Efficient turbulent amplification of magnetic field driven by dynamo effect at supernova remnant shocks

Federico Fraschetti

Dept.s of Planetary Sciences and Astronomy
Theoretical Astrophysics Program
University of Arizona

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Outline

- Multiwavelength evidence of amplified magnetic field
- MHD approach to 2D rippled shocks
- Secular evolution of magnetic energy at the shock
Evidence of large $B$ in supernova remnant shocks

Sharp X-ray edges (Berezhko et al. 2003)

Time variability of synchrotron emission from filaments ~0.03 pc (Uchiyama 2007)

..and energetic particles?

Acciari et al. 2011
Real shocks are corrugated

SNR1006

Chandra

HST

shock ripples $\sim 10^{17}$ cm

Smaller for SNR closer to galactic plane

Raymond et al. (2007)
Shocks: numerical simulations

Significant amplification of magnetic energy (Giacalone Jokipii 2007)

Evidence of efficient magnetic field amplification downstream of gamma-ray burst outflows (numerical simulations, Mizuno et al. 2011)
MHD analytical approach to rippled shock

2D shock, arbitrary Alfvén Mach number

Jump conditions can be applied locally at rippled shocks

ω downstream at distance smaller than local curvature radius

\[ \mathbf{v} = (v_x, v_y, 0) \]

\[ \omega = \nabla \times \mathbf{v} = (0, 0, \omega_z) \]

Local orthonormal frame:

\[(x, y) \quad \rightarrow \quad (n, s)\]

Prasad (2001)

To first order in \( \theta \)

(large curvature radius)

Perpendicular seed field upstream

Fraschetti (2013)
Average shock direction of motion

$\nabla \rho \times \nabla P \over \rho^2 = \ell_F$

non-zero
Vorticity downstream

\[ \delta \omega_z = \frac{r - 1}{r} \left[ \left( \frac{C_r}{\rho} \right) \frac{\partial_s \rho + \partial_s C_r}{u} \right] - \frac{B_n \delta B_s}{4\pi \rho C_r} \partial_s \partial \]

Fraschetti (2013)

Energy deposited in vortical motion grows with shock speed
Shear or power spectrum

Finite curvature radius (zero for planar shock)

Turbulent field backreaction
Strongly rippled \( \rightarrow \) higher amplified field
Large \( B_0 \) makes resistance to filed lines tangling

\[ M_A = C_r \sqrt{4\pi \rho / B_0} \]

r: compression
\( C_r \): shock speed

growth rate

backreaction
Small-scale dynamo

At each scale, the growth of magnetic field depends on vorticity.
No assumption on the magnetic power spectrum

Exponential growth

\[
\frac{d\varepsilon}{dt} = 2\beta \varepsilon
\]

\[
\varepsilon = \frac{B^2}{8\pi \rho}
\]

Kulsrud, 2005

\[
\frac{d\varepsilon}{dt} = 2(\tau^{-1} - \alpha \varepsilon) \varepsilon
\]

Growth time-scale

\[
\tau \sim \frac{r}{r - 1} \frac{1}{C_r R_c \ell_F}
\]

\[
\alpha \sim \vartheta/(R_c C_r)
\]

Frascetti (2013)

Back-reaction

Exact solution

\[
\left( \frac{B}{B_0} \right)^2(t) = \frac{e^{2t/\tau}}{1 - \alpha \tau (1 - e^{2t/\tau}) v_A^2/2}
\]

Saturation

\[
t \gg \tau
\]

\[
B/B_0 \sim M_A
\]
Ripples scale $=10^{17}$ cm, rapid growth (Raymond et al. 2007)
Bohm diffusion?

Energetic electrons

\[ D_B(E) \simeq (3.3 \times 10^{23} \text{ cm}^2 \text{ s}^{-1}) \times E_{\text{TeV}} \times B_{100}^{-1} \]

\[ \tau_{\text{acc}} \simeq D(E)/V_{sh}^2 \] (energy losses)

Field growth

\[ \tau \sim \ell_F/C_r \]
Turbulent vortical motions are an efficient tracker of strong magnetic field in astrophysical shocks.

Real shocks in nature are rippled but MHD jump conditions can still be applied locally.

Magnetic field amplification with saturation as short as a few months agrees with observations (X, optical).

Prediction of turbulence evolution on secular scale.