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

Mikhail Malkov

University of California, San Diego

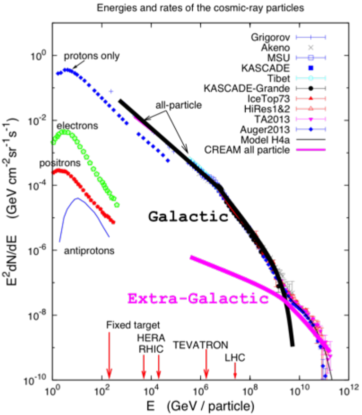
Ackn: Pat Diamond, Adrian Hanusch, Tatjana Liseykina, and Roald Sagdeev
Supported by NASA Astrophysics Theory Program
under Grants No. NNX14AH36G and 80NSSC17K0255

UCSD

AMS-02 days at La Palma, April 12, 2018

CASS

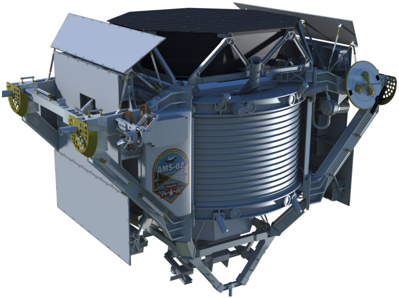
After More than 100 years of research...



IceCube compilation of CR spectrum

- 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

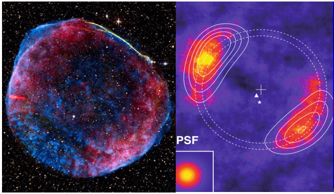


Alpha Magnetic Spectrometer (AMS-02):
Particle detector operating on the International Space Station

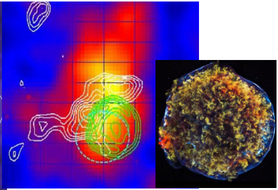
- Both energy (rigidity) spectrum and composition aspects of DSA scrutinized using modern instruments and proved not true in some instances
- Either we do not understand how DSA works and/or there are additional, probably exotic CR sources, such as dark matter decay or annihilation
- In any event, the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

Goals and Issues

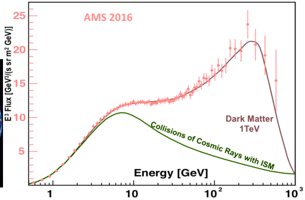
- Goal: where and how are CR accelerated?
- long-standing hypothesis for galactic CRs: Supernova Remnant (SNR) shocks
- proof “beyond a *reasonable* doubt”, by only indirect reasoning. Why?
  - impossible to trace CR particle from Earth back to its putative sources (e.g., SNR)
  - difficult to disentangle hadronic and leptonic emission
  - ....
- New goal: establishing (raising) a baseline for “new physics” (DM)



SNR 1006: X, radio, optical, gamma



Tycho (1572): radio, mol. gas, gamma



The current AMS positron flux measurement compared with theoretical models.

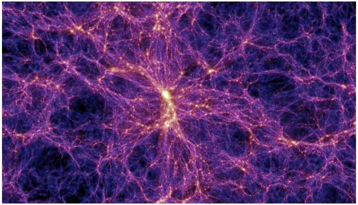
Outline

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

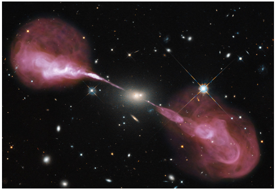
Generic source: gravitational energy of

- 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)

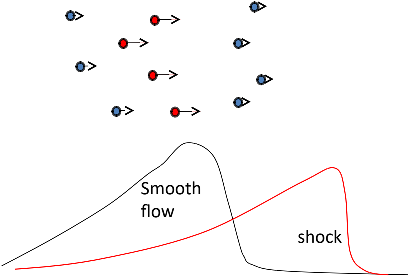


Energy extraction mechanisms:

- 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)



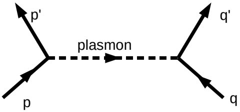
flow velocity

-Most shocks of interest are collisionless

-Big old field in plasma physics

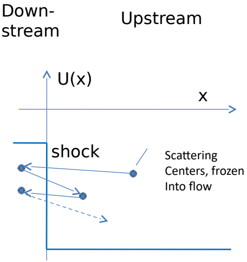
Problems:

- 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. . .



