Shocks

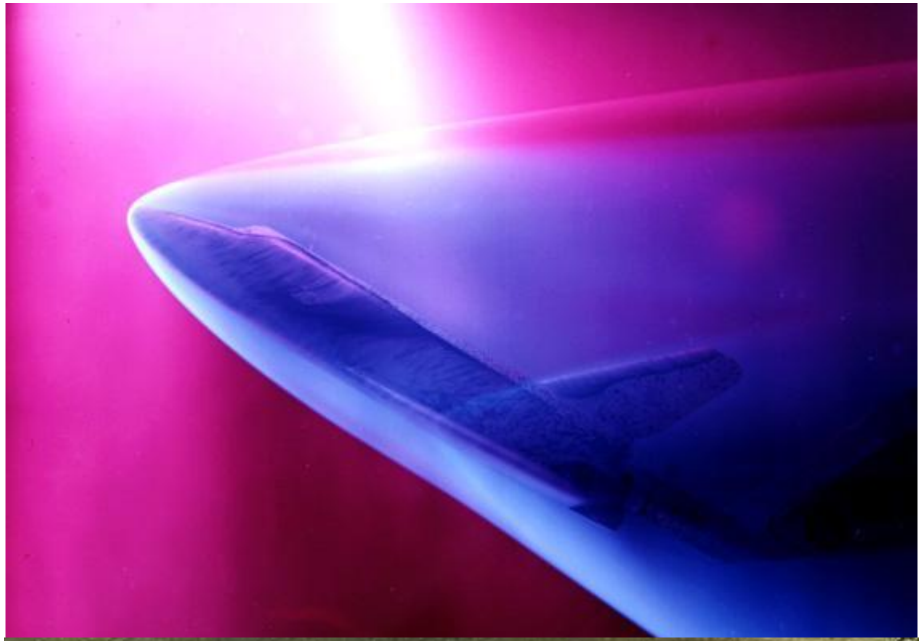
Tim Horbury

PG Lectures

- What is a shock?
- Hydrodynamics shocks: fluid view
- Plasma shocks: fluid view
- Kinetic effects
- Stuff we've learned from solar system shocks

What is a shock?

- Occurs when velocity change is larger than wave speed
- Acts to decelerate and deflect supersonic flow around an obstacle
- Compresses and heats the fluid
- Fluid phenomenon
- But, shock transition is **kinetic**, not **fluid**



A hydrodynamic shock

Another one

Shocks and waves: information speed

- Body moving through fluid
- Waves propagate upstream: send information to deflect flow

- If body moves faster than waves, something else must propagate information – shock
- Fundamentally nonlinear
- Related to wave mode

- Mach number: ratio of inflow speed to sound speed
- Plasmas: 3 wave speeds, so 3 Mach numbers

How do shocks form?

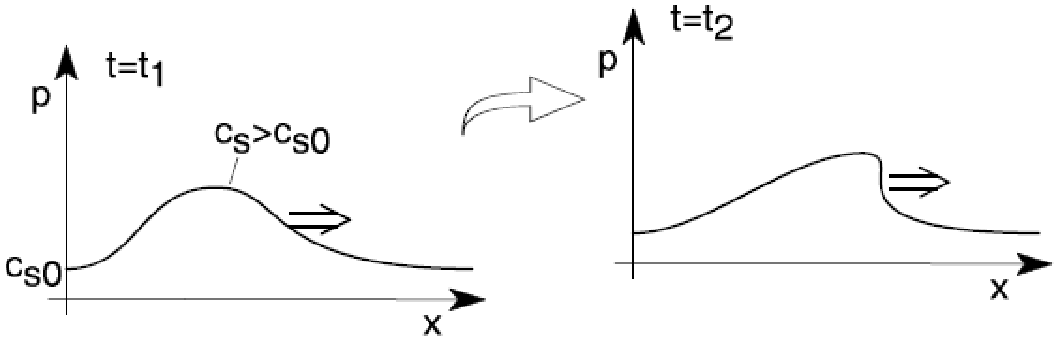
- Consider a sound wave in an Ideal gas (adiabatic)
  - Compressional wave – perturbation in pressure ΔP

$$c_s = \sqrt{\frac{\gamma P}{\rho}} \quad \text{where} \quad \gamma = C_p / C_v$$

- Small ΔP
  - No significant change in c_s within wave
  - Wave profile does not evolve

