CR Acceleration Mechanisms in SNRs: Stress Test by AMS-02 recent data

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After More than 100 years of research...

- CR energy spectrum long thought to be featureless (power law):
  - consistent with popular acceleration mechanism: **diffusive shock acceleration, DSA**
- DSA rigidity ($p/Z$) spectra should be the same for all species
- propagation through the ISM may only change the PL-index
  - steepening by propagation losses (0.3-0.6 [!] in PL index)
- some predictions proved inaccurate
  - difference in elemental rigidity spectra: not expected
  - breaks in individual spectra
- **however**, conclusion about PL holds up!
An incredibly exciting time for CR physics

- 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.
- In any event, the future of this field looks exciting!

Alpha Magnetic Spectrometer (AMS-02): Particle detector operating on the International Space Station.
Goal: where and how are CR accelerated?

- long-standing hypothesis for galactic CRs: Supernova Remnant (SNR) shocks
- proof “beyond a reasonable doubt”, by only indirect reasoning. Why?
  - impossible to trace CR particle from Earth back to its putative sources (e.g., SNR)
  - difficult to disentangle hadronic and leptonic emission
  - ....

- New goal: establishing (raising) a baseline for “new physics” (DM)
Outline

1. Diffusive Shock Acceleration (DSA) - Robust, Universal Mechanism
   - Possible Sources for High Energy Particles
   - SNRs as the main source of galactic CRs ("Standard Model")
   - Disagreements: anything wrong with DSA?
     - Anomalies in positron spectrum
     - EXISTING explanations, issues

2. NEW: Minimal assumptions, single source (SNR) scenario
   - $e^\pm$ asymmetry of acceleration: Molecular Clumps

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: Not Much Room for DM/Pulsars contribution, but...

5. Facing other challenges
   - Disagreement #2: Violation of Rigidity Law: $p$/He,C,O anomaly
Macroscopic Energy Sources for Cosmic Rays

**Generic source:** gravitational energy of
- stars, black holes
- clouds of dense molecular gases
- dark matter filaments and nodes of the “cosmic web” (galaxy clusters)
- more exotic sources like strings (primordial topological defects)

**Energy extraction mechanisms:**
- inhomogeneous flows of conducting gases (plasmas) usually terminated by **SHOCKS**
- accreting flows on galactic clusters, BHs, jets, ..
- stellar winds, colliding winds, galactic winds, **SNR explosions**
CR mechanism: Diffusive Shock Acceleration (DSA)

- 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, $$r$$:
  $$f \sim p^{-q}, \quad q = 3r/(r - 1), \quad r = q = 4, \quad \text{Mach } M \to \infty$$

- Downstream 
  \[ \text{U(x)} \]
- Upstream 
  \[ \text{U(x)} \]
- Shock 
  \[ \text{Scattering Centers, frozen into flow} \]

**Linear (TP) phase of acceleration**

- NL, with CR back-reaction
  - Downstream 
    \[ \text{U(x)} \]
  - Upstream 
    \[ \text{U(x)} \]
  - Sub-shock
  - NL-modified flow

- Ind $$q \to q(p)$$: soft at low $$p$$:
  $$q = 3r_s/(r_s - 1) \sim 5$$
- hard at high $$p$$: $$q \to 3.5$$
- for $$M > 10$$, $$E_{\text{max}} \gtrsim 1 \text{ TeV}$$
  (MM’97) acceleration must go nonlinear (supported by numerics and other analyses)
CR acceleration in SNRs

At least some of the galactic SNR are expected to produce CR up to $10^{15}\text{eV}$ (knee energy)

“Direct” detection is possible only as secondary emission

- observed from radio to gamma
- electron acceleration up to $\sim 10^{14}\text{eV}$ is vindicated by synchrotron emission in x-ray band (Koyama et al 1995)
- strong indication of proton acceleration: $\gamma$- emission from molecular clouds in SNR surroundings:

$$pp \rightarrow \gamma$$

SN 1006 and SN 1572 (Tycho), Reynolds 2008 and Warren et al 2005
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 \( \approx 8 \text{ GeV} \)
- 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
- $\rightarrow$ 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

