PARTICLE ACCELERATION IN SUPERNOVA REMNANTS

AND

THE ORIGIN OF COSMIC RAYS

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WHICH QUESTIONS TO ANSWER TO?

ARE CRs ACCELERATED IN SNRs WITH AN EFFICIENCY AND SPECTRAL SHAPE COMPATIBLE WITH B/C AND WITH ANISOTROPY?

ARE THE EXISTING GAMMA RAY OBSERVATIONS (AND THE WHOLE MULTI-SHEBANG) UNDERSTOOD IN TERMS OF KNOWN PHYSICS OF PARTICLE ACCELERATION?

DO WE SEE (and CAN WE SEE) EVIDENCE FOR CR ACCELERATION UP TO THE KNEE (IN PROTONS)?

WHAT IS THE CHEMICAL COMPOSITION AT THE SOURCE AND AT EARTH?

WHERE DO GALACTIC CRs END?
THEORY OF CHARGE ACCELERATION IN SNRs

**Diffusive Shock Acceleration**

Berekhko, Ellison, Voelk; end of nineties +
First order FERMI ACCELERATION
Test particle theory

DIFFUSION OF CHARGED PARTICLES BACK AND FORTH THROUGH THE SHOCK LEADS TO

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

PARTICLES ARE ACCELERATED TO A POWER LAW SPECTRUM

THE SLOPE OF THE SPECTRUM ONLY DEPENDS ON THE COMPRESSION

NOT ON THE DIFFUSION COEFFICIENT

FOR STRONG SHOCKS: \( E^{-2} \)
A theory of particle acceleration that allows one to describe:

1. Dynamical reaction of accelerated particles
2. CR-induced B-field and their reaction
3. Recipe for injection (self-regulation)
4. Escape of particles (Cosmic Rays)
DIFFUSIVE ACCELERATION AT COLLISIONLESS NEWTONIAN SHOCKS

non linear theory: BASIC PHYSICAL ASPECTS

COMPRESSION FACTOR BECOMES FUNCTION OF ENERGY

SPECTRA ARE NOT PERFECT POWER LAWS (CONCAVE)

GAS BEHIND THE SHOCK IS COOLER FOR EFFICIENT SHOCK ACCELERATION

SYSTEM SELF REGULATED

EFFICIENT GROWTH OF B-FIELD IF ACCELERATION EFFICIENT
Particle Diffusion $\leftrightarrow$ Wave Growth: STREAMING INSTABILITY

$n_{CR}m v_D \rightarrow n_{CR} m V_A \Rightarrow \frac{dP_{CR}}{dt} = \frac{n_{CR}m(v_D - V_A)}{\tau}$

$\frac{dP_{w}}{dt} = \gamma_W \frac{\delta B^2}{8 \pi} \frac{1}{V_A}$

$\gamma_W = \sqrt{2} \frac{n_{CR} v_D - V_A}{n_{gas} V_A} \Omega_{cyc}$

GROWTH RATE

In the ISM this is $\sim 10^{-3} \text{ yr}^{-1}$ but close to a shock front the growth can be much larger!!

$\gamma_W \approx \sqrt{2} \xi_{CR} \left( \frac{V_s}{c} \right)^2 \frac{V_s}{V_A} \Omega_{cyc} \sim \mathcal{O}(\text{seconds}^{-1})$

$\nabla B$ IS AMPLIFIED BY PARTICLES
MAGNETIC FIELD AMPLIFICATION

SMALL PERTURBATIONS IN THE LOCAL B-FIELD CAN BE AMPLIFIED BY THE SUPER-ALFVENIC STREAMING OF THE ACCELERATED PARTICLES

Particles are accelerated because there is High magnetic field in the acceleration region

High magnetic field is present because particles are accelerated efficiently

Without this non-linear process, no acceleration of CR to High energies (and especially not to the knee!)
X-ray rims and B-field amplification

TYPICAL THICKNESS OF FILAMENTS: \( \sim 10^{-2} \) pc

The synchrotron limited thickness is:

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

\[
B \approx 100 \ \mu\text{Gauss}
\]

\[
E_{\text{max}} \approx 10 \ B_{100}^{-1/2} \ u_8 \ \text{TeV}
\]

\[
\nu_{\text{max}} \approx 0.2 \ u_8^2 \ \text{keV}
\]

In some cases the strong fields are confirmed by time variability of X-rays

Uchiyama & Aharonian, 2007
TROUBLE WITH SPECTRA

THE SPECTRA OF ACCELERATED PARTICLES ARE IN GENERAL CONCAVE AND FLATTER THAN $E^{-2}$ AT HIGH ENERGY.

