Antimatter in cosmic rays: new physics or old astrophysics?



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Supernova remnants are believed to be 'Pevatrons' – responsible for the acceleration of galactic cosmic rays upto the 'knee' at ~few x 10³ TeV



If O(10%) of the shock K.E. of $\sim 10^{51}$ erg can be converted into cosmic rays, then the observed ~ 3 SN/century can maintain the cosmic ray energy density of ~ 0.3 eV/cm³

The **PAMELA** 'anomaly'

PAMELA has measured the positron fraction:

 $\frac{\phi_{e^+}}{\phi_{e^+}+\phi_{e^-}}$

Anomaly \Rightarrow excess above 'astrophysical background'

Source of anomaly:

- Dark matter?
- Nearby pulsars?
- Nearby SNRs?



Anti matter is indeed expected to be produced by the annihilations or decays of dark matter in the Galaxy



Such searches usefully complement attempts to detect dark matter *directly* using shielded underground nuclear recoil detectors Indeed dark matter has been widely invoked as the source of the 'excess' et

DM annihilation

Rate $\propto n_{\rm DM}^2$

(e.g. few hundred GeV neutralino LSP or Kaluza-Klein state)



Bergström, Bringmann, Edjsö, PR D78:127850,2008

<u>DM decay</u>

Rate $\propto n_{\rm DM} / \tau_{\rm DM}$ (lifetime ~10⁹ x age of universe e.g. dim-6 operator suppressed by $M_{\rm GUT}$ for TeV mass techni-baryon)



The Fermi excess



Inclusive Jet Cross Section in $\overline{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

The inclusive jet differential cross section has been measured for jet transverse energies, E_T , from 15 to 440 GeV, in the pseudorapidity region $0.1 \le |\eta| \le 0.7$. The results are based on 19.5 pb⁻¹ of data collected by the CDF Collaboration at the Fermilab Tevatron collider. The data are compared with QCD predictions for various sets of parton distribution functions. The cross section for jets with $E_T > 200$ GeV is significantly higher than current predictions based on $O(\alpha_s^3)$ perturbative QCD calculations. Various possible explanations for the high- E_T excess are discussed.

Abe et al, PRL 77:438,1996

... it turned out to be a mis-estimation of the QCD background – *not* new physics!



FIG. 1. The percent difference between the CDF inclusive jet cross section (points) and a next-to-leading order (NLO) QCD prediction using MRSD0' PDFs. The CDF data (points) are compared directly to the NLO QCD prediction (line) in the inset. The normalization shown is absolute. The error bars represent uncertainties uncorrelated from point to point. The hatched region at the bottom shows the quadratic sum of the correlated (E_T dependent) systematic uncertainties which are shown individually in Fig. 2. NLO QCD predictions using different PDFs are also compared with the one using MRSD0'.

What particle physicists have learnt through experience (UAI monojets, NuTeV anomaly, CDF high E_T excess, ...)

Yesterday's discovery is today's calibration Richard Feynman ... and tomorrow's background! Val Telegdi

... is also now a major issue for astroparticle physics viz. how well do we know the 'astrophysical background' for signals of (apparently) new particle physics?

The 'background' is the production of secondary e^{\pm} during propagation of nuclear cosmic rays in Galaxy



Diffusion of galactic cosmic rays



Green's function: describes flux from a discrete, burst-like source ... integrate over spatial distribution and time-variation of injection

Expectation: secondary/primary ratio $\propto E^{-\delta}$, where the diffusion co-efficient $D \propto E^{\delta}$... fit to nuclear ratios (e.g. B/C) gives: $\delta \sim 0.3-0.7$ However e[±] lose energy readily during propagation, so only *nearby* sources dominate at such high energies ... the usual background calculation is then *irrelevant*



<u>A nearby cosmic ray accelerator?</u>

Rise in e^+ fraction could be due to secondaries produced during acceleration ... which are then accelerated along with the primaries (Blasi, PRL 103:051104,2009)



Propagation in Galaxy

pp

This component *naturally* has a harder spectrum so fits *PAMELA* excess!

