Fit of PAMELA and ATIC data with pulsars

I. Büsching

Unit for Space Physics
North-West University, Potchefstroom Campus
South Africa

Tango in Paris, 5. May 2009

Outline

General considerations

Galactic propagation of cosmic ray electrons and positrons

Cosmic Ray Anisotropy

Pulsars

Interpreting PAMELA data with mature pulsars

Interpreting PAMELA and ATIC data with mature pulsars

Pulsar Wind Nebulae (PWN)

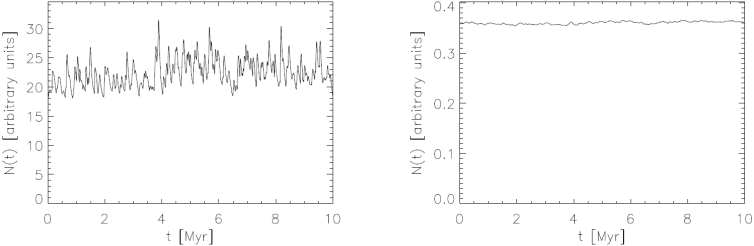
Interpreting PAMELA, ATIC and H.E.S.S. data: PWN

General Considerations

- Propagation model
  - Leaky box not suitable for high energy leptons
  - Time dependent 3D diffusion model (e.g. Syrovatskii 1959, Atoyan et al. 1995)
  - Magnitude and energy dependency of diffusion coefficient $k = k_0 E^{\delta}$
- Pulsar model
  - Polar cap models (Goldreich & Julian (1969), Sturrock (1971))
  - Polar gap models (Ruderman & Sutherland (1975))
  - Outer gap models (Cheng et al. 1986a,b)
  - Slot gap models (Muslimov & Harding 2003)
  - Simple power law models (Atoyan et al. 1995)
  - PWN calorimetric models (Venter & deJager 2006, Büsching et al. 2008)
- Working with positron fraction:
  - CR positron background?
  - CR electron background?

Propagation Model

- 3D diffusion model
- B/C, ^{10}B/B ratios mainly probe propagation perpendicular to the Galactic disc
- Secondary to primary ratios have to be calculated in a 3D time dependent model if the SNR paradigm is correct



Primary ^{12}C (left) and secondary ^{11}B (right) @10 GeV/nuc (see e.g. Büsching et al. 2005)

- $k = k_0\,(E/3\mathrm{GeV})^{\delta}$, $k_0 = 0.003\ldots 1\mathrm{kpc}^2\mathrm{Myr}^{-1}$, $\delta = 0.3\ldots 0.9$ (Ptuskin et al. 2006, Delahaye et al. 2008)

Galactic propagation of cosmic ray electrons and positrons

Propagation equation:

$$\frac{\partial N}{\partial t} - S = \nabla \cdot (k \nabla N) - \frac{\partial}{\partial E}(bN)$$

Source function:

$$S = Q(E)\delta\left(\vec{r} - \vec{r}_{\mathrm{s}}\right)\delta\left(t - t_{\mathrm{injection}}\right)$$

Diffusion coefficient

$$k = k_0 \left(\frac{E}{3\ \mathrm{GeV}}\right)^{0.6},$$

Energy losses due to synchrotron and inverse Compton radiation ($\propto E^2$)

$$b = b_0 E^2;$$

Galactic propagation of cosmic ray electrons and positrons

Propagation equation:

$$\frac{\partial N}{\partial t} - S = \nabla \cdot (k \nabla N) - \frac{\partial}{\partial E}(bN)$$

Green's Function

$$G = \delta\left(t - t_0 - \frac{1}{b_0}\left(E_0^{-1} - E^{-1}\right)\right)\frac{\exp\left(-\frac{(\vec{r}-\vec{r_0})^2}{\lambda}\right)}{b(\pi\lambda)^{1.5}},$$

with

$$\lambda = 4\frac{k_0\left(E^{\alpha-1} - E_0^{\alpha-1}\right)}{(1-\alpha)\,b_0}.$$

(Berezinskii et al. 1990)

Distinguishing Pulsar from Dark Matter Signal

Anisotropy in the diffusion model:

$$\delta = \frac{I_{\rm max} - I_{\rm min}}{I_{\rm max} + I_{\rm min}} = \frac{3\,k\,|\nabla N|}{c\,N}$$

