Cosmic Rays and Magnetic Fields in a multiwavelength context

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DFG FOR 1254  Workshop on Magnetic Fields in galaxies
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Victor Hess before his 1912 balloon flight in Austria, during which he discovered cosmic rays
WHY?

Why consider the high-energy astrophysics connection?

High-energy astrophysics = cosmic-rays, gamma rays, synchrotron
+ magnetic fields.

Gives insight into the synchrotron emission – spectral and spatial

Polarized synchrotron is essential part of this topic.
Topics

Synchrotron in high-energy context

Spectral aspects

Polarization, magnetic fields

Gamma rays
High energy particles and radiation in the Galaxy
cosmic-ray sources: electrons

γ-rays

synchrotron

halo

inverse Compton

ISRF

B-field

intergalactic space
COSMIC RAYS produce many observables

- **cosmic-ray sources**: p, He .. Ni, e
- **Secondary**: $^{10}$Be, $^{10,11}$B ... Fe...
- **Secondary**: $e^+$, $\bar{p}$

- **energy loss**
- **decay**
- **reacceleration**

**HALO**

**intergalactic space**

**γ − rays**

**π**

**gas**

**ISRF**

**synchrotron**

**bremsstrahlung**

**inverse Compton**

**B-field**

**GALPROP model**
Galaxy luminosity over 20 decades of energy
Cosmic-ray interactions probed by their photon emission
The **goal**: use all types of data in self-consistent way to test models of cosmic-ray propagation.

Observed *directly, near Sun*: primary spectra (p, He ... Fe; e⁻) secondary/primary (B/C etc) secondary e⁺, antiprotons...

Observed *from whole Galaxy*: γ - rays synchrotron
\[ \frac{\partial \psi (r, p)}{\partial t} = q(r, p) \]

- cosmic-ray sources (primary and secondary)

\[ + \nabla \cdot (D_{xx} \nabla \psi - v \psi) \]
- diffusion
- convection

\[ + \frac{\partial}{\partial p} \left[ p^2 D_{pp} \frac{\partial}{\partial p} \psi / p^2 \right] \]
- diffusive reacceleration (diffusion in p)

\[ - \frac{\partial}{\partial p} \left[ \frac{d}{dt} \frac{d p}{d t} \psi - \frac{p}{3} (\nabla \cdot v) \psi \right] \]
- momentum loss
- adiabatic momentum loss
- ionization, bremsstrahlung

\[ - \psi / \tau_f \]
- nuclear fragmentation

\[ - \psi / \tau_r \]
- radioactive decay
Producing the cosmic-ray electron spectrum
Producing the cosmic-ray electron spectrum

Diagram:
- Flux
- Injection
- Energy-dependent diffusion
- Energy
Producing the cosmic-ray electron spectrum

Diagram:
- Flux
- Injection
- Energy-dependent diffusion
- Energy losses
- Energy
Producing the cosmic-ray electron spectrum

Flux

- Injection
- (diffusive reacceleration)
- Energy-dependent diffusion
- Energy losses

Energy
Producing the cosmic-ray electron spectrum
Cosmic-ray secondary/primary ratios: e.g. Boron/Carbon probes cosmic-ray propagation

Peak in Boron/Carbon could be explained by diffusive reacceleration with Kolmogorov spectrum giving momentum-dependence of diffusion coefficient

Spatial diffusion
\[ D_{xx} \sim p^{1/3} \]

Momentum space diffusion
\[ D_{pp} \sim 1 / D_{xx} \]

However reacceleration not proven, maybe does not happen → 'pure diffusion' model: \[ D_{xx}(p) \sim p^{0.5} \], constant < 3 GeV.
For any model, first adjust parameters to fit Boron/Carbon
then predict the other cosmic-ray spectra

**antiprotons**
plain diffusion
diffusive reacceleration
wave damping

ELECTRONS

positrons

PD model
\( \Phi = 600 \text{ MV} \)

AMS I
CAPRIE 94
HEAT 94-95
MASS 91
Sanriku

DR model
\( \Phi = 600 \text{ MV} \)

AMS I
CAPRIE 94
HEAT 94-95
MASS 91
Sanriku

DRD model
\( \Phi = 600 \text{ MV} \)

AMS I
CAPRIE 94
HEAT 94-95
MASS 91
Sanriku

PD model
\( \Phi = 600 \text{ MV} \)

AMS I
CAPRIE 94
HEAT 94-95
MASS 91

DR model
\( \Phi = 800 \text{ MV} \)

AMS I
CAPRIE 94
HEAT 94-95
MASS 91

DRD model
\( \Phi = 500 \text{ MV} \)

