Heliospheric and astrophysical shocks: Common features and differences

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Motivation and objectives

- Heliospheric shocks: low-Mach number magnetized shocks
- Astrophysical shocks: very high-Mach number shocks, sub-relativistic (SNR) or ultrarelativistic (GRB), low-magnetized or unmagnetized plasmas
- Internal structure very different?
- Magnetized shocks:ion convective gyroradius determines the main scale of the transition layer
- Unmagnetized shocks: filamentary instability responsible, extended foreshock
- Common necessary processes: ion deceleration and heating, electron energization
- Similarity: cross-shock electric fields and non-adiabatic dynamics of the ions in the shock front

Outline

Observations: in situ measurements of heliospheric shocks vs indirect evidence from astrophysical shocks

Magnetized vs un-magnetized

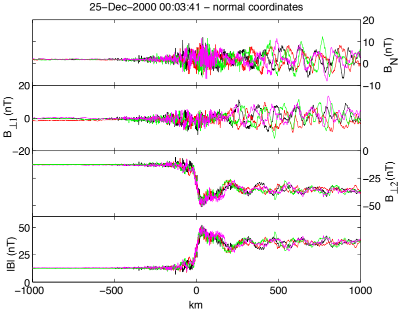
Ions as designers of the shock profile

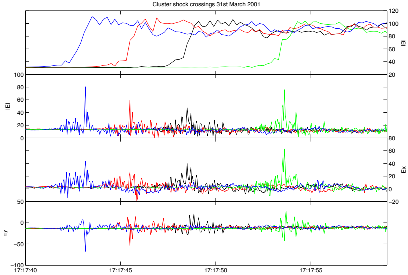
Electron heating

Why quasi-perpendicular shocks ?

- Random direction of the magnetic field in interstellar medium
- More likely to have quasi-perpendicular regime in the ISM frame
- More likely to have quasi-perpendicular regime in the non-relativistic shocks frame
- In the relativistic shock frame the tangential magnetic field is enhanced by the factor γ while the normal field does not change
- In the shock frame $\tan\theta \gtrsim \gamma$, that is, the shock is essentially perpendicular.

Heliospheric shocks: in situ observations (fields)



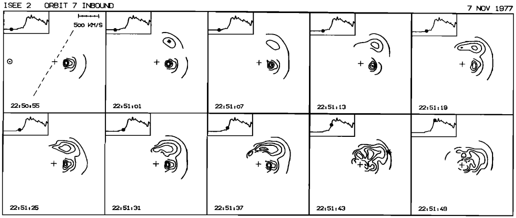


From Walker et al. (2004)

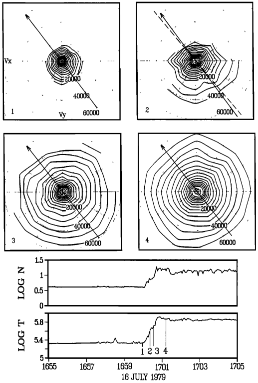
From Horbury et al. (2001)

Cluster measurements of magnetic (left) and electric (right) fields at the quasi-perpendicular terrestrial bow shock

Heliospheric shocks: in situ observations (particles)



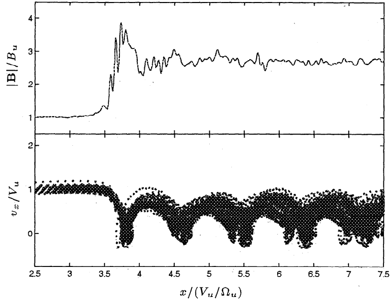
From Sckopke et al. (1983)



From Gosling et al. (1989)

ISEE measurements of ion (left) and electron (right) distributions at the quasi-perpendicular terrestrial bow shock

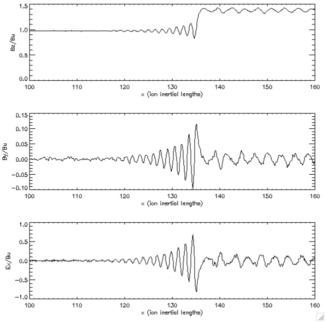
Magnetized shocks: cross-shock fields and ion motion

