Collisionless Shocks and Particle Acceleration

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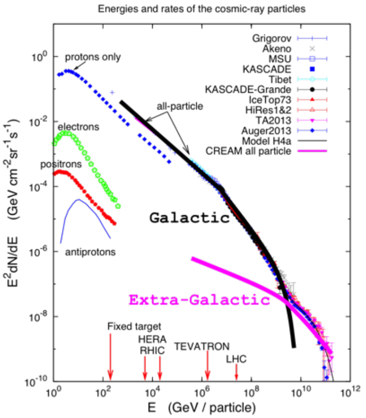
Supported by the NASA Astrophysics Theory Program, Grant No. NNX14AH36G

Collisionless Shocks and Cosmic Ray Acceleration

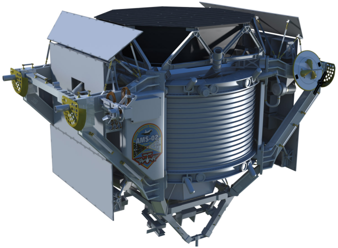


IceCube compilation of CR spectrum

- CR energy spectrum was long thought to be a featureless power law:
  - a hallmark of the underlying acceleration mechanism:
  - diffusive shock acceleration (DSA) operating in supernova remnant (SNR) shocks
- DSA rigidity (p/Z) spectra should be the same for all CR species
- Any variations in power-law index are interpreted as changes of acceleration regimes, or sources (galactic-extragalactic, etc.)

New Era in Observation Technology

- DSA predictions of energy spectra and composition of CRs scrutinized
- **proved not true in many instances**



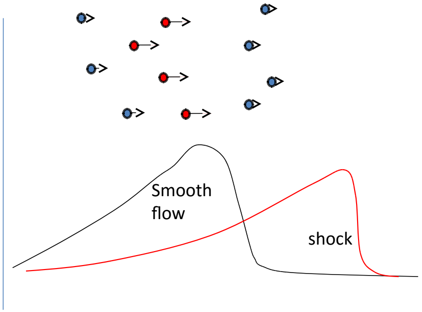
Alpha Magnetic Spectrometer (AMS-02): Particle detector operating on the International Space Station

- Either we do not quite understand how DSA works or there are additional, (exotic) CR sources, including dark matter decay or annihilation
- major problem: lack of understanding of collisionless shock mechanism
- especially particle injection into DSA
- elemental selectivity (A/Z - dependence, not just rigidity?)

Outline

1. Exciting time for the field, challenging time for DSA
   - DSA: collisionless shock process
   - SNRs as main source of galactic CRs ("Standard Model" ?)
2. Objection 1
   - Anomalies in Helium/proton fraction rigidity spectrum
   - Possible explanations
3. Objection 2
   - Positron Anomaly: Charge-sign dependent CR acceleration
   - Physics of rising and falling branches of positron fraction: NL DSA
   - Physics of the spectral minimum
4. Conclusions:
   - He/p anomaly: fully accounted for by A/Z injection dependence
   - Positron Anomaly: Explained but Room for DM/Pulsars contribution

CR production mechanism: Diffusive Shock Acceleration (DSA)



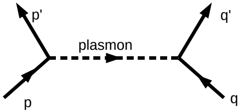
flow velocity

-Most shocks of interest are collisionless

-Big old field in plasma physics

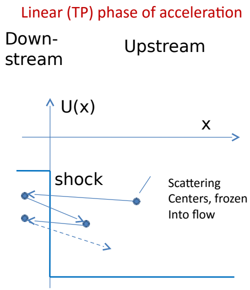
Problems:

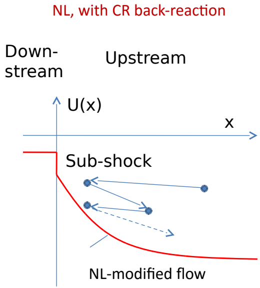
- How to transfer momentum and energy from fast to slow gas envelopes if there are no binary collisions?
- waves. . .
- driven by particles whose distribution is almost certainly unstable. . .



