Positron Anomaly in Galactic Cosmic Rays: Constraining Dark Matter Contribution

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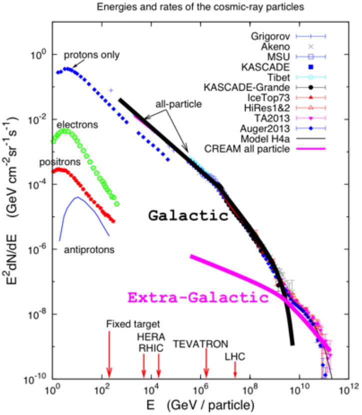
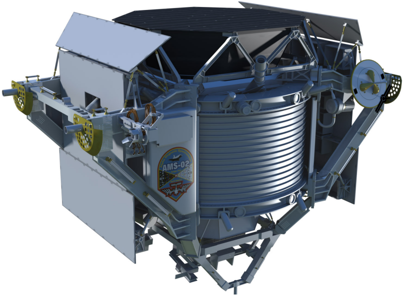
More than 100 years of cosmic ray research...



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 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.)

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

Contents

1. Difficult times for DSA
   - DSA: too big to fail?
   - SNRs as main source of galactic CRs ("Standard Model")
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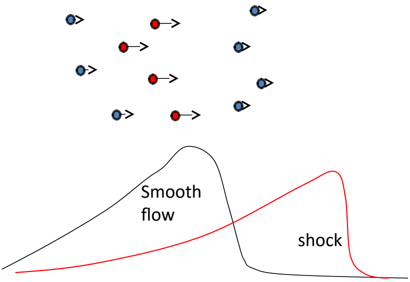
   - Possible explanations and their weaknesses
3. A new look at positron anomaly
   - Charge-sign dependent CR acceleration: molecular gas ahead of the SNR shock
   - Physics of rising and falling branches of positron fraction: NL DSA
   - Physics of the spectral minimum
4. Conclusions: Room for DM/Pulsars contribution

CR production mechanism: Diffusive Shock Acceleration (DSA)



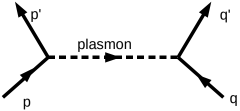
flow velocity

-Most shocks of interest are collisionless

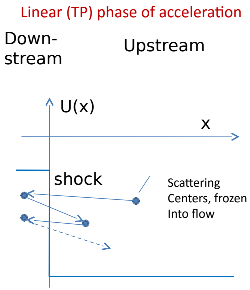
-Big old field in plasma physics

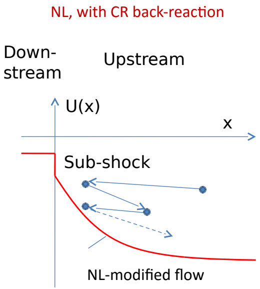
Problems:

- 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)

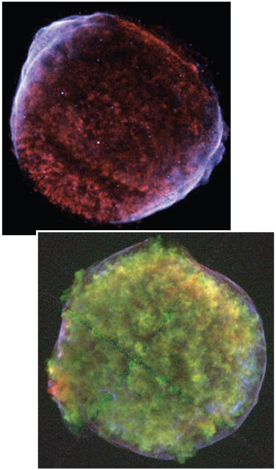




- Particles are trapped between converging mirrors: $p\Delta x \approx const$
- CR spectrum: determined by shock compression, r: $f \sim p^{-q}$, $q = 3r/(r-1)$, $r = q = 4$ for strong shocks $M \to \infty$

- Index q becomes $q(p)$:
  - soft at low p: $q = 3r_s/(r_s - 1)$ $r_s < 4$ $(\sim 2-3)$
  - hard at high p: $q \to 3.5$ (largely independent of $r \gg 1$)

CR acceleration in SNRs



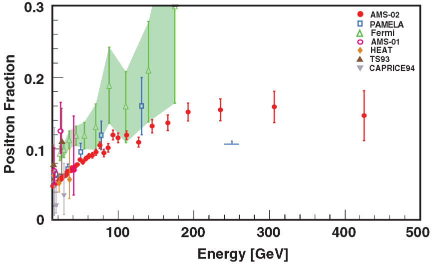
SN 1006 and SN 1572 (Tycho), Reynolds 2008 and Warren et al 2005

