CR Acceleration Mechanisms: New Challenges From High-Fidelity Observations

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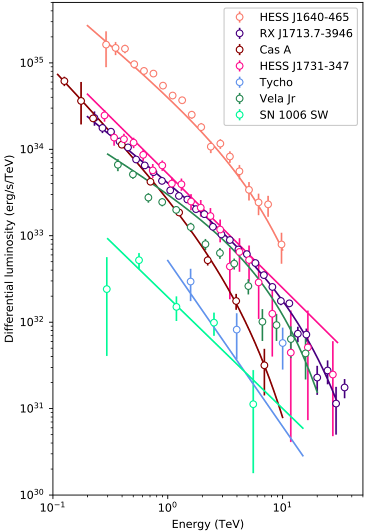
Outline

1. Why tweak the "robust" diffusive shock acceleration (DSA) -spectrum?
   1. Source- and local CR-spectra appear steeper than the DSA predicts (Celli and Brose talks on Tue PM, CR session)
   2. Helium/proton enhancement also perceived inconsistent with DSA
   3. Positron/electron "excess": DM, again?
   4. Flattening at 500 GeV steepening at 10 TeV (CALET, DAMPE)
2. Bilateral SNRs (1006) and their CR production spectra
   1. self-similar loss-free solution
   2. comparison with the "standard" DSA predictions
   3. strong dependence on the turbulence spectrum
   4. inclusion of particle losses (escape)
   5. possible relevance to hot-spot type acceleration, RXJ 1713?
3. p/He ratio, e^+/e^- spectral anomaly (backup slides)Up Slides)

Overview/Motivations

- measurements of $\gamma-$ spectra in a number of SNR allow inferences, in real time, about the spectra of accelerated cosmic rays (CR)
- two parameters, the spectral index q, and the maximum (cut-off) momentum, $p_{\max}$, are key predictions of the diffusive shock acceleration (DSA) theory
- recent observations, however, proved these parameters insufficient to understand the acceleration process
- energy spectra are often better represented by a gradual steepening with no sharp energy cut-off (F. Aharonian + 2018)

Observation Overview (from Aharonian et al, '18)



Conclusion

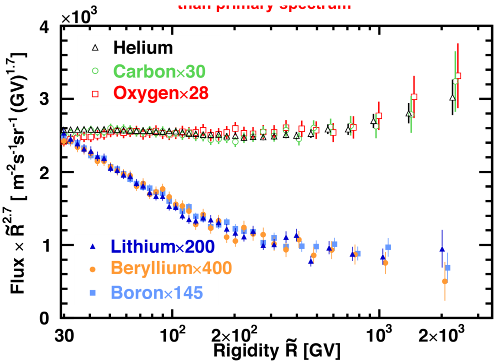
if the **DSA mechanism** is at work in SNRs, observations point to its important aspects not included in standard treatments

Note

most models are based on planar or spherically symmetric, slowly varying shock conditions

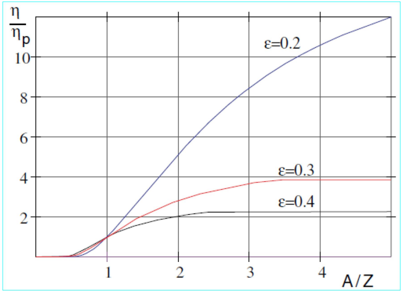
Recent AMS-02 hint on the origin of p/He Anomaly

AMS-02 (PRL, 2018) (Weiwei Xu talk 12:30 for update)



- flat C,O/He ratio eliminates most scenarios
- points to initial phase of acceleration, *injection*, where elemental similarity does not apply
- A/Z is enhanced similarly for He,O and C
- $\mathcal{R}_0 = Am_pc^2/Ze$ that determines the injection from thermal plasma simply follows the enhancement

Occam's approach to p/He acceleration by DSA@SNR



Injection efficiency (normalized to proton, MM'98)

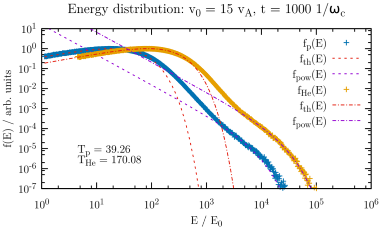
Assumptions:

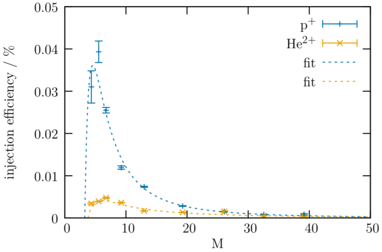
- single source (SNR)
  - shock propagates into homogeneous plasma
- shock radius $R(t)$ and Mach # obey Sedov-Taylor solution

Main ideas:

- preferential injection of He into DSA for higher Mach numbers
- injection dependence on A/Z and on ϵ, inverse wave amplitude $\epsilon \sim B_0/\delta B \propto M^{-1}$
- $\eta_{\rm inj}$ saturates with A/Z. Not significant for incomplete ionization with $A/Z \gg 2-3$. Physically, should eventually $\to 0$ for $A/Z \to \infty$
- injection bias is due to Alfven waves driven by protons, thus retaining protons downstream more efficiently than He, C and other high A/Z species

