at the base of the jet acceleration of > 100 TeV protons is problematic)

- TeV gamma-rays of hadronic origin with high luminosity, and consequently high **detectable TeV neutrino fluxes (!?)**
**TeV γ-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 HESS! and can be probed down to a flux level $10^{-13}$ erg/cm² s and localized within $<< 1$ arcmin
TeV γ-rays from central <10 pc region of GC

- *annihilation of DM?*  mass of DM particles > 10 TeV?

- *Sgr A*: $3 \times 10^6 M_\odot$ BH?  yes, but lack of variability ...  even the inner $R < 10 R_g$ region is transparent for TeV γ-rays!

- *SNR Sgr A East?*  why not?

- *Plerionic (IC) source(s)*  why not?

- *Interaction of CRs with GMCs?*  easily
GC - point-like but not variable ...

one needs a factor of few better sensitivity to probe fluctuations of the TeV signal on <1 hour timescales

power-law index 2.3
pp gamma-rays in the central 10 pc region

$$Q_p(E) = Q_o E^{-\alpha} \exp(-E/1 \text{ PeV}), \quad D(E) = 10^{28}(E/1\text{GeV})^{\beta} \kappa \text{ cm}^2/\text{s}; \quad \kappa=1, \quad \beta=0.5-0.6$$ - diffusion in GD

if $t_{pp} < t_{esc} \Rightarrow \pi^0$-decay $\gamma$-ray production in "saturated" regime $\Rightarrow L_\gamma = 1/3 L_p$, otherwise the flux and spectrum of $\gamma$s depend not only on CR injection power and spectrum, but also on the (energy dependent) propagation of CRs in ISM

1. fast diffusion: $\Gamma \rightarrow \alpha+\beta$
   $$L_p = 7.5 \times 10^{37} \text{ erg/s}$$

2. slow diffusion: $\Gamma \rightarrow \alpha$
   $$L_p = 6.9 \times 10^{36} \text{ erg/s}$$

3. Diffusion-to-rectilinear prop.
   $$\Gamma = \alpha+\beta \rightarrow \Gamma = \alpha$$
   $$L_p = 1.1 \times 10^{39} \text{ erg/s}$$
Residuals after source subtraction

diffuse emission along the plane!

HESS collaboration: Nature  Feb 9, 2006
concluding remarks:

we are at the gates of Heaven of
GeV/TeV astrophysics and Cosmology

- condition for entrance? $F_E = 10^{-14}$ erg/cm$^2$ s (0.03-30 TeV)
- realization? 1 to 10 km$^2$ scale IACT arrays
- timescales short (years) - no technological challenges
- price for the ticket very reasonable, plus (almost) 100% guarantee for success (great results and many discoveries)

my favored option: 30 GeV – 30 TeV array
several tens of 10 to 15m diameter class 5 (to 10?) deg FoV telescopes located on 3.5-4 km a.s.l.

sites? many good places in Argentina, Chile, Mexico
two possible designs of IACT arrays (Aharonian 1997, LP97, Hamburg 1997)
HESS Phase-2

1st large (28m diameter) telescope on H.E.S.S. site can serve as prototype and yet will be a powerful instrument in its own right, and will improve significantly the H.E.S.S. potential.
TeV/PeV astrophysics with $>>1 \text{ km}^2$ area array of small IACTs

Detector: tens of 4-to-6m diameter and 5-to-8 deg FoV IACTs located at 300m distances from each other

Energy Interval: 1 TeV to 1000 TeV

Scientific Objective: search for Cosmic PeVatrons

Site: southern hemisphere and low elevations preferable - Australia

Timescales: a few years