Relativistic Particles, Magnetic Fluctuations and Their Observational Appearance in Astrophysical Shocks

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Collisionless Shock as Particle Accelerators

• The growing body of evidences for supernova shocks to accelerate particles to very high energies ~ 100 TeV and possibly above

• The apparent morphology of X-ray structures in supernova shells indicated a super-adiabatic magnetic field amplification in the shock vicinity (e.g. Vink & Laming, Bamba ea, Voelk ea, Reynolds, Uchiyama, Patnaude and many others)
The Collider Detector at Fermilab (Tevatron)

Collisionless Shock Tevatron?
Diffusive Shock Acceleration

- the Diffusive Shock Acceleration to be fast and efficient requires strong magnetic field fluctuations of scales many orders of magnitude larger than the ion inertial length (and the shock width) …

How to produce the fluctuation?
Magnetic field amplification in DSA

Resonant models of wave generation
e.g. Wentzel (1969), Kulsrud & Cesarsky (1971), Skilling (1975), Achterberg (1981) and many others

Non-resonant models e.g. by Drury and Dorfi (1985) (long wavelength CR pressure gradient instability),
A.Bell (2004) discovered a fast efficient short-wavelength CR current instability),
see also Pelletier ea (2006), Niemec, Pohl ea (2008), Requelme & Spitkovsky (2009)

Long-wavelength instability by Malkov and Diamond

Ohira (2009) instability and others
Interplanetary Shock Turbulence Amplification

Bame et al. 2004
The instabilities can be implemented in DSA models in an attempt to study in a consistent way the effect of magnetic fluctuation growth on particle spectra (e.g. Amato & Blasi ‘06; Vladimirov ea ’06, ’08, ’09; Zirakashvili ea ‘08 and others)
MC model of DSA

- Particle scattering rate or MFP prescription (diffusion model)

- Magnetic Turbulence Model:
  (i) Turbulence amplification and dissipation
  (ii) Turbulence spectral transfer

The models will be discussed by Andrey Vladimirov on the Wednesday
a **nonlinear model*** of DSA based on Monte Carlo particle transport

- Magnetic turbulence, bulk flow, super-thermal particles derived consistently with each other

Two models of the turbulence spectral energy transfer

(i) Kolmogorov-type cascade
(ii) No-cascade in the mean-field direction

We used Bell’s short wavelength instability as the magnetic field amplification mechanism
The Structure of Supersonic Flow

![Graph showing supersonic flow parameters](image-url)
Particle Spectra

Solid: No Cascading
Dotted: Cascading

$p^4 f(p)$

$\log_{10} \lambda [r_{90}]$

$\log_{10} p [m_p c]$
Magnetic Fluctuation Spectra

\[ kW(x,k) / (B_0^2 / 8\pi) \]

Solid: No Cascading
Dotted: Cascading

\[ W \propto k^{-5/3} \]

DS
prec
at FEB

\[ \log_{10} k \left[ r_{g0}^{-1} \right] \]
MC model of DSA

How the turbulence dissipation may change the flow and particle spectra?
MC Simulations

- Here the shock structure and injection are determined self-consistently (momentum and energy are conserved).
Optical and UV absorption and emission spectra and the line shapes are the natural tools to constrain the magnetic field dissipation in the shock upstream.

What about synchrotron?
Efficient DSA is accompanied with strong magnetic turbulence where stochastic m-field amplitude is well above the regular m-field in the shock upstream

How that stochastic field affects the X-ray synchrotron emission?

Work done with Yu.A. Uvarov and D.C.Ellison

Synchrotron Radiation:

Ginzburg and Syrovatskii 1969
Synchrotron Radiation Stockes Parameters:

\[
\hat{S} = \begin{pmatrix}
\tilde{I}(r, t, \nu) \\
\tilde{Q}(r, t, \nu) \\
\tilde{U}(r, t, \nu) \\
\tilde{V}(r, t, \nu)
\end{pmatrix} = \begin{pmatrix}
p^{(1)}_\nu + p^{(2)}_\nu \\
(p^{(1)}_\nu - p^{(2)}_\nu) \cdot \cos 2\chi \\
(p^{(1)}_\nu - p^{(2)}_\nu) \cdot \sin 2\chi \\
(p^{(1)}_\nu - p^{(2)}_\nu) \cdot \tan 2\beta
\end{pmatrix}
\]
Local Synchrotron Emissivity for a power-law electron distribution:

\[ I_{\text{syn}}(\nu, r) \sim N_e \cdot (B \sin \chi)^{(\alpha+1)/2} \cdot \nu^{-(\alpha-1)/2} \]

\[ N(\gamma) = N_e \cdot \gamma^{-\alpha} \]

Note the strong dependence of the emissivity \( I \) on \( B \) in the spectral cut-off regime!
Because of the strong dependence of the emissivity $I$ on $B$ in the cut-off spectral regime a strong local magnetic field enhancement could even dominate the integral over the line of sight...

