Anomalies in Galactic Cosmic Rays: Time for Exotic Scenarios?[1]

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From R. Battiston, 02

Table 1. Discovery of elementary particles

Particle	Year	Discoverer (Nobel Prize)	Method
e^-	1897	Thomson (1906)	Discharges in gases
p	1919	Rutherford	Natural radioactivity
n	1932	Chadwik (1935)	Natural radioactivity
e^+	1933	Anderson (1936)	Cosmic Rays
$\mu^\pm$	1937	Neddermeyer, Anderson	Cosmic Rays
$\pi^\pm$	1947	Powell (1950) , Occhialini	Cosmic Rays
$K^\pm$	1949	Powell (1950)	Cosmic Rays
π^0	1949	Bjorklund	Accelerator
K^0	1951	Armenteros	Cosmic Rays
Λ^0	1951	Armenteros	Cosmic Rays
Δ	1932	Anderson	Cosmic Rays
Ξ^-	1932	Armenteros	Cosmic Rays
$\Sigma^\pm$	1953	Bonetti	Cosmic Rays
p^-	1955	Chamberlain, Segre' (1959)	Accelerators
anything else	1955 $\Longrightarrow$ today	various groups	Accelerators
$m_\nu \neq 0$	2000	KAMIOKANDE	Cosmic rays

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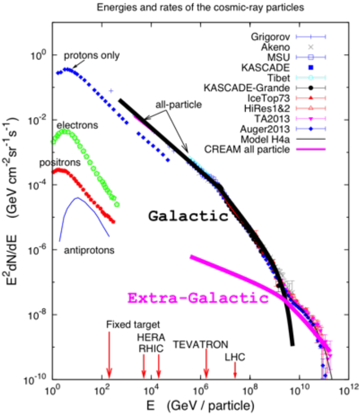
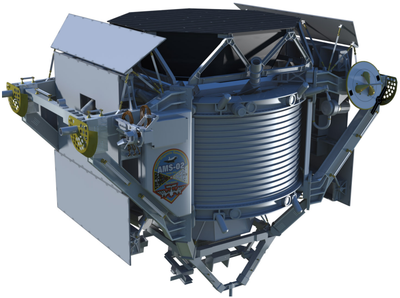
More than 100 years of cosmic ray research...



IceCube compilation of CR spectrum

- CR energy spectrum was long thought to be a featureless power law:
  - a hallmark of the underlying acceleration mechanism:
  - diffusive shock acceleration, DSA
- DSA rigidity (p/Z) spectra should be the same for all CR species
- Any change in power-law index interpreted as change of acceleration regime, source (galactic-extragalactic, etc.)

An incredibly exciting time for this field...



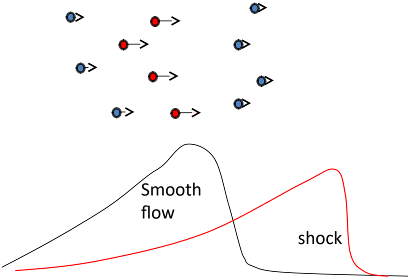
Alpha Magnetic Spectrometer (AMS-02):
Particle detector operating on the International Space Station

- Both energy (rigidity) spectrum and composition aspects of DSA scrutinized using modern instruments and proved not true in some instances
- Either we do not understand how DSA works and/or there are additional, probably exotic CR sources, such as dark matter decay or annihilation

Outline

1. Preliminary Information
   - DSA - The Diffusive Shock Acceleration
   - DSA@SNR: Test Particle vs Nonlinear
2. Disagreements with the standard DSA
   - Anomalies in positron spectrum
   - EXISTING explanations and their weaknesses
3. NEW: Minimum assumptions, single source (SNR) scenario
   - $e^{\pm}$ asymmetry of acceleration: Molecular Clumps
   - Minimum in $e^{+}/(e^{+}+e^{-})$: NL DSA
4. Conclusions: no room (almost) for DM/Pulsars contribution

CR production mechanism: Diffusive Shock Acceleration (DSA)



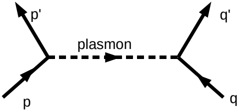
flow velocity

-Most shocks of interest are collisionless

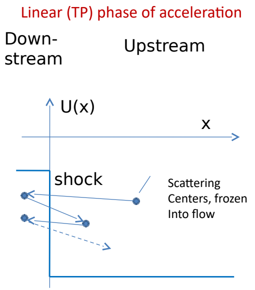
-Big old field in plasma physics

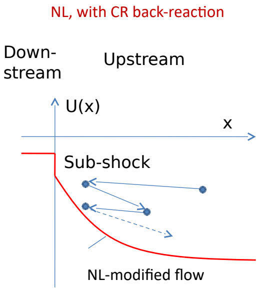
Problems:

- How to transfer momentum and energy from fast to slow gas envelopes if there are no binary collisions?
- waves. . .
- driven by particles whose distribution is almost certainly unstable. . .