(Ginzburg & Syrovatskii 1964) for instantaneous injection:

$$\delta = \frac{3}{2\,c} r_i\, b_0\, (\alpha - 1)\, E^{\alpha} \left(E^{\alpha-1} - E_0^{\alpha-1} \right)^{-1}$$

with

$$E_0 = E / \left((t - t_i)\, b_0 E + 1 \right)$$

(Büsching et al. 2008) for $E \to 0$:

$$\delta = \frac{3}{2c} \frac{r_i}{t_i}.$$

as derived for energy independent diffusion (Mao & Shen 1972).

- BUT for $E < 10\,\mathrm{GeV}$ solar cycle dependent anisotropy due to modulation!

Pulsars

- Rotating Neutron star (NS)
- "Birth" in Supernova explosions of stars with 4 to 8 Solar masses
- Mass 1.4 to 3 Solar masses
- Radius 10–30 km
  $\hookrightarrow$ $I \approx 10^{45}\,\mathrm{g\,cm^2}$
- Density $\approx 10^{14}\,\mathrm{g\,cm^{-3}}$
- Conservation of magnetic flux and angular momentum during collapse
- Magnetic field $\approx 10^{12}$G
- Period at "birth" $P_0 \approx 10$ to 500 ms (Faucher-Giguere & Kaspi 2006) '

Pulsar Energetics

Spin down power: $L_{\rm SD} = I\Omega\dot{\Omega}$

$$L_{\rm SD}(t) = L_{\rm sd,0}\left(1+\frac{t}{\tau_0}\right)^{-\frac{n+1}{n-1}},$$

(Rees & Gunn 1974)

$$\tau_0 = P_0/((n-1)\dot{P}_0)$$

$n = 3$ for magnetic dipole field
P_0, $\dot{P}_0$ pulsar period and its time derivative at “birth”

$$L_{\rm SD,0} = \left|-\frac{4\pi^2 I\dot{P}_0}{P_0^3}\right|.$$

or for constant magnetic field (Flowers 1976)

$$L_{\rm sd,0} = \left|-\frac{4\pi^2 I\dot{P}P}{P_0^4}\right|.$$

Pulsar as particle accelerators: ST model

Simple power law

$$N(E) = \frac{L_{SD} f}{\int_{E_{\min}}^{E_{\max}} \prime E^{a+1} d\prime E} E^{a}$$

with

$$L_{SD} = I\Omega\dot{\Omega}$$

f fraction of spin down power deposited into particles. Energy deposited into particles integrated over the time $\tau << \tau_0$:

$$E_{tot} = \frac{f}{2} I\Omega_0^2 \approx f \cdot 2. \times 10^{46} P_0^{-2} \text{ erg}$$

Pulsar as particle accelerators: HR Model

Harding & Ramaty [Proc. 20th ICRC, **2**, 92 (1987)]
Positrons from one pulsar:

$$N(E) = 2.3 \times 10^{46} f\, B_{12}^{-0.7} t^{-0.85} E^{-2.2} \mathrm{s}^{-1} \mathrm{GeV}^{-1}$$

Integrated over the γ emitting lifetime τ

$$N(E) = 8.1 \times 10^{48} f\, B_{12}^{-0.7} \left(\frac{\tau}{10^4\,\mathrm{yr}} \right)^{0.15} E^{-2.2} \mathrm{GeV}^{-1}$$

Total galactic positron production rate

$$Q(E) = 8.6 \times 10^{39} b_{30} f\, B_{12}^{-0.7} \left(\frac{\tau}{10^4\,\mathrm{yr}} \right)^{0.15} E^{-2.2} \mathrm{s}^{-1} \mathrm{GeV}^{-1}$$

f ratio of positrons to γ-rays, b_{30} pulsar birthrate normalized to 1/(30 yr), E in GeV, B_{12} magnetic field in units of 10^{12}G

Pulsar as particle accelerators: CCY Model

Chi, Cheng & Young [ApJ **459**, L83 (1996)]