Validating Physical ideas by hybrid Simulations

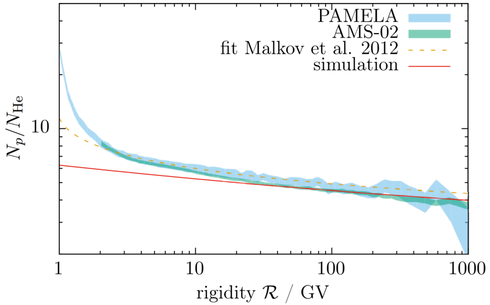




- 1D in configuration space, full velocity space simulations
  - shock propagates into ionized homogeneous plasma
- p and He are thermalized downstream according to Rankine-Hugoniot relations
- preferential injection of He into DSA for higher Mach numbers is evident
- injection dependence on Mach is close to theoretically predicted $\eta \sim M^{-1} \ln M$ (MM'98)

plots from A. Hanusch, T. Liseykina, MM, 2017

p/He ratio integrated over SNR life



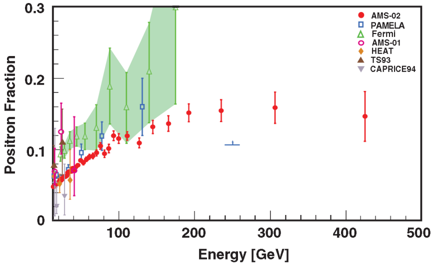
p/He from A. Hanusch, T. Liseykina, MM, 2017

- p/He result is valid for p/C,O ratios since the injection rate saturates at $A/Z > 2$-3

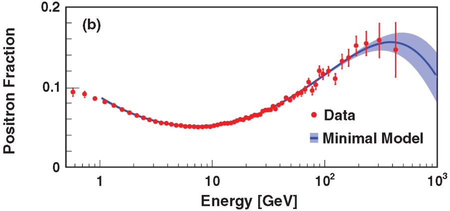
Some Conclusions

- 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 confirm p and He injection scalings with Mach number
  Hanusch et al, ApJ, 2019

Positron Anomaly - excess (Weiwei Xu talk 12:30)



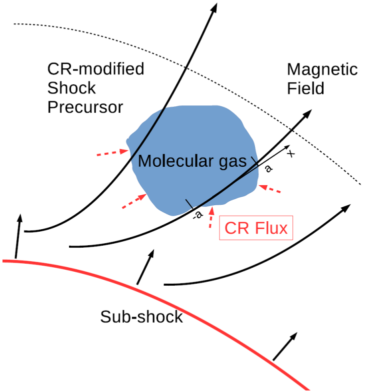
- Positron excess (Accardo et al 2014)
- Observed by different instruments for several years
- Dramatically improved statistics by AMS-02 (published in 2014)



Things to note:

- Remarkable min at ≈ 8 GeV
- Unprecedented accuracy in the range 1-100 GeV
- Saturation - decline (?) trend > 200-300 GeV

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; for $\kappa = \kappa_B$ $\simeq c r_g(p)/3$, r_g -gyro-radius

- CR number density increases towards subshock

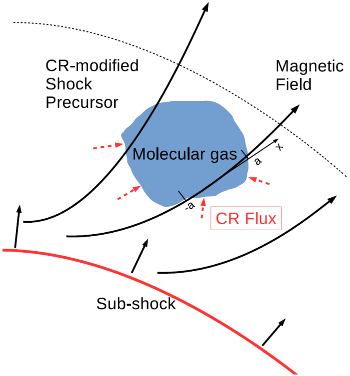
$$n_{CR}(x_{MC}) = \frac{x_0 n_{CR}^0}{x_0 + x_{MC}}$$

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

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

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

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

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

- maximum ES potential inside

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

Electric field in MC: some consequences

- 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 screens the MC interior from penetrating CR

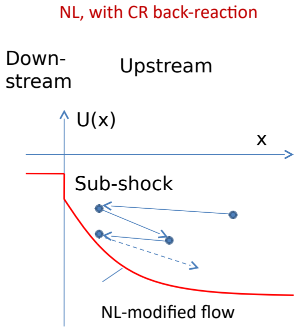
$$\frac{e\phi_{\max}}{m_p c^2} \sim \frac{a}{1pc} \frac{u_1}{c} \frac{n_{CR}}{1cm^{-3}} \left(\frac{1eV}{T_e} \right)^{3/2}$$

- A 1-parcec MC (r_g of a PeV proton) occupies only a $u_1/c \ll 1$- fraction of CR precursor
- $\phi \sim m_p c^2$ keeps low-energy CRs away from the MC interior (not edge), expels e^+, sucks in e^- but not $\bar{p}$ (reaction kinematics)
- charge sign asymmetry of $e^{\pm}$ injection into DSA established

e^+ and $\bar{p}$ Injection into DSA

- $e^+, \bar{p}$ and e^- are produced all across MC as secondaries
  - e^+ are preaccelerated in E and injected into DSA
  - $\bar{p}$ injected kinematically with insignificant momentum loss
  - e^- are trapped in MC, carried downstream unshocked
- injection from many MCs, occasionally crossing the shock, occurs with a time-averaged rate $Q\left(p,x\right)$
  - $Q(x,p)$ decays sharply with x, the distance from the subshock
  - $Q\left(p\right)$ has a broad maximum at $p \lesssim e\phi_{\max}/c$
  - typical energy of expelled positrons $\lesssim 1$ GeV, similar to $\bar{p}$

