COSMIC RAY ACCELERATION AND TRANSPORT

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From afar the spectrum looks like a power law.

Power laws → No Scales.

Broken power laws more interesting (scale→physics).

After knee and ankle, first evidence of scales also in the spectra of individual elements.

Substantial change in mass composition at the knee.

Mass composition at the ankle unclear.
CR Spectrum

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Basics of CR Physics

Measurements of the B-Li-Be in CRs show that CR live for tens of million years in the Galaxy

DIFFUSIVE TRANSPORT

Garcia-Munoz et al. 1977
Basics of CR Physics

\[ \frac{\partial}{\partial z} \left[ D \frac{\partial f}{\partial z} \right] = Q_0(p) \delta(z) \]

\[ f_0(p) = \frac{N_{inj}(p) R_{SN}}{\pi R_{disc}^2 2H} \frac{H^2}{D(p)} \sim p^{-\gamma-\delta} \]

\[ D \frac{\partial f}{\partial z} = \text{Constant} \rightarrow f(z) = f_0 \left( 1 - \frac{z}{H} \right) \]

Particles escape at \(|z|=H \rightarrow \text{Free Escape Boundary}!\)
The Physics of the origin of CRs is mainly in the injection term (sources) and in the diffusion term (transport).

Both are often assumed — far from being realistic...

Particles escape at $|z| = H \rightarrow$ Free Escape Boundary!
Inner Space - Outer Space

- Charged Particles
- Ordered B Field
- Turbulent B Field

Wave-particle resonances:
Diffusion
Inner Space - Outer Space

- Charged Particles
- Ordered B Field
- Turbulent B Field
- Wave-particle resonances: Diffusion
- Plasma Instabilities
Inner Space - Outer Space

CHARGED PARTICLES

ORDERED B FIELD

TURBULENT B FIELD

Wave-particle resonances: DIFFUSION

PLASMA INSTABILITIES
Inner Space - Outer Space

- **ORDERED B FIELD**
- **CHARGED PARTICLES**
- **TURBULENT B FIELD**
- **PLASMA INSTABILITIES**

Wave-particle resonances: DIFFUSION

Recall that resonance occurs on scales $(1/3) \text{ A.U. } E_{GeV} / B \mu$
Despite some efforts to work in different directions, SNR still remain the main candidate sources of Galactic CRs.

They may be of different types, explode in different environments, have different energetics, but…

They all lead to the formation of strong collisionless shocks.

The main process of particle acceleration is diffusive shock acceleration (DSA) at such shocks.

But… many loose ends… as for any good theory, its weaknesses are proof if its testability.
FREE EXPANSION VELOCITY:

\[ V_s = \sqrt{\frac{2E_{ej}}{M_{ej}}} = 10^9 E_{51}^{1/2} M_{ej,0}^{-1/2} \text{ cm/s} \]

THE EXPANSION SPEED DROPS DURING THE SEDOV-TAYLOR PHASE BUT THE MACH NUMBER STAYS \(>10-100\)

STRONG COLLISIONLESS SHOCK WAVE
Diffusive Shock Acceleration
Test Particle Approach

Diffusion of charged particles back and forth across the shock leads to

\[ \frac{\Delta E}{E} = \frac{4}{3} (U_1 - U_2) \]

**Power Law Spectrum**

The spectral slope only depends on shock compression

Independent of the diffusion coefficient

For strong shocks: \( E^{-2} \)

The efficiency required per SNR ~10%: Test particles?
First need for a non-linear theory
Virtually all young SNRs show evidence of thin non-thermal X-ray filaments. They are the result of synchrotron emission of high energy electrons accelerated at the shock.

\[ \Delta x \approx \sqrt{D(E_{\text{max}}) \tau_{\text{loss}}(E_{\text{max}})} \approx 0.04 B_{100}^{-3/2} \text{ pc} \]

Second need for a non-linear theory
Basic predictions of NLDSA

- Compression factor becomes function of energy
- Spectra are not perfect power laws (concave)
- Gas behind the shock is cooler when particle acceleration is efficient
- Rapid growth of B-field if acceleration efficient
Basic predictions of NLDSA

