Short Course on High Energy Astrophysics
“Exploring the Nonthermal Universe with High Energy Gamma Rays”

Lecture 5: Galactic Sources of VHE Gamma Rays

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potential galactic gamma-ray sources

- Supernova Remnants (SNRs)
- Colliding Stellar Winds
- Giant Molecular Clouds (GMCs)
- Galaxy itself (the Disk and the Hallo)
- Pulsars, Pulsar Winds, Pulsar Wind Nebulae (PWNe)
- Binary Pulsars
- Microquasars (accreting Black Holes)
Topics

Theory of Particle Acceleration
Origin of Galactic Cosmic Rays

Structure of our Galaxy
Physics of the Interstellar Medium
Star Formation

Physics of Pulsar Magnetospheres and Winds
Relativistic hydrodynamics in PWNe and in Binary Pulsars

Nonthermal aspects of Accreting Black Holes
Potential VHE Gamma Ray Sources

Galactic

- GeV ISM
- GeV SFRs
- GeV SNRs
- GeV Pulsars
- GeV Binaries
- GMCs
- Magnetosphere
- Cold Wind
- Pulsar Nebula
- Microquasars
- Binary Pulsars

Extragalactic

- GeV GRBs
- GeV AGN
- GeV GLX
- GeV CLUST
- GeV IGM
- Blazars
- Radiogalaxies
- Normal
- Starburst

origin of GCRs
Relativistic Outflows
Compact Objects
EXG-CRs
Cosmology

Major Scientific Topics
Origin of Cosmic rays - “after 100yr of the discovery still a mystery”

energy range: $10^9$ to $10^{20}$ eV

what do we know about CRs:

- before the knee - galactic
- after the ankle - extragalactic
- between knee and ankle - ?
Supernova Remnants? two attractive features:

- available energy: \( W_{\text{CR}} \approx 0.1 E_{\text{SN}} \)
- effective mechanism: Diffusive Shock Acceleration

one of the key objectives of VHE \( \gamma \)-ray astronomy: confirmation that SNRs operate as PeVatrons, and provide the bulk of Galactic CRs up to \( E \sim 10^{15} \) eV

other possible sources?

Pulsars/PWNes  OB stars  Binaries  Galactic Center  …
acceleration of protons and/or electrons in SNR shells to energies up to 100 TeV

leptonic or hadronic?

\[ e + 2.7K \rightarrow \gamma \quad \text{and} \quad pp \rightarrow \pi^0 \rightarrow 2\gamma \]

\[ B = 15 \mu G \]
\[ W_e \approx 3 \times 10^{47} \text{ erg} \]

\[ B = 200 \mu G \]
\[ W_p \approx 10^{50} (n/1 \text{cm}^{-3})^{-1} \text{ erg} \]

unfortunately we cannot give a preference to hadronic or leptonic models - both have attractive features but also serious problems
RXJ1713.7-4639

TeV γ-rays and shell type morphology: acceleration of protons and/or electrons in shell up to 100TeV (not much higher)

can be explained by γ-rays from $pp \rightarrow \pi^0 \rightarrow 2\gamma$

HESS: $\frac{dN}{dE} = K E^{-\alpha} \exp[-(E/E_0)^\beta]$ 

$\alpha=2.0 \quad E_0=17.9 \text{ TeV} \quad \beta=1$

$\alpha=1.79 \quad E_0=3.7 \text{ TeV} \quad \beta=0.5$

with just ”right” energetics:

$W_p=10^{50} \left(\frac{n}{1\text{ cm}^{-3}}\right)^{-1} \text{ erg}$

but IC models generally are more preferred… because of TeV-X correlations (?)

IC origin of γ-rays cannot indeed be excluded, but this is not a good argument

definite answer – detect neutrinos (very difficult)

more realistic approach – γ-ray: morphology with 1 arcmin resolution and spectrometry, especially above 10 TeV
HESS update (see Egert et al.)