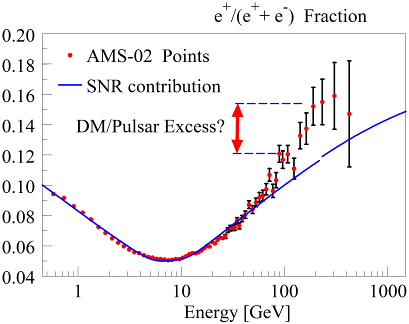
Shock Acceleration of Positrons -- just like $p, \bar{p}$



- 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 $q \to 3.5$

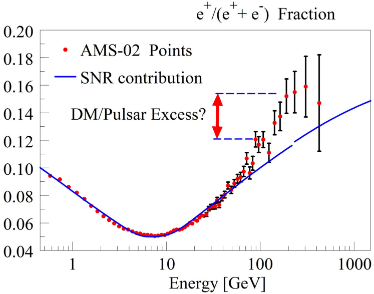
Positron spectra



- Shock structure is self-consistently adjusted to the pressure of accelerated protons

- 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
- $e^+$are enhanced while e^- suppressed because of charge-asymmetric injection from MC
- plausible assumption: e^+/e^- *injection rate* $\gg 1$.

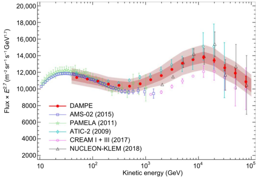
Positron spectra cont'd

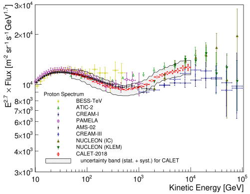


- In calculating $e^+/\left(e^- + e^+\right)$, e^- are assumed to be from conventional shocks with p^{-4} source spectra
- $\Longrightarrow$ $e^+/\left(e^- + e^+\right)$ spectrum = proton spectrum in $p^4 f(p)$ customary normalization

- background e^- (with p^{-4} spectrum) propagate distance similar to that of e^+
- $\Longrightarrow$ratio $e^+/\left(e^- + e^+\right)$ is de-propagated and probes directly into the positron accelerator!
- excess above the blue curve is not in this model – DM or pulsars possibly contribute
- much less room for DM/Pulsar signal in 200-400 GeV range compared to secondary e^+(decaying) without acceleration
  - this room can shrink completely

CR local spectrum: new features

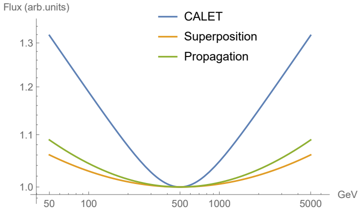




Fit near 500 GeV kink, presented by CALET, 2019

$$F \propto E^{-\gamma}\left[1+\left(\frac{E}{500}\right)^{\Delta\gamma/s}\right]^{s}$$

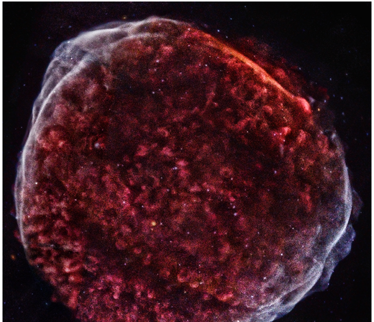
$\Delta\gamma = 0.3, \qquad s = 0.1$

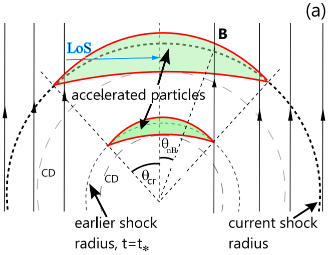


- Superposition of two sources
  - does no work
- Transition between different propagation regimes, e.g., self-confinement of CRs near the source to "free" propagation in weakly turbulent ISM
  - does not work either

Main Topic: Bilateral Morphology SNR

- active acceleration zone is shown at two consecutive moments
- accelerated particles are in expanding region as injection is efficient only $\vartheta_{cr} \lesssim \pi/4$ (supported by simple theory and hybrid simulations, e.g., Thomas, '90)





- in acceleration zone seen edge-on the LoS-integrated emission samples particles with different acceleration history
- fresh particles contribute to lower momenta, thus making the LoS-integrated spectrum steeper

Convection-Diffusion Equation

- describes particle acceleration at shock where $\theta_{nB} < \pi/4$ using cylindrical coordinates, (r, z), with $\mathbf{B} \parallel \hat{\mathbf{z}}$ -unit vector along the $z-$ axis passing through the center of the remnant
- convection-diffusion equation for a layer near $z = z_s(t)$ and $r \leq r_{\rm cr}(t) = R_s(t) \sin\vartheta_{\rm cr}$:

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial z} - \frac{\partial}{\partial z}\kappa_{\parallel}\frac{\partial f}{\partial z} - \frac{1}{r}\frac{\partial}{\partial r}r\kappa_{\perp}\frac{\partial f}{\partial r} - \frac{1}{3}\frac{\partial u}{\partial z}p\frac{\partial f}{\partial p} = Q(r_{\perp}, t)\,\delta(z)\,\delta(p - p_0) \qquad (1)$$

- shifted the origin of z- coordinate to the shock position, $z \rightarrow z_s(t) + z$.