- **Compression factor becomes function of energy**

- **Spectra are not perfect power laws (concave)**

- **Gas behind the shock is cooler when particle acceleration is efficient**

- **Rapid growth of B-field if acceleration efficient**

\[
1 - \frac{u_1}{u_0} \approx \frac{P_{\gamma}}{\rho_0 u_0^2}
\]

\[
\frac{u_0}{u_2} = 5 \times 10^8 \text{ cm/s}, \quad \xi = 3.5, \quad \frac{P_{\text{max}}}{mc} = 10^6
\]

[Graph showing upstream and downstream conditions with labels for shock and subshock.]
Basic predictions of NLDSA

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\[ u_0 = 5 \times 10^8 \text{ cm/s} \]
\[ \xi = 3.5 \]
\[ \frac{P_{\max}}{mc} = 10^6 \]
THE QUEST FOR $E_{\text{max}}$

Maximum energy fixed by:

$$\tau_{\text{accel}}(E_{\text{max}}) = \text{Min} [\text{Age}, \tau_{\text{losses}}(E_{\text{max}})]$$

$$\sim \frac{D(E_{\text{max}})}{v_s^2} \sim \frac{E^\delta}{B^\alpha}$$

With $D(E)$ derived from B/C:

$E_{\text{max}} \sim \text{GeV}$

With $D(E) = Ec/eB$ [Bohm diffusion]:

$E_{\text{max}} \sim 10^{4-5} \text{ GeV}$

Lagage & Cesarsky 1983

TURBULENT MAGNETIC FIELD NEEDS TO BE STRONGLY AMPLIFIED IF TO REACH KNEE
Particle acceleration at shocks is basically a problem of electro-dynamics, just very complex.

\[ J_{CR} = n_{CR} v_{sh} \]
\[ n_{CR} + n_i = n_e \]

The background plasma reacts to the presence of CR by creating a return current.

It is this RETURN CURRENT that induces the plasma instabilities responsible for magnetic field amplification and regulates the MAXIMUM ENERGY [Bell 2004].
THE CRUCIAL ROLE OF ESCAPING CR

Bell & Schure 2013
Cardillo, Amato & PB 2015

Escaping particles
Generating seed turbulence

Caprioli & Spitkovsky 2013
THE CRUCIAL ROLE OF ESCAPING CR

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Caprioli & Spitkovsky 2013
The fastest growing modes
quasi purely growing non-resonant modes

Bell (2004): for parameters of a young SNR - new instability when

\[ n_{CR}(> E) E \frac{v_s}{c} > \frac{B_0^2}{4\pi} = U_{mag} \]

Energy density of escaping CRs

\[ \gamma_{\text{max}} = k_{\text{max}} v_A \]

Growth rate

\[ k_{\text{max}} B_0 = \frac{4\pi}{c} J_{CR}^{\text{esc}} \]

Force on fluid element \( \rightarrow \) scale of the field increases

THE FIELD SATURATION \( \rightarrow \) EQUIPARTITION BETWEEN MAGNETIC ENERGY AND ENERGY OF ESCAPING CR \( \rightarrow \) TYPICALLY SEVERAL HUNDRED MICROGAUSS AFTER COMPRESSION, FOR A YOUNG SNR
IMPLICATIONS FOR MAXIMUM ENERGY
Supernovae Type Ia

FOR A SN TYPE Ia EXPLODING IN THE ISM THE MAXIMUM ENERGY CAN BE ESTIMATED AS:

\[ E_M \simeq \frac{2e}{10c} \xi_{CR} v_0^2 \sqrt{4\pi \rho R_0^2} = 130 \left( \frac{\xi_{CR}}{0.1} \right) \left( \frac{M_{ej}}{M_\odot} \right)^{-\frac{2}{3}} \left( \frac{E_{SN}}{10^{51} \text{erg}} \right) \left( \frac{n_{ISM}}{\text{cm}^{-3}} \right)^{\frac{1}{6}} \text{ TeV} \]

FOR TYPICAL VALUES OF THE PARAMETERS THE MAXIMUM ENERGY REACHABLE IS WELL BELOW THE KNEE
The case of Tycho

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**Graph:**
- **Title:** Morlino & Caprioli 2012
- **Description:**
  - Log(νFν) [Jy Hz]
  - Log(ν) [Hz]
  - Data points: Radio, FermiLAT, Sazaku, VERITAS
  - The graph shows the spectral energy distribution of Tycho's γ-ray emission.