BO-QIANG LU and HONG-SHI ZONG

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 $\tilde{p}$

AMS-02: Aguilar+ 2016

<table>
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<tr>
<th>particle\property</th>
<th>charge</th>
<th>mass</th>
<th>secondary?</th>
<th>pulsar?</th>
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<td>$e^-$</td>
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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

→ 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**

- $p, \bar{p}, e^+$ strikingly similar at $E > E_{\text{min}} \approx 8 \text{ GeV}$

- Opposite trends in $e^+/e^-$ and $\bar{p}/p$ spectra at $E < 8 \text{ GeV}$

- 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)

**Analytic sol. MM’97, E. Amato, P. Blasi, D. Caprioli, ’00-s**
The Assumptions

- SNR shock propagates in “clumpy” molecular gas ($n_H \gtrsim 30 \text{cm}^{-3}$, filling factor $f_V \sim 0.01$)
- High-energy protons are already accelerated to (at least) $E \sim 10^{12} \text{eV}$ 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 $E \gtrsim 1 \text{TeV}$, $M \gtrsim 10 - 15$ and the fraction of accelerated protons $\gtrsim 10^{-4} - 10^{-3}$)

- 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 $L_p \sim \kappa / u_1$: $\kappa$ - CR diff. coeff., $u_1$ shock velocity $\kappa = \kappa_B$
  $\sim cr_g(p)/3$, $r_g$ - 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)

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

$$\sim \frac{L_{MC}}{L_{CR}} \cdot \frac{u_1 n_{CR}}{V_{Te} n_0 + V_i n_i}$$
Interaction of shock-acc’d CRs with gas clumps (MC)

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

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

- Maximum ES potential inside

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

- Shock-acc’d CRs form a precursor: $\kappa$ - CR diff. coeff.,

$$L_p \sim \frac{\kappa}{u_{\text{sh}}}$$
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:

\[ n_{CR}(t) = \frac{n_{CR}^0 x_0}{x_0 - u_1 t} \]

\[ (-\infty < t \leq 0) \]

- 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 asymmetry 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 $i$ and $e$ to distance $r = 0.5$ cm
the resulting force

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

As $N \sim 10^{19}$, $l = 13.6$ eV
ionization energy only $\sim 100$ 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:

\[
\frac{dV_i}{dt} = \frac{e}{m_i} E(x, t) - \nu_{in} V_i
\]

\[
\frac{dV_e}{dt} = -\frac{e}{m_e} E - \nu_{ei} (V_e - V_i)
\]

\[
\frac{\partial n_{e,i}}{\partial t} = -\frac{\partial}{\partial x} n_{e,i} V_{e,i}
\]

\[
n_e = n_i + n_{CR}
\]

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

\[
E(x, t) = \frac{m_e \nu_{ei} n_{CR}}{e n_{CR} + n_i} \left( \frac{\dot{n}_{CR}}{n_{CR}} x + V_i \right)
\]
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 \((-\infty < t < 0)\):

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

with dimensionless parameter that characterizes ion depletion

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

\((t\) measured in \(i-e\) collision times)
Solution for electric field in MC, cont’d

- Maximum electric field (at MC edge)