$-p_0$ refers to the particle injection and the source of injected particles.

New ingredients

- eq.1 includes cross field transport with the diffusivity $\kappa_{\perp}$
- injection rate $Q(r)$ vanishes at $r \gtrsim r_{\rm cr}(t)$
- injection area grows as the shock expands and $r_{\rm cr}$ increases, $Q(t)$ grows, $u = u(t)$ decreases
    - acceleration process is fundamentally time-dependent

Radially-integrated Equation

- as particle density vanishes beyond $r > r_{cr}(t)$, we integrate to $r = \infty$:

$$\bar{F}(z,p,t) = 2\pi \int_0^\infty rf(z,r,p,t)\,dr \quad \text{and} \quad S(t) = 2\pi \int_0^\infty rQ(r,t)\,dr,$$

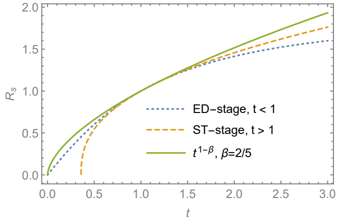
- With these definitions, from CD eq.(1) we obtain

$$\frac{\partial \bar{F}}{\partial t} + u\frac{\partial \bar{F}}{\partial z} - \frac{\partial}{\partial z}\kappa_{\|}\frac{\partial \bar{F}}{\partial z} = \frac{1}{3}\frac{\partial u}{\partial z}p\frac{\partial \bar{F}}{\partial p} + S(t)\,\delta(z)\,\delta(p-p_0) \qquad (2)$$

u and $\kappa_{\|}$ do not depend on r; this assumption is acceptable for $\kappa_{\|}$ in the area of particle localization, $r \leq r_{cr}$

- parallel diffusion strongly **increases** at $r > r_{cr}$ (turbulence level is low)
- perpendicular transport strongly **decreases** beyond the point $r = r_{cr}$
- $\rightarrow$ accept the value $\kappa_{\|}(r < r_{cr}) \approx const$ in eq.(2), e.g., Bohm limit
- $\rightarrow$ radially integrated CD equation, eq.(2) does not contain radial losses $\rightarrow$ flattest spectrum possible

Selection of SNR Expansion Stage



three useful approximations for $R_s(t)$:

1. ED compliant fit, $t < 1$, ST, $t > 1$
2. single power-law, $R_s \propto t^{3/5}$

SNR	t/t_{ST}	$1-\beta$
Cas A	0.57-2.3	0.79-0.48
Kepler	0.44	0.85
Tycho	0.83	0.69
SN 1006	1.4	0.54

- stages of SNR evolution $\rightarrow$ the strongest impact on CR production:
  - ejecta-dominated (ED), shock radius grows $R_s \propto t$
  - Sedov-Taylor (ST) stages, $R_s \propto t^{2/5}$
- **transition**: $t_{ST} \equiv t_0 \approx 0.495 M_e^{5/6}/\rho_0^{1/3}\sqrt{E} \approx 209\left(M_e/M_\odot\right)^{5/6}/n_0^{1/3}\sqrt{E_{51}}$.
- $n_0 = \rho_0/2.34\times10^{-24}\mathrm{g}$
- well described by a single power-law, $R_s/R_{\mathrm{ST}} = t^{1-\beta}$, with $\beta = 2/5$ (slower than ED but faster than ST)
- employ the single power-law approximation

Solution of Convection-Diffusion Equation

- Flow $u(z)$: planar shock approximation: $u = -u_1$, for $z > 0$ and $u = -u_2$, for $z \leq 0$, where $u_1 > u_2 > 0$ (justified *a posteriori* if the acceleration zone $\ll R_s$)
- BUT: u and $\kappa_{\|}$ - time dependent

$$u = -\left(\frac{t_0}{t}\right)^{\beta}\begin{cases} u_1, & z > 0 \\ u_2, & z \leq 0 \end{cases}$$

$u_{1,2} > 0$. In Sedov-Taylor $\beta = 3/5$, so that the shock propagates at $u_1 \equiv U_s \propto t^{-3/5}$ and its radius grows as $R_s \propto t^{2/5}$.

- The choice of $\kappa_{\|} \propto U_s R_s$

$$\kappa_{\|}(p,t) = \kappa(p)\left(\frac{t}{t_0}\right)^{1-2\beta}$$

- seek a self similar solution to eq.(2) in the following form

$$\bar{F}(t,z,p) = \phi(t,p)\, F(p,\xi), \qquad \xi = z\left(\frac{t}{t_0}\right)^{\beta-1}$$

Solution of DC cont'd

For $z, \xi \neq 0$ eq.(2) rewrites

$$\kappa \frac{d^2 F}{d\xi^2} + (u_{1,2} + a\xi) \frac{\partial F}{\partial \xi} - \zeta F = 0 \tag{3}$$

$$\zeta = \frac{t}{t_0 \phi} \frac{\partial \phi}{\partial t}, \qquad a = \frac{1-\beta}{t_0} \tag{4}$$

for arbitrary ξ

$$\kappa \frac{d^2 F}{d\xi^2} + [U(\xi) + a\xi] \frac{\partial F}{\partial \xi} - \zeta F = \frac{1}{3\phi} \frac{\partial U}{\partial \xi} p \frac{\partial}{\partial p} (\phi F) - \left(\frac{t}{t_0}\right)^{\beta} \frac{S(t)}{\phi} \delta(\xi) \delta(p - p_0) \tag{5}$$

where

$$U(\xi) = u_2 + (u_1 - u_2) H(\xi)$$

$H(\xi)$ is the Heaviside unit function $(H'(x) = \delta(x))$.