Model-independent spectra of p and e (see V. Zabalza)

Proton spectrum assuming $n_H = 1 \text{ cm}^{-3}$
$$W_p(E_p > 1 \text{ TeV}) = (6.27 \pm 0.14) \times 10^{49} \text{ erg} \left(\frac{n_H}{1 \text{ cm}^{-3}}\right)^{-1}$$

Electron spectrum
$$W_e(E_e > 1 \text{ TeV}) = (1.12 \pm 0.04) \times 10^{47} \text{ erg}$$
**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:**

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

\( \beta = 1 \quad \Gamma = 2.1; \ E_0 = 15.7 \text{ TeV} \)

\( \beta = 1/2 \quad \Gamma = 1.9; \ E_0 = 4.0 \text{ TeV} \)

γ-rays from GMCs in GC: a result of an active phase in Sgr A* with acceleration of CRs some \(10^4\)yr ago?
Galactic Center at high energies

$L_p \approx 10^{39}$ erg/s

FIG. 5. — Spectral energy distribution of gamma-rays expected from a region filled with relativistic and non-relativistic protons within different assumptions concerning the injection, diffusion and the region geometry (see text for a discussion of parameters for each specific model). The data points have been derived from the Fermi and HESS data.
Cosmic-ray density distribution

- Correlation with molecular clouds $\Rightarrow$ pp interaction target mass ($M$)
- Gamma-ray luminosity ($L$) in several regions
- $\Rightarrow$ CR density $\propto \frac{L}{M}$

CR density radial distributions:
- Homogeneous $\Rightarrow$ Impulsive injection of CRs and diffusive propagation
- $\frac{1}{r^2} \Rightarrow$ Wind-driven propagation
- $\frac{1}{r} \Rightarrow$ continuous injection and diffusive propagation

Central accelerator located within 10 pc and injecting CRs continuously for $> 1$ kyr
new!

GC: the central source and the diffuse emission of CMZ
Galactic Center (GC) harbors a hadronic PeVatron within a few pc region around Sgr A* a suspected SMBH

1/r type distribution of the CR density implies (quasi)continuous regime of operation of the accelerator with a power $10^{38}$ erg/s (on timescales 1 to 10 kyr) - a non negligible fraction of the current accretion power

this accelerator alone can account for most of the flux of Galactic CRs around the “knee” if its power over the last $10^6$ years or so, has been maintained at average level of $10^{39}$ erg/s.

escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration

the expected $>10$ TeV neutrino flux is within the range of sensitivity of a several km$^3$ volumee neutrino detector

perfect target for CTA - to search for the variability of the central source, to measure the spectrum of diffuse (CMZ) gamma-rays up to 100 TeV and beyond
Fermi Bubbles!

Finkbeiner and collaborators  2010
**Fermi Bubbles** - result of pp interactions of CRs produced in the GC and accumulated in R ~10 kpc regions over 10Gyr comparable to the age of the Galaxy? (Crocker&FA 2011)

*Size - because of slow diffusion in turbulent environment (10 times slower than in the Galactic Disk)*

plasma density: $n \sim 0.01$ cm$^{-3}$  
timescale: $t_{pp} \sim 5$ Gyr < $t_{Galaxy}$

saturation (calorimetric) regime can explains:

generally *homogeneous distribution of gamma-rays* (local $\gamma$-ray production rate does not depend on density), unless possible gradients in the CR spatial distribution, e.g. due to propagation effects; if the sharp edges tentatively found in the Fermi images is a real effect, they can be naturally explained by higher turbulence introduced by shocks => slower diffusion => accumulation of CRs close to the edges

modest requirements to CR rate: $L_p \sim 10^{39}$ erg/s

are FBs sites (reservoirs or accelerators) of PeV CRs? The answer can be provided by $\gamma$-ray observation at multi-Tev energies, and CTA is the best hope!
Fermi Bubbles - alternative explanation:

IC scattering of electrons:
age: \(10^7\) yr, electron inj. rate \(10^{38-39}\) erg/s

Problem: how transport \(E > 1\) TeV electrons to distances 10 kpc - in situ acceleration?

stochastic (2nd order Fermi) most viable option (Mertsch & Sarkar 2011)

shock fronts at Bubble edges (ROSAT) =>
higher turbulence - concentration of electrons close to the edges => sharp \(\gamma\)-ray edges

narrow electron distribution + limited \(E_{\text{max}} \sim 1\) TeV only 2.7K MBR as a target cannot for IC explain the 1-100 GeV \(\gamma\)-radiation: galactic FIR/O target field helps to explain the average 1-100 GeV \(E^{-2}\) type flat gamma-ray spectrum

distinct feature of the model - much steeper energy spectra of gamma-rays at large heights compared to region close to the galactic plain. can be checked very soon …
Pulsar Wind Nebulae:
electron PeVatrons
Fig. 1.8 Three regions of nonthermal radiation associated with a rotation powered pulsar: pulsar – magnetospheric pulsed γ-ray emission produced within the light cylinder due to the curvature, synchrotron, and inverse Compton processes; unshocked wind – gamma-radiation of the cold wind at GeV and TeV energies through the relativistic bulk-motion Comptonization; synchrotron nebula – broad-band, synchrotron and IC emission of the nonthermal nebulae (from Aharonian and Bogovalov, 2003).
Crab Nebula – a powerful \( L_e = \frac{1}{5} L_{\text{rot}} \sim 10^{38} \text{ erg/s} \)

and extreme accelerator: \( E_e \gg 100 \text{ TeV} \)

\[
E_{\text{max}} = 60 \left( \frac{B}{1 \text{G}} \right)^{-1/2} \eta^{-1/2} \text{ TeV} \quad \text{and} \quad \hbar \nu_{\text{cut}} \sim 150 \eta^{-1} \text{ MeV}
\]