For γ-ray pulsars $f = 6.3 P^{9/7} B_{12}^{-4/7} < 1$

Positrons from one pulsar:

$$
\begin{aligned}
N(E) &= 3.4 \times 10^{37} f\, B_{12}^{10/7} P^{-8/21} \delta\left((E - E_{ep}\right) \mathrm{GeV}^{-1} \mathrm{s}^{-1} \\
E_{ep} &= 1.1 \times 10^{-3} B_{12}^{4/7} P^{-76/21}\ \mathrm{GeV}
\end{aligned}
$$

Pulsar as particle accelerators: ZC Model

Zhang & Chen [A&A **368**, 1070 (2001)]

For γ-ray pulsars $f = 5.5 P^{26/21} B_{12}^{-4/7} < 1$

Positrons from one pulsar:

$$\begin{aligned} N(E) &\approx 9.7 \times 10^{35} \, (100\zeta)^2 \, f^2 B_{12}^2 P^{2/3} \delta \left(E - 0.1 \cdot E_{ep}\right) \mathrm{GeV}^{-1} \mathrm{s}^{-1} \\ E_{ep} &\approx 0.61 \, f^{-1} \, (100\zeta)^1 \, P^{-7/3} \; \mathrm{GeV} \end{aligned}$$

with

$$\zeta \approx 3.8 \times 10^{-4} f^{1/2} B_{12}^{7/12} P^{-19/12} \left(\frac{4\,(\pi/2 - \alpha)}{9} \right)^{-0.54}$$

α magnetic inclination

Positron production rate above 1.5 GeV from all Galactic γ-ray pulsars older than 10^5yr:

$$N(E) \approx 8.6 \times 10^{38} b_{100} \, (E/\mathrm{GeV})^{-1.6} \exp\left(-E/80\,\mathrm{GeV}\right) \mathrm{GeV}^{-1} \, \mathrm{s}^{-1},$$

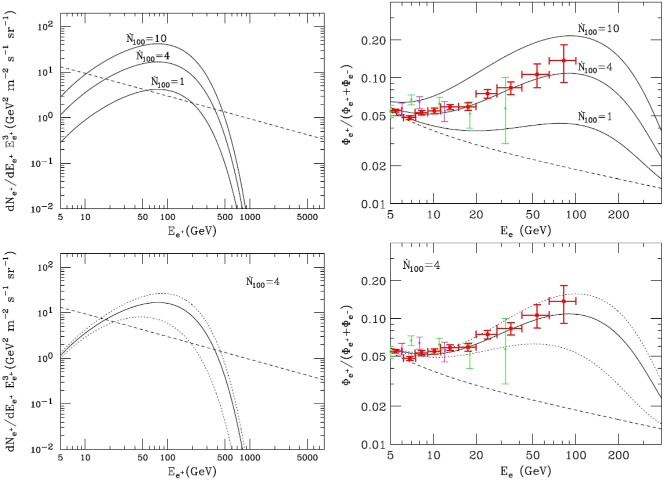
b_{100} pulsar birthrate normalized to 1/(100 yr)

Interpreting PAMELA data with mature pulsars

Hooper et al. [astro-ph 0810.1527v2]

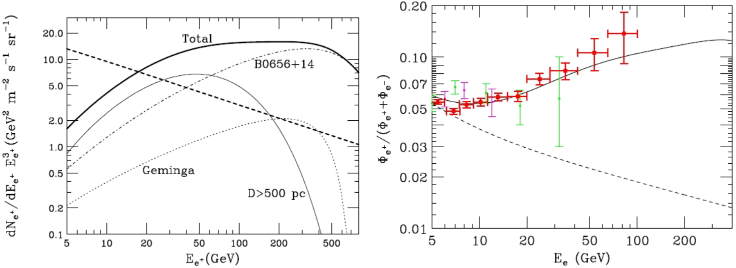
- Upper limit for the total injected energy at time t after pulsar "birth" $\approx 10^{49}$ erg for $P_0 = 40\,\mathrm{ms}$
- MC model for Galactic pulsar population, distribution from (Paczynski 1990, Sturner & Dermer 1996)
- Injection spectrum per pulsar given by the Galactic positron production rate as given by the ZC Model
- 3D diffusion model with $k = k_0\,(1 + E/3\mathrm{GeV})^{0.6}$, $k_0 = 3.4 \times 10^{28} cm^2 s^{-1}$
- Primary electrons and secondary electrons/positrons from Moskalenko & Strong 1998
- Contributions of Geminga and B0656+14 is modelled in the context of the ST model
- Anisotropy (up to 0.5%) as way to distinguish from DM signal