**X-ray morphology:**
- **Title:** X-ray morphology
- **Description:** X-ray profile @ 1 keV
- **Axes:**
  - Brightness [erg/cm² Hz/s]
  - R/Rₛ [0.94 to 1.00]

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**Text:**
- The X-ray emission is mainly from several emission lines, which contribute only about 1 to 2% to the total X-ray flux in the cut-off energy. The spectral slope of the electron spectrum is close to 2.2 at low energies, which is a hint of magnetic field thickness. The radio data suggest the position of the cut-off and the total X-ray flux in the cut-off region only depend on the shock velocity alone.

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**Figure:**
- An image of Tycho's X-ray profile at 1 keV, showing the projected radial profile of synchrotron emission convolved with the Chandra point spread function.
- The graph illustrates the energy distribution of Tycho's γ-ray and X-ray emissions, with data from FermiLAT, Sazaku, and VERITAS.

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**Experiment:**
- The experiment is to measure the brightness and energy distribution of Tycho's X-ray and γ-ray emissions, using FermiLAT, Sazaku, and VERITAS data.
- The results show a remarkable agreement with the Chandra point spread function (PSF) of about 0.5 arcsec.

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**Analysis:**
- The analysis of the data suggests that the actual amplitude of the magnetic field is not determined to fit the X-ray rim profile, but it turns out to be independent of the magnetic field strength, and the loss time as discussed in Cassam-Chenaï et al. 2007.
- The projection behind the shock is due to the rapid synchrotron losses of the electrons in a magnetic field as large as 100 GeV. Above this energy, the spectral efficiency and the ISM forest is, however, beyond the main goal of this paper.
- The projection profile computed from our model using Eq. (2) is shown in Fig. 6. The radio profile is also plotted without magnetic effects induced by damping and adiabatic mechanisms that may be responsible for such an emission. In the so-called hadronic scenario, that hadrons have to be accelerated up to energies as high as a few PeV.

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**Conclusion:**
- The case of Tycho illustrates the importance of understanding the magnetic field and its effect on the synchrotron emission. The rapid synchrotron losses of the electrons in a magnetic field as large as 100 GeV are crucial in shaping the X-ray rim profile. The analysis of the data shows that the loss time is independent of the magnetic field strength and the shock velocity alone.

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**References:**
- Cassam-Chenaï et al. 2007
- Morlino & Caprioli 2012
- Giordano et al. 2012
- Fermi LAT collaboration (courtesy of Toru Tamagawa)
MAXIMUM ENERGY FOR A CORE COLLAPSE SN IN A RED SUPERGIANT WIND

Core collapse SN often explode in the wind of the giant progenitor. The gas density in the wind is

\[
\rho(r) = \frac{\dot{M}}{4\pi r^2 v_W}
\]

In the dense wind the Sedov phase is reached at distance

\[
R = \frac{M_{ej} v_W}{\dot{M}}
\]

(About 30 years after explosion)

\[
E_M \approx \frac{2e}{5c} \xi_{CR} v_0^2 \sqrt{4\pi \rho R_0^2} \approx 1 \left( \frac{\xi_{CR}}{0.1} \right) \left( \frac{M_{ej}}{M_\odot} \right)^{-1} \left( \frac{E_{SN}}{10^{51} \text{erg}} \right) \left( \frac{\dot{M}}{10^{-5} M_\odot \text{yr}^{-1}} \right)^{\frac{1}{2}} \left( \frac{V_w}{10 \text{ km s}^{-1}} \right)^{-\frac{1}{2}} \text{ PeV}
\]
Some points...

- Effective max energy at the beginning of Sedov phase (~30 years...) - not easy to catch Pevatrons with gamma rays...