Essential DSA (aka Fermi-I process, E. Fermi, ~1950s)

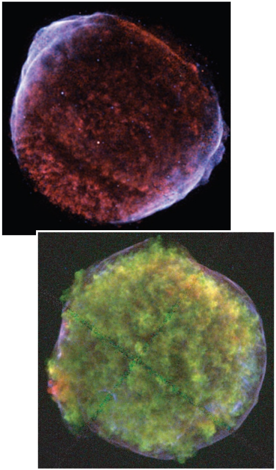




- CR trapped between converging mirrors: $p\Delta x \approx const$
- CR spectrum depends on shock compression, r: $f \sim p^{-q}$, $q = 3r/(r-1)$, $r = q = 4$, Mach $M \to \infty$

- Index q becomes $q(p)$:
  - soft at low p:
    - $q = 3r_s/(r_s - 1) \sim 5$
  - hard at high p : $q \to 3.5$
  - for $M > 10$, $E_{max} \gtrsim 1$ TeV acceleration must go nonlinear

CR acceleration in SNRs



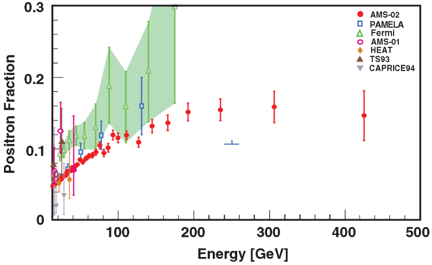
SN 1006 and SN 1572 (Tycho), Reynolds 2008 and Warren et al 2005

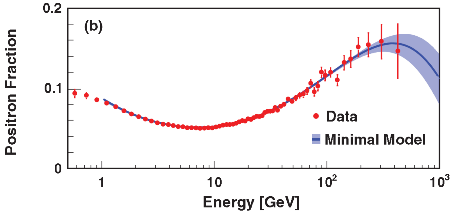
- At least some of the galactic SNR are expected to produce CR up to $10^{15} eV$ (knee energy)
- "Direct" detection is possible only as secondary emission
  - observed from radio to gamma
  - electron acceleration up to $\sim 10^{14} eV$ is considered well established, synchrotron emission in x-ray band (Koyama et al 1995, Bamba et al 2003)
  - tentative evidence of proton acceleration from nearby molecular clouds:

    $$pp \to \gamma$$

    Fermi-LAT, HESS, Agile,..

Positron Anomaly (excess)





- Positron excess (Accardo et al 2014)
- Observed by different instruments for several years
- Dramatically improved statistics by AMS-02 (published in 2014)

Things to note:

- Remarkable min at ≈ 8 GeV
- Unprecedented accuracy in the range 1-100 GeV
- Saturation (slight decline?) trend beyond 200 GeV
- Eagerly awaiting next data release!

Suggested explanations of positron excess

- focus on the rising branch of $e^+/(e^+ + e^-)$
- invoke secondary e^+ from CR pp with thermal gas

Problems:

- Tensions with $\bar{p}$: secondaries with differing spectra
- Poor fits, free parameters, no physics of 8 GeV upturn...

Alternative suggestions:

- Pulsars (lacking accurate acceleration models)
- Dark matter contribution ??

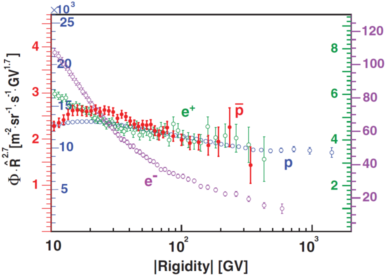
Stating the Obvious ....