Interpreting PAMELA data with mature pulsars



Positron spectrum (left) and positron fraction (right) for different pulsar birth rates (top) and varying local birth rate (bottom)

Interpreting PAMELA data with mature pulsars



Left: Contributions to the positron spectrum from B0656+14, Geminga and pulsars with $D > 400\,\mathrm{pc}$ and positron fraction (right) for a Galactic pulsar birthrate of 1/25 yr^{-1}, injection spectrum $\propto E^{-1.5} exp(-E/600\mathrm{GeV})$ and 3×10^{47} erg in pairs.

Interpreting PAMELA & ATIC data: mature pulsars

Profumo [astro-ph 0812.4457v1,2]

- Uses ST, HR, CCY, ZC models to get total energy deposited in pairs up to time T after pulsar "birth"
- The total energy is then used as input for a ST model
- Comparison of the different models
- 3D diffusion model with parameters from Delahaye et al. 2008
- Anisotropy (up to 20% for CTA-1 pulsar) as way to distinguish from DM signal

Interpreting PAMELA & ATIC data: mature pulsars

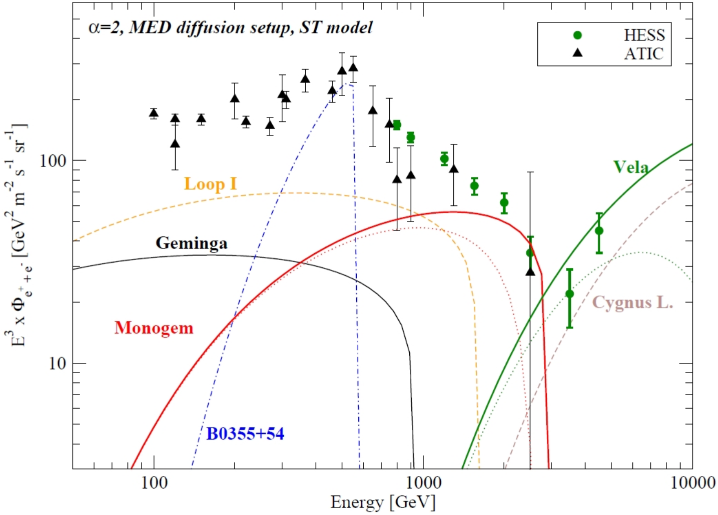
Name	Distance [kpc]	Age [yr]	$\dot{E}$ [ergs/s]	$E_{\rm out}$ [ST]	$E_{\rm out}$ [CCY]	$E_{\rm out}$ [HR]	$E_{\rm out}$ [ZC]	$f_{e^\pm}$	g
Geminga [J0633+1746]	0.16	3.42×10^5	3.2×10^{34}	0.360	0.344	0.013	0.053	0.005	0.70
Monogem [B0656+14]	0.29	1.11×10^5	3.8×10^{34}	0.044	0.133	0.006	0.020	0.020	0.70
Vela [B0833-45]	0.29	1.13×10^4	6.9×10^{36}	0.084	0.456	0.006	0.372	0.0015	0.14
B0355+54	1.10	5.64×10^5	4.5×10^{34}	1.366	0.677	0.022	0.121	0.2	0.61
Loop I [SNR]	0.17	2×10^5		*0.3*				0.006	
Cygnus Loop [SNR]	0.44	2×10^4		*0.03*				0.01	

Selected nearby pulsars and SNR, $E_{\rm out}$ in units of 10^{48}erg, g is f from ZC model