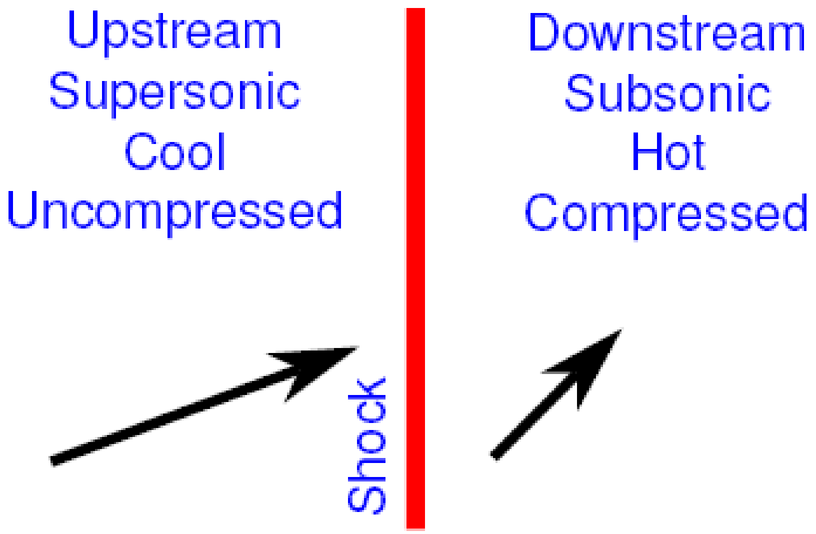
- Large ΔP
  - Wave steepens
  - Shock forms
  - Mach number
    - shock strength

$$M = V_{flow} / c_s$$



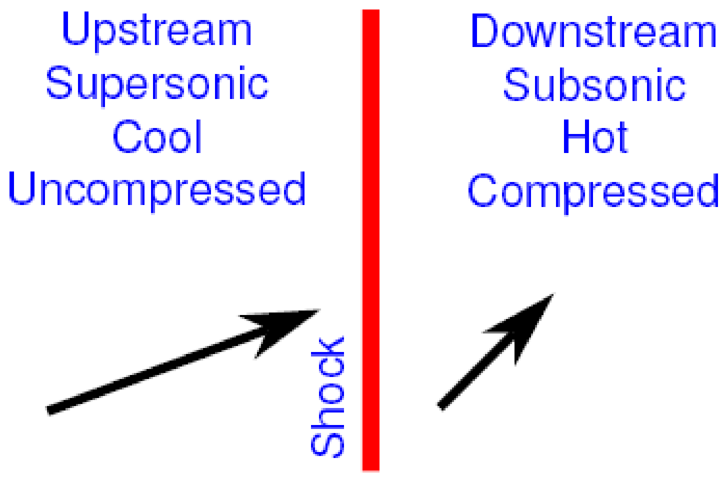
What happens at a shock?

- Consider ideal "thin" shock
- Propagating/standing shock?
  - Work in rest frame of shock
- **Mass IN = Mass OUT**
- **Momentum IN =Momentum OUT**
- **Energy IN = Energy OUT**
- Internal distribution of energy given by
  - Equation of state
  - Easy for Ideal gases $PV = nkT \quad \Rightarrow P = \rho kT$



Shocks: fluid view

- Take a fluid approximation
  - Mass density ρ
  - Flow velocity **v**
  - Pressure p (isotropic)
  - Assume static, 1D shock
  - Assume perfect gas
  - Assume fluid reacts adiabatically



Rankine-Hugoniot relations

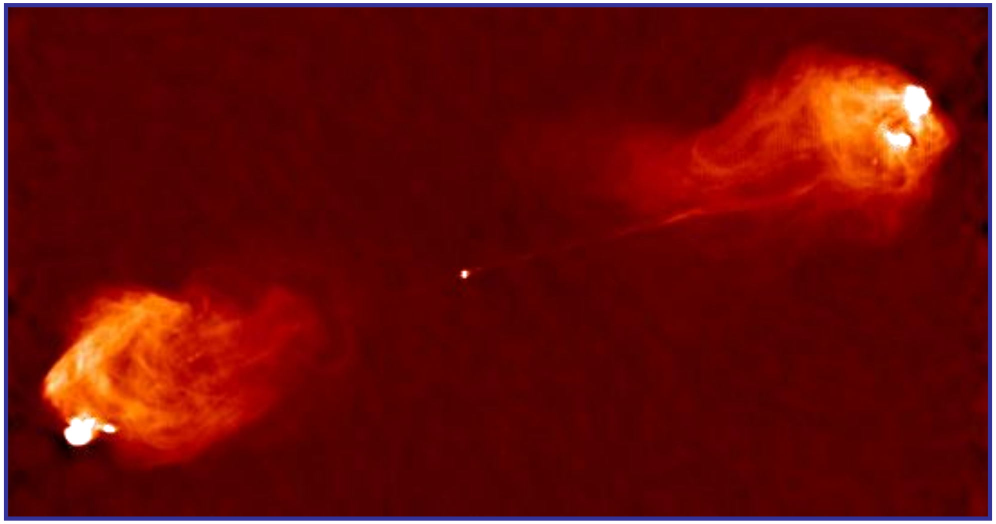
- Conservation laws across shock surface
- Mass flux: $[\rho u] = 0$
- Momentum: $[P - \rho u^2] = 0$
- Energy: $\left[\rho u \left(\frac{1}{2}u^2 + \frac{\gamma}{\gamma-1}\frac{P}{\rho}\right)\right] = 0$