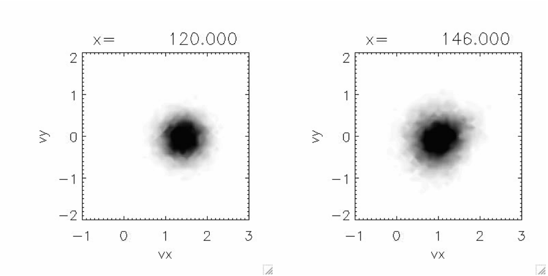


From Gedalin et al. (2000)

- Cross-shock potential decelerates ions at the ramp
- Magnetic field jump reduces the drift velocity
- Downstream ions drift and gyrate
- Some gyrate back to ramp, cross it and become reflected ions

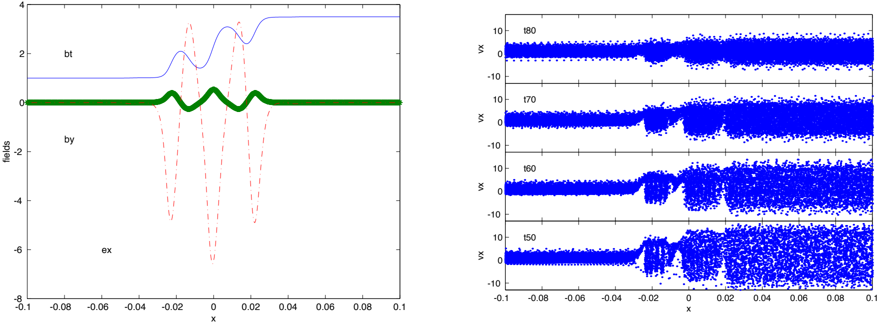
Magnetized shocks: gyrating ions and heating





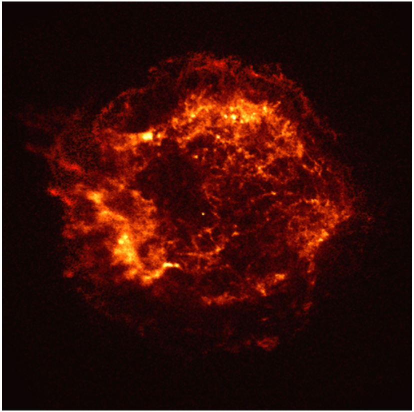
Heating because of the ion gyration upon crossing the ramp with the cross-shock potential. From Ofman et al. (2010).

Magnetized shocks: cross-shock fields and electron motion



From Gedalin and Griv (1999). Electrons are accelerated across the ramp by the cross-shock electric field. Acceleration along the magnetic field (adiabatic regime) changed into acceleration across (non-adiabatic regime) when the inhomogeneity scale is small.

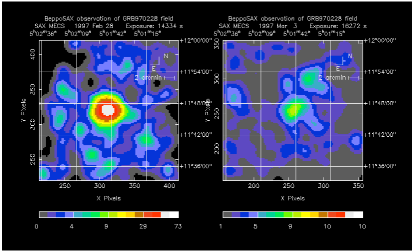
Astrophysical shocks (sub-relativistic SNR)



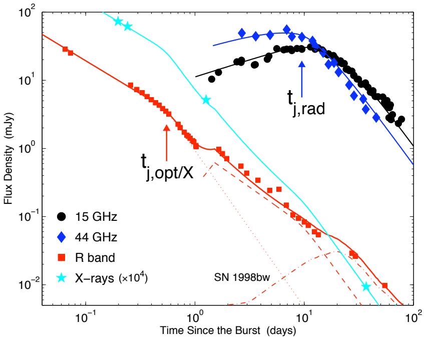
Cas A supernova remnant in X-ray (NASA/CXC/SAO).
Produced by a blast wave, observed by emission in X, optical, and radio ranges.