Scenario	D_1	δ
MAX	1.8×10^{27}	0.55
MED	3.4×10^{27}	0.7
MIN	2.3×10^{28}	0.46

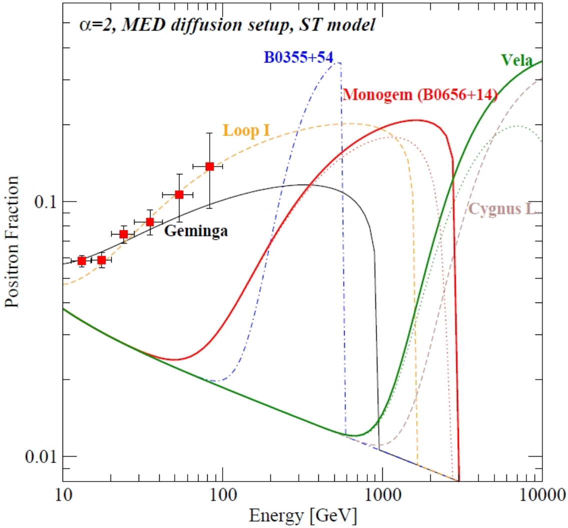
Diffusion setups, D_1 is diffusion coefficient @ 1 GeV in $\rm cm^2 s^{-1}$

Interpreting PAMELA & ATIC data: mature pulsars



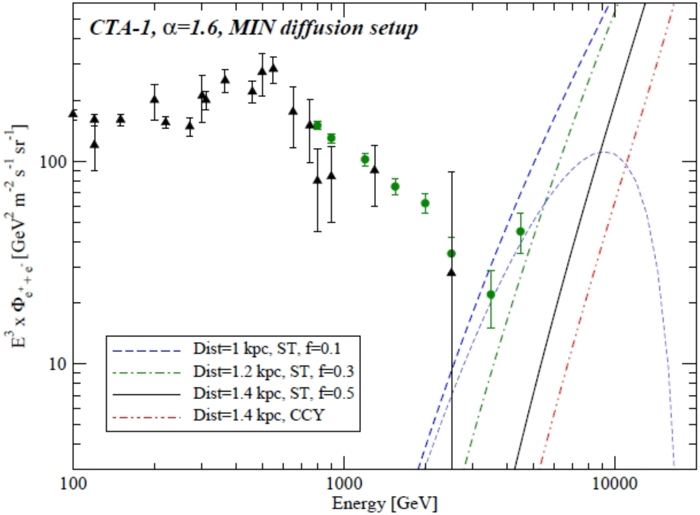
Combined positron and electron flux

Interpreting PAMELA & ATIC data: mature pulsars



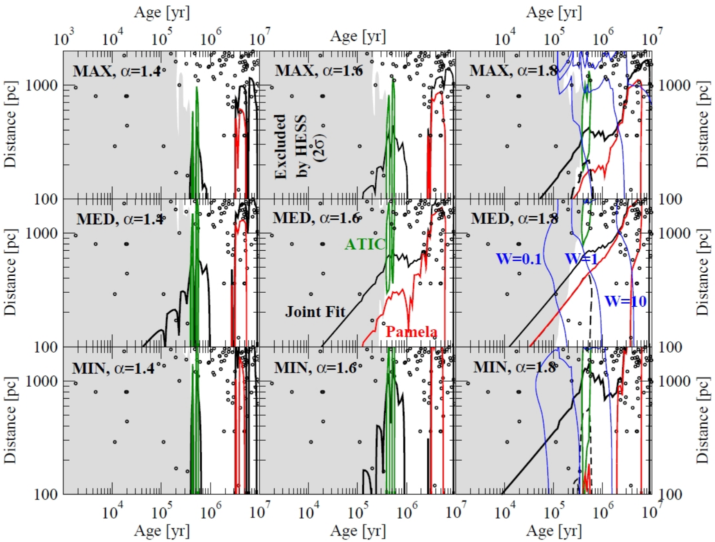
Positron fraction, secondary positrons/electrons from Moskalenko & Strong 1998

Interpreting PAMELA & ATIC data: mature pulsars



Combined positron and electron flux from CTA-1

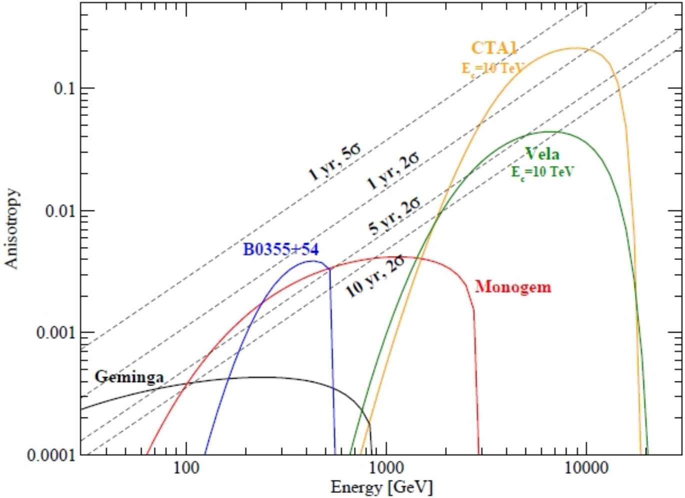
Interpreting PAMELA & ATIC data: mature pulsars