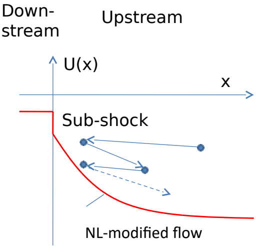
Essential DSA (aka Fermi-I process, E. Fermi, ~1950s)

Linear (TP) phase of acceleration



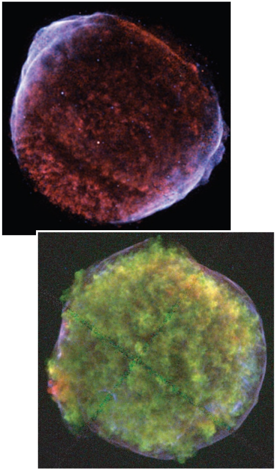
- CR trapped between converging mirrors: $p\Delta x \approx const$
- CR spectrum depends on shock compression, r: $f \sim p^{-q}, \quad q = 3r/(r-1)$, $r = q = 4$, Mach $M \to \infty$

NL, with CR back-reaction



- 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 $M > 10$, $E_{max} \gtrsim 1$ TeV** (MM'97) acceleration must go nonlinear (supported by numerics and other analyses)

CR acceleration in SNRs



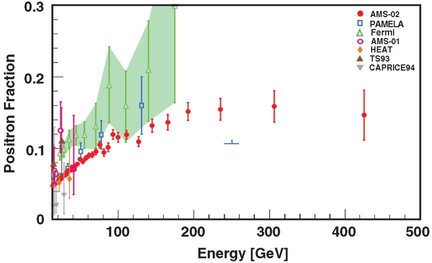
SN 1006 and SN 1572 (Tycho), Reynolds 2008 and Warren et al 2005

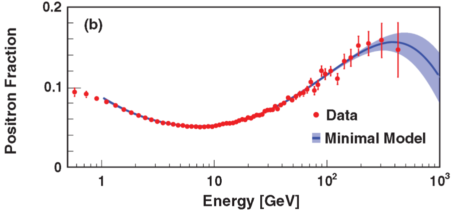
- At least some of the galactic SNR are expected to produce CR up to $10^{15} eV$ (knee energy)
- "Direct" detection is possible only as secondary emission
  - observed from radio to gamma
  - electron acceleration up to $\sim 10^{14} eV$ is vindicated by synchrotron emission in x-ray band (Koyama et al 1995)
  - strong indication of proton acceleration:γ- emission from molecular clouds in SNR surroundings:

$$pp \to \gamma$$

Fermi-LAT, HESS, Agile,..

Positron Anomaly (excess)





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

Things to note:

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

Suggested explanations of positron excess

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

Problems:

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

Alternative suggestions:

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

Stating the Obvious ....

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

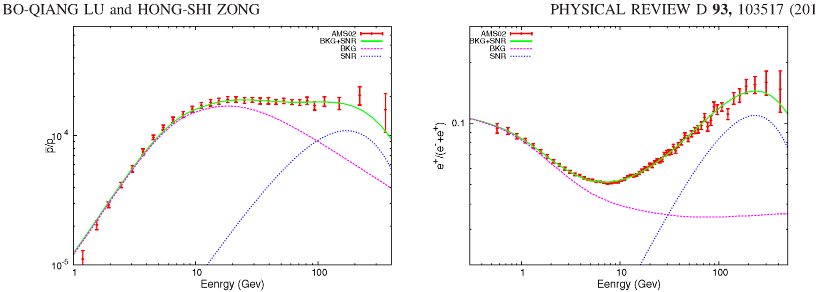
Upshot

- SNR contribution constrains DM/Pulsar contributions

Weaknesses of explanations – Motivation

Bottom line:

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

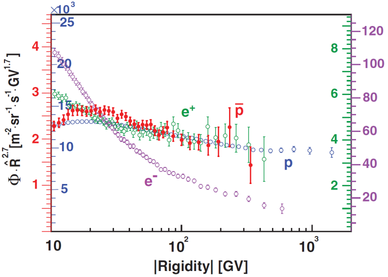


BO-QIANG LU and HONG-SHI ZONG PHYSICAL REVIEW D **93,** 103517 (201

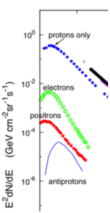
Weaknesses:

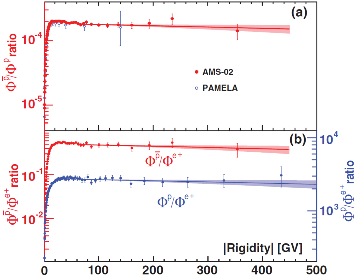
- Flatness of $\bar{p}/p$ and position of minimum in e^+/e^- are coincidental
- B/C, $\bar{p}/p$ secondary constraints put a 25% upper bound on SNR contribution to the positron rise (Cholis&Hooper, 2014)

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



AMS-02:Aguilar+ 2016



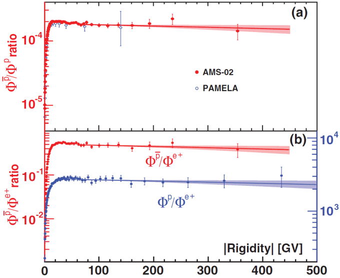


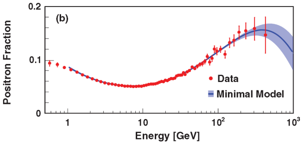
particle\property	charge	mass	secondary?	pulsar?
p	+	M	no	no
$\bar{p}$	-	M	yes	no
e^+	+	m	both	yes
e^-	-	m	no	both

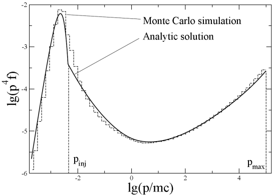
The Wishlist

- account for e^+ fraction by a single-source, a nearby SNR (contribution from similar sources not excluded)
- explain physics of decreasing and increasing branches, 8 GeV min
  - → 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

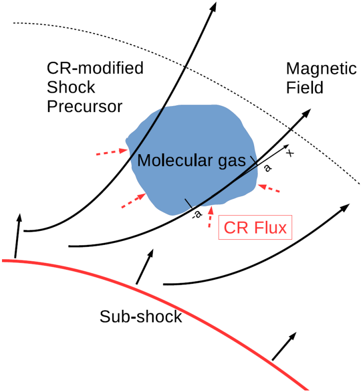
- p, $\bar{p}$, e^+ strikingly similar at $E > E_{min} \simeq 8$ GeV
- Opposite trends in e^+/e^- and $\bar{p}/p$ spectra at $E < 8$ GeV
- Both are *fractions*, thus eliminating charge-sign independent aspects of propagation and acceleration (still, HS effects?)
- Striking similarity with NL DSA solution, 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 $\gtrsim 10^{-4} - 10^{-3}$)

- 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 $L_p \sim \kappa / u_1$: κ - CR diff. coeff., u_1 shock velocity $\kappa = \kappa_B \simeq c r_g(p)/3$, r_g -gyro-radius

- CR number density increases towards subshock

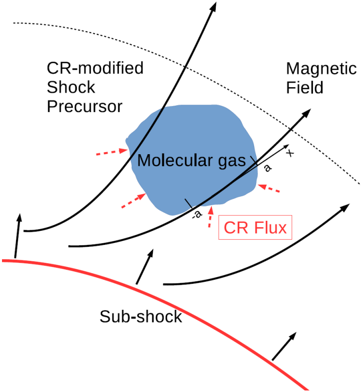
$$n_{CR}(x_{MC}) = \frac{x_0 n_{CR}^0}{x_0 + x_{MC}}$$

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

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

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

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



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

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

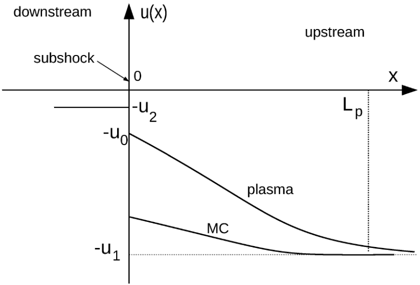
- With some help from plasma textbooks...
- Maximum electric field due to $e - i$ collisions

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

- maximum ES potential inside

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

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:

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

$$(-\infty < t \leq 0)$$

- 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 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 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 $N \sim 10^{19}$, $I = 13.6$ 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, $|x| \le a$
- 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

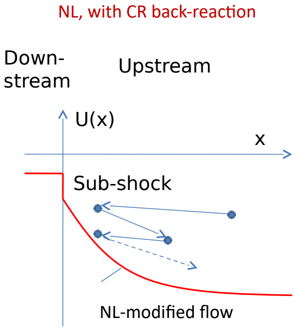
$$\frac{e\phi_{\max}}{m_p c^2} \sim \frac{a}{1pc} \frac{u_1}{c} \frac{n_{CR}}{1cm^{-3}} \left(\frac{1eV}{T_e} \right)^{3/2}$$

