COSMIC RAYS

above and below the knee

PASQUALE BLASI

INAF/Arcetri Astrophysical Observatory
OUTLINE

Acceleration of CR protons below the knee

The knee and its possible connection to Chemistry

The end of Galactic CRs

The transition to UHECRs
Spectrum of Protons

Data from Bertaina et al. 2008
Spectra of nuclei (1)

See Talk by Eun-Suk Seo
Secondary/Primary Ratios

CREAM 2008

C/O Ratio

B/C Ratio

N/O Ratio

Energy (GeV/n)

Energy (GeV/n)
Anisotropy

One should see an anisotropy also in the diffusive regime... and it should become of order unity when:

\[ \frac{L^2}{4D(E)} < \frac{L}{3c} \]

Anisotropy should be steadily increasing with energy

And reach unity around the knee (for slope of \( D(E) \) 0.6)

But both conclusions are known to be affected by stochasticity

Ptuskin 2006
All-Particle Spectrum

$F \cdot E^{2.5} \left( \text{m}^2 \text{s}^{-1} \text{sr}^{-1} \right)$ vs. Kinetic Energy (GeV/particle)
THE SUPERNova PARADIGM
PARTICLE ACCELERATION
TEST PARTICLE THEORY OF DIFFUSIVE SHOCK ACCELERATION

Krymskii 77, Blandford & Ostriker 1978, ...

1. POWER LAW SPECTRUM WITH SLOPE

\[ \gamma = \frac{R + 2}{R - 1} \to 4 \]

2. LOW ACCELERATION EFFICIENCY REQUIRED

3. MAXIMUM ENERGY

\[ \tau_{acc} = \frac{3}{U_1 - U_2} \left[ \frac{D_1(E)}{U_1} + \frac{D_2(E)}{U_2} \right] \]

\[ \tau_{acc} \approx \tau_{age} \]

\[ E_{max} \sim 1-100 \text{ GeV} \ll \text{Knee} \]
BEYOND TEST PARTICLES: Non linear DSA

Malkov, Berezhko & Voelk, Ellison et al, PB, Amato & PB...

NON LINEAR THEORY

DYNAMICAL REACTION OF ACCELERATED PARTICLES

CR INDUCED B-FIELD AMPLIFICATION

DYNAMICAL REACTION OF AMPLIFIED B-FIELDS

Cosmic ray acceleration up to The knee
DYNAMICAL REACTION

CR TRANSPORT EQUATION

+ MASS, MOMENTUM, ENERGY
CONSERVATION EQUATIONS

1. CONCAVE SPECTRA
2. HIGH ACCEL. EFFICIENCY
3. REDUCED HEATING
4. ESCAPE FLUX
REDUCED HEATING

SHOCK MODIFICATION

\[ u_0 = 5 \times 10^8 \text{ cm/s} \]
\[ \xi = 3.5 \]
\[ \frac{p_{\text{max}}}{mc} = 10^5 \]
MAGNETIC FIELD AMPLIFICATION

Small perturbations in the local B-field can be amplified by the super-Alfvénic streaming of the accelerated particles.

Perturbative METHOD:
Write a Vlasov eq for each particle type

Write Maxwell eqs for the fields

Perturb them all

Check if there are fourier modes that develop a negative $\text{im}(\omega)$ unstable modes
GROWING MODES

Amato & PB 2009, Bell 2004
NON-RESONANT MODES grow faster only in the early phases of a SN

Amato & PB 2009
SATURATION OF GROWTH

ALL RESULTS ARE OBTAINED IN PERTURBATIVE THEORY BUT THEY LEAD TO NON-PERTURBATIVE CONCLUSIONS ($\delta B/B >> 1$).

HARD TO PREDICT THE REAL SATURATION LEVEL (Talk of Arons for PIC SIMULATIONS)

BUT IT IS SUGGESTIVE THAT THE VALUES INFERRED FROM PERTURBATIVE THEORY HINT TO

$$\delta B \approx 100 \ \mu G$$
WHY IS IT INTERESTING:
I. Reaching the knee?

PB, Amato & Caprioli, 2007
Amato & PB, 2006
Ellison & Vladimirov 2008
WHY IS IT INTERESTING:
II. Large B observed?

TYPICAL THICKNESS OF FILAMENTS: $10^{-2} - 10^{-3}$ pc

The synchrotron limited thickness is:

$$\Delta x = \sqrt{4D(E)\tau_{\text{syn}}(E)} \approx 4\text{ pc } B_{\mu}^{-3/2}$$

$$B \approx 100 \, \mu\text{Gauss}$$
WHAT DO STRONG B DO?

EVEN VERY LARGE B FIELDS HAVE NEGLIGIBLE PRESSURE COMPARED WITH THE RAM PRESSURE, BUT WHEN

\[ \frac{B^2}{8\pi} > nkT \Rightarrow B > 6\mu G n^{1/2} \left( \frac{T}{10^4 K} \right) \]

THE MAGNETIC PRESSURE BECOMES LARGER THAN THE THERMAL PRESSURE UPSTREAM AND THE COMPRESSIBILITY IS REDUCED.