Likelihood contours for a single pulsar-like source for data from PAMELA (red) ATIC (green) combined (black). Blue

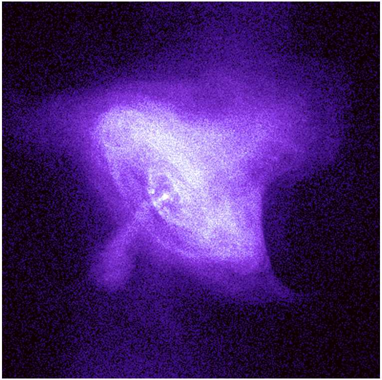
E_{tot} contours in units of 10^{48}erg

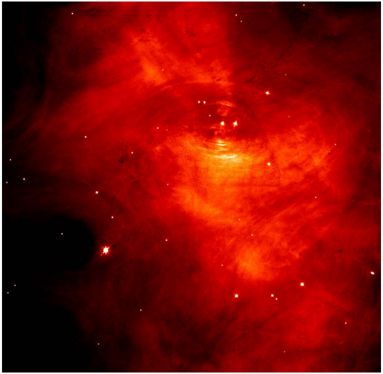
Interpreting PAMELA & ATIC data: mature pulsars



Expected anisotropy

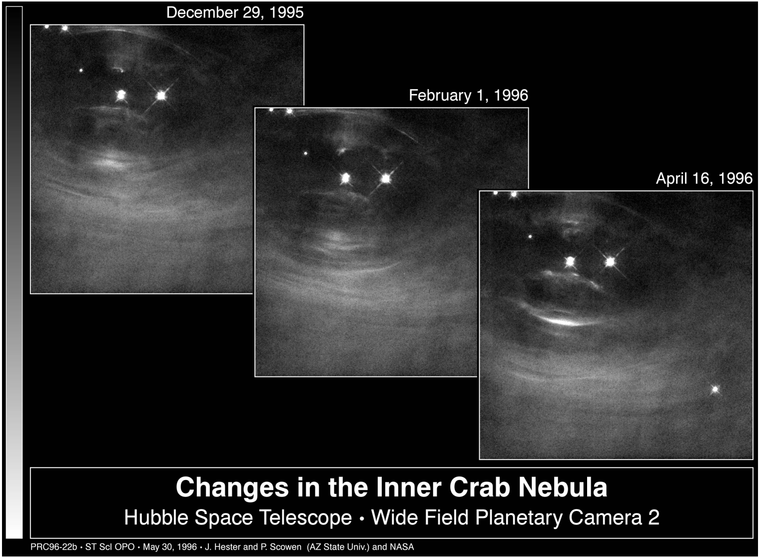
Pulsar Wind Nebulae (PWN)





Crab in X-Rays (Chandra) (left) and optical (HST) (right)

Pulsar Wind Nebulae (PWN)



Pulsar as particle accelerators: Caliometric PWN

Assume:

- Energy source: rotational energy of NS
  (Spin-down energy $L_{\mathrm{SD}} = I\Omega\dot{\Omega}$)
- Particles from the pulsar are re-accelerated at the pulsar shock
  $\rightsquigarrow$ power law spectrum with index -1...-2
- Relativistic particles produced by the pulsar are confined inside the PWN
- PWN breakup $\tau \approx 10 - 100\,\mathrm{kyr}$ after the birth of the pulsar
- PWN releases relativistic particles on breakup
- $N_{e^+} \approx N_{e^-}$

Pulsar as particle accelerators: Caliometric PWN

Büsching et al. [ApJ **678**, L39 (2008)]