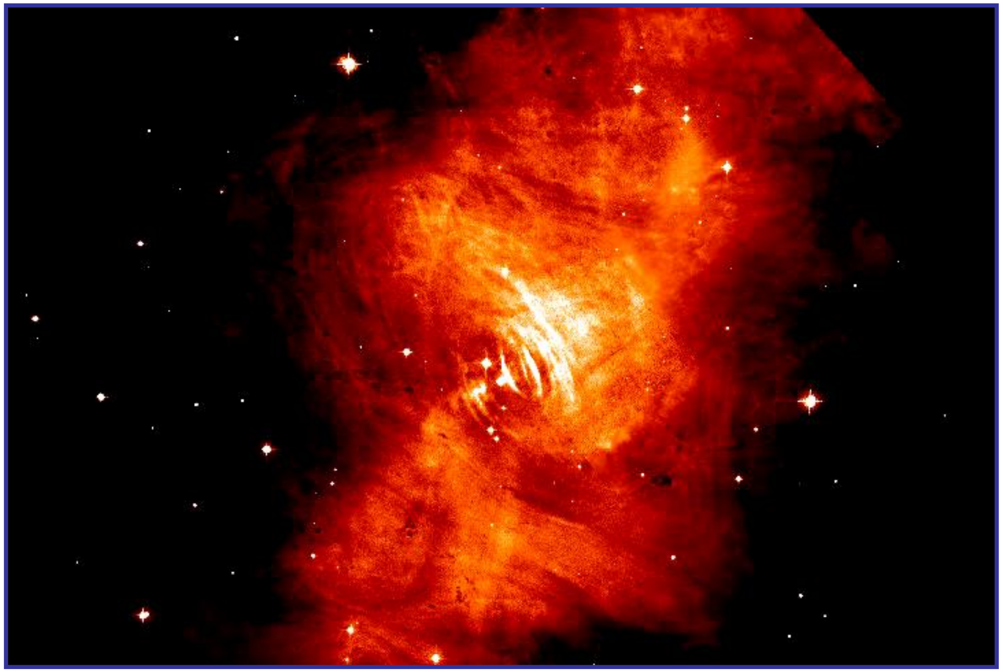
Hydrodynamic shocks: kinetic view

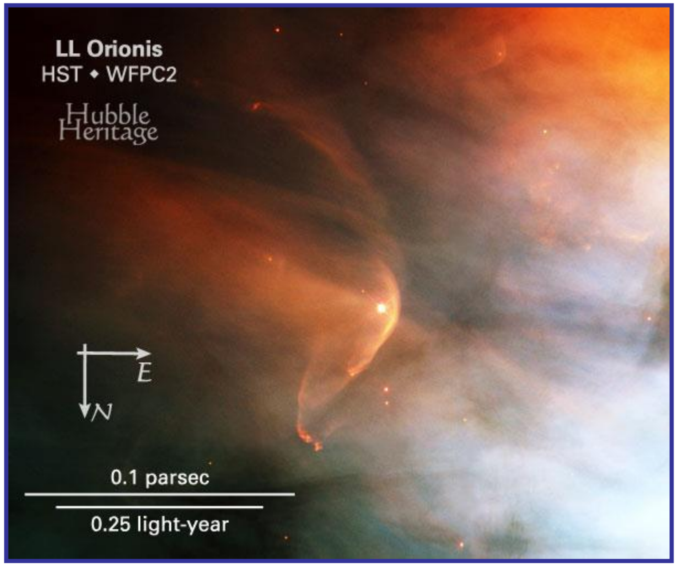
- Where does the kinetic energy go?
  - Heating
- Collisions rapidly thermalise the particles
- Shock thickness around the mean free path?