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

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

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

- A 1-parsec MC \((r_g\text{ of a PeV proton})\) 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, preaccelerated in $E$ and easily injected into DSA
- injection from many MCs occasionally crossing the shock occurs with a time-averaged rate $Q(p, x)$
- $Q(x, p)$ decays sharply with $x$, the distance from the subshock
- $Q(p)$ has a broad maximum at $p \sim e\phi_{\text{max}}/c$
- near subshock, CR number density sharply increases on account of GeV particles. They generate secondary $e^\pm$ and $\bar{\nu}$, 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, $\bar{\nu}$
- typical energy of expelled positrons $\sim 1$ 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 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.
- 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.
- $e^+/(e^- + e^+)$ spectrum = proton spectrum in $p^4f(p)$ customary normalization.
- Background $e^-$ (with $p^{-4}$ spectrum) propagate distance similar to that of $e^+$.
- $\Rightarrow$ ratio $e^+/(e^- + e^+)$ 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.
- 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.
If most of $\bar{p}$ and $p$ come from the same source as $e^+$ (both 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 MCs.
- 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 $p \sim p_{\text{max}}$; should decline at $p \gtrsim p_{\text{max}}$ (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:
   - an MC of size $L_{MC}$ is charged (positively) by penetrating protons to $\sim (L_{MC}/pc)(V_{sh}/c)(1\text{eV}/T_e)^{3/2}(n_{CR}/cm^{-3})\text{GV}$
   - 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”)
   - most of the negatively charged light secondaries ($e^-$), 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 to the subshock reduction, and flattening resulting from acceleration in the smooth 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 secondary $\bar{p}$ and, in part, heavier nuclei accumulated in its interior largely evade shock acceleration.

- AMS-02 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).

- In addition, an $e^+/e^-$ run-away break down in MC with $e^\pm$ production may alter the last conclusion.

Rigidity Law of Shock Acceleration and Propagation

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

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

\[
\frac{1}{c} \frac{dr}{dt} = \frac{\mathcal{R}}{\sqrt{\mathcal{R}_0^2 + \mathcal{R}^2}}.
\]

- EM-fields $E(r, t)$ and $B(r, t)$ are arbitrary.

- All species with $\mathcal{R} \gg \mathcal{R}_0 = A m_p c^2 / Z e$ ($A$ is the atomic number and $m_p$- proton mass, so $\mathcal{R}_0 \sim A / Z$ GV), have identical orbits in the phase space $(r, \mathcal{R})$.

- Species with different $A / Z$ should develop the same rigidity spectra at $\mathcal{R} \gg \mathcal{R}_0$, if they enter acceleration at a constant ratio.
Some support for Rigidity Law

- cut-offs of different elements are organized by rigidity rule for acceleration and propagation
- if \( p \)'s and \( \text{He}^{2+} \) start acceleration at \( R \gg R_0 \) in a ratio \( N_p/N_{\text{He}} \)
- 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 \( N_p/N_{\text{He}} \)
- DSA predicts distribution \( \propto R^{-q} \)
  where, \( q \) depends on Mach number as \( q = 4/(1 - M^{-2}) \)
Key Distinction:

- Several instruments revealed deviation ($\approx 0.1$ 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

Zatsepin et al. 2004 (ATIC')

AMS-02 (2015) results along with earlier data
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, Moscalenko, Porter 2012)
Recent AMS-02 hint on the origin of p/He Anomaly

Kounine, AMS-02 (2017) ICRC 2017

- 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
- $R_0 = \frac{Ampc^2}{Ze}$ that determines the injection from thermal plasma also the same
Occam’s approach to $p$/He acceleration by DSA@SNR

**Assumptions:**
- single source (SNR)
  - shock propagates into ionized 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 $\epsilon$, inverse wave amplitude $\epsilon \sim B_0/\delta B \propto M^{-1}$
- $\eta_{\text{inj}}$ saturates with $A/Z$.
  Physically, should even $\to 0$ 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

Injection efficiency (normalized to proton, MM’98)
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

Some Conclusions
- the p/He ratio at $R \gg 1$, is not affected by CR propagation, regardless the individual spectra
- telltale signs, intrinsic to the particle acceleration mechanism
- reproducible theoretically with no free parameters

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

p/He result automatically predicts the p/C, O ratios since the rest rigidity ($A/Z$) is similar for C, O and He