Cutoff at \( \hbar \nu_{\text{cut}} = 10-20 \text{ MeV} \) \( \Rightarrow \) \( \eta \sim 10 \) - acceleration at 10 % of the maximum rate

\( \gamma \)-rays: \( E_{\gamma} \sim 50 \text{ TeV} \) (HEGRA, HESS) \( \Rightarrow E_e > 200 \text{ TeV} \)

\( B \)-field \( \sim 100 \text{ mG} \) \( \Rightarrow \) \( \eta \sim 10 \) - independent and more robust estimate

\( 1 \text{ mG} \) \( \Rightarrow \) \( \eta \sim 1 \) ?

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 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 agreement 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, $B > 1mG$, etc.

observations of 100TeV gamma-rays - IC photons produced by electrons responsible for synchrotron flares - a key towards understanding of the nature of MeV/GeV flares
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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 $<<$ “spin-down flux“ because of large B-field

If the B-field is small (environments with small external gas pressure), higher $\gamma$-ray efficiency leads to 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, ...
PWNe - *perfect electron accelerators and perfect γ-ray emitters!*

(1) rot. energy $\Rightarrow$ (2) Poynting flux $\Rightarrow$ (3) cold ultrarelativistic wind $\Rightarrow$
(4) termination of the wind/acceleration of electrons $\Rightarrow$ gamma-radiation:

*efficiency at each stage $>50\%$!*

**HESS J 13030-62 = PSR J1301-6305?**

![Image of HESS J 13030-62 and PSR J1301-6305 with energy spectra]

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 $L_\gamma/L_{SD} = 0.07$; 3 arcmin $\sim 10$ pc

because of small B-field we see “relic” electrons produced at early epochs of the pulsar
pulsar–wind–nebula paradigm
Pulsed component extends to VHE energies!

where pulsed VHE signal is produced:

in the magnetosphere
or in the pulsar wind?

very low fluxes – for adequate spectrometry and lightcurve – we need more sensitive instruments between 10 GeV and 1000 GeV

if the VHE gamma-ray emission is due to the “cold” wind

✓ wind is accelerated at $R \sim 30R_L$ to bulk motion Lorentz factor $\Gamma \sim 0.5-1 \times 10^6$
✓ no need to revise dramatically the magnetospheric models of GeV emission
TeV pulsed emission mimics the lightcurve of soft X-rays: at $R_w >> R_L$, $\Delta t \approx T/4\pi (R_L/R_w)$, for $R_w=30R_L$, $\Delta t \approx 0.003T$
binary systems - unique high energy laboratories

**binary pulsars** - a special case with strong effects associated with the optical star on both the dynamics of the pulsar wind and 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 detectable IC γ-rays

“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 γ-ray emission

(characteristic timescales 1 h or shorter !)

the target photon field is function of time, thus the only unknown parameter is B-field => predictable gamma-ray emission?
**HESS: detection of γ-rays at < 0.1Crab level -**

tendency of minimum flux close to periastron;

Several possible explanations, but many things uncertain and confusing.

Special expectations/hopes from Fermi related to the periastron passage in Dec 2010

Fermi LAT - weak signal far around periastron, but flares after 1 month!

IC emission of unshocked wind with Lorentz factor $10^4$ ?
flare – Comptonization of the unshocked wind by IR of the disk just after the exit of the pulsar from the disk $\Rightarrow \Gamma \sim 10^4$
LS 5039 works as a perfect TeV clock and an extreme accelerator close to inferior conjunction - maximum close to superior conjunction – minimum

modulation of the gamma-ray signal? a quite natural reason (because of $\gamma-\gamma$ 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 energies up to 20 TeV in presence of dense radiation? yes, but accelerator should not be located deep inside binary system; even at the edge of the system $\eta < 10 =>$ although the origin of the compact object is not yet known (pulsar or a BH) and we do not understand many details, it is clear that this binary system works as an extreme accelerator