Solution of DC eq. cont'd

Since $t\partial\phi/\partial t \propto \phi$, while S must scale with time as $S(t) \propto r_{cr}^2(t)\,Q(t) \propto R_s^2(t)\,U_s(t) \propto t^{2-3\beta}$, so $\phi \propto t^{2(1-\beta)}$. Therefore, ζ/a is $\zeta/a = t\dot{\phi}/(1-\beta)\,\phi = 2$ and the solution upstream simplifies

$$\bar{F}_u = \phi\left[\sqrt{\frac{\pi}{2}}\left(1+\eta^2\right)\mathrm{erfc}\left(\frac{\eta}{\sqrt{2}}\right) - \eta\exp\left(-\frac{1}{2}\eta^2\right)\right] \tag{6}$$

where $\mathrm{erfc}(x) = 1 - \mathrm{erf}(x) = \left(2/\sqrt{\pi}\right)\int_x^\infty \exp\left(-t^2\right)dt$ and $\xi = \sqrt{\kappa/a}\eta - u_{1,2}/a$. The momentum spectrum at the shock takes the form:

$$\bar{F}_0 = \phi(t,p)\left[\sqrt{\frac{\pi}{2}}\left(1+\frac{u_1^2}{\kappa a}\right)\mathrm{erfc}\left(\frac{u_1}{\sqrt{2\kappa a}}\right) - \frac{u_1}{\sqrt{\kappa a}}\exp\left(-\frac{u_1^2}{2\kappa a}\right)\right] \tag{7}$$

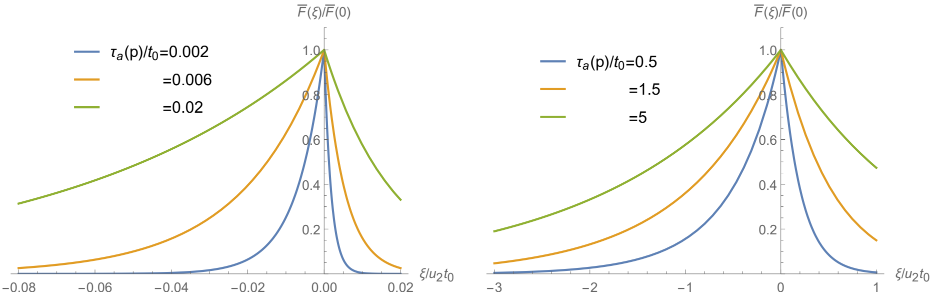
Downstream:

$$\bar{F}_d = \phi(t,p)\,\Lambda(p)\left[\sqrt{\frac{\pi}{2}}\left(1+\eta^2\right)\mathrm{erfc}\left(-\frac{\eta}{\sqrt{2}}\right) + \eta\exp\left(-\frac{1}{2}\eta^2\right)\right] \tag{8}$$

with

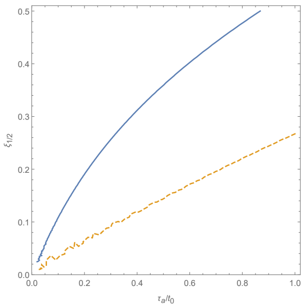
$$\Lambda(p) \equiv \frac{\sqrt{\frac{\pi}{2}}\left(1+u_1^2/\kappa a\right)\mathrm{erfc}\left(u_1/\sqrt{2\kappa a}\right) - \left(u_1/\sqrt{\kappa a}\right)\exp\left(-u_1^2/2\kappa a\right)}{\sqrt{\frac{\pi}{2}}\left(1+u_2^2/\kappa a\right)\mathrm{erfc}\left(-u_2/\sqrt{2\kappa a}\right) + \left(u_2/\sqrt{\kappa a}\right)\exp\left(-u_2^2/2\kappa a\right)}$$

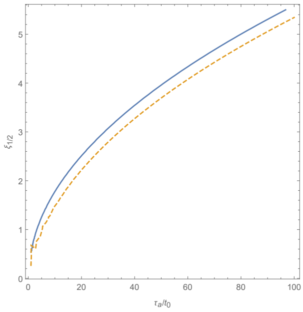
Spatial profiles of accelerated particles



- upstream and downstream particle distributions $\bar{F}_{u,d}$, normalized to $\bar{F}_0(p)$ (shock value), depending on the dimensionless distance from the shock front $\xi/u_2 t_0 = z/u_2 t_0^{2/5} t^{3/5}$ ($\xi > 0$- upstream, $\xi \leq 0$- downstream)
- low/high -momentum range given as acceleration time $\tau_a(p)$
- downstream profile is a notable contrast to the standard DSA solution which has flat particle distribution downstream.