Acceleration in SNR





Diffusive (1^{s†}-order Fermi) shock acceleration

Consider flux:

$$\Phi(p) = \int \mathrm{d}^3 x \, \frac{4\pi p^2}{3} f(p) (-\nabla \cdot \vec{u})$$

Conservation equation:

$$\underbrace{\frac{\partial}{\partial t} \left(4\pi p^2 f^0(p)L \right)}_{\text{density change}} + \underbrace{\frac{\partial \Phi}{\partial p}}_{\text{acceleration}} = \underbrace{-4\pi p^2 f^0(p)u_2}_{\text{convection injection}} + Q(p)$$

downstream upstream

$$\vec{u}_2, n_2$$
 \vec{u}_1, n_1

Steady state:
$$\frac{u_1 - u_2}{3} p \frac{\partial f}{\partial p} + u_1 f = 0 \quad \log f$$
$$\Rightarrow f(p) \propto p^{-3u_1/(u_1 - u_2)} = p^{-\gamma}$$

i.e. $\gamma = 4$ for strong shock $(u_1/u_2 = 4)$



Diffusive (1st-order Fermi) shock acceleration



As long as $\,f_{
m inj}(p)$ is softer than $p^{-\gamma}$ at high energies: $f(x,p)\sim p^{-\gamma}$

DSA with secondary production

• Secondaries have *same* spectrum as primaries (Feynman):

$$q_{e^{\pm}} \propto f_{CR} \propto p^{-\gamma}, \quad \gamma = \frac{3r}{r-1} \qquad r = \frac{u_1}{u_2} = \frac{n_2}{n_1}$$

 \bullet Only particles with $|x| \lesssim D(p)/u$ are accelerated

Bohm diffusion: $D(p) \propto p$

 \Rightarrow fraction of secondaries which are accelerated: $\propto p$

f(x, p) $f_0(p)$ $D(p)/u_1$ xdownstream upstream \vec{u}_2, n_2 \vec{u}_{1}, n_{1}

... consequently the spectrum has 2 components: $\log n$ $n_{e^{\pm}} \propto q_{e^{\pm}} \left(1 + \frac{p}{p_0}\right) \propto p^{-\gamma} + p^{-\gamma+1}$ $\Rightarrow rising positron fraction!$

<u>Diffusion near shock front</u>

- Diffusion coefficient not known
 a priori in neighbourhood of shock
- Bohm diffusion' sets a *lower* limit:

$$D^{\text{Bohm}} = r_{\ell} \frac{c}{3} \propto \frac{E}{Z}$$

Parameterise actual rate by 'fudge factor': $D = D^{Bohm} \mathcal{F}^{-1}$

- Can try and determine diffusion rate from simulations (difficult!)
- So determine \mathcal{F}^{-1} by fitting to *Fermi* e^{\pm} excess ... can then *predict* $e^{+}/(e^{+}+e^{-})$ for *PAMELA*, and other secondary/primary ratios e.g. B/C

(can also model differences in SNR shock velocity, ambient density etc)



It is not just the few (optically) observed SNRs which contribute to observed cosmic rays ... there must be many other *hidden* SNRs (sincethere are ~3 SN/century and cosmic rays diffuse in Galaxy for ~10⁷ yr)



Statistical distribution of SNRs in our neighbourhood





• Draw source positions from this distribution

0

20

15

10

5

0

• Inject e^- & e^+ normalized to observables (HESS ...)

5

10

distance r' [kpc]

15

Sarkar, PRD80:123017, 200

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Ahlers, Mertsch

25

20

- Propagate to Earth accounting for synchrotron and inverse-Compton scattering energy losses
- Confront total $e^{-}+e^{+}$ flux at Earth with *Fermi* data

The *best fit* to data is closest to actual distribution!

Parameters of the Monte Carlo

Diffusion Model						
	$ \begin{array}{r} 10^{28} \mathrm{cm}^{2} \mathrm{s}^{-1} \\ 0.6 \\ 3 \mathrm{kpc} \end{array} $	<pre>from GCR nuclear secondary-to-primary ratios</pre>				
b	$10^{-16} \mathrm{GeV}^{-1} \mathrm{s}^{-1}$	CMB, IBL and \vec{B} energy densities				
Source Distribution						
$t_{\rm max}$	$1 \times 10^8 \mathrm{yr}$	from $E_{\rm min} \simeq 3.3 {\rm GeV}$				
$ au_{ m SNR}$	$10^4{ m yr}$	from observations				
N	3×10^6	from number of observed SNRs				
Source Model						
$R_{e^{-}}^{0}$	$1.8 \times 10^{50} \mathrm{GeV^{-1}}$	fit to e^- flux at $10 \mathrm{GeV}$				
Γ	2.4	average γ -ray spectral index				
E_{\max}	$20\mathrm{TeV}$	typical γ -ray maximum energy				
$E_{\rm cut}$	$20\mathrm{TeV}$	DSA theory				
R^0_+	$7.4 \times 10^{48} {\rm GeV^{-1}}$	$\gamma ext{-rays}$				
$K_{\rm B}$	15	free parameter (for fixed Γ)				