AMS I
CAPRIE 94
HEAT 94-95
MASS 91

ELECTRONS

POSITRONS

Kinetic energy, GeV

Flux, m\(^2\)s\(^{-1}\)sr\(^{-1}\)GeV\(^{-1}\)

44-9997256

44-9997258

44-999714sr

44-9997256

44-9997258

44-999714sr
Connecting Synchrotron, Cosmic Rays, and Magnetic Fields in the Plane of the Galaxy

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Uses RM, polarization, MCMC.
Cosmic-ray electrons from sources + propagation
The interstellar cosmic-ray electron spectrum from synchrotron radiation and direct measurements

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ABSTRACT

Aims. We exploit synchrotron radiation to constrain the low-energy interstellar electron spectrum, using various radio surveys and connecting with electron data from Fermi-LAT and other experiments.

Methods. The GALPROP programme for cosmic-ray propagation, gamma-ray and synchrotron radiation is used. Secondary electrons and positrons are included. Propagation models based on cosmic-ray and gamma-ray data are tested against synchrotron data from 22 MHz to 94 GHz.

Results. The synchrotron data confirm the need for a low-energy break in the cosmic-ray electron injection spectrum. The interstellar spectrum below a few GeV has to be lower than standard models predict, and this suggests less solar modulation than usually assumed. Reacceleration models are more difficult to reconcile with the synchrotron constraints. We show that secondary leptons are important for the interpretation of synchrotron emission. We also consider a cosmic-ray propagation origin for the low-energy break.

Conclusions. Exploiting the complementary information on cosmic rays and synchrotron gives unique and essential constraints on electrons, and has implications for gamma rays. This connection is especially relevant now in view of the ongoing Planck and Fermi missions.

Following results based on this paper.
Continuum sky surveys

- 22 MHz
- 45 MHz
- 150 MHz
- 23 GHz
- 408 MHz
- 2.3 GHz
- 820 MHz
- 1.4 GHz
SYNCHROTRON
SAME ELECTRONS for RADIO and GAMMA RAYS!
good constraints on models

COSMIC RAY ELECTRONS

GAMMA RAYS

INVERSE COMPTON
Radio surveys

Radio provides essential probe of interstellar electron spectrum at $E < \text{few GeV}$ to complement direct measurements and determine solar modulation.

Electrons have huge uncertainty due to modulation here.
Galactic center region
Radio surveys
SYNCHROTRON
microwaves probe interstellar electron spectrum 10 - 100 GeV
No solar modulation of directly-measured electrons > 10 GeV
Secondary positrons (and secondary electrons) are important for synchrotron!
Cosmic-ray electrons

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.
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.
Model predicts small but systematic variations due to propagation effects.

Reality is of course much more complex (Loop I etc not modelled).

The model gives a minimum underlying variation from electron propagation.
Total B (local) = 7.5 µG from this analysis

Using high latitudes only, avoiding Loop I etc
Orlando and Strong 2013, submitted

What is new:

Polarized synchrotron

Separates regular from random B

Now modelled in GALPROP

B-fields from literature, basic modifications to fit data.
Cosmic-ray electron distribution is a main input from gamma rays.

CR source distributions from Strong et al. (2010) (blue line) and pulsar-based Lorimer et al. (2006) (red dashed line). $R$ is the Galactocentric radius in kpc. The distributions are normalized at $R=8.5$ kpc.
INNER GALAXY

synchrotron

thermal dust

free-free

thermal + spinning dust

P

Total

synchrotron

synchrotron

synchrotron

INNER GALAXY
HIGH LATITUDES

- Synchrotron
- Thermal dust
- Total
- Synchrotron
- Free-free
- Thermal + Spinning dust
Using various B-field and cosmic-ray models

Haslam

Regular B-field models from Sun et al., Pshirkov et al. Scaling factor applied.
Using various B-field and cosmic-ray models

Regular B-field models from Sun et al, Pshirkov et al. Scaling factor applied.
B-field from Strong & Orlando 2013

Using:
Fermi-LAT cosmic-ray electrons
408 MHz
23 GHz WMAP polarized

Local B-field:

**Regular**: 3-4 $\mu$G:
factor 1.5-2 higher than original models of Sun, Pshirkov

**Random**: 6 $\mu$G
Exploiting gamma rays

1 – 10 GeV

Cosmic-ray protons interacting with gas: hadronic (pion-decay)

Cosmic-ray electrons and positrons interacting with gas: bremsstrahlung

interacting with interstellar radiation: inverse Compton
A lot of common astrophysics, cosmic rays, gas, magnetic fields!
Fermi-LAT
Inner Galaxy Gamma Ray Spectrum

Interstellar Cosmic ray spectra derived from gamma rays

Gamma-ray 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

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 electrons from synchrotron, gamma rays and direct measurements
This model shown in previous two slides

\[ \begin{align*}
\| & \\
\text{V} & \\
\end{align*} \]