Spatial widths upstream and downstream





- Half-width of particle distribution ($\xi_{1/2}$- distance from the shock where $\bar{F}$ decreases by half from its maximum at $\xi = 0$) upstream (dashed lines) and downstream (solid lines) depending on momentum, expressed in the acceleration time $\tau_a = 2\,(1-\beta)\,\kappa\,(p)\,/\,u_2^2$

Calculation of Particle spectra

to obtain the momentum distribution at the shock front, we integrate the CD eq.(2) across its velocity jump

$$\frac{\Delta u}{3} p \frac{\partial \bar{F}_0}{\partial p} - \kappa \frac{\partial \bar{F}}{\partial \xi}\Big|_{\xi=0-}^{\xi=0+} = S(t) \left(\frac{t}{t_0}\right)^{\beta} \delta(p - p_0) \quad (9)$$

where $\Delta u = u_1 - u_2$. Using the notation

$$\Phi(v) = \int_v^{\infty} \exp\left[v^2 - x^2\right] dx, \qquad v_2(p) \equiv \frac{u_2}{\sqrt{2\kappa(p) a}}$$

the power-law index of the distribution at the shock front has the form

$$q(p) \equiv -\frac{p}{\bar{F}_0} \frac{\partial \bar{F}_0}{\partial p} = \quad (10)$$

$$-\frac{6}{r-1}\left[\frac{1}{v} \frac{1/2 - rv\Phi(rv)}{rv - (2r^2 v^2 + 1)\Phi(rv)} + \frac{v - \Phi(-v)}{v + (2v^2 + 1)\Phi(-v)}\right] \quad (11)$$

Momentum Distribution

- spectral index depends on momentum: $v_2(p) \equiv \sqrt{t_0/\tau_a(p)} \propto \kappa^{-1/2}(p)$.
- dynamical time scale of accelerator, t_0, enters as its ratio to the acceleration time scale
- stationary loss-free accelerator, on the contrary, has no time scale, to be compared with the particle acceleration time, $\tau_a(p)$
- hence, its spectral index is momentum-independent.

- in the limit $\tau_a \ll t_0$ there should be no significance difference between the two cases. For $v_2 \gg 1$ we have

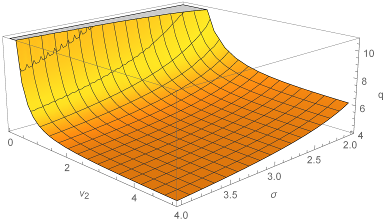
$$q \approx \frac{3\sigma}{\sigma - 1}\left(1 + \frac{3 + 2\sigma}{2\sigma^2 v_2^2}\right)$$

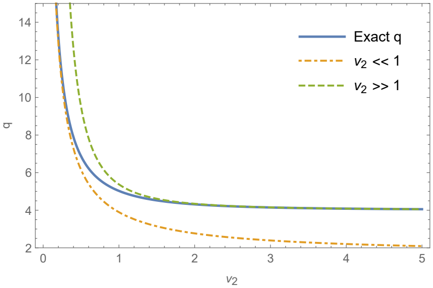
- In the opposite case of $v_2 \ll 1$, one obtains progressively steepening spectrum toward smaller v_2 (higher p)

$$q = \frac{12}{\sqrt{\pi}\,(\sigma - 1)}\frac{1}{v_2} + 6\left(\frac{4}{\pi} - 1\right)$$

Spectral index

- Spectral index q as a function of $v_2 = \sqrt{t_0/\tau_a(p)}$. Dashed and dashed-dotted curves: the low- and high-momentum approximations





- spectral index $q(\sigma, v_2)$
  $v_2 \gg 1$:

$$q \approx \frac{3\sigma}{\sigma - 1}\left(1 + \frac{3 + 2\sigma}{2\sigma^2 v_2^2}\right)$$

$v_2 \ll 1$:

$$q = \frac{12}{\sqrt{\pi}(\sigma - 1)}\frac{1}{v_2} + 6\left(\frac{4}{\pi} - 1\right)$$

Comparison with standard DSA

escape term Λ

$$\Lambda\bar{F} + u\frac{\partial \bar{F}}{\partial z} - \frac{\partial}{\partial z}\kappa_{\|}\frac{\partial \bar{F}}{\partial z} = \frac{1}{3}\frac{\partial u}{\partial z}p\frac{\partial \bar{F}}{\partial p} \tag{12}$$

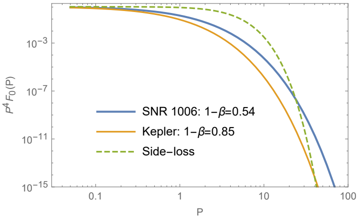
replaced the diffusive flux through $r_{\perp} = r_{\mathrm{cr}}$ by

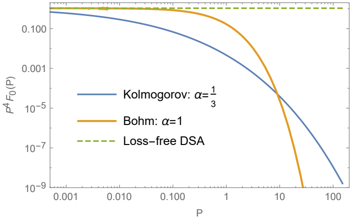
$$-r\kappa_{\perp}\frac{\partial f}{\partial r}\bigg|_{r=r_{\mathrm{cr}}} = \Lambda\bar{F}$$