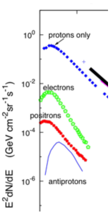
- DSA@SNR' predictive capability $\gg$ Pulsar or DM models
- $\to$ DM/P– only if the DSA@SNR fails

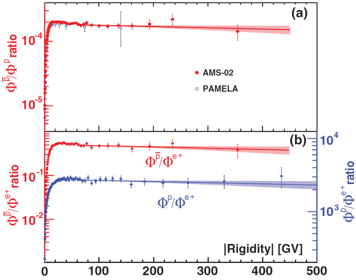
Upshot

- SNR contribution constrains DM/Pulsar contributions

Possible hints from p and $\bar{p}$







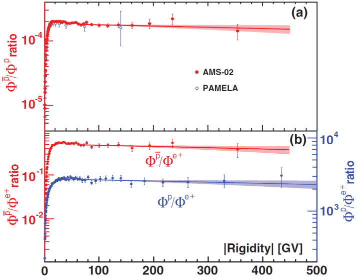
AMS-02:Aguilar+ 2016

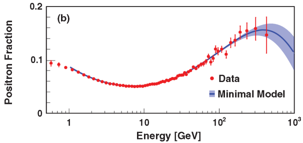
particle\property	charge	mass	secondary?	pulsar?
p	+	M	no	no
$\bar{p}$	-	M	yes	no
e^+	+	m	both	yes
e^-	-	m	no	both

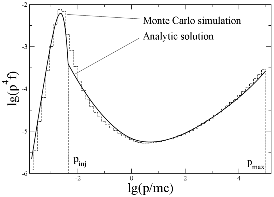
The Wishlist

- account for e^+ fraction by a single-source, a nearby SNR (contribution from similar sources not excluded)
- explain physics of decreasing and increasing branches, 8 GeV min
  - $\rightarrow$ lends credence to high energy predictions
- understand $\bar{p}/p$ and e^+/p flat spectra as intrinsic, not coincidental:
  - most likely $\bar{p}$ and e^+accelerated similarly to protons, whenever injected BUT:
  - $\bar{p}/p = e^+/p \neq e^+/e^-$ - Why so?
- plausible answer: acceleration/injection is *charge-sign and mass/charge ratio dependent*
- understand the physics of charge-sign and m/e selectivity

The Hints







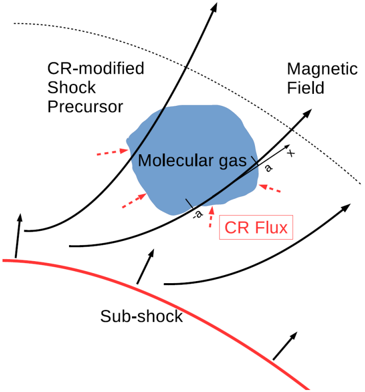
- $\bar{p}$ fraction is flat on the rising e^+ fraction branch $E > 8$ GeV
  - Opposite trends in e^+/e^- and $\bar{p}/p$ spectra at $E < 8$ GeV
  - Both are *fractions*, thus eliminating charge-sign independent aspects of propagation and acceleration (still, HS effects?)
  - Striking similarity with NL DSA solution, assuming most of e^- are accelerated to p^{-4} (standard DSA)

The Assumptions

- SNR shock propagates in "clumpy" molecular gas ($n_{\mathrm{H}} \gtrsim 30\mathrm{cm}^{-3}$, filling factor $f_V \sim 0.01$)
- High-energy protons are already accelerated to (at least) $E \sim 10^{12} eV$ to make a strong impact on the shock structure (CR back reaction, NL shock modification)
  - Acceleration process thus transitioned into an efficient regime (in fact, required to, once $E \gtrsim$1 TeV, $M \gtrsim 10 - 15$ and the fraction of accelerated protons $\sim 10^{-4} - 10^{-3}$)

- The SNR is not too far away, possibly magnetically connected, thus making significant contribution to the local CR spectrum
- Other SNRs of this kind may or may not contribute

Interaction of shock-acc'd CRs with gas clumps (MC)



- Shock-acc'd CRs form a precursor : κ - CR diff. coeff.,

$$L_p \sim \kappa / u_{sh}$$

- With some help from plasma textbooks...
- Maximum electric field due to $e - i$ collisions

$$E_{\max} \simeq \frac{m_e}{e} u_{sh} \nu_{ei} \frac{n_{CR}^0}{n_i}$$

- maximum ES potential inside

$$\frac{e\phi_{\max}}{m_p c^2} \sim \frac{a}{1pc} \frac{u_{sh}}{c} \frac{n_{CR}}{1cm^{-3}} \left(\frac{1eV}{T_e} \right)^{3/2}$$

Short digression into elementary plasma physics

- plasmas enforce almost “zero-tolerance” policy in regard to violation of their charge neutrality

Example

take 1cm^3 of air
ionize and separate p and e to distance r =0.5 cm
the resulting force

$$F = e^2 N^2 / r^2 \sim 10^{16}\ \text{lb}$$

As $N \sim 10^{19}$, $I = 13.6$ eV
ionization energy only~ 100 Jouls

- similarly, injection of an external charge into plasma must lead to enormous electrostatic forces
- key words here are “separate” and “inject”
- need a powerful mechanism
- energetic CRs can do that