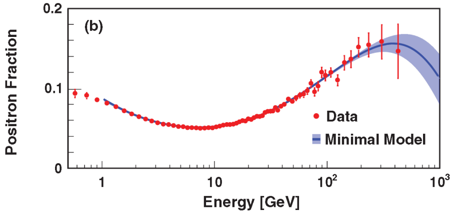
- At least some of the galactic SNR are expected to produce CR up to $10^{15} eV$ (knee energy)
- "Direct" detection is possible only as secondary emission
  - observed from radio to gamma
  - electron acceleration up to $\sim 10^{14} eV$ is considered well established, synchrotron emission in x-ray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

    $$pp \rightarrow \gamma$$

    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

- Early explanations focused on the rising branch of positron anomaly
- Most of the SNR related suggestions invoke secondary e^+ produced by galactic CR protons colliding with:
  - ambient dense gas in surroundings of SNR accelerator (Fujita+ 2009)
  - elsewhere in the Galaxy (Blum+2013, Cowsik+ 2014)
  - immediately at shock front (Blasi 2009, Mertsch 2014, Cholis+ 2014)
- Tensions with $\bar{p}$ observations (should show similar trends, as both are secondaries)
- Poor fits to high-precision AMS-02 data or too many *ad hoc* assumptions (e.g. multiple sources with, often, arbitrary power-law indices)

Further explanations

- Pulsars (e.g. Profumo 2012, big review). Possible, but have disadvantage of lacking accurate acceleration models
- Dark matter contribution ??
- Positrons injected into DSA by radioactive elements of SN ejecta

Obvious remarks

- As Pulsars and particularly DM have much weaker predictive capabilities than the DSA-SNR- based models, they should be considered seriously only if (or where) the SNR contribution falls short to account for the positron excess
- SNR contribution to the phenomenon thus constrains possible DM/pulsar contributions

Weaknesses of explanations – Motivation

Bottom line:

e^+/e^- explained only by adjusting independent sources

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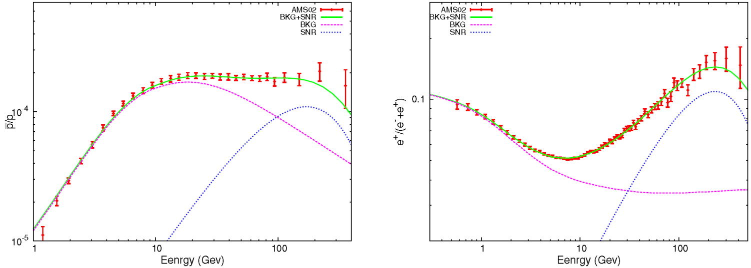


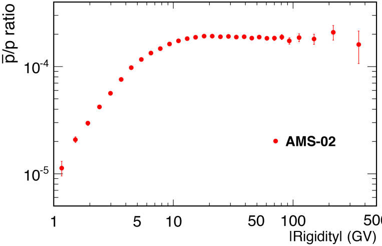
Weaknesses:

- Flatness of $\bar{p}/p$ and position of minimum in e^+/e^- are coincidental
- B/C, $\bar{p}/p$ secondary constraints put a 25% upper bound on SNR contribution to the positron rise (Cholis&Hooper, 2014)

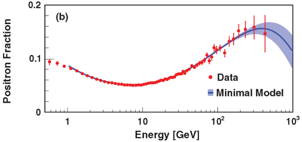
Desirable aspects of the mechanism (Wishlist)

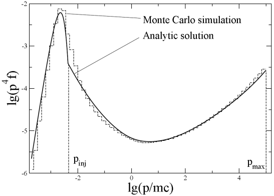
- account for e^+ fraction by a single-source, a nearby SNR
- explain physics of decreasing and increasing branches
- identify physics of the minimum at 8 GeV
- understand $\bar{p}$ flat spectrum as intrinsic, not coincidental: most likely, accelerated just like protons, whenever injected BUT: $\bar{p}/p \neq e^+/e^-$
- $\Longrightarrow$acceleration mechanism ought to be *charge-sign dependent*
- physics of charge-sign selectivity