Astrophysical shocks

- Supernovae
- Jets
- Bowshocks
- Blast waves

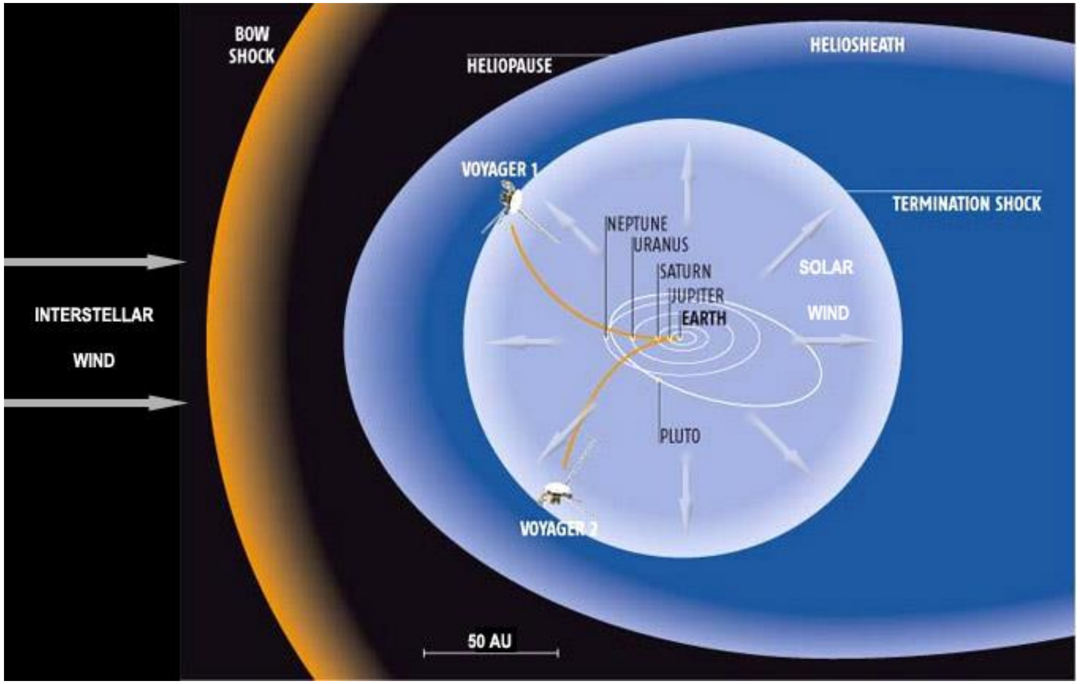






Shocks in the solar system

- Planetary bow shocks
- CME and CIR shocks
- Termination shock
- Heliospheric bow shock (maybe)



Plasma shocks

- More complex than hydrodynamic shocks
  - Multiple wave modes possible

- Presence of magnetic field
- Interactions via charges and fields – not just collisions

- Collisionless shocks possible
  - Particles can travel far upstream
  - Must more complex behaviour
  - Energy partitioning

Rankine-Hugoniot relations

$$[\rho u_n] = 0$$ Mass conservation

$$[B_n] = 0$$ Continuity of B_n

$$[u_n \mathbf{B}_t - B_n u_t] = 0$$ Continuity of E_t

$$\left[\rho u_n \left(\frac{u^2}{2} + \frac{\gamma}{\gamma - 1}\frac{p}{\rho}\right) + u_n \frac{B^2}{\mu_0} - (\mathbf{u}\cdot\mathbf{B})\frac{B_n}{\mu_0}\right] = 0$$ Energy conservation

$$\left[\rho u_n^2 + p + \frac{B^2}{2\mu_0}\right] = 0$$ Momentum conservation || **n**

$$\left[\rho u_n \mathbf{u}_t - \frac{B_n}{\mu_0}\mathbf{B}_t\right] = 0$$ Momentum conservation ⊥ **n**

- R-H relations true for all discontinuities, not just shocks
- If inflow velocity → subsonic; solutions revert to MHD waves: fast, slow, Alfvén

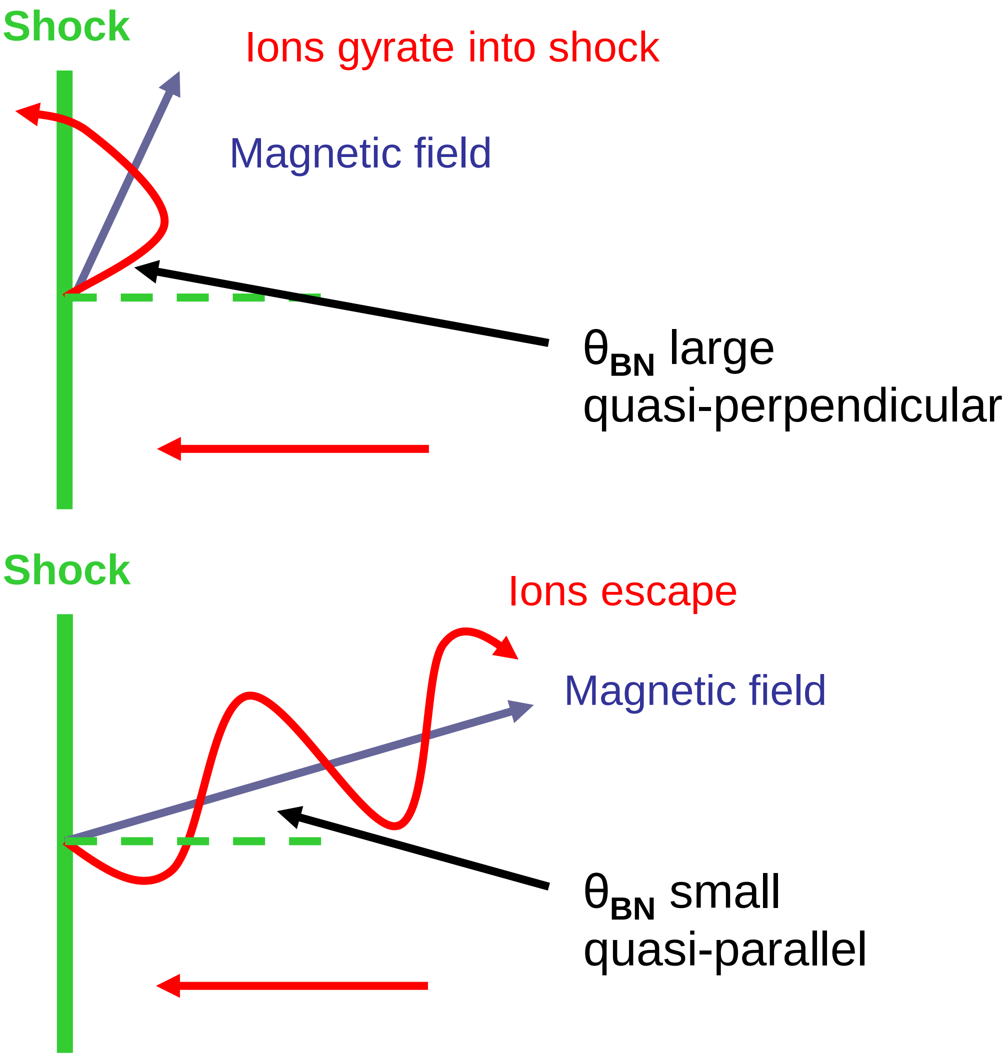
Collisionless shocks: magnetic field angle

