MeV astronomy of the interstellar medium

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Cosmic-ray interactions probed by their photon emission
COSMIC RAYS produce many observables

- cosmic-ray sources: p, He .. Ni, e
- Secondary: \(^{10}\)Be, \(^{10,11}\)B ...
- synchrotron
- reacceleration
- energy loss
- decay
- \(\gamma - \) rays
- \(\pi\)
- gas
- ISRF
- bremsstrahlung
- inverse Compton
- B-field

intergalactic space
Most photons from cosmic-rays:

- nuclei interacting with interstellar gas: hadronic
- electrons and positrons interacting with interstellar radiation: inverse Compton
- Interstellar gas: bremsstrahlung
Fermi-LAT
Inner Galaxy Gamma Ray Spectrum

Interstellar Cosmic ray spectra derived from gamma rays

Gammaray gas emissivity used to derive Cosmic-ray protons

Below 10 GeV affected by solar modulation, but gamma rays probe the interstellar spectrum.

Emissivity of local interstellar gas – Jean-Marc Casandjian (Fermi-LAT Collab).

Power-law in momentum overall, but low-energy break? e.g. from power-law injection and interstellar propagation (diffusion = f(E))

Interstellar spectrum essential to test heliospheric modulation models.
Interstellar Cosmic ray spectra derived from gamma rays

Method: Bayesian analysis

Gamma-ray gas emissivity used to derive Cosmic-ray protons

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Power-law in momentum overall, but low-energy break?
  e.g. from power-law injection and interstellar propagation (diffusion = f(E))

Interstellar spectrum essential to test heliospheric modulation models.
Interstellar Electrons
from synchrotron, gamma rays and direct measurements

![Graph showing the distribution of interstellar electrons with momentum on the x-axis and differential intensity on the y-axis. The graph includes data points from PAMELA, AMS01, and Fermi-LAT with a model line fitted to the data. The legend indicates the sources of the data.]

PRELIMINARY
Mainly cosmic-ray electrons interacting with interstellar radiation and matter? 
or glow from myriad unresolved sources?
A real mix of processes!
Inner Galaxy
INTEGRAL / SPI
Non-thermal: Cosmic-ray interactions
Inner Galaxy: keV to TeV

**Inner Galaxy: keV to TeV**

- GeV electrons – inverse Compton - important for MeV gamma rays!
- Bremsstrahlung from MeV electrons – only from theory, perhaps much larger.
NB low angular and energy resolution!
*Nominal energy range*: photons may originate from range 10 to <100 MeV. But valuable to bridge the MeV gap.
Fermi-LAT 25-40 MeV

meets

COMPTEL 10-30 MeV
Fermi meets COMPTEL

Fermi-LAT 25-40 MeV

COMPTEL 10-30 MeV

 Galactic Plane

Cyg X-1  LS5039  Vela PSR  Crab
Continuum sky surveys

- 22 MHz
- 45 MHz
- 150 MHz
- 23 GHz
- 408 MHz
- 2.3 GHz
- 820 MHz
- 1.4 GHz
cosmic-ray sources: electrons

γ-rays

synchrotron

B-field

inverse Compton

ISRF

γ-rays

intergalactic space

HALO
SYNCHROTRON ELECTRONS for RADIO and GAMMA RAYS!
good constraints on models

SAME ELECTRONS for RADIO and GAMMA RAYS!
good constraints on models

E\(^2\) J(E) (GeV\(^2\) m\(^{-2}\) s\(^{-1}\) sr\(^{-1}\))

E (GeV)

\(E^2 J(E)\) (GeV\(^2\) m\(^{-2}\) s\(^{-1}\) sr\(^{-1}\))
Radio surveys

Galactic center region

SYNCHROTRON

microwaves probe
interstellar electron spectrum
10 - 100 GeV

No solar modulation of directly-measured electrons > 10 GeV
Galactic center region
Northern Sky
SYNCHROTRON

Radio surveys

radio probes
interstellar electron spectrum at
E ~ 1 GeV
to complement direct measurements
and determine solar modulation

electrons have huge uncertainty
due to modulation here

Only MeV gammas can probe electrons below 100 MeV via bremsstrahlung!

(Q: Voyager direct measurements Now approaching interstellar? )
Secondary positrons (and secondary electrons) are important for synchrotron.
Fig. 4. Electron spectra for pure diffusion model, low-energy electron injection index 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Modulation $\Phi = 0, 200, 400, 600, 800$ MV. Data as in Fig. 1.

