Pulsar emission of positrons and electrons, and its connections with gamma rays

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works done in collaboration with Mattia Di Mauro and Silvia Manconi
The journey started with the attempt - shared by many - to interpret the \( e^+ \) data.

Unprecedented energy coverage, high statistical accuracy.

Unprecedented statistics and energy coverage.
Sources of $e^\pm$ in the Milky Way

- Inelastic hadronic collisions (asymm.)
- Pulsar wind nebulae (PWN) (symm.)
- Supernova remnants (SNR) (only $e^+$)
- (Particle Dark Matter annihilation)
From the source to a detector

Sources: production mechanism
acceleration to high energies
injection into the interstellar space

Propagation: diffusion on the magnetic inhomogeneities of the Galaxy
energy losses and gains (B, E, cross sections)
convection

Energy losses: from the production site to the detector
Propagation in the Galaxy

The galactic disc is embedded in a diffusive halo \((L\sim4-10\ kpc)\) where particle diffuse and can loose energy.
**Propagation equation**

\[
\frac{\partial \psi}{\partial t} - \nabla \cdot \{ D(E) \nabla \psi \} + \frac{\partial}{\partial E} \left\{ \frac{dE}{dt} \psi \right\} = Q(E, x, t)
\]

**Diffusion**

D(x, R) a priori

usually assumed isotropic in the Galaxy: \( D(R) = D_0 R^\delta \)

\( D_0 \) and \( \delta \) fixed by secondary/primary nuclei \( \text{Kappler+15; Genolini+15 (K15)} \)

**Energy losses**

Synchrotron on the galactic B \( \sim 3.6 \) \( \mu \)G

full relativistic of Compton effect (w/ Klein-Nishijna)

on photon fields (stellar, CMB, UV, IR)

**Solution of the eq.:** semi-analytic (Maurin+ 2001, Donato+ 2004, ...), USINE codes

or fully numerical: GALPROP, DRAGON codes

**Geometry of the Galaxy:** cylinder with height \( L \)
Detected $e^\pm$ are local

$$\lambda^2(E, E_S) = 4 \int_E^{E_S} dE' \frac{D(E')}{b_{\text{loss}}(E')}$$

Typical propagation length in the Galaxy

$e^-, e^+$ have strong radiative cooling and arrive at Earth if produced within few kpc around it

Most powerful sources within 3 kpc from the Sun.
SNRs ($e^-$) and PWN ($e^+e^-$)

Manconi, Di Mauro, FD JCAP 2017
A word worth on $e^\pm$ energy losses

**Inverse Compton**

$$e^\pm(E_0) + \gamma(E) \rightarrow e^\pm(E_1) + \gamma(E')$$

- $E_0 > E_1$ a loss
- $E < E'$ a gain, and a **MESSANGER** X-rays, $\gamma$-rays

**Synchrotron emission** radiated from the interaction with a $B$
- $e^\pm$ losses energy
- a photon is created, a **MESSANGER** radio, X-ray
Secondary $e^+e^-$

Produced by inelastic collisions of CRs ($p$ and He mostly) on the interstellar GAS ($H$ and He)

$$p + H \rightarrow \pi^\pm + X$$
$$p + H \rightarrow K^\pm + X$$

$d\sigma (p + H \rightarrow \pi^\pm + X)$ has to be measured $\rightarrow$ UNCERTAINTY $\sim 2$

$P(\pi^\pm \rightarrow e^\pm)$ is computed by QED

Need for high energy data cross sections from collider experiments

Di Mauro + JCAP 2019

Di Mauro + JCAP 2014
Electrons from supernova remnants

SNR are considered the main sources of galactic CRs – nuclei from p to Fe, and e–

- Hadronic acceleration: evidence of $\pi^0$ bump (Fermi-LAT+ 2010)
- Leptonic acceleration: evidence of synchrotron emission in radio and X-rays

Injection spectrum:

$$Q(E) = Q_0 \left( \frac{E}{E_0} \right)^{-\gamma} \exp \left( -\frac{E}{E_c} \right)$$

$\gamma$ flux from near SNR (Vela XY and Cygnus Loop at $d<0.5$ kpc)

Few SNR can contribute to TeV flux

Additional e– from a smooth SNR distribution
SNR acceleration & radio emission

Hyp: Radio flux due to synchrotron emission from accelerated e⁻ in the SNR

\[ Q_{0,\text{SNR}} = 1.2 \cdot 10^{47} \text{ GeV}^{-1} (0.79) \gamma \frac{B_r'(\nu)}{Jy} \left( \frac{d}{\text{kpc}} \right)^2 \left( \frac{\nu}{\text{GHz}} \right)^{\gamma - 1} \left( \frac{B}{100 \mu\text{G}} \right)^{\frac{\gamma + 1}{2}} \]

Manconi, Di Mauro, FD JCAP 2019

We fit all the available radio data fixing B\text{Vela} = 36 \mu\text{G} and B\text{Cygnus} = 60 \mu\text{G}

Vela has energetic trapped e⁻, and only E > 88 \text{ GeV} have escaped (17 \text{ GeV} for Cygnus).