- Shock velocities ~ 5000 km/s from radial expansion of X-image
- Interstellar magnetic field $\sim 5 \cdot 10^{-6}$ G, compressed by a factor of 4 (?) or more (?)
- Ion (proton) density ~ 5 cm^{-3}, up to ~ 100 cm^{-3} in dense regions
- X-emission: bremsstrahlung from heated electrons and synchrotron (?) from accelerated electrons

Astrophysical shocks (ultra-relativistic GRB)



BeppoSAX follow-up observations (X-ray) of the region of the Gamma-ray burst GRB 970228. From 10 hours to 4 days.



Afterglow in various ranges. From Zhang & Meszaros (2003).

Magnetization and scales

	Terrestrial bow shock	SNR shock	GRB shock
Velocity	$\sim 10^{-3}c$	$\sim 10^{-2} - 10^{-1}c$	$\gamma \sim 10^2$
Magnetic field	$\sim 10^{-4}$G	$\sim 10^{-5} - 10^{-6}$G	$\sim 10^{-6}$G
Ion convective gyroradius	$\sim 10^3$km	$\sim 10^5 - 10^7$km	$\sim 10^{10}$km
Shock size	$\sim 10^5$km	10^{13}km	$\sim 10^9 - 10^{11}$km

Low magnetization = high Mach number

- Let $\sigma \equiv B^2/4\pi nmc^2 = (V_A/c)^2 \ll 1$
- Mach number: $M = V/V_A = (V/c)(1/\sqrt{\sigma})$

	Terrestrial bow shock	SNR shock	GRB shock
Alfven speed, km/s	$\sim 10^1 - 10^2$	~ 10	~ 10
σ	10^{-8}	$10^{-8} - 10^{-10}$	10^{-10}
Mach number	~ 10	$\sim 10^2 - 10^3$	$\sim 10^4$

- σ does not change much
- Alfven speed differs by an order of magnitude
- Mach number increases due to the increase of V/c !

High $V/c \Rightarrow$

Displacement current important

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{j} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t}$$

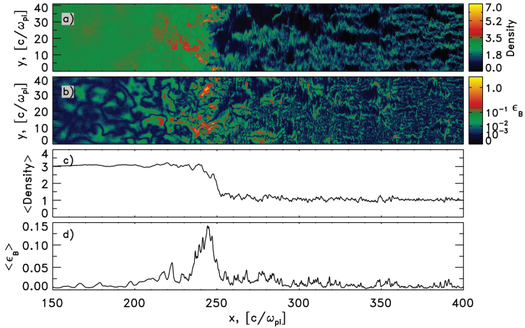
Electromagnetic counterparts of instabilities more important

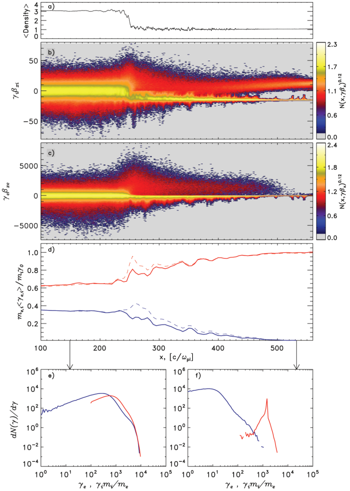
Suppression of (parallel) electrostatic two-stream instability and development of (perpendicular) electromagnetic filamentary instability

Magnetic field generation by counterstreaming beams

Magnetic field no longer compressed but produced (different pattern) in the inflow and reflected flow interaction

Unmagnetized shocks: filamentary instability



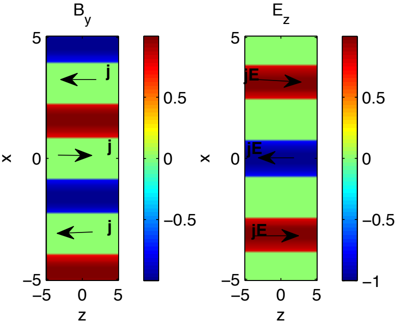


From Spitkovsky (2008)