ST type injection at the pulsar wind shock (reacceleration at the shock):

$$\int_{E_{\rm min}}^{E_{\rm max}} Q'(E,t) E dE = f_{\rm part} L_{\rm SD}(t)$$

with

$$Q'(E,t) = \begin{cases} k'(t)\left(\frac{E}{E_B}\right)^{-2} & \text{for } E > E_B \\ k'(t)\left(\frac{E}{E_B}\right)^{-1} & \text{for } E < E_B \end{cases}$$

Fraction of the spin down power deposited in particles:

$$f_{\rm part} = \eta \frac{1}{1+\sigma}$$

Magnetisation parameter

$$\sigma(t) = 0.003 \left(\frac{t}{1\,\rm kyr}\right)^{3/2}$$

Pulsar as particle accelerators: Caliometric PWN

Maximum particle energy at shock:

$$E_{\rm max} = \epsilon e \kappa \sqrt{\frac{\sigma}{\sigma+1}}\sqrt{\frac{L_{\rm SD}}{c}}$$

$\epsilon = r_L/r_{\rm shock}$ = 0.001 ... 0.1, $\kappa = 3$: Compression ratio at shock.

Evolution of particle spectrum:

$$\frac{\partial Q(E,t)}{\partial t} - Q'(E,t) = \frac{\partial}{\partial E}\left(B_{\rm PWN}(t)^2 E^2 Q(E,t)\right)$$

Mean PWN magnetic field:

$$B_{\rm PWN}(t) = \frac{1200}{(1+t/{\rm kyr})^2}\ [\mu{\rm G}].$$

Particle spectrum at time T is:

$$Q(E,T) = \int_0^T Q'(E_0,t_0) E_0^2 E^{-2} \Theta\left(E_0 - E_{\rm min}\right)\Theta\left(E_{\rm max} - E_0\right) dt_0,$$

with

$$E_0 = \frac{E}{E\int_t^{t_0} B_{\rm PWN}(t')^2 dt' + 1}$$

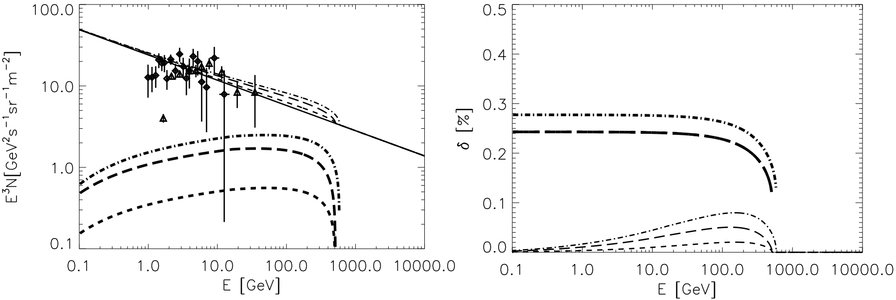
Sources

Near pulsars with ages in the range $10^5 - 10^6$ yr

	Geminga	B0656+14	Unit
Distance	0.16	0.29	kpc
Age	340	110	kyr
L_{SD}	3.2e+34	3.8e+34	erg/sec
Magnetic field	1.63e+12	4.66e+12	G
P	0.237099	0.384891	sec

(Manchester et al. 2005)
www.atnf.csiro.au/research/pulsar/psrcat

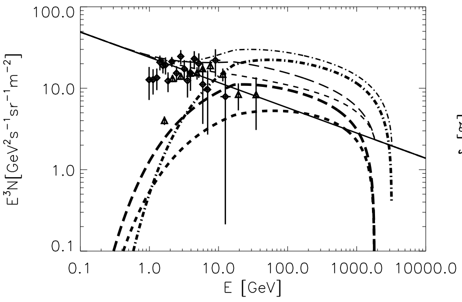
Results: Geminga

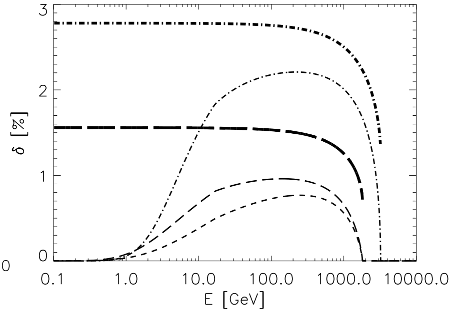


long dashed: $k_0 = 0.1\,\mathrm{kpc^2\,Myr^{-1}}$, $P_0 = 40\,\mathrm{ms}$, $T = 20\,\mathrm{kyr}$
dot-dased: $k_0 = 0.1\,\mathrm{kpc^2\,Myr^{-1}}$, $P_0 = 40\,\mathrm{ms}$, $T = 60\,\mathrm{kyr}$
dashed: $k_0 = 0.1\,\mathrm{kpc^2\,Myr^{-1}}$, $P_0 = 60\,\mathrm{ms}$, $T = 20\,\mathrm{kyr}$
solid: isotropic background (Barwick et al. 1998)