The flux of e⁻ as constrained by radio data contribute few % to the (e⁺e⁻) data.
**Pulsars (PWN) as CR e⁺e⁻ sources**

Shen ApJL 1970; Amato arvin:1312.5945; Di Mauro+ JCAP 2014

**Pulsar wind nebulae (PWNe) as engines of e±**

- High magnetic fields ($10^9$--$10^{12}$ G) extract wind of $e^-$ from the pulsar surface, e± pairs produced in EM cascades

- Pulsar spin-down energy ($W_0$) is transferred to e± pairs, accelerated to very high energy with $Q(E) \sim E^{-\gamma}$.

- After several kyrs e± can be released in the ISM

- These e± pairs radiate by IC and synch., and shine at many frequencies

\[
E_{\text{tot}} = \eta W_0 = \int_0^T dt \int_{E_1}^{\infty} dE EQ(E, t)
\]

The total energy $E_{\text{tot}}$ emitted in e± by a PWN is a fraction $\eta$ (efficiency conversion) of the spin-down energy $W_0$. Relevant parameters: $\gamma$ and $\eta$
Anisotropy in a diffusion model

Anisotropy should be computed by development on spherical harmonics. For one or few sources, we can expect only the dipole term to have some relevance (if any). In diffusive propagation regime (Ginzburg & Syrovatskii 1964):

\[
\Delta = \frac{3K}{c} \left| \nabla \psi \right|
\]

For example, for a source at \(d_s\):

\[
\Delta(E)_{e^+e^-} = \frac{3K(E)}{c} \frac{2d_s}{\lambda^2(E, E_s)} \frac{\psi_{e^+e^-}^s(E)}{\psi_{e^+e^-}^{tot}(E)}
\]


\[
\Delta(n_{\text{max}}, E) = \frac{1}{\psi^{\text{tot}}(E)} \cdot \sum_i \frac{r_i \cdot n_{\text{max}}}{\|r_i\|} \cdot \psi_i(E) \Delta_i(E)
\]
A multi-wavelength & multi-messenger analysis

We fit the parameters selected by radio and $e^+e^-$ flux data and check against dipole anisotropy data

We find models compatible with three independent observables:
radio flux from SNR; $e^+e^-$ flux; $e^+e^-$ dipole anisotropy

Manconi, Di Mauro, FD JCAP 2019
Bounds from dipole anisotropy

Fermi-LAT data from e+e- dipole anisotropy are upper bounds vs E (Abdollahi+ PRL 2017)

Maximal anisotropy from e+e- flux
selected configurations

Dipole anisotropy in CR leptons is a valuable observable to
study the properties of local sources - SNRs

Anisotropy excludes configurations
selected by e+e- flux
The positron flux shows (Pamela, AMS data) the need of primary source at high energies. Pulsars could do the job.

HAWC has detected a TeV gamma-ray halo around Geminga and Monogem pulsars. Interpreted as e⁺e⁻ accelerated by the pulsar, then released in the ISM, a low diffusion region around the pulsars is favored by data.
What we learn from HAWC data

- The $e^\pm$ injection is continuous (not burst-like)

\[
Q(E, t) = L(t) \left( \frac{E}{E_0} \right)^{-\gamma} \exp \left( -\frac{E}{E_c} \right) \quad \text{and} \quad L(t) = \frac{L_0}{(1 + \frac{t}{\tau_0})^2}
\]

- The spin-down luminosity converted into HAWC high energy $e^+e^-$ is $\eta W_0 = 1.5 \times 10^{48} \ (4.2 \times 10^{46}) \text{ erg for Geminga (Monogem)}$

- The diffusion is inhibited around the pulsar by $\sim 500$ times wrt the average in the ISM: $D_0 (1 \text{ GeV}) = 5 \times 10^{25} \text{ cm}^2/\text{s}$

![Image of data analysis and fit to Geminga surface brightness]
Which $e^\pm$ produce HAWC photons?

The fit to HAWC surface brightness comes with uncertainties / degeneracies.

The extrapolation down to Fermi-LAT energies gives remarkable differences.

The HAWC data do not constrain the $e^+$ measured by experiments (AMS02).