Filamentary instability in brief

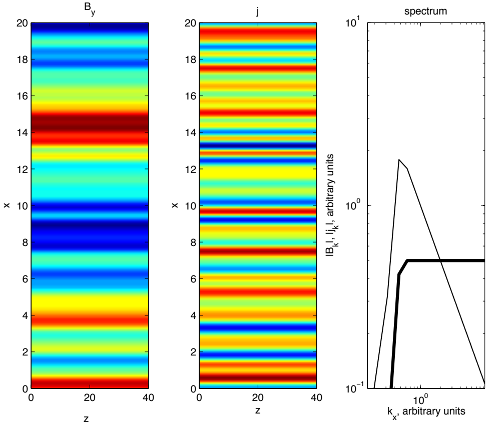
- Counterstreaming beams move in z direction
- Perpendicular (k_x) filamentary mode: develop B_y and E_z
- Particles (ions and electrons) keep moving near the nodes of the magnetic field
- Ions are moving against E_z

Inductive electric field directed against current



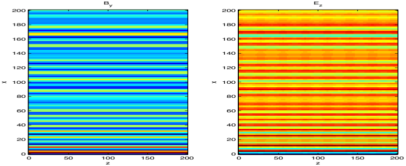
Model for visualization only

Filamentary instability in brief

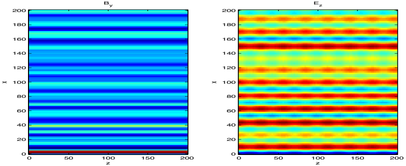


Wide spectrum of k_x is excited, saturation due to current limitation, growth nearly linear for all mode, largest scale dominates in magnetic field, the dominant scale growth with time, global saturation at equipartition field.
From Gedalin et al. (2010).

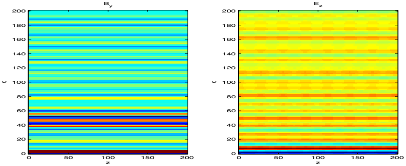
Filamentary instability: field pattern



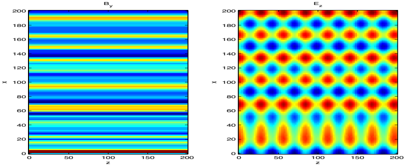
$t = 10$



$t = 40$



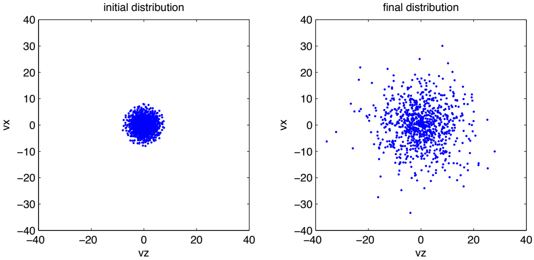
$t = 20$



$t = 80$

Magnetic and electric (inductive and electrostatic) fields expected to develop simultaneously during filamentary instability (two proton beams + electron background). After Yalinewich and Gedalin (2010).

Electron heating by developing filamentary instability



Model:

- Time-dependent magnetic and electric (inductive and electrostatic) fields - corresponds to the proton stage of the instability in the foreshock (counter-streaming proton beams with hot electron background)
- Initially Maxwellian background electrons - corresponds to the heated electrons produced at the electron stage of the instability in the foreshock

Filamentary structure: ion and electron motion

- The fields are time-dependent during the instability development up to the global saturation at the highest (nearly equipartition) magnetic field
- Ions are moving against E_z, are not sensitive to electrostatic modulations, are decelerated
- Electrons are moving against E_z, are accelerated, non-stationary filamentary fields together with electrostatic modulations scatter electrons
- Cross-shock electric field is not ordered as in magnetized shocks
- BUT - may produce net cross-shock potential due to the inhomogeneous density of backstreaming particles (Spitkovsky, private communication)
- Cross-shock electric field is responsible for ion deceleration, electron acceleration and heating, provides energy transfer from ions and electrons, similarly to magnetized shocks

Conclusions

Similar

- Cross-shock electric field (along the shock normal = along the plasma flow) develops
- The cross-shock electric field is responsible for the ion deceleration and electron energization
- Magnetic field responsible for ion reflection

Different

- Nonstationary fields
- Electron reflection at the shock front
- Extended foreshock