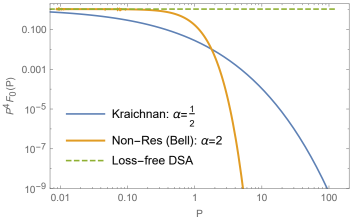
standard

$$\frac{\partial \ln \bar{F}_0}{\partial \ln p} = -\frac{3}{2\Delta u}\left[u_1\left(1+\sqrt{1+\frac{4\Lambda\kappa_{\|}}{u_1^2}}\right) + u_2\left(-1+\sqrt{1+\frac{4\Lambda\kappa_{\|}}{u_2^2}}\right)\right]$$

Spectral index







Solid lines: loss-free spectrum from self-similar solution for indicated values of expansion index $1-\beta$ and Bohm diffusion. Dashed line: stationary solution with sideways losses

Conclusions and Outlook

- The most significant disagreements between the high-precision observations and the DSA predictions can be reconciled by:
  - including SNR environmental factors (molecular gas, B-field geometry)
  - including A/Z and Mach # dependence of particle injection from the thermal plasma
  - time dependence of SNR evolution
  - magnetic field – shock normal relation
- integrating the spectrum in $r_{\perp}$ over the acceleration zone and neglecting particle losses leads to minimal spectral steepening, still significant at high energies
- It is accounted for by a mere broadening of particle injection area in time, and slowing down the pace of their acceleration
- minimal softening at low energies is attributed to a continuation of particle acceleration after they have transported across the field line to the boundary of acceleration zone
- more realistic treatment including the boundary losses will results in a steeper spectrum
- such losses are caused by a decreased particle self-confinement under a weakening magnetic turbulence

Backup slides

p/He intro: Rigidity Law of Acc'n/Propagation

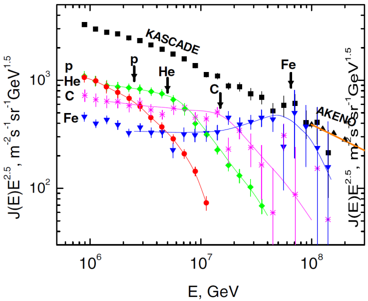
- Equations of motion, written for particle rigidity $\boldsymbol{\mathcal{R}} = \mathbf{p}c/eZ$

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

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

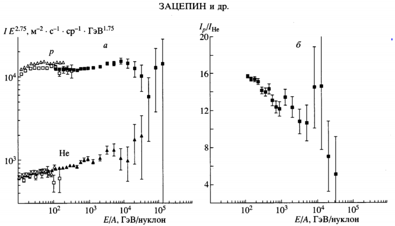
- EM-fields $\mathbf{E}\left(\mathbf{r},t\right)$ and $\mathbf{B}\left(\mathbf{r},t\right)$ are arbitrary
- $\rightarrow$ all species with $\mathcal{R} \gg \mathcal{R}_0 = Am_pc^2/Ze$ (A is the atomic number and m_p- proton mass, so $\mathcal{R}_0 \sim A/Z$ GV), have identical orbits in the phase space $(\mathbf{r}, \boldsymbol{\mathcal{R}})$.
- species with different A/Z should develop the same rigidity spectra at $\mathcal{R} \gg \mathcal{R}_0$, if they enter acceleration at steady ratio

Some support for Rigidity Law

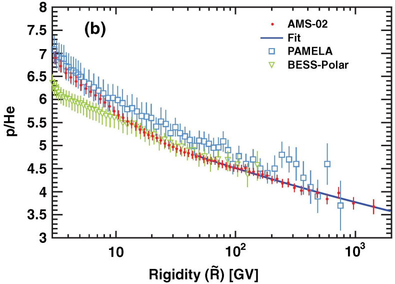


CR spectra of different elements in the knee area (from Berezinsky Review)

- cut-offs of different elements are organized by rigidity rule for acceleration and propagation
- 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 must be identical
- if both species propagate to observer without collisions, they should maintain the same N_p/N_{He}
- DSA predicts distribution $\propto \mathcal{R}^{-q}$ where, q depends on Mach number as $q = 4/\left(1 - M^{-2}\right)$



Zatsepin et al. 2004 (ATIC)



Key Distinction:

- Several instruments revealed deviation (≈ 0.1 in spectral index) between He and p's, claimed inconsistent with DSA (e.g., Adriani et al 2011)
- DSA predicts a flat spectrum for the He/p ratio
- similar result obtained recently by AMS-02 for C,O/p ratio
- points to initial phase of acceleration where elemental similarity (rigidity dependence only) does not apply
- A/Z values are close for He,O, and C

Some 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
- p/He --Forward/reverse SNR shock, Ptuskin & Zirakashvili, 2012
- Onion-shell model of presupernova wind, Bierman et al

Issues:

- most suggestions are hard to reconcile with Occam's razor principle
- tension with the He-C-O striking similarity
- spallation scenarios overproduce CR secondaries (Vladimirov, Johannesson, Moskalenko, Porter 2012)

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
- $\rightarrow$ DM/P– only if the DSA@SNR fails