Quasi-perpendicular

- Ions gyrate back into shock
- Sharp transition

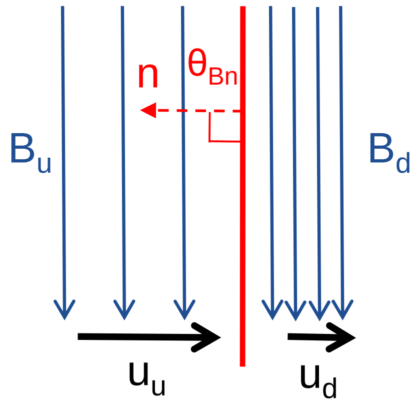
Quasi-parallel

- Ions travel upstream
- Unstable: generate waves
- Extended, messy shock

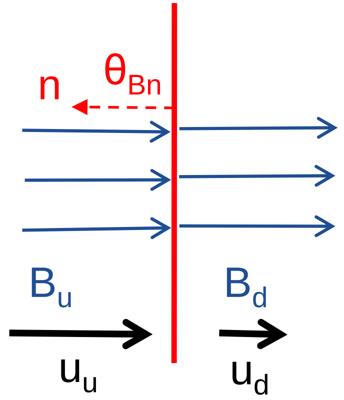


Perpendicular and parallel shocks

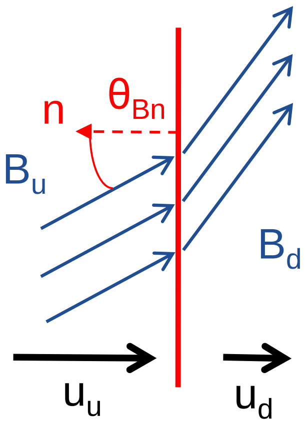
- Exactly perpendicular shock
  - Magnetic pressure forms part of R-H relations



- Exactly parallel shock
  - B drops out of R-H
  - Same as a gas dynamic shock
  - Real parallel shocks don't look anything like this!



Oblique shocks: Fast shocks and slow shocks



– Most shocks are fast mode

–
$$M_{MS} = \frac{u_u}{c_{MS}} = \frac{u_u}{\sqrt{c_s^2 + v_A^2}} \; ; \quad v_A^2 = \frac{B^2}{\mu_0 \rho_u} ; \quad c_s^2 = \frac{\gamma \; p_u}{\rho_u}$$