The $e^\pm$ injection power spectrum is one key parameter.
Searching for γ-rays around Geminga in the Fermi-LAT data

- We implement a Inverse Compton Scattering template with background Interstellar radiation field (ISRF, needs a model)

- Pulsar proper motion: $v_T = 211 \text{ km/s}$ (Faherty+AS2007) (70 pc travelled)

![Without proper motion](image1)

![With proper motion](image2)
Detection of a $\gamma$-ray halo in Fermi-LAT data around Geminga

We detect a $\gamma$-ray halo around Geminga at 7.8-11.8$\sigma$ (depending on background models)

- Fit improves with proper motion included.
- Diffusion $D(1\text{GeV}) = 1.6-3.6 \times 10^{26} \text{ cm}^2/\text{s}$ (compatible w/ HAWK)
- Extension $\sim 60 \text{ pc}$ at 100 GeV
- $\gamma_e = 1.8-2$

Di Mauro, Manconi, FD PRD 2020
γ-ray haloes influence e+ at the Earth

2-zones diffusion model:

\[ D(r) = \begin{cases} 
D_0 (E/1 \text{ GeV})^\delta & \text{for } 0 < r < r_b, \\
D_2 (E/1 \text{ GeV})^\delta & \text{for } r \geq r_b, 
\end{cases} \]

\( r_b \) is the boundary between low and high diffusion zones

Geminga contributes few % to the e+ flux at the Earth. The ICS halo is about 80 pc at Fermi-LAT energies.
Halo extension depends on energy and diffusion physics.

Smaller haloes expected at higher energies.

Higher diffusion coefficients get the halo spread out.

ISM $D(E)$ values ($\sim 10^{28}$ cm$^2$/s) would get low energy $\gamma$-rays around Geminga spread widely in the ISM (no longer a halo...).
γ-ray haloes: a general property of pulsars?  
M. Di MAuro, S. Manconi, FD arxiv:1908.03216

We select sources from ATNF catalog with highest ICS halo above 1 TeV

Compute the number of sources above HESS, HAWC and CTA sensitivity as a function of $\eta$, efficiency conversion into $e^\pm$.

Tens of haloes could/will be detected even with 1% efficiency conversion into $e^\pm$.
A low diffusion zone around PWNe

We select sources detected mainly by HESS (they provide flux maps). Interpret the data in terms of ICS halo and fit $D(1\text{TeV})$ and size

The diffusion coefficient around PWNe is systematically lower by 2 orders of magnitude w.r.t. the ISM diffusion coefficient found from CR data ($B/C$).
γ-ray haloes have tens pc size

We fit also the ICS halo size

The trend with the age is compatible with models of PWN evolution

The low diffusion zone around PWN should be larger than the halo size

Di Mauro, Manconi, FD 1908.03216 to app. PRD

Manconi, Di Mauro, FD 2001.09985, subm. PRD

The halo size can shape the high energy e+ flux
**ATNF pulsar catalog**

**Distance d, age T (50kyr<T<10^5kyr), spin-down energy dE/dt**

**Continuous injection:**

\[
Q(E,t) = L(t) \left( \frac{E}{E_0} \right)^{-\gamma_e} \exp \left( -\frac{E}{E_c} \right) \quad L(t) = \frac{L_0}{(1 + \frac{t}{\tau_0})^{\frac{b+1}{2}}},
\]

**From catalog data:**

\[
W_0 = \tau_0 \dot{E} \left( 1 + \frac{T}{\tau_0} \right)^{\frac{b+1}{2}} \quad E_{tot} = \eta W_0 = \int_0^T dt \int_{E_1}^{\infty} dE W(E,t).
\]

\[r_b=120\text{ pc}, \quad D_0=7.8 \times 10^{25} \text{ cm}^2/\text{s}, \quad \eta=0.12, \quad \gamma_e=1.9\]

\[r_b=90\text{ pc}, \quad D_0=7.8 \times 10^{25} \text{ cm}^2/\text{s}, \quad \eta=[0.02,0.30], \quad \gamma_e=[1.4,2.0]\]

Few sources above 10% data - Cumulative flux ~ AMS-02 data

The h.e. trend dictated by low diffusion (D_0) within r_b
Simulations of galactic pulsar population

The ATNF catalog may be incomplete.

We simulate a galactic Pulsar population with physics inputs:

- The uncertainty band is $\sim 10$
- The flux is NEVER negligible up to TeV
- Predictions fall around AMS-02 data
Conclusions

- Leptons at Earth have a composite origin: e- from far smooth and near catalog SNR, e+e- from PWN, e+e- as secondaries in the ISM.

- e+ (with p-) are a major antimatter CR component in the Galaxy.

- The violent radiative cooling provides invaluable and different messengers.

- We discovered an ICS γ-ray halo around Geminga pulsar (U.L. for Monogem) in the Fermi-LAT data at 8-100 GeV.

- CRs at high energies, dipole anisotropy, radiation from radio to γ rays are giving us an innovative view of the Galaxy and an explanation of the CR e+ data on the whole energy range.
Contribution of pulsars to e+ flux as a function of distance from Earth

Manconi, Di Mauro, FD 2001.09985, subm. PRD
Burst-like or continuous injection

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