Normalising the source spectra



Normalisation of primary e^- : fit absolute e^- flux at low energies Normalisation of secondary $e^{\pm}: p + p \rightarrow \begin{cases} \pi^0 + \dots \rightarrow 2\gamma + \dots \\ \pi^{\pm} + \dots \rightarrow e^{\pm} + \dots \end{cases}$

Source	Other name(s)	Γ	$J^0_{\gamma} \div 10^{-12}$	E_{\max}	d	$Q^0_{\gamma} \div 10^{33}$
			$[(\mathrm{cm}^2\mathrm{s}\mathrm{TeV})^{-1}]$	$[\mathrm{TeV}]$	[kpc]	$[(s TeV)^{-1}]$
HESS J0852-463 RX J0852.0-4622 (Vela Junior)		2.1 ± 0.1	21 ± 2	> 10	0.2	0.10
HESS J1442 -624	RCW 86, SN 185 (?)	2.54 ± 0.12	3.72 ± 0.50	$\gtrsim 20$	1	0.46
HESS J1713-381	CTB 37B, G348.7+0.3	2.65 ± 0.19	0.65 ± 0.11	$\gtrsim 15$	7	3.812
HESS J1713-397	RX J1713.7-3946, G347.3-0.5	2.04 ± 0.04	21.3 ± 0.5	17.9 ± 3.3	1	2.55
HESS J1714-385	CTB 37A	2.30 ± 0.13	0.87 ± 0.1	$\gtrsim 12$	11.3	13.3
HESS $J1731 - 347$	G 353.6-07	2.26 ± 0.10	6.1 ± 0.8	$\gtrsim 80$	3.2	7.48
HESS J1801 -233^{a}	W 28, GRO J1801-2320	2.66 ± 0.27	0.75 ± 0.11	$\gtrsim 4$	2	0.359
HESS J1804 -216^{b}	W 30, G8.7-0.1	2.72 ± 0.06	5.74	$\gtrsim 10$	6	24.73
HESS J1834-087	W 41, G23.3-0.3	2.45 ± 0.16	2.63	$\gtrsim 3$	5	7.87
MAGIC J0616+225	IC 443	3.1 ± 0.3	0.58	$\gtrsim 1$	1.5	0.156
Cassiopeia A		2.4 ± 0.2	1.0 ± 0.1	$\gtrsim 40$	3.4	1.38
J0632 + 057	Monoceros	2.53 ± 0.26	0.91 ± 0.17	N/A	1.6	0.279
Mean	~ 2.5		$\gtrsim 20$		~ 5.2	
Mean, excluding sour	~ 2.4		$\gtrsim 20$		~ 5.7	
Mean, excluding sour	~ 2.3		$\gtrsim 20$		~ 4.2	

Fitting the $e^+ + e^-$ flux



The propagated primary *e* spectrum is too *steep* to match the data

but the *accelerated* secondary e^++e^- component has a *harder* spectrum

... so fits the 'bump'!



We can then *predict the* resulting positron fraction



Nearby pulsars as source of e^{\pm}

- Highly magnetized, fast spinning neutron stars
- $\bullet\gamma$ -rays and electron/ positron pairs produced along the magnetic axis
- Spectrum *speculated* to be harder than background from propagation:

 $N \propto E_e^{\pm -1.6} e^{-E_e^{\pm}/100 \,\text{GeV}}$



Combination of Galactic contribution and two nearby pulsars, Geminga (157 pc) and B0656+14 (290 pc), can fit PAMELA excess (and perhaps also Fermi bump)



Hooper, Blasi & Serpico, JCAP 0901:025,2009

However ~40% of rotational energy must be released as energetic *e*⁺ (plausible?) *Fermi* can detect expected anisotropy towards B0656+14 in ~5 years

What about the antiproton-to-proton ratio?