THE MAXIMUM ENERGY WITH B-FIELD AMPLIFICATION MAY REACH UP TO $\sim 10^{15}$ eV FOR PROTONS (Z TIMES HIGHER FOR NUCLEI).

THESE SPECTRA SHOULD REFLECT IN THE GAMMA RAY SPECTRA (IF DUE TO PP SCATTERING) AND NEUTRINO SPECTRA.

BUT THE OBSERVED SPECTRA OF GAMMAS ARE TYPICALLY $\sim E^{-2.3}$.

OFTEN INCOMPATIBLE WITH LEPTONIC MODELS! BUT ALSO NOT COMPATIBLE WITH THE SIMPLEST PREDICTION OF NLDSA.
THE EFFECT OF THE WAVE SPEED?

One should remember that the compression factor that counts in shock acceleration is not that of fluid velocity, but that of the scattering centers velocity:

\[ r = \frac{u_1}{u_2} \quad \rightarrow \quad \tilde{r} = \frac{u_1 + u_{A,1}}{u_2 + u_{A,2}} \]

When the magnetic field is amplified the Alfven speed is not well defined and one may argue that it should be calculated in the amplified field (it depends on helicity!):

\[ \tilde{r} = r \left(1 - \frac{1}{M_{A,1}} \right) = \frac{\gamma_{\text{eff}} + 1}{\gamma_{\text{eff}} - 1 + 2/M_s^2} \left[ 1 - \frac{\xi_{cr}(2 - \xi_{cr})}{2(1 - \xi_{cr})^{5/2}} \right] \]

\[ \gamma_{\text{eff}} = \frac{1}{3} \frac{15 + 3\xi_{cr}}{1 + \xi_{cr}} \]

THIS EFFECT MAY LEAD TO STEEPER SPECTRA WHEN ACCELERATION IS EFFICIENT (BUT VERY MODEL DEPENDENT...could lead to opposite effect depending on wave helicity)
Trouble with slopes?

Very surprising to see that the required acceleration eff. are high but the spectra are steep.
IMPLICATIONS FOR CR PROPAGATION

IN PRINCIPLE $B/C \sim 1/D(E)$ IN THE HIGH RIGIDITY REGIME

BUT UNCERTAINTIES ARE STILL LARGE

NOT EASY TO DISCRIMINATE AMONG DIFFERENT DIFFUSION COEFFICIENTS

Adapted from Obermeier et al. 2011
CR spectra and SNRs

Blasi & Amato 2011

Deficit compensated by extragalactic CRs

\[ \delta = 1/3 \]
\[ \gamma + \delta = 2.67 \text{ H=2 kpc} \]
Hardening of Helium?

ONLY FOR $\frac{d}{A}=1/3$ SPECTRUM OF He HARDER THAN SPECTRUM OF PROTONS AS A RESULT OF MODEST SPALLATION

Blasi & Amato 2011
Large Scale CR Anisotropy

Naïve expectation:

\[ \delta_A = \frac{3}{2^{3/2}} \frac{1}{\pi^{1/2}} \frac{D(E)}{H \epsilon} \]

proportional to \( E^{\Omega} \)

Blasi & Amato 2011
The prototypical case of Tycho

Molino & Caprioli 2011

STEEP SPECTRUM
BASICALLY IMPOSSIBLE TO EXPLAIN WITH LEPTONS
HOW DO ACCELERATED PARTICLES BECOME CRs?
THE PROBLEM OF ESCAPE

DURING THE EJECTA DOMINATED PHASE
PARTICLES ARE ADVECTED WITH PLASMA

ESCAPE OCCURS DURING SEDOV PHASE

\[
\Phi_{esc}(E, x) = D(E) \left( \frac{\partial f(E, x)}{\partial x} \right)_{x=x_{fe}}
\]

Caprioli et al. 2009
Caprioli et al. 2010
CR ESCAPE AND CLOUDS

TWO SCENARIOS:

**SNR SHOCK ENTERS THE MOLECULAR CLOUD**
Collisionless shock only involves ions (very low density)

Ion-neutral density kills waves $\rightarrow$ low $E_{\text{max}}$

Rate of damping $\Gamma_{i\text{on}-n} = \frac{1}{2} < n_H \sigma > \approx 4.2 \times 10^{-9} T_4^{0.4} n_1 \text{ s}^{-1}$