CROSS-SECTIONS

<table>
<thead>
<tr>
<th></th>
<th>Kamae</th>
<th>Kachelriess &amp; Ostapchenko</th>
<th>Dermer, Stecker Stephens &amp; Badhwar</th>
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<td>6.7 (±2.5) GeV</td>
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<tr>
<td>proton index below break</td>
<td>2.4 (0.1)</td>
<td>2.5 (0.1)</td>
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<tr>
<td>proton index above break</td>
<td>2.9 (0.1)</td>
<td>2.8 (0.1)</td>
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<tr>
<td>proton normalization</td>
<td>1.3 (0.1)</td>
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<tr>
<td>electron break momentum</td>
<td>3.0</td>
<td>3.0 (fixed from synchrotron)</td>
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</tr>
<tr>
<td>electron index below break</td>
<td>1.8 (0.1)</td>
<td>1.9 (0.1)</td>
<td></td>
</tr>
</tbody>
</table>

PRELIMINARY

See also talk by Chuck Dermer, this conference and Fermi Symposium 2012
Mainly cosmic-ray electrons interacting with interstellar radiation and matter? or glow from many unresolved sources?
A real mix of processes!
Inner Galaxy
INTEGRAL / SPI
Inner Galaxy
INTEGRAL / SPI

Non-thermal: Cosmic-ray interactions
Inner Galaxy: keV to TeV

Inner Galaxy: keV to TeV

- Inverse Compton
- bremsstrahlung
- positronium sources

$^{26}\text{Al}$, $^{60}\text{Fe}$

$E^2 \times \text{Intensity, cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}$

- $e^+e^-$
- Inverse Compton
- Bremsstrahlung

GeV electrons – inverse Compton - important for MeV gamma rays!
Fermi-LAT 25 – 40 MeV

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

PRELIMINARY

COMPTEL 10-30 MeV

Galactic Plane

Cyg X-1  LS5039  Vela PSR  Crab
Fermi Bubbles

(related to WMAP Haze ?)

Planck haze (arXiv:1208.5483)
Overlaid on Fermi Bubbles

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 .. Ni, $\gamma$ - rays

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

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

HALO

intergalactic space

synchrotron

B-field

gas

ISRF

bremsstrahlung

inverse Compton

$\pi$

$\gamma$ – rays

EXPERIMENTS

THEORY
Galaxy luminosity over 20 decades of energy
Galaxy luminosity over 20 decades of energy

IR/optical

cosmic rays

Cosmic-ray Electron Calorimeter!
Interstellar chemistry → ionization rates → cosmic rays → nuclear lines

Low energy cosmic rays

Ionization rate

ENHANCED

STANDARD

FROM CHEMISTRY OF $H_3^+$

Cutoff energy

Fig. 4.— Calculated ionization rates of cosmic rays in dense molecular clouds supposing that particles with energies below 10 MeV per nucleon do not penetrate these places. Red symbols (connected by the dashed lines) show the values for SA-LECRs with spectral indices $s = 2.0$ (triangles), $s = 2.35$ (squares) and $s = 2.7$ (circles), blue symbols (connected by the full lines) the values for ACR-LECRs, $s = 2.0$ (triangles), $s = 2.4$ (squares) and $s = 2.7$ (circles). The ionization rate of standard CRs ($0.35 \times 10^{-18}$ s$^{-1}$) is added. The dashed line and the hatched area show the recommended value of van der Tak & van Dishoeck (2000) for the cosmic-ray ionization rate and its uncertainty in dense molecular cloud cores ($\zeta_{CR} = (0.29 \pm 0.14) \times 10^{-18}$ s$^{-1}$). The dotted line represents their upper limit ($\sim 1.3 \times 10^{-18}$ s$^{-1}$).

Nuclear lines and line quasi-continuum using low-energy cosmic rays based on ionization rates from interstellar cloud chemistry


Fig. 6.— Calculated nuclear γ-ray line emissions from the inner Galaxy for CRs with ACR-LECR components following the model of Scherer et al. (2008a) with $s = 2.4$, $E_c = 5$, 25 and 1200 MeV (magenta, red and green lines, resp.) and SA-LECR with $s = 2.0$ and $E_c = 120$ MeV (blue line). The emission due to the standard CR component alone is shown by the dashed black line.

More chance to detect nuclear lines!
Inner Galaxy: keV to TeV

- **26**Al
- **60**Fe
- positronium
- sources
- Inverse Compton
- bremsstrahlung
- posion sources
Need 10-100 times more sensitivity to study nuclear lines and line continuum
But enhance fluxes already competitive with inverse Compton at 10 MeV!
END