– M_{MS} often hard to calculate so often use the Alfvén Mach number

–
$$M_A = \frac{u_u}{v_A}$$

– Evolves from fast mode wave

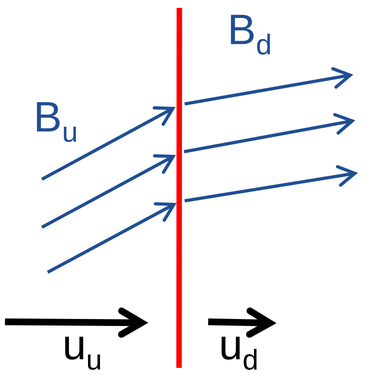
– Density rises

– Magnetic field increases

- B_n = constant: **B** turns away from shock normal **n**

Slow shocks

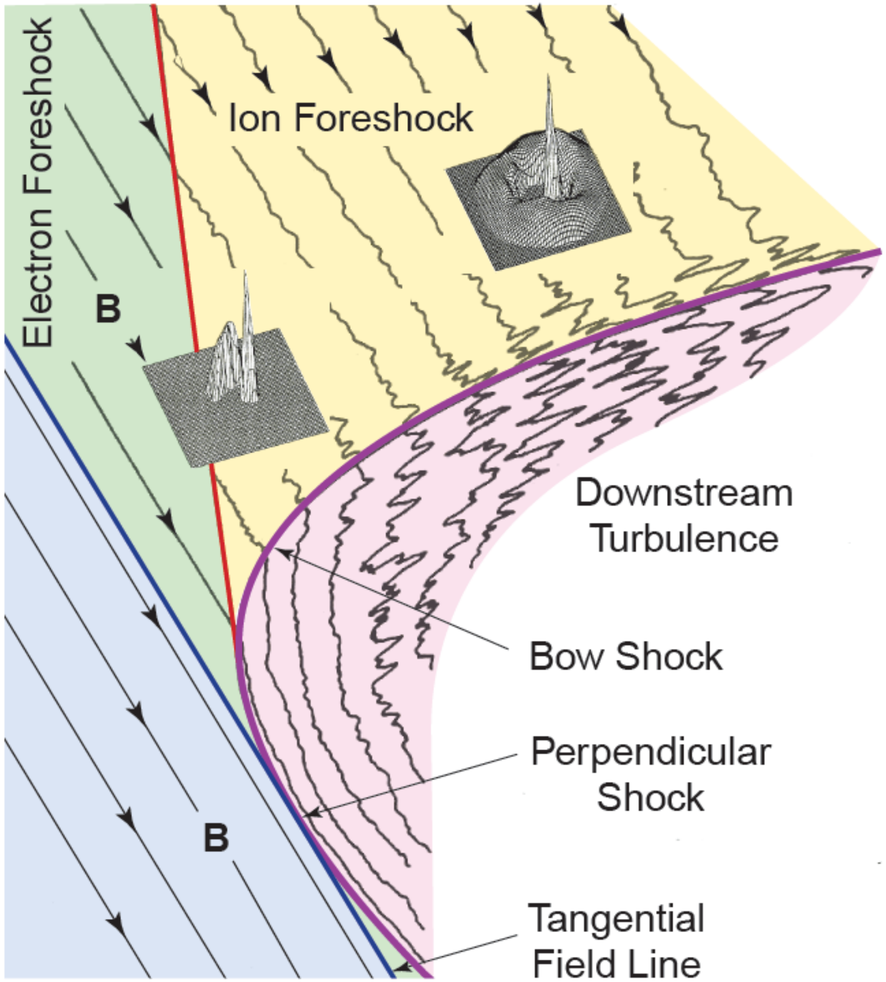
- Rare – associated with reconnection
- Density rises
- Magnetic field decreases
  - B_n = constant
  - **B** turns towards shock normal **n**



- Sound speed: $$c_s^2 = \frac{\gamma p_u}{\rho_u}$$
- Sonic Mach number: $$M_{cs} = \frac{u_u}{c_s}$$
- Evolves from slow mode waves

The Earth's bow shock

- Curved geometry
  - Shock orientation (θ_{Bn}) varies
- Electrons and ions reflected/escape to form foreshock
  - Morphology depends on **B**, particle energy, cross-field drift speed
  - Not steady state but time varying
- Upstream particles generate waves
  - ULF wave foreshock
- ULF waves convect back towards the shock
  - Potential to modify shock geometry
  - Seen in modulation of reflected ion populations
- Rankine-Hugoniot only true if include foreshock



From Treumann and Scholer, 2001

Cluster

- Four spacecraft in formation
- Magnetic field experiment built in our labs
- Fly through Earth’s bowshock regularly
- Four together gives us shock orientation and velocity