(Büsching et al. 2008)

Results: B0656+14

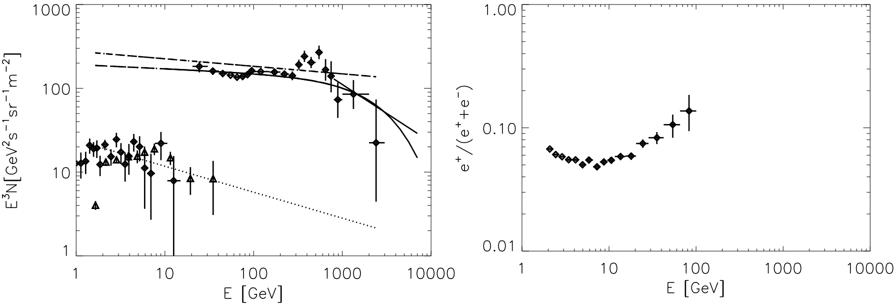




long dashed:	$k_0 = 0.1\,\mathrm{kpc}^2\,\mathrm{Myr}^{-1}$, $P_0 = 40\,\mathrm{ms}$, $T = 20\,\mathrm{kyr}$
dot-dased:	$k_0 = 0.1\,\mathrm{kpc}^2\,\mathrm{Myr}^{-1}$, $P_0 = 40\,\mathrm{ms}$, $T = 60\,\mathrm{kyr}$
dashed:	$k_0 = 0.1\,\mathrm{kpc}^2\,\mathrm{Myr}^{-1}$, $P_0 = 60\,\mathrm{ms}$, $T = 20\,\mathrm{kyr}$
solid:	isotropic background (Barwick et al. 1998)

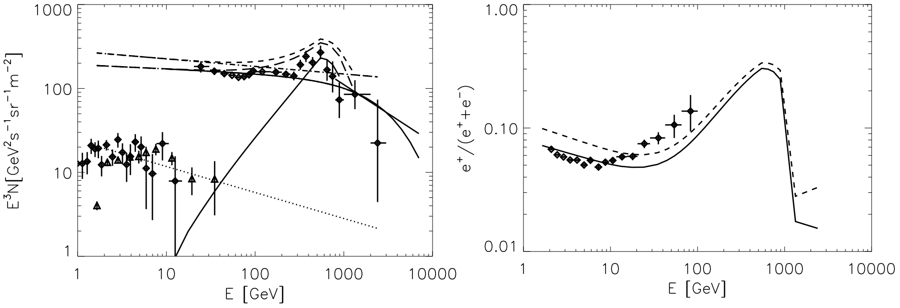
(Büsching et al. 2008)

Interpreting PAMELA, ATIC UN H.E.S.S. data



left: electron/positron data from ATIC (Chang et al. 2008), fits to H.E.S.S. (Aharonian et al. 2008) and PPB-BETS (Yoshida 2008) data. positron data from Boezio et al. (2000), DuVernois et al. (2001)
right: PAMELA positron fraction (Adriani e al. 2008)

Interpreting PAMELA, ATIC and H.E.S.S. data



Model for B0656+14:

P_0=100 ms, ϵ=0.01, T=30 kyr, E_B=1.25 TeV, k_0=0.0069 kpc^{2}Myr^{-1}

Left: Combined electron positron flux

Right: Positron fraction

Summary

- It **is** possible to explain the PAMELA and ATIC data with pulsars
- Expected: anisotropy in the direction of the **outer** Galaxy (for Geminga & B0656+14).
- Pulsar models can be constraint by CR data
- Possibility to constrain propagation parameters?
- Not discussed here Yüksel et al. [astro-ph 0810.2784]