Fig. 5. Synchrotron spectra for pure diffusion model with low-energy electron injection index (left to right, top to bottom) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Data as in Fig. 2.
**Fig. 6.** Synchrotron spectral index for pure diffusion model with low-energy electron injection index (left to right, top to bottom) 1.0, 1.3, 1.6, 1.8, 2.0, 2.5. Including secondary leptons. Experimental ranges are based on the references reviewed in Sect. 4.1, and are intended to be representative not exhaustive. Data as in Fig. 3.

**Galactic Synchrotron**

**$T_B$**

**Spectral Index**

Strong, Orlando & Jaffe (2011)
Luca Maccione. ArXiv 1211.6905

PAMELA, charge and polarity dependence of e+/e-

DRAGON propagation model, interstellar spectrum, solar modulation model

**FIG. 1.** The positron fraction measured by Fermi, PAMELA and AMS-01 is shown. The LIS is shown as the red dashed curve. Solid curves show the Earth positron fraction computed evolving the LIS for $\alpha = 30^\circ$ and positive polarity (black) or negative polarity (violet).

**FIG. 6.** The absolute $e^-$ and $e^+$ spectra measured by different experiments are compared with our calculations for $\alpha = 30^\circ$ and both polarities.
From Luca Maccione, see also arXiv 1211.6905

PAMELA, charge and polarity dependence of e- and e+

MeV gammas probe this region via bremsstrahlung
(neither synchrotron nor direct measurements useful)
Polarized synchrotron

* Separates regular from random B

* Separates synchrotron from spinning dust and free-free emission

Now modelled in GALPROP

B-field models implemented

Orlando and Strong 2013
INNER GALAXY

- Synchrotron
- Thermal dust

Total

- Synchrotron
- Free-free
- Thermal + spinning dust

INNERR GALAXY
Using various B-field and cosmic-ray models

Haslam

Regular B-field models from Sun et al., Pshirkov et al. Scaling factor applied.

Synchrotron from GeV electrons
Using various B-field and cosmic-ray models

Synchrotron from 10 GeV electrons

Regular B-field models from Sun et al, Pshirkov et al. Scaling factor applied.
A lot of common astrophysics, cosmic rays, gas, magnetic fields! *Will be also the case at MeV.*
Fermi Bubbles

(related to WMAP Haze ?)

Planck haze (arXiv:1208.5483) Overlaid on Fermi Bubbles

What about MeV ?

connection to 511 keV line ?

All are - centred on Galactic Centre leptonic unknown origin
"Giant magnetized outflows from the centre of the Milky Way”
Correlates with Fermi Bubbles.
Produced by repeated episodes of star-formation at Galactic Centre?
Since we live inside the Galaxy, global properties like multiwavelength luminosity (SED) are not easy to deduce.

SEDs of AGN etc are common, but not Milky Way
what does it look from out there?
cosmic-ray sources: $p, He \ldots Ni, e^-$

Secondary: $^{10}Be, ^{10,11}B \ldots Fe$...

Secondary: $e^+, \bar{p}$

cosmic-ray sources: $p, He \ldots Ni, e^-$

γ − rays

gas

Bremsstrahlung

ISRF

Inverse Compton

Synchrotron

B-field

HALO

Intergalactic space

EXPERIMENTS

THEORY
Galaxy luminosity over 20 decades of energy

[Graph showing galactic luminosity across different energy bands: IR/optical, cosmic rays, radio, MeV γ-rays, very uncertain, with specific labels and scales.]
Nuclear lines and line quasi-continuum using low-energy cosmic rays based on ionization rates from interstellar cloud chemistry


More chance to detect nuclear lines!

See talk by Juergen Kiener, this meeting
Inner Galaxy: keV to TeV

Need 10-100 times more sensitivity to study nuclear lines and line continuum
But enhanced fluxes already competitive with inverse Compton at 10 MeV!

from Juergen Kiener
MeV astronomy of interstellar medium provides:

Essential region below Fermi-LAT range for astrophysical interpretation
Enormous added value from complementarity.

Probe of electrons (and positrons) below 100 MeV (bremsstrahlung)
and below 1 GeV (inverse Compton)

MeV view of Fermi Bubbles / WMAP-Planck haze: changing our view of the Galaxy.

Probe of source populations in the Galaxy (cf COMPTEL excess)

+ Who knows what else?
The last great unexplored region of the electromagnetic spectrum!
Enormous discovery potential!