- No exponential cutoff at E_{max} (broken power law)

- Overall spectrum of galactic CRs should end around $10^{17}$ eV<<Ankle

- Mass composition should become heavy at the transition

- Transition to what?
GALACTIC COSMIC RAY PROPAGATION

Aside from phenomenological approaches, the Physics is in the understanding of the two-ways connection between CR and the scattering they suffer (diffusion, winds...)

- Turbulence on scales resonant with particle gyration is the cause for DIFFUSION
- WAVES INJECTED ON LARGE SCALES AND CASCADING TO SMALLER SCALER SCALES (Kolmogorov)
- WAVES ARE GENERATED BY CR THEMSELVES AT THE RESONANT SCALE (STREAMING INSTABILITY)
Proton and He spectral breaks

- Both protons and helium spectra show a break @~200-300 GV (PAMELA and AMS-02)
- The He spectrum is slightly harder than that of protons
- There is some indication that a similar break exists for heavier nuclei (CREAM)
Secondary/Primary: B/C

Evidence for CR diffusive transport

primary equilibrium
\[ n_{pr}(E/n) \propto Q(E/n)\tau_{diff}(E/n) \]

secondary injection
\[ q_{sec}(E/n) \approx n_{pr}(E/n)\sigma v n_{gas} \]

secondary equilibrium
\[ n_{sec}(E/n) \approx q_{sec}(E/n)\tau_{diff}(E/n) \]

GRAMMAGE: \[ X(E/n) \propto \tau_{diff}(E/n) \sim 1/D(E/n) \]
Secondary/Primary: $e^+/(e^-+e^+)$

Reacceleration of secondary Pairs in old SNRs
PB 2009, PB & Serpico 2009
Mertsch & Sarkar 2009

Pulsar Wind Nebulae
Hooper, PB & Serpico (2009)
PB & Amato 2010

Dark Matter Annihilation
Difficult: high annihilation
Cross section, leptophilia,
Boosting factor [Serpico (2012)]
Non-linear diffusion

The CR gradient excites Alfvén waves at a rate:

$$\Gamma_{CR}(k) = \frac{16\pi^2}{3} \frac{v_A}{B^2 F} \left[ p^4 v(p) \frac{\partial f}{\partial z} \right]_{k=k_{res}}$$

$$D(p) = \frac{1}{3} r_L(p) v \frac{1}{F} \sim f_0/H$$

In Nature we expect that \( f(p,z) \) and \( D(p,z) \) determine each other... THEY ARE NOT INDEPENDENT QUANTITIES!

Interesting: WHEN REQUIRING \( p^2 f(p) \sim p^{-2.7} \) one gets for free \( D(p) \sim p^{0.7} \)
Spectral Breaks: self-generation and cascade

PAMELA and AMS-02 data — combination of self-generated and pre-existing waves

Voyager data are automatically fitted with no additional breaks… advection with self-generated waves at \( E<10 \text{ GeV} \)?

AMS-02 B/C shows an excess at \( E>100\text{ GeV} \), compatible with the grammage inside sources:

\[
X_{\text{SNR}} \approx 1.4 r s m_p n_{\text{ISM}} c T_{\text{SNR}} \approx 0.17 \text{ g cm}^{-2} \frac{n_{\text{ISM}}}{\text{cm}^{-3}} \frac{T_{\text{SNR}}}{2 \times 10^4 \text{yr}}
\]
Near-source grammage?

Both CR density and gradients near a source are huge for quite some time after explosion.

\[ X(E) \text{ close to sources important below } \sim \text{TeV} \]

\[ X(E) \text{ inside sources important } > \text{TeV} \]

**NON LINEAR DIFFUSION CHANGES GRAMMAGE**

\[ X(g/cm^2) \]

\[ p(\text{GeV/c}) \]

D’Angelo, PB & Amato 2016
Near-source grammage?

Both CR density and gradients near a source are huge for quite some time after explosion.

Non linear diffusion changes grammage.

$X(E)$ close to sources important below ~TeV.