THE SHOCK MODIFICATION INDUCED BY COSMIC RAYS IS REDUCED.

Caprioli, PB, Amato & Vietri 2008, 2009
HADRONIC

LEPTONIC

RXJ1713

Mrlino, Amato & PB 2009
THE MISSING LINK BETWEEN CRs AND ACCELERATED PARTICLES

WHAT IS THE SPECTRUM OF CR AT EARTH?

Expanding Shell + Adiabatic Losses during the Sedov-Taylor Phase

In the absence of this escape flux adiabatic losses would make reaching the knee impossible.

Caprioli, PB & Amato 2009
Zirakashvili & Ptuskin 2005
ESCAPE FLUX WITH TIME

Caprioli, PB & Amato 2009
Zirakashvili & Ptuskin 2005

\[ E_{MAX}(t) \propto \xi_c(t) t^{-1/2} \]

\[ R_{sh}(t) = 2.7 \times 10^{19} \text{cm} \left( \frac{E_{51}}{n_1} \right)^{1/5} t_{kyr}^{2/5} \]

\[ V_{sh}(t) = 4.7 \times 10^8 \text{cm/s} \left( \frac{E_{51}}{n_1} \right)^{1/5} t_{kyr}^{-3/5} \]

\[ Q(E)dE \approx F_{esc}(t) \frac{1}{2} \rho V_s^3 4\pi R_{sh}^2 \frac{dE_{max}}{dt} \frac{dE}{E} \propto t^{1/2} \frac{dE}{E} \propto E^{-2} dE \]

\[ E^{-2} \text{ WITH NO CONNECTION WITH THE INTRINSIC SPECTRUM} \]
So...

The spectrum of CR observed at the Earth is **NOT** the same as in the sources!

What we see on Earth is the result of convolution of the escape time over the Sedov-Taylor phase of the SNR evolution, including the crucial effect of **adiabatic energy losses**.

In the absence of this escape flux, SNR would be unable to account for acceleration to the knee.
PREDICTED SPECTRUM

Caprioli, PB & Amato 2009
SOME IMPLICATIONS

1. PROTONS ARE EXPECTED TO BE ACCELERATED TO \( \sim 10^6 \) GeV

2. ACCELERATION IS Z DEPENDENT \( \Rightarrow E_{\text{MAX}}(Z) = Z E_{\text{MAX}} \)

3. THE KNEE IS LIKELY TO BE THE RESULT OF OVERLAP ON THE MAX ENERGY OF EACH SPECIE

4. GALACTIC CRs SHOULD END WITH IRON @ \( \sim 10^{17} \) eV
THE TRANSITION

1. The SNR paradigm hints to a galactic CR spectrum ending at ~ a few $10^{17}$ eV

2. Observations also suggest (not prove) the same trend
PROPAGATION OF PROTONS

Log(loss length(Mpc)]

5
4
3
2
1

17 18 19 20 21 22

Log[E(eV)]

100 Mpc

Size of the Universe

DIP

GZK

10^{19} eV

10^{20} eV
MODIFICATION FACTOR

\[ \eta = \left( \frac{J_p(E)}{J_{\mu m}^p(E)} \right) \]

Akeno-AGASA

HiRes I - HiRes II

Yakutsk

Auger

Aloisio, Berezinsky, PB & Ostapchenko 2008
How does the spectrum look like? The Dip

Berezinsky et al. 2005
Aloisio et al. 2007
to calibrate the Auger data by the protons dip it is required an energy shift of about 50% (outside the experimental systematic)

Berezinsky et al. 2005
Aloisio et al. 2007

ENERGY SHIFTS WITHIN SYSTEMATICS FOR ALL EXPS BUT Auger
HISTORICAL INTERPRETATION OF THE TRANSITION: THE ANKLE
ALTERNATIVE INTERPRETATION OF THE TRANSITION: **MIXED COMPOSITION**

Allard et al. 2005-2008
UNDERSTANDING THE DIFFERENCE:  
DIP VS MIXED

From Kampert 2008

From Sokolsky, SoCoR Workshop

Fig. 25.— Comparison of current HiRes stereo $<X_{\max}>$ results with results from the HiRes-prototype/MIA hybrid (Abi-Zayyad et al. 2001) and previously published HiRes stereo results (Abbasi et al. 2005).
UNDERSTANDING THE DIFFERENCE: DIP VS ANKLE

DIP

ANKLE

Aloisio, Berezinsky, PB & Ostapchenko 2008
CONCLUSIONS

Though not proved yet, the SNR paradigm for the origin of Galactic CR is in excellent shape.

The most interesting recent discovery supporting it has come from X-ray observations: thin filaments $\rightarrow$ large B-fields.

Protons can be accelerated up to the knee...and heavier nuclei to energies $Z$ times larger.

If the observed proton knee is due to the max energy, then Galactic CRs should end at the second knee.

It is of the utmost importance to measure the chemical composition in the energy region $10^{17}$-$10^{19}$ eV in order to

1. understand the transition
2. understand what is going on for UHECR