The Hints



(AMS Days at CERN, Kounine 2015)



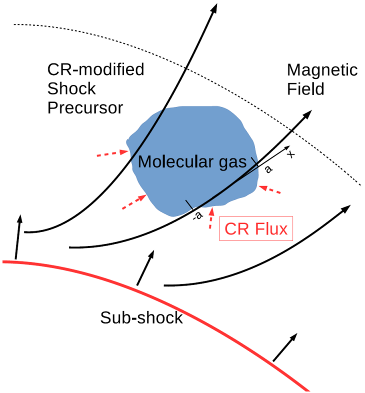


- $\bar{p}$ fraction is flat on the rising e^+ fraction branch $E > 8$ GeV
- Opposite trends on the declining e^+ fraction branch $E < 8$ GeV
- Both data sets relate to *fractions*, thus eliminating all charge-sign independent aspects of propagation and acceleration
- Striking similarity with NL DSA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

Assumptions of the present model

- A strong SNR propagates in "clumpy" molecular gas, $n_{\rm H} \gtrsim 30 {\rm cm}^{-3}$ with filling factor $f_V \sim 0.01$, but mass $\gg$ ambient plasma
- The SNR is not too far away, likely magnetically connected, thus making significant contribution to the local CR spectrum
- Other SNRs of this kind may or may not contribute
- Consider a moderately oblique (shock normal to the ambient magnetic field) portions of SNR shock surface
- High-energy protons are already accelerated to $E \gtrsim 10^{12} eV$ 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 $\sim 10^{-4} - 10^{-3}$)

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



- Shock-acc'd CRs form a precursor $L_p \sim \kappa/u_1$: κ - CR diff. coeff., u_1 shock velocity $\kappa = \kappa_B \simeq cr_g(p)/3$, r_g -gyro-radius

- CR number density increases towards subshock

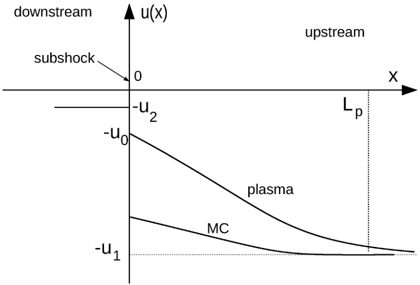
$$n_{CR}(x) = \frac{x_0 n_{CR}^0}{x_0 + x_{MC}}$$

- CR charge the MC at a relative rate (charge/discharge)

$$\eta = \frac{\dot{n}_{\rm CR} L_{\rm MC}}{V_{Te} n_0 + V_i n_i}$$

$$\sim \frac{L_{\rm MC}}{L_{\rm CR}} \cdot \frac{u_1 n_{\rm CR}}{V_{Te} n_0 + V_i n_i}$$

Electrodynamics of CR-MC interaction



- MC move faster (in the shock frame) than the upstream flow (bow-shocks form)
- CR number density in MC increases explosively:

$$n_{CR}\left(t\right) = n_{CR}^{0} x_0 / \left(x_0 - u_1 t\right)$$

- Reaction from the MC:
- buildup of electric field of a *positive* electrostatic potential
- minus-charge particles are attracted and stay inside MC during the subsequent shock crossing → evade acceleration
- plus-charge particles are expelled and injected into DSA
- charge-sign asimmetry of injection/acceleration

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

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

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

Electrodynamics inside MC

- Two-fluid equations:

$$\begin{aligned}\frac{dV_i}{dt} &= \frac{e}{m_i}E(x,t) - \nu_{in}V_i \\ \frac{dV_e}{dt} &= -\frac{e}{m_e}E - \nu_{ei}(V_e - V_i) \\ \frac{\partial n_{e,i}}{\partial t} &= -\frac{\partial}{\partial x}n_{e,i}V_{e,i} \\ n_e &= n_i + n_{CR}\end{aligned}$$