$X(E)$ inside sources important $>$ TeV.
Cosmic Rays vs Gravity

The force exerted by CR may win over gravity and a wind may be launched.

Close to the Galaxy: Diffusion
Farther away: Advection with wind

\[
\frac{z^2}{D(p)} \simeq \frac{z}{u(z)} \rightarrow z_*(p) \propto p^{\delta/2} \quad D(p) \sim p^\delta
\]

No effective halo size \( H \)

\[
f_0(p) = \frac{Q(p)}{2A_{disc}} \frac{H}{D(p)} \sim E^{-\gamma-\delta}
\]

\[
f_0(p) = \frac{Q(p)}{2A_{disc}} \frac{z_*(p)}{D(p)} \sim E^{-\gamma-\delta/2}
\]

STANDARD CASE

CR-INDUCED WIND WITH SELF-GENERATION
Ends and Beginnings

- The end of Galactic CRs (GCRs) should be around $10^{17}$ eV

- Observationally ~ second knee

- GCR end with heavy composition

- At 1 EeV TA and Auger agree on light composition!

- Yet, at >10 EeV mixed composition (Auger)
Transitions

Berezinsky et al.
chemical composition incompatible with Auger data

Dip

Mixed Compositions
Allard et al.; Aloisio et al.
Mixed composition with $E_{\text{max}} \sim 5 \times 10^{18}$ eV

Additional extra-gal protons
SUMMARY (I)

- Microphysics of CRs (inner space) determines what we see on large scales (outer space) and even the electrodynamics of the plasmas where CRs move.

- This simple concept is crucial to understand both acceleration and transport.

- Even accounting for such effects SNIa only reach few 100 TeV. For SN II $E_{\text{max}} \sim \text{PeV}$.

- But only ~20-30 years after bang (not so good news for gamma ray observations).

- CR transport in the Galaxy still poorly understood: NL effects generate many surprises – e.g. grammage.
Interplay between NL effects and gravity $\rightarrow$ CR induced winds

Galactic CR are expected to end at 0.1 EeV (second knee?) ... with a heavy composition

Yet at 1 EeV we have mainly light elements again

Transition to extragalactic CRs? Also anisotropy changes phase (Auger)

At higher E Mixed mass composition (hard injection)

Extragalactic CR sources: $E_{\text{max}} \sim 5 \times 10^{18}$ eV !!!!
Supplementary Slides

...and low value of $E_{\text{max}} \sim 10^{18}$ eV...

Quite a change of paradigm
If the required additional component is galactic in origin, it has to be light. But this is not consistent with the anisotropy measured by Auger at $10^{18}$ eV.
THE REQUIRED ADDITIONAL LIGHT COMPONENT MUST HAVE A STEEP SPECTRUM AND A CUTOFF AT \( \sim 10^{19} \) eV
TRANSITION AND UHECR

Additional Extragalactic Component and KASCADE-Grande

Aloisio, Berezinsky & PB 2014
A physical model

Globus et al. and Unger et al. (2015) propose a similar idea: spectra of nuclei appear hard because at low energies photo disintegration inside sources has been at work.
CR self-confinement

The electric current due to escaping CR leads to excitation of a non-resonant instability

$[PB^+, 2015, \text{Phys. Rev. Lett. 115, 121101}]$

Saturation of the instability $\rightarrow$ CR self-confined around the source if

$E < E_c \sim 10^7 \text{ GeV } L_{44}^{2/3}$

within a distance

$r_{\text{max}} \sim 3.8 \text{ Mpc } L_{44}^{1/6}$

THESE CR DO NOT REACH THE EARTH AND MORE SO IF THE SOURCE IS BRIGHT
The case of W44

New calculation of CR reacceleration and compression using Voyager+AMS-02 CR data for H and He (Cardillo et al. 2015)

Both radio and gamma ray data appear to be perfectly well fitted if Galactic CRs are reaccelerated and compressed (Blandford & Cowie 1982)… The same conclusion previously reached by Uchiyama et al. 2010 and Lee et al. 2015, though with CR spectrum not normalised to Voyager and with no He + ad hoc steepening