Electron or proton acceleration & acceleration efficiency:

Spectra of gamma rays in RX J1713.7-3946

Fermi-LAT Collab.
arXiv:1103.5727

Model curves:

Electron acceleration

Spectra differ due to different energy dependence of pp and $e\gamma$ cross sections

H.E.S.S.
Index 2.0 + Cutoff

Fermi
Index 1.5

\[ \frac{E^2 dN/dE}{\text{MeV cm}^{-2} \text{s}^{-1}} \]

Energy [MeV]

\[10^3 \quad 10^4 \quad 10^5 \quad 10^6 \quad 10^7 \quad 10^8\]
Beam meets target: Supernova remnants & Clouds
$10^5$ M$_o$ cloud near SNR

Gabici et al
arXiv:0901.4549

High-energy particles with large diffusion reach cloud first

→ Determine diffusion coefficient
The SNR W28

CRs escaping from 35-150 kyr old SNR interacting with clouds?

HESS:
Aharonian et al., arXiv:0801.3555

Fermi:

AGILE
Giuliani et al., arXiv:1005.0784

Models:
Gabici et al., arXiv:1009.5291
Li & Chen, arXiv:1009.0894
Ohira et al., arXiv:1007.4869
The SNR W28 & clouds seen in CO
The SNR W28 @ TeV and GeV

One interpretation: CRs diffuse faster @ TeV energies
GeV CRs have not yet reached all clouds
Similar results in Gabici et al., arXiv:1009.5291

4x10^4 \, M_\odot

d = 22 \, pc

0.2x10^4 \, M_\odot

d = 140 \, pc

8x10^4 \, M_\odot

d = 140 \, pc

2.4x10^4 \, M_\odot

d = 100 \, pc
Cosmic rays in other galaxies
Magellanic Clouds

LMC
Fermi-LAT
arXiv:1001.3298

SMC
Fermi-LAT
arXiv:1008.2127

LMC
Distance
~50 kpc

Gamma rays per H atom
≈ CR density

our Galaxy

\[ \text{Gamma rays per H atom} \approx \text{CR density} \]
Magellanic Clouds

LMC
Fermi-LAT
arXiv:1001.3298

SMC
Fermi-LAT
arXiv:1008.2127

LMC
Distance
~50 kpc
M31 - Andromeda

Distance
~800 kpc

Fermi-Collab.
arXiv: 1012:1952
Supernovae in other galaxies

Starburst Galaxy M82
detected by
Fermi (GeV)
arXiv:911.5327
and
VERITAS (TeV)
arXiv:0911.0873
Cosmic ray factories: Starburst galaxies

Starburst Galaxy NGC 253 detected by Fermi (GeV) arXiv:911.5327 and H.E.S.S. (TeV) arXiv:0909.4651

Blue: DSS optical
Red: ROSAT X-rays
Starburst Galaxy NGC 253

detected by
Fermi (GeV)
arXiv:911.5327
and
H.E.S.S. (TeV)
arXiv:0909.4651

Blue: DSS optical
Red: ROSAT X-rays
Green: H.E.S.S. gamma rays
Correlation with star formation rate

Cosmic rays are (more or less) universal
Large-scale cosmic ray distribution in the Galaxy
Cosmic rays in our Galaxy

Fermi-LAT:
diffuse emission from interacting cosmic rays
CR density throughout the Galaxy


Graph (b) shows the variation of CR density with Galactic Radius [kpc].

Graph (a) depicts the distribution of CR density across the Galaxy, with zones I, II, III, and IV.
CR density throughout the Galaxy

The Galactic Center
Diffuse emission from the GC

white contours: density of molecular clouds

TeV gamma rays, HESS 2006
Diffusion from source @ GC?

$1^\circ \approx 150 \text{ pc}$

$\langle r_{pc}^2 \rangle^{1/2} \approx 10 \ E_{\text{PeV}}^{0.25} t_{\text{yr}}^{0.5} \rightarrow \text{need } O(10^4 \ \text{yrs})$

$\rightarrow \text{Sgr A East SNR ?}$
Diffusion in the GC region

Field > 50 $\mu$G on 400 pc ($2^\circ$) scales
Crocker et al.
arXiv:1001.1275

Log scale spanning 8 orders of magnitude

Simulated point source at GC
Wommer et al.
arXiv:0804.3111
Back to the Milky Way: The Fermi Bubbles
Fermi bubbles

Dobler et al. arXiv:0910.4583
Su et al., arXiv:1005.5480

Fermi data reveal giant gamma-ray bubbles
Similar structures in radio, X-rays

→ electronic origin
AGN activity or Galactic wind?
Su et al., arXiv:1005.5480

Electron injection at the GC:
hard to transport electrons over 10 kpc within cooling times of $10^5$ to $10^6$ y

AGN (GC) jet:
• somewhat atypical morphology
• bubbles may contain some $10^8$ solar masses

Duo & Mathews, arXiv:1103.0055

Wind from starbursts
• transports / generates proton CR
• electrons from proton interactions in bubble
• wind sustained over long timescales (Gyr, Crocker & Aharonian, arXiv:1008.2658)
• but need to trap protons for Gyrs
What is driving all the other very high energy gamma-ray sources?
Each γ-ray source is a cosmic multi-TeV particle accelerator.
Pulsar wind nebulae

HESS J1303-631

E < 2 TeV
E 2-10 TeV
E > 10 TeV

PSR J1301-6305
PSR B1259-63

\( e^\pm \)
Census of Galactic Sources

- PWN
- Binary
- Resolved SNR
- Unresolved SNR
- Unidentified
  - Confused / dark
- 1-2 Stellar clusters ?
- 1-2 WR ?
- PWN ?

- Winds of massive stars
- Supernova shocks (interacting with clouds?)
- Pulsar winds
- Pulsar relics
Pulsar wind nebulae

van der Swaluw, Downes, & Keegan 2003

Why so many?

SNR shock accelerates particles for few kys

Pulsar wind lasts tens of kys & electrons are efficient emitters

Why are most PWN offset from pulsar?

Interaction with shell / reverse shock / non-uniform medium
Take home messages

“Standard model” of cosmic rays
- Acceleration in supernova remnants
- Energy-dependent diffusive propagation
- Extragalactic sources dominate at $E >> E_{\text{knee}}$

... however
Detection: Knowledge of nuclear collisions at highest energies is a serious bottleneck.

CR propagation in the Galaxy is poorly understood, especially at higher energies, which impacts interpretation of sources.

Many puzzling features: anisotropy, kinks in spectra, ...

 Fundamental science or just a messy Galaxy??

Clues could come from precision gamma-ray astronomy and hopefully from neutrino astronomy.

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Don’t (yet) invoke Dark Matter, Aliens etc. if you see strange things in cosmic rays!

OCCAM'S RAZOR
Your theory is too complex