$\mathbf{E}$ in MC: Injection/acceleration of e^+ and $\bar{p}$ into DSA

- electric field traps e^- and some $\bar{p}$ inside MC
- ejects secondary e^+ $\rightarrow$charge-sign asymmetry

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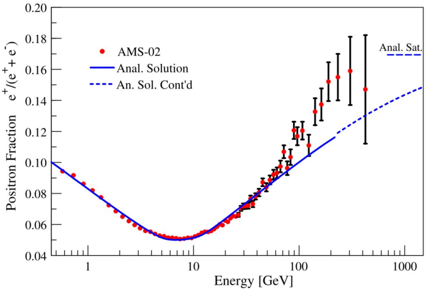
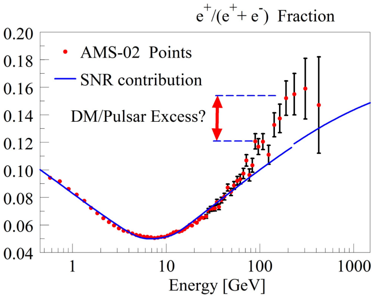


- $e^+$are pre-accelerated in $\mathbf{E}$ to $\lesssim 1$ GeV and readily injected into DSA
- at $E_e \lesssim$ few GeV, e^+ spectrum is dominated by the subshock compression ratio, r_s
  - spectral index $q = q_s \equiv 3r_s/(r_s - 1)$ and the spectrum $f_{e^+} \propto p^{-q_s}$.
- at higher energies, particles perceive higher flow compression
  - PL-index inside the source $q \rightarrow 3.5$

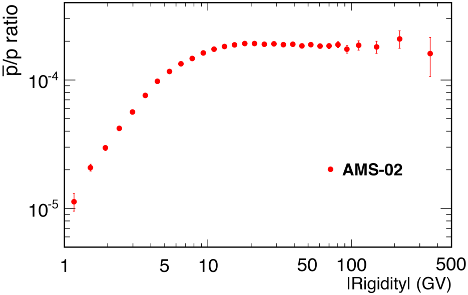
Positron spectra cont'd



- e^- are from the TP phase with p^{-4} source spectra (and other TP-SNRs)
- $\Longrightarrow$ $e^+/(e^- + e^+)$-spectrum $=$ p−spectrum in $p^4 f(p)$ customary normalization

- ratio $e^+/(e^- + e^+)$ is de-propagated and probes directly into the positron accelerator!
- before DM/pulsars are declared responsible for the excess above the SNR (blue curve), the following (prosaic) aspects may be considered:
  1. e^+ release from MC farther upstream (additional spectrum hardening)
  2. synchrotron pile-up near the cut-off energy
  3. electrostatic breakdown of MC with enhanced e^+ generation

Antiprotons



- If most of $\bar{p}$ and p come from the same source as e^+ ($\bar{p}$ generated in MCs ahead of SNR shock), the $\bar{p}$ and e^+ spectra should be the same as p at $E \gtrsim 10$ GeV
- Similarly, $\bar{p}/p$ should be flat if $\bar{p}$ are co-injected (albeit as secondaries) into any SNR-DSA process
- Decline of $\bar{p}$ at lower energies is consistent with electrostatic retention in MC
- Solar modulation may also contribute to $p - \bar{p}$ difference at lower energies
- Flat $\bar{p}/p$ should continue up to $p \sim p_{\max}$ and decline at $p \gtrsim p_{\max}$ (secondaries with no acceleration)

Conclusions

- secondary positrons produced in pp collisions inside MCs ahead of SNR shocks and expelled into shock precursor make a seed population for the DSA
- shock-accelerated positrons develop a concave spectrum, characteristic for the NL DSA.
- most of the negatively charged light secondaries (e^-), and to some extent, $\bar{p}$, along with the primary electrons, remain inside MCs and make less contributions to the overall spectrum
- due to the NL subshock reduction, the MC remains unshocked, so that secondary $\bar{p}$ and, in part, heavier nuclei accumulated in its interior largely evade shock acceleration
- the AMS-02 positron excess is not fully accounted for only in the range $\sim 200-400$GeV, BUT:
- physical phenomena to be included in the next-step model (e^+/e^- run-away breakdown, Syn. pile-up, etc.) are likely to suffice for a conventional explanation of the residual excess

Message to the Observers

Not every bump in the data is from DM