Remember: $D(E)=(1/3) \frac{c r_L}{F(k)}$ and here $F(k) \rightarrow 0$ in clouds

**MOLECULAR CLOUD IS ILLUMINATED BY CR FROM SNR**
The MC only acts as a target for pp. Gamma ray flux depends on

- Age of SNR
- Diffusion coefficient around the SNR (LIKELY SELF GENERATED IF CR DENSITY DOMINATED BY LOCAL SNR)
- Escape physics
SOME NEW WAYS TO MEASURE THE CR ACCELERATION EFFICIENCY IN SUPERNOVA REMNANTS

COLLISIONLESS SNR SHOCKS IN PARTIALLY IONIZED MEDIA
SUBTLE ASPECTS OF ACCELERATION AT A COLLISIONLESS SHOCK

NEUTRALS AND IONS

SHOCK VELOCITY

PB+, 2012

Δυ

CHARGE EXCHANGE \rightarrow BROAD BALMER LINE (NEUTRALS THAT MADE CHARGE EXCHANGE) REFLECTING THE TEMPERATURE OF IONS...

BUT THE LATTER AFFECTED BY EFFICIENT CR ACCELERATION
BROAD BALMER LINES NARROWER THAN FOR UNMODIFIED SHOCKS

\[ W_{\text{broad}} = \sqrt{8 \ln 2 \frac{kT_2}{m}} \approx 1.02 \ v_{\text{sh}} \]

\[ W_{\text{broad}} = 1100 \pm 63 \text{ km/s} \rightarrow T_2 = 2.3 \pm 0.3 \text{ keV} \]

Helder et al. 2009

Shock speed from proper motion

\[ v_{\text{shock}} = 6000 \pm 2800 \text{ km/s} \left( \frac{d}{2.5 \pm 0.5 \text{kpc}} \right) \left( \frac{\dot{\theta}_{\text{obs}}}{0.5 \pm 0.2'' \text{ yr}^{-1}} \right) \rightarrow T_2 = 20-150 \text{ keV (no equilibration)} \quad 12-90 \text{ keV (equilibration)} \]

INFERRED EFFICIENCY of CR ACCELERATION 50-60% !!! (BUT model dependent)
NARROW BALMER LINES BROADER THAN FOR UNMODIFIED SHOCKS

\[ W_{\text{broad}} = \sqrt{8 \ln 2 \frac{kT_0}{m}} \approx 21 \text{ km/s} \left( \frac{T_0}{10^4 K} \right)^{1/2} \]

\[ W_n \sim 30 - 50 \text{ km/s} \rightarrow T \sim 2 - 6 \times 10^4 K \]
The neutral return flux

A neutral atom can charge exchange with an ion with $v < 0$, thereby giving rise to a neutral which is now free to return upstream.

This neutral return flux leads to energy and momentum deposition upstream of the shock!

Blasi + 2012
arXiv:1202.3080
SHOCK MODIFIED BY THE NEUTRAL RETURN FLUX

PB+2012
arXiv:1202.3080
EVEN FOR A STRONG SHOCK (M>>1) THE EFFECTIVE MACH NUMBER OF THE PLASMA IS DRAMATICALLY REDUCED DUE TO THE ACTION OF THE NEUTRAL RETURN FLUX
ACCELERATION OF TEST PARTICLES

PB+ 2012 arXiv:1202.3080

![Graph showing acceleration of test particles at different energies.](image)
CONCLUSIONS

THE SN PARADIGM EXPLAINS THE GENERAL OBSERVATIONAL PICTURE OF THE ORIGIN OF COSMIC RAYS

BUT MISSING PIECES: STEEP SPECTRA, ANISOTROPY, SPECTRAL FEATURES IN THE NUCLEAR SPECTRA

MAGNETIC FIELD AMPLIFICATION INDUCED BY CR IS NOW ONE OF THE HOT TOPICS IN EXPLAINING X-RAY MORPHOLOGY AND REACH THE KNEE

THE KNEE CAN BE EXPLAINED REASONABLY WELL IN TERMS OF CHANGE OF CHEMICAL COMPOSITION, BUT TRANSITION WELL BELOW THE ANKLE

PRESENCE OF NEUTRALS EXTREMELY IMPORTANT DIAGNOSTIC TOOL FOR CR ACCELERATION AS WELL AS POSSIBLE CAUSE FOR SPECTRAL STEEPENING