- Can also look at shock variability

Large scale shock orientation

Horbury et al, *J. Geophys. Res.*, 2002

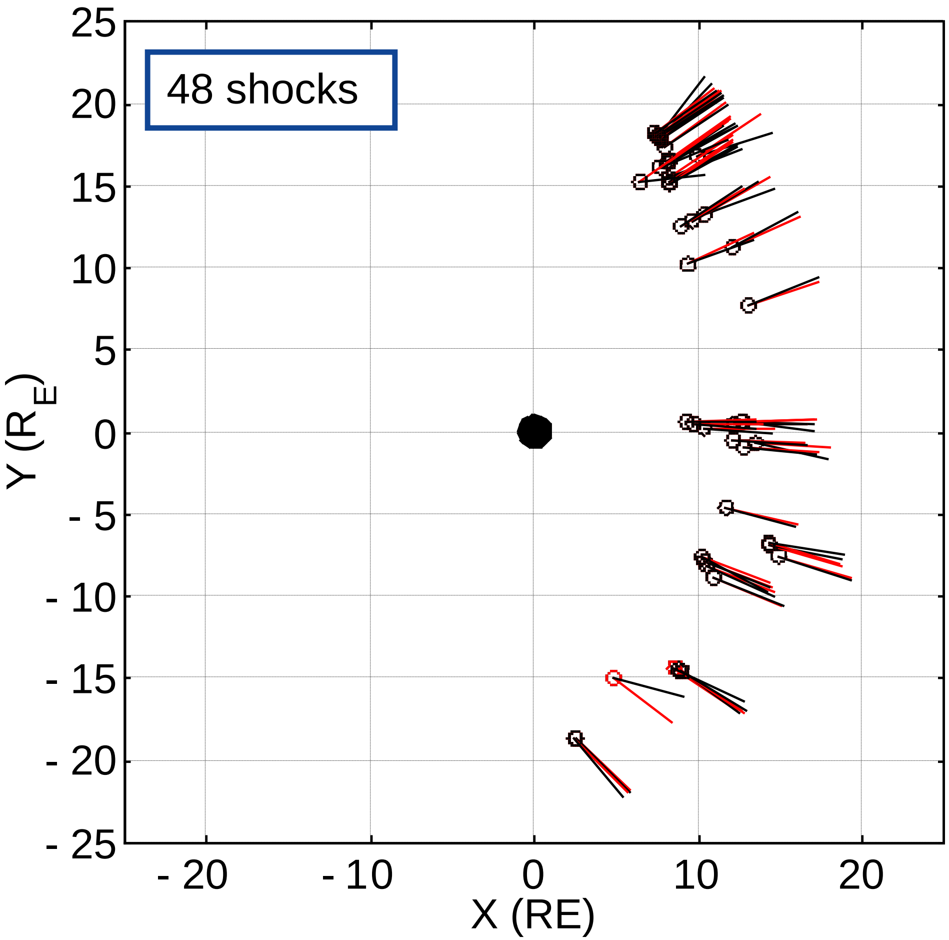
- Timing → $\mathbf{n}_{sh}$ and $\mathbf{V.n}_{sh}$
  - Velocities: typically ~35 km/s, maximum ~150 km/s
  - Stable direction over variety of upstream conditions

- Good agreement with model normal: ~80% within 10°

  ⇒Model is good estimate for quasi-perpendicular shocks

- Selection effect: can only analyse ‘well behaved’ crossings

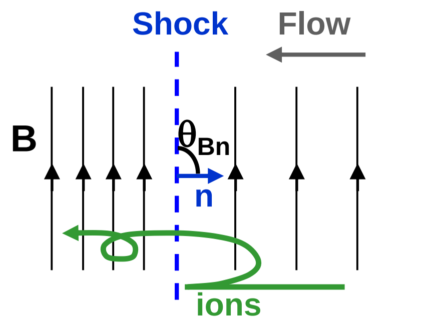
Comparison: timing (k) with model (r)

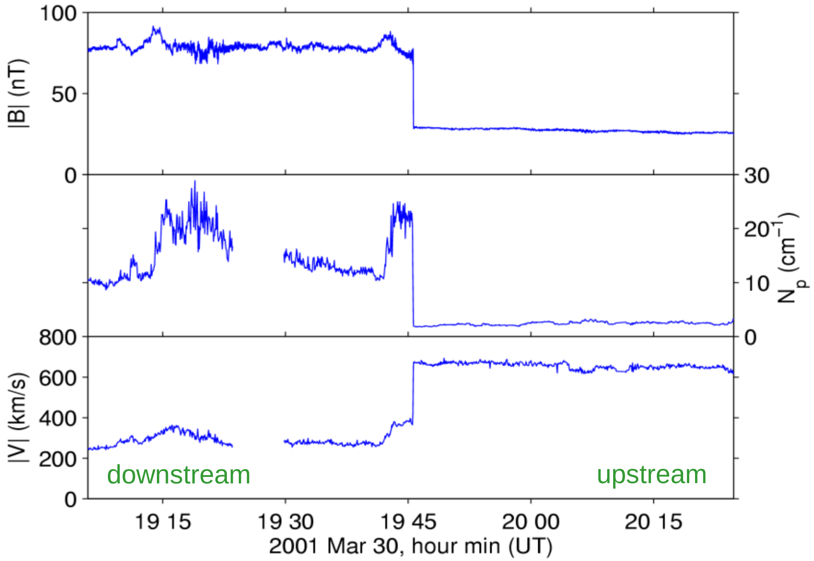


(Horbury et al, JGR, 2002)

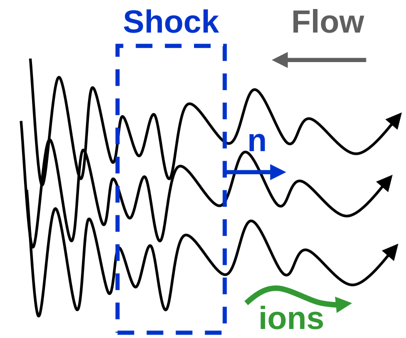
Real shocks – must take account of particles