- 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 $Q\left(p,x\right)$
- $Q(x,p)$ decays sharply with x, the distance from the subshock
- $Q\left(p\right)$ 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 GeV

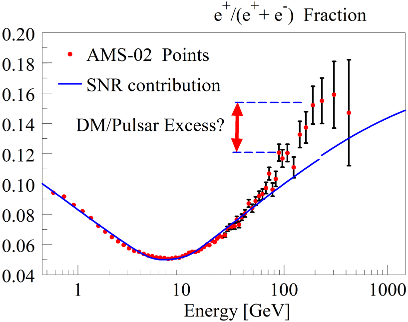
Shock Acceleration of Positrons



- 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 $q \to 3.5$

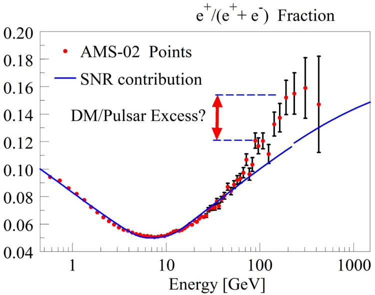
Positron spectra



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

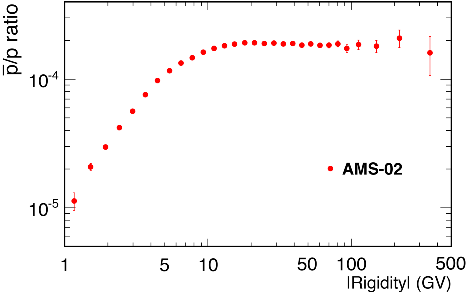
- e^+ and other secondaries produced in pp collisions of shock accelerated CRs with MC gas, as well as e^- can be treated as test particles in a given shock structure
- positively charged particles are enhanced while negatively charged suppressed because of charge-asymmetric injection from MC
- plausible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

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 up to $p \sim p_{\max}$; should decline at $p \gtrsim p_{\max}$ (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 $L_{\rm MC}$ is charged (positively) by penetrating protons to$\sim (L_{\rm MC}/pc)(V_{sh}/c)(1eV/T_e)^{3/2}(n_{CR}/cm^{-3})$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”)
    - 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

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

Rigidity Law of Shock Acceleration and Propagation

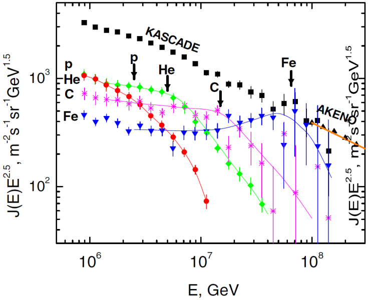
- Equations of motion, written for particle rigidity $\boldsymbol{\mathcal{R}} = \mathbf{p}c/eZ$ instead of momentum:

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

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

- EM-fields $\mathbf{E}(\mathbf{r},t)$ and $\mathbf{B}(\mathbf{r},t)$ are arbitrary
- → 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 a constant ratio

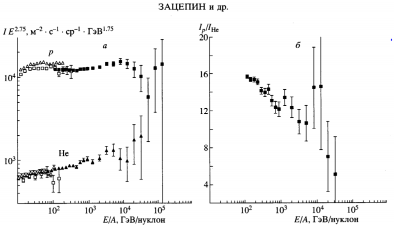
Some support for Rigidity Law



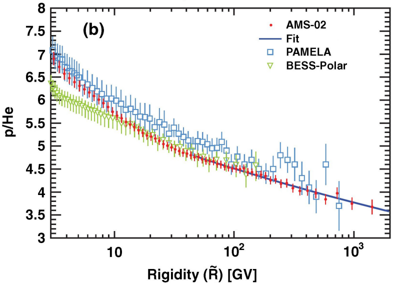
CR spectra of different elements in the knee area (from Berezinsky Review)

- 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 $q = 4/\left(1 - M^{-2}\right)$

Violation of Rigidity Law



Zatsepin et al. 2004 (ATIC)