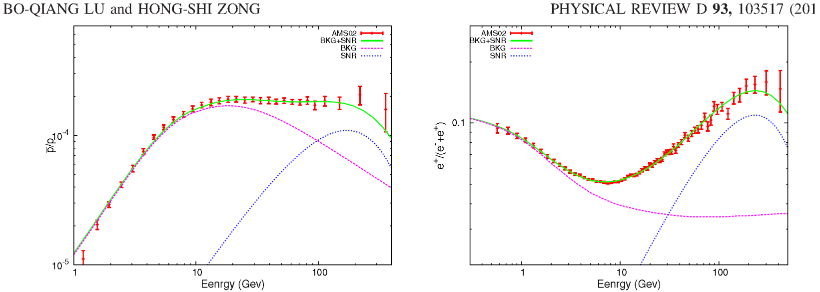
Upshot

- SNR contribution constrains DM/Pulsar contributions

Weaknesses of explanations – Motivation

Bottom line:

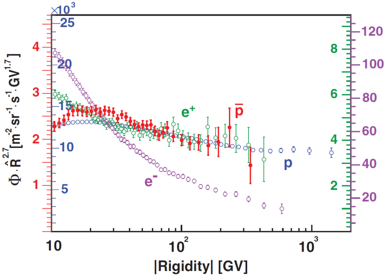
e^+/e^- explained only by adjusting independent sources

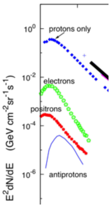


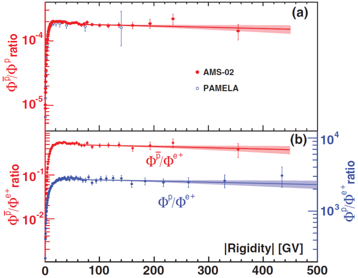
Weaknesses:

- 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)

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







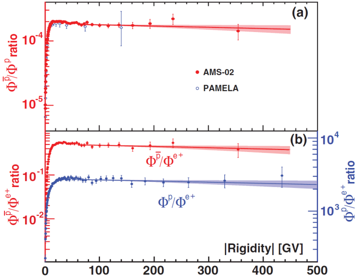
AMS-02:Aguilar+ 2016

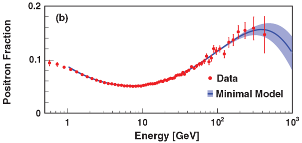
particle\property	charge	mass	secondary?	pulsar?
p	$+$	M	no	no
$\bar{p}$	-	M	yes	no
e^+	$+$	m	both	yes
e^-	-	m	no	both

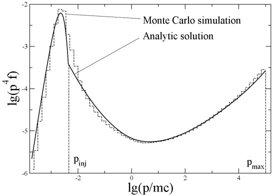
The Wish-list

- 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







MC-Don Ellison

Analytic sol. MM'97,
E.Amato, P. Blasi, D.Caprioli, '00-s

- p, $\bar{p}$, e^+ strikingly similar at $E > E_{min} \simeq 8$ 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)

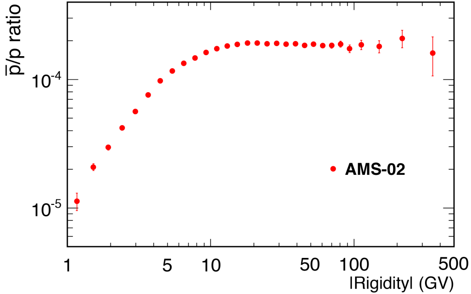
The Assumptions

- SNR shock propagates in "clumpy" molecular gas ($n_{\rm H} \gtrsim 30{\rm cm}^{-3}$, 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 $\gtrsim 10^{-4} - 10^{-3}$)

Less important

- 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

Antiprotons



- If $\bar{p}$, e^+ and p are from the same (similar) SNR(s), their spectra should be similar above injection, say $E \gtrsim 10$ GeV
- Decline of $\bar{p}$ towards lower energies is consistent with their injection at higher (than p) energy
- 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 up to $p \sim p_{max}$; may decline at $p \gtrsim p_{\max}$ (secondaries with no acceleration)

Conclusions

1. Illumination of molecular gas (MC) ahead of a SNR shock by accelerated protons results in the following phenomena:
   - an MC of size L_{MC} is charged (positively) by penetrating protons to$\sim (L_{\mathrm{MC}}/pc)\,(V_{sh}/c)\,(1eV/T_e)^{3/2}\,(n_{CR}/cm^{-3})$GV
   - 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")
   - negatively charged light secondaries (e^-), 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 becomes concave, which physically corresponds to a steepening due to the subshock reduction, and flattening resulting from acceleration in the smooth, more compressive, part of the shock

Conclusions cont'd

- the crossover energy is related to the change in proton transport (diff. coeff. changes 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
- due to the NL subshock reduction, the MC remains unshocked so that electrons (but to much lesser extent $\bar{p}$) accumulated in its interior evade shock acceleration
- Residual positron excess in the range $\sim 200 - 400$GeV is not accounted for by this SNR model and is available for alternative interpretations (DM, Pulsars, synchrotron pile-up)
- More likely, an e^+/e^- run-away break down in MC with enhanced $e^\pm$ production may eliminate the exotic scenarios completely

Further details at https://arxiv.org/abs/1703.05772, http://adsabs.harvard.edu/abs/2016PhRvD..94f3006M