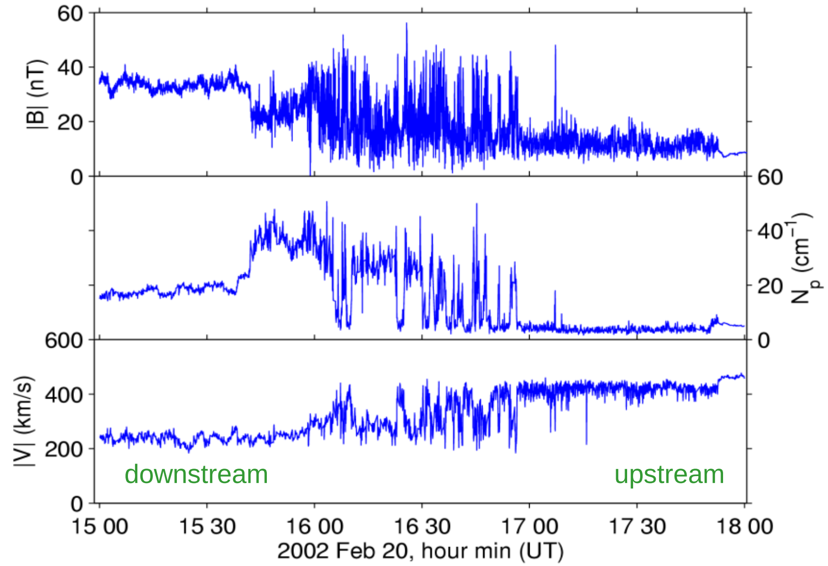
Perpendicular
(θ_{Bn}~90°)





Parallel
(θ_{Bn}~0°)





Quasi-perpendicular shocks (θ_{Bn}~90°)

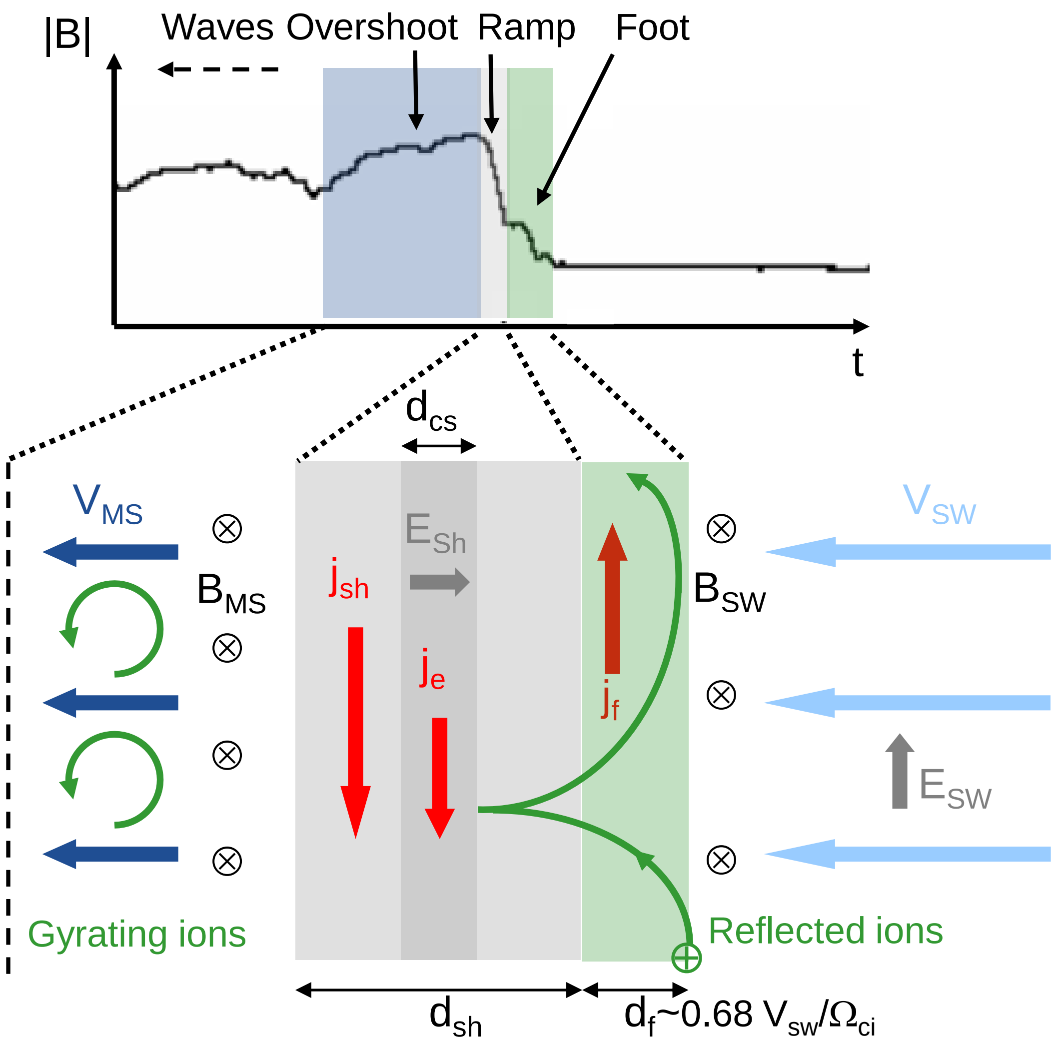