High statistical moments of the magnetic field distribution are important... intermittency
Synchrotron Radiation Stockes Parameters:

\[
\hat{S}(\mathbf{R}_\perp, t, \nu) = \int dl \, d\gamma \, N(\mathbf{r}, \gamma, t') \, \hat{S}(\mathbf{r}, t', \nu, \gamma), \quad t' = t - |\mathbf{r} - \mathbf{R}_\perp|/c.
\]
Electron Distribution/Spectra in the SNR Shock vicinity Simulated with the Kinetic Equation Model

- Shock velocity is 2,000 km/s,
- Bohm diffusion model
Electron distribution function
• A model of stochastic magnetic field

We simulated random magnetic fields with given fluctuation spectra and Probability Distribution Function in four decade wave-number band
• Synchrotron Emission Images and Spectra
Synchrotron Emission Images
Synchrotron Emission Images (Zoom)

0.5 keV
5 keV
20 keV
50 keV

BUE 2008
Synchrotron Images for different turbulence spectra

\[ \delta = 1.0 \]

\[ \delta = 2.0 \]
Chandra image of RXJ1713 NW
Light Curves for Clump D1

BUE 2008
• Variability time scale is about a year
- **RX J1713.7-3946**

  Uchiyama et al. 2007

  Nonthermal clump “lifetime” $\sim$ 1yr !!
RX J1713.73946 What is the cause for the fast variability?


\[ t_{\text{synch}} \approx 1.5 \left( \frac{\dot{B}}{\text{mG}} \right)^{-1.5} \left( \frac{\dot{\epsilon}}{\text{keV}} \right)^{-0.5} \text{ years} \]

Synch. cooling time \(~ 1\text{yr}\) result in high \(~ \text{mG}\) regime magnetic field??

Extremely fast acceleration of cosmic rays in a supernova remnant

Well, that is possible, but not necessarily. Strong fluctuations of random magnetic field could produce twinkling clumps of synchrotron emission
Synchrotron Emission Spectra

![Graph depicting synchrotron emission spectra with different regions and magnetic field strengths.]
The account for magnetic field magnitude fluctuations (not just the random field directions of a homogeneous field, as it was done before) result in a very strong enhancement of synchrotron surface brightness in the spectral cut-off regime.
The effect should be accounted for in the models that are making the turbulent magnetic fields estimations using the observed roll-off frequency...
Synchrotron Spectra Simulated for Different PDFs of Fluctuation against Suzaku data on RXJ1713
The Synchrotron radiation is polarized

Fig. 5. Oscillation ellipse of the electric vector in a wave radiated by particles moving in a magnetic field, where the charge is taken as a positive. For negatively charged particles (electrons) the direction of rotation is opposite to that shown. The plane $K$ is the plane of the figure (the plane perpendicular to the direction of the radiation or, equivalently, to the direction of the observer), and $l_1$ and $l_2$ are two mutually orthogonal unit vectors in the plane of the figure, of which $l_2$ is directed along the projection of the magnetic field $H$ on the plane $K$. 
SNR shell polarized emission modeling
X-ray Polarization Modeling

Bykov, Uvarov, Bloemen, der Herder, Kaastra MNRAS v.399, 2009
X-ray Polarization at 5 keV

Bykov, Uvarov, Bloemen, der Herder, Kaastra MNRAS v399, 2009
X-ray Polarization at 50 keV

$\delta = 1.0$
X-ray Polarization @5 keV $\delta = 2.0$
X-ray Polarimetry with IXO?
9”  18”  36”

Bykov, Uvarov, Bloemen, der Herder, Kaastra MNRAS v.399, 2009
X-ray Polarization with GEMS?
3’ and 7.5’ pixels

\( \delta = 1.0 \)
Sensitive High Resolution X-ray Observations of Synchrotron Radiation from SNR Shells can provide unique Information on Magnetic Fluctuations and the DSA
Thank You for Attention!