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

DSA giant step: 1977-78: Krymsky, Blandford, Bell, Axford

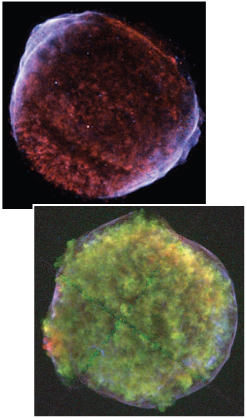




- Particles are trapped between converging mirrors: $p\Delta x \approx const$, MM, P. Diamond,2006
- $\Rightarrow$ CR spectrum: determined by shock compression, r: $f \sim p^{-q}$, $q = 3r/(r-1)$, $r = q = 4$ for strong shocks $M \to \infty$

- 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 $r \gg 1$) MM, 1997, 1999

CR acceleration in SNRs



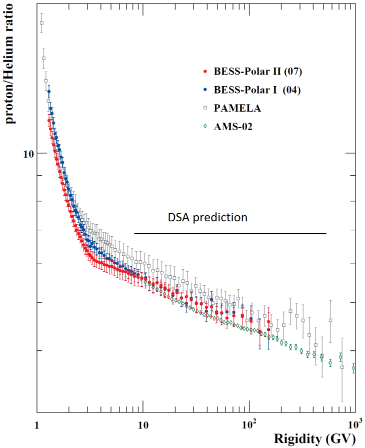
- SN 1006 and SN 1572 (Tycho), Reynolds 2008 and Warren et al 2005

- 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,..

Pamela p/He Anomaly



AMS-02 (2015) results along with earlier data

- The PAMELA orbital telescope revealed deviation (≈ 0.1 in spectral index) between He and protons, deemed inconsistent with DSA (Adriani et al 2011)
- DSA predicts a flat spectrum for the He/p ratio
- similar result obtained recently by AMS-02 for C/p ratio
- points to initial phase of acceleration where elemental similarity (rigidity dependence only) does not apply
- A/Z is the same for He and C

Suggested explanations of He spectral hardening

- three different types of SNRs contribute Zatsepin & Sokolskaya (2006)
- outward-decreasing He abundance in certain SNR, such as super-bubbles, result in harder He spectra, as generated in stronger shocks Ohira & Ioka (2011)
- He is neutral when processed by weak shocks. It is ionized when the SNR shocks are young and strong, Drury, 2011
- spallation processes lead to deficiency of He at lower energies as it has longer confinement time in the Galaxy, Blasi & Amato 2011
- p/He --Forward/reverse SNR shock, Ptuskin & Zirakashvili, 2012

Issues:

- most suggestions hard to reconcile with Occam's razor approach
- tension with the He-C striking similarity
- spallation scenario overproduces CR secondaries

Simple Proof of Elemental Invariance

- write equations using rigidity instead of momentum, $\vec{\mathcal{R}} = \mathbf{p}c/eZ$

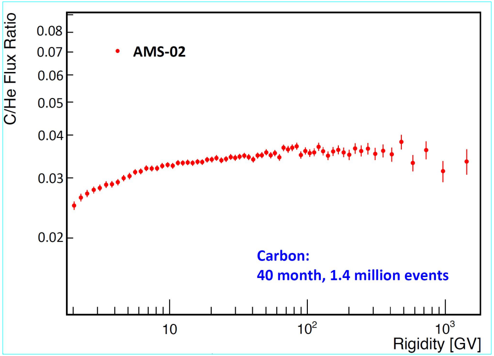
$$\frac{1}{c}\frac{d\vec{\mathcal{R}}}{dt} = \mathbf{E}(\mathbf{r},t) + \frac{\vec{\mathcal{R}} \times \mathbf{B}(\mathbf{r},t)}{\sqrt{\mathcal{R}_0^2 + \mathcal{R}^2}}$$

$$\frac{1}{c}\frac{d\mathbf{r}}{dt} = \frac{\vec{\mathcal{R}}}{\sqrt{\mathcal{R}_0^2 + \mathcal{R}^2}}$$

where $\mathcal{R}_0 = Am_p c^2/Ze$, A -atomic number

- if p's and He^{2+} start acceleration at $\mathcal{R} \gg \mathcal{R}_0$ in a ratio N_p/N_{He}
- this ratio is maintained in course of acceleration and the rigidity spectra are identical
- if both species propagate to observer without collisions, they maintain the same N_p/N_{He}
- DSA predicts distribution $\propto \mathcal{R}^{-q}$ where, q depends on Mach number as $q = 4/\left(1 - M^{-2}\right)$