- Electric field is related to CR charging rate and ion outflow:

$$E(x,t) = \frac{m_e}{e}\nu_{ei}\frac{n_{CR}}{n_{CR}+n_i}\left(\frac{\dot{n}_{CR}}{n_{CR}}x + V_i\right)$$

Self-similar solution

- Ions leave the MC symmetrically: $V_i(x,t) = xV(t)$, $E \propto V_i$, assuming $x = 0$ being a midpoint of the field line threading the MC, $|x| \leq a$
- All other solutions converge to this form
- Electric field $(-\infty < t < 0)$:

$$E(x,t) \simeq \frac{m_i}{e} a \nu_{in}^2 \frac{x\alpha}{(t_0 - t)^2} \left[1 + \frac{\alpha}{t_0 - t} \right]$$

with dimensionless parameter that characterizes ion depletion

$$\frac{\alpha}{t_0} \sim \left(\frac{1eV}{T_e} \right)^2 \frac{n_{CR}^0}{n_n} \sqrt{\frac{m_n}{m_i} \left(\frac{m_n}{m_i} + 1 \right) \frac{m_e}{m_i}} \sim \Delta n_i / n_i \ll 1$$

(t measured in $i - e$ collision times)

Solution for electric field in MC, cont'd

- Maximum electric field (at MC edge)

$$E_{\max} \simeq \frac{m_e}{e} u_1 \nu_{ei} \frac{n_{CR}^0}{n_i}$$

- electrostatic potential with a maximum in the middle of the MC ($x = 0$) screens the MC interior from penetrating CR

$$\frac{e\phi_{\max}}{m_p c^2} \sim \frac{a}{1pc} \frac{u_1}{c} \frac{n_{CR}}{1cm^{-3}} \left(\frac{1eV}{T_e}\right)^{3/2}$$

- A 1-parcec MC (r_g of a PeV proton) is acceptable as it occupies only a $u_1/c \ll 1$- fraction of CR precursor
- electric field is strong enough to keep low-energy CRs away from the MC interior
- keeps secondary e^- (and $\bar{p}$, to much lesser extent) inside, ejects secondary e^+
- charge sign asymmetry of injection into DSA established

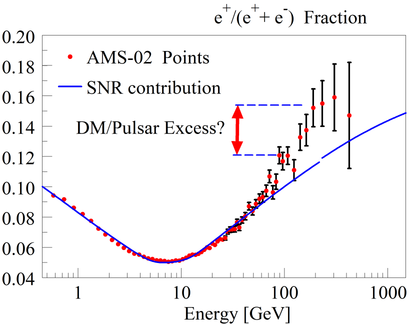
Positron Injection into DSA

- secondary e^+ are largely produced deep inside MC, preaccelrated in E and easily injected into DSA
- injection from many MCs occasionally crossing the shock occurs with a time-averaged rate $Q\left(p,x\right)$
- Q decays sharply with x, the distance from the subshock
- it has a broad maximum at $p\sim e\phi_{\max}/c$
- near subshock, CR number density sharply increases on account of GeV particles. They generate secondary $e^{\pm}$ and $\bar{p}$, on the periphery of MC. The edge electric field then expels positively charged secondaries $\left(e^{+}\right)$ and sucks in negatively charged ones, such as e^{-} and, to some extent, $\bar{p}$
- typical energy of expelled positrons $<1-2$ GeV

Shock Acceleration of Positrons

- As the shock is modified, acceleration starts in its precursor since $\partial u/\partial x \neq 0$
- However, most of the positrons are released from the MC near the subshock
- at lower energies, their spectrum is dominated by the subshock compression ratio, $r_s = u_0/u_2$
- spectral index $q = q_s \equiv 3r_s/(r_s - 1)$ and the spectrum $f_{e^+} \propto p^{-q_s}$.
- at higher energies, positrons feel progressively higher flow compression (diffuse farther ahead of the subshock)
- their spectrum tends to a universal form with $q \to 3.5$

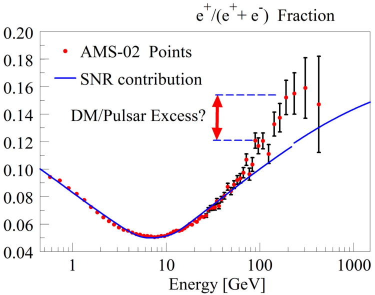
Positron spectra



- Shock structure is created by accelerated protons through their pressure distribution

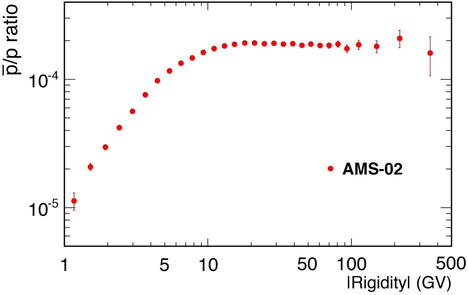
- e^+ and other secondaries produced in pp collisions of shock accelerated CRs with MC gas, as well as e^- can be treated as test particles in a given shock structure
- positively charged particles are enhanced while negatively charged suppressed because of charge-asymmetric injection from MC
- plausible assumption: e^+/e^- *injection rate* $\gg 1$.

Positron spectra cont'd



- In calculating $e^+/(e^- + e^+)$, e^- are assumed to be from conventional shocks with p^{-4} source spectra
- $\Longrightarrow$ $e^+/(e^- + e^+)$ spectrum = proton spectrum in $p^4 f(p)$ customary normalization
- background e^- (with p^{-4} spectrum) propagate distance similar to that of e^+
- $\Longrightarrow$ratio $e^+/(e^- + e^+)$ is de-propagated and probes directly into the positron accelerator!
- excess above the blue curve is not SNR – e.g., DM or pulsars
- as SNR contrib. is rising with E, constraints on DM signal in 200-400 GeV range are weaker compared to secondary e^+(decaying) without acceleration

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 $\bar{p}$ spectrum should be the same as p at $E \gtrsim 10$ GeV

- Similarly, $\bar{p}/p$ should be flat if $\bar{p}$ are injected as secondaries into any SNR-DSA process
- Decline of $\bar{p}$ towards lower energies is consistent with electrostatic retention in MC
- This effect has not been quantified for $\bar{p}$
- Solar modulation may also contribute to $p - \bar{p}$ difference at low energy
- Flat $\bar{p}/p$ should continue till $p_{\max}$ then it should start declining (secondaries with no acceleration)

Conclusions

1. A weakly ionized dense molecular gas (MC) in SNR shock environment, illuminated by shock accelerated protons results in the following phenomena:
    1. an MC of size $L_{\rm MC}$ is charged (positively) by penetrating protons to$\sim \left(L_{\rm MC}/pc\right)\left(V_{sh}/c\right)\left(1eV/T_e\right)^{3/2}\left(n_{CR}/cm^{-3}\right)$GV
    2. secondary positrons produced in pp collisions inside the MC are pre-accelerated by the MC electric potential and expelled from the MC to become a seed population for the DSA (get "injected")
    3. most of the negatively charged light secondaries $\left(e^{-}\right)$, and to some extent, $\bar{p}$, along with the primary electrons, remain locked inside the MC
2. Assuming that the shock Mach number, proton injection rate, and cut-off momentum all exceed the thresholds of NL acceleration, the spectrum of injected positrons has concave form, which physically corresponds to a steepening due the subshock reduction, and flattening resulting from acceleration in the smooth part of the shock

Conclusions cont'd

1. the crossover energy is related to the change in proton transport (from $\kappa \propto p^2$ to $\kappa \propto p$) and respective contribution to the CR partial pressure in a mildly-relativistic regime. The crossover pinpoints the 8 GeV minimum in the $e^+/(e^+ + e^-)$ fraction measured by AMS-02
2. 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
3. The AMS-02 positron excess in the range $\sim 200 - 400$GeV is not accounted for by the SNR positron spectrum and is available for alternative interpretations (DM, Pulsars, ???)