Blasi & Serpico, PRL 103:081103,2009



Secondary acceleration model predicts rise *beyond* 100 GeV ... will be tested soon by AMS-02

Nuclear secondary-to-primary Ratios

Dark matter	X
Pulsars	×
Acceleration of secondaries (TBD)	√

If we see this, *both* dark matter and pulsar origin models would be ruled out! Since nuclei are accelerated in the same sources, the ratio of secondaries (e.g. Li, Be, B) to primaries (C, N, O) must also rise with energy beyond ~100 GeV



Can solve problem analytically ... but more complicated than for \bar{p}/p since energy losses must now be included

$$\Box \text{ Transport equation: } u \frac{\partial f_i}{\partial x} = D_i \frac{\partial^2 f_i}{\partial x^2} + \frac{1}{3} \frac{du}{dx} p \frac{\partial f_i}{\partial p} - \Gamma_i f_i + q_i$$

with boundary condition: $f_i(x,p) \xrightarrow{x \to -\infty} Y_i \delta(p-p_0)$

Solution:
$$f_i^+ = f_i^0 + \frac{q_i^+(x=0) - \Gamma_i^+ f_i^0}{u_+} x \text{ for } x > 0$$

$$f_{i}^{0}(p) = \int_{0}^{p} \frac{\mathrm{d}p'}{p'} \left(\frac{p'}{p}\right)^{\gamma} \mathrm{e}^{-\gamma(1+r^{2})(D_{i}^{-}(p)-D_{i}^{-}(p'))\Gamma_{i}^{-}/u_{-}^{2}}$$
$$\times \gamma \left[(1+r^{2}) \frac{D_{i}^{-}(p')q_{i}^{-}(x=0)}{u_{-}^{2}} + Y_{i}\delta(p'-p_{0}) \right]$$
$$\sim ``q_{i}^{-}(p) + D_{i}^{-}(p)q_{i}^{-}(p)''$$

Mertsch & Sarkar, PRL 103:081104,2009

Titanium-to-Iron Ratio



Titanium-to-iron ratio used to fix diffusion coefficient to be $\mathcal{F}^{-1}\simeq 40$ (NB: to fit e^+ excess requires ~10-20)

Mertsch & Sarkar, PRL 103:081104,2009



We can then predict another secondary/primary ratio e.g. B/C ...

AMS-02 will provide high energy measurents of B/C ... a rise would confirm the nearby hadronic accelerator model Present data are *consistent* with a *rising* B/C ratio at high energies (due to a nearby SNR where secondaries produced during the acceleration of the primaries are themselves accelerated) ... recently the model predictions have been recalculated with specific assumptions concerning the SNR shock velocity, ambient density, acceleration period *etc*



Case studies of type I/a and core-collapse SNRs.

SNR Model		$n_1 ({\rm cm}^{-3})$	$\tau_{\rm st}$ (yr)	$\bar{u}_1 ({\rm cms^{-1}})$
	I/a #1	0.5	330	1.3×10 ⁸
type I/a	I/a #2	1.5	230	1.0×10^{8}
	I/a #3	3.0	183	8.9×10 ⁷
core	CC #1	0.003	1829	3.5×10^{8}
collapse	CC #2	0.01	1225	2.8×10^{8}
-	CC #3	0.1	568	1.8×10^{8}

Tomasetti & Donato, arXiv:1203.6094



Have some of these old SNRs been seen already?



Galactic Longitude (deg)



MILAGRO survey of Galactic γ -ray sources at ~20 TeV

Eight candidate sources of TeV emission are detected with pre-trials significance >4.5 σ in Galactic longitude [300⁰, 220⁰] and latitude $[-10^{0}, 10^{0}]$. Four of these, including the Crab nebula and the recently published MGRO J2019+37, are observed with significances > 4σ after accounting for the trials involved in searching the 3800 degree² region. All four are also coincident with EGRET sources. Two of the lower significance sources are coincident with EGRET sources and one of these sources is Geminga. The other two candidates are in the Cygnus region of the Galaxy. Several of the sources appear to be spatially extended. The fluxes of the sources at 20 TeV range from 25% of the Crab flux to nearly as bright as the Crab. Abdo *et al*, arXiv:0805.0417

A definitive test would be to detect neutrinos from these old SNRs ...





<u>Summary</u>

The PAMELA anomaly may be the signature of a nearby **hadronic** accelerator (rather than of dark matter) ... forthcoming data on p^{-}/p & B/C ratio (AMS-02) will provide a resolution

The source(s) should also be detectable *directly* in *y*-rays (*HAWC*, *CTA*) and neutrinos (*IceCube*)

This would be the *first* astronomical identification of cosmic 'pevatrons'