AMS-02 (2015) results along with earlier data

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

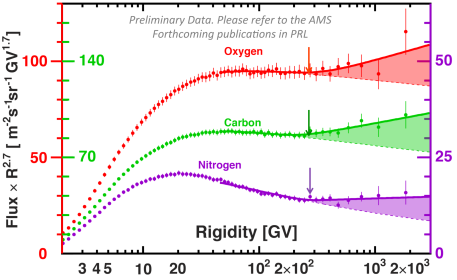
- three different types of SNRs contribute Zatsepin & Sokolskaya (2006)
- outward-decreasing He abundance in certain SNR, such as super-bubbles, result in harder He spectra, as generated in stronger shocks Ohira & Ioka (2011)
- He is neutral when processed by weak shocks. It is ionized when the SNR shocks are young and strong, Drury, 2011
- p/He --Forward/reverse SNR shock, Ptuskin & Zirakashvili, 2012
- Onion-shell model of presupernova wind, Bierman et al

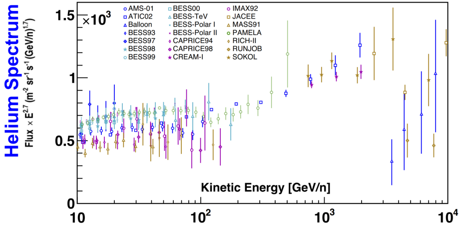
Issues:

- 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, Moscalenko, Porter 2012)

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

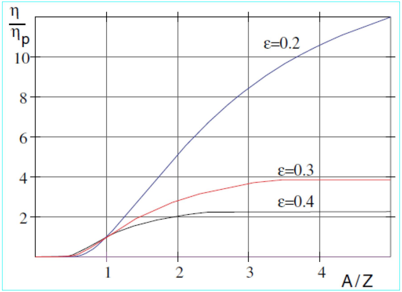
Kounine, AMS-02 (2017) ICRC 2017





- 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
- $\mathcal{R}_0 = A m_p c^2 / Ze$ that determines the injection from thermal plasma also the same

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



Injection efficiency (normalized to proton, MM'98)

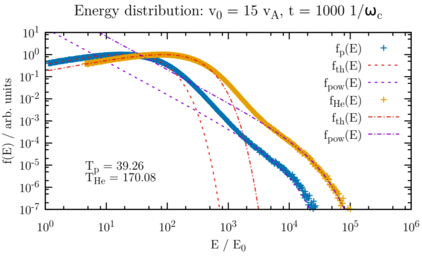
Assumptions:

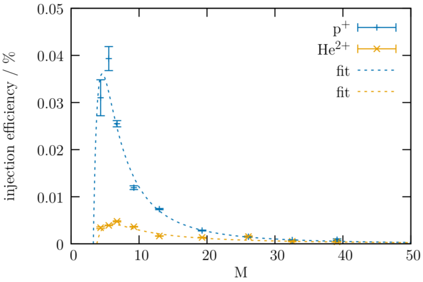
- single source (SNR)
  - shock propagates into ionized homogeneous plasma
- shock radius $R(t)$ and Mach # obey Sedov-Taylor solution

Main ideas:

- preferential injection of He into DSA for higher Mach numbers
- injection dependence on A/Z and on ϵ, inverse wave amplitude $\epsilon \sim B_0/\delta B \propto M^{-1}$
- η_{inj} saturates with A/Z. Physically, should even $\rightarrow 0$ for $A/Z \rightarrow \infty$
- 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

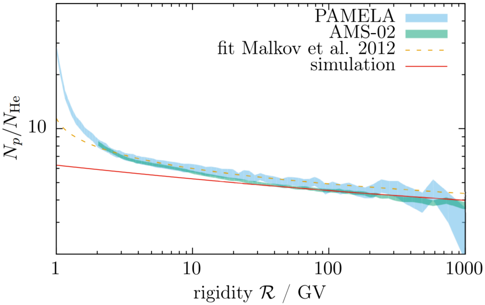




- 1D in configuration space, full velocity space simulations
  - shock propagates into ionized homogeneous plasma
- p and He are thermalized downstream according to Rankine-Hugoniot relations
- preferential injection of He into DSA for higher Mach numbers is evident
- injection dependence on Mach is 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 automatically predicts the p/C,O ratios since the rest rigidity (A/Z) is similar for C,O 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 confirm p and He injection scalings with Mach number Hanusch et al, ICRC 2017, `https://arxiv.org/abs/1803.00428`