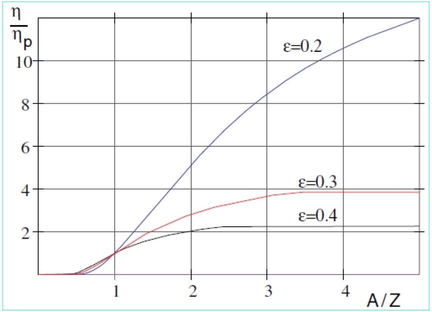
Recent AMS-02 hint on the origin of p/He Anomaly



- AMS-02 (2015) from M. Heil talk at CERN (not yet official)

- flat C/He ratio eliminates most scenarios
- points to initial phase of acceleration, *injection*, where elemental similarity (rigidity dependence only) does not apply
- A/Z is the same for He and C
- $\mathcal{R}_0 = Am_pc^2/Ze$ that determines the injection from thermal plasma also the same

Occam's approach to resolve Pamela puzzle within DSA



Injection efficiency (normalized to proton, MM'98)

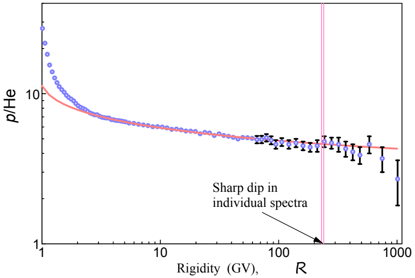
Assumptions:

- single source (SNR)
  - shock propagates into ionized homogeneous plasma
  - shock radius and Mach number evolve according to Sedov-Taylor point explosion

Main ideas:

- preferential injection of He into DSA for higher Mach numbers
- injection dependence on A/Z and on ϵ, inverse wave amplitude $\epsilon \sim B_0/\delta B$
- ϵ decreases with growing Mach number
- injection bias is due to Alfven waves driven by protons, thus retaining protons downstream more efficiently than He and C

p/He ratio integrated over SNR life



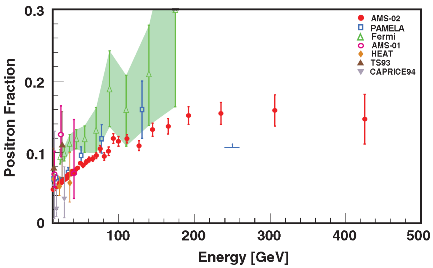
He/p from MM, Diamond and Sagdeev, 2012

- automatically predicts the p/C ratio since the rest rigidity (A/Z) is the same for C and He

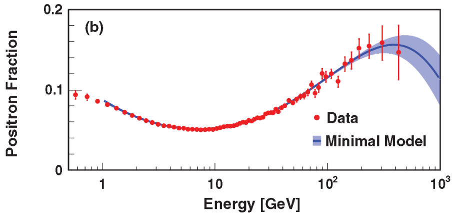
Some Conclusions

- the p/He ratio at $\mathcal{R} \gg 1$, is not affected by CR propagation, regardless the individual spectra
- telltale signs, intrinsic to the particle acceleration mechanism
- reproducible theoretically with no free parameters
- PIC and hybrid simulations will be instrumental in computing p and He injection scalings with Mach number, e.g. Hanusch et al, APS 2016, + in preparation

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)
- Tensions with γ-s

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

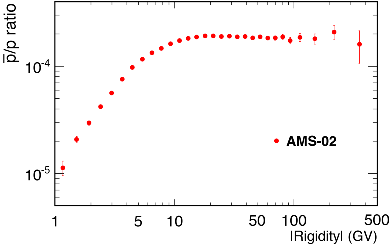
Obvious remarks

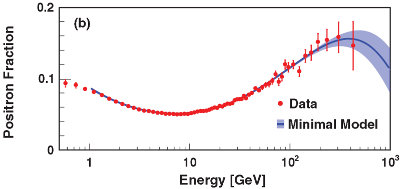
- Pulsars and particularly DM have much weaker predictive capabilities than the DSA-SNR- based models
- should be considered if the SNR contribution falls short to account for positron excess
- SNR contribution to the phenomenon constrains possible DM/pulsar contributions

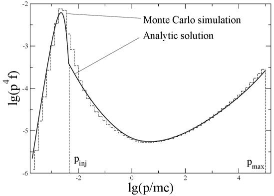
Desirable aspects of the mechanism (Wishlist)

- 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



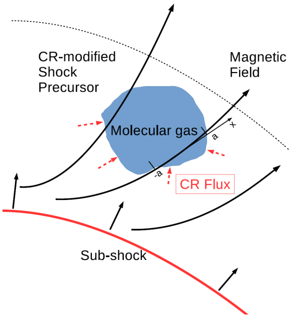




(AMS Days at CERN, Kounine 2015)

- $\bar{p}$ 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 (MM, 1997), assuming most of e^- are accelerated to p^{-4} (standard DSA)

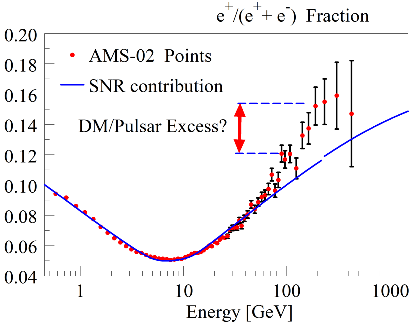
Assumptions of the present model



- shock propagates in "clumpy" molecular gas, $n_{\rm H} \gtrsim 30{\rm cm}^{-3}$ $f_V \sim 0.01$, big mass
- SNR is nearby, likely magnetically connected, big contribution to local CRs

- Other SNRs of this kind may or may not contribute
- Moderately oblique shock
- 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 transitioned into efficient regime (hard to avoid for $E \gtrsim$1 TeV, $M \gtrsim 10 - 15$ and the fraction of accelerated p's $\sim 10^{-4} - 10^{-3}$)

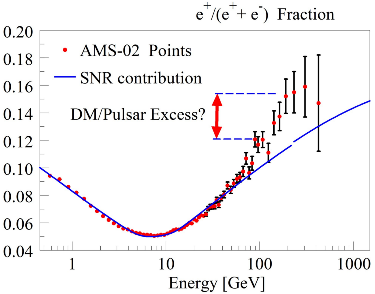
Salient Features of Calculated Positron Spectrum (MM, Diamond, Sagdeev 2016)



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

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

e^+Spectrum 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

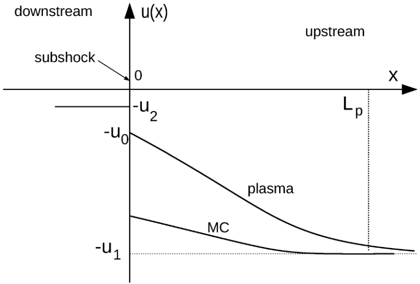
- background e^- (with p^{-4} spectrum) propagate distance similar to that of e^+
- $\Longrightarrow$ratio $e^+/(e^- + e^+)$ is de-propagated and probes directly into the positron accelerator!
- excess above the blue curve is not SNR – e.g., DM or pulsars
- as SNR contrib. is rising with E, constraints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

Conclusions

1. A weakly ionized dense molecular cloud (MC) in SNR shock environment, illuminated by shock accelerated protons results in the following phenomena:
   1. penetrating protons charge MC positievely
   2. secondary positrons produced in pp collisions inside the MC are pre-accelerated by the MC electric field and injected into DSA
   3. most of the negatively charged light secondaries (e^-), and to some extent, $\bar{p}$, remain locked inside the MC
2. the spectrum of accelerated e^+ has the observed concave form due to steepening caused by NL subshock reduction, and flattening resulting from acceleration in the smooth part of the shock transition
3. the crossover pinpoints the 8 GeV minimum in the $e^+/(e^+ + e^-)$ fraction measured by AMS-02
4. 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, ???)

Back up slides

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:

$$n_{CR}(t) = n^0_{CR} x_0 / (x_0 - u_1 t)$$

- 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 <u>separate</u> 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$\sim$ 100 Jouls

- similarly, <u>injection</u> 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

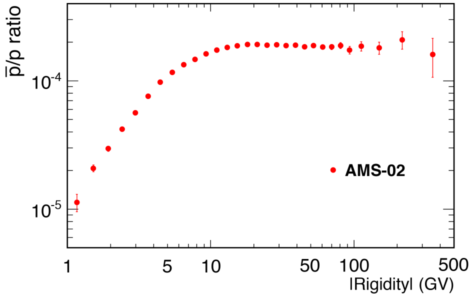
Positron Injection into DSA

- 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 $Q(p, x)$
- Q decays sharply with x, the distance from the subshock
- it has a broad maximum at $p \sim e\phi_{\rm max}/c$
- 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 (e^+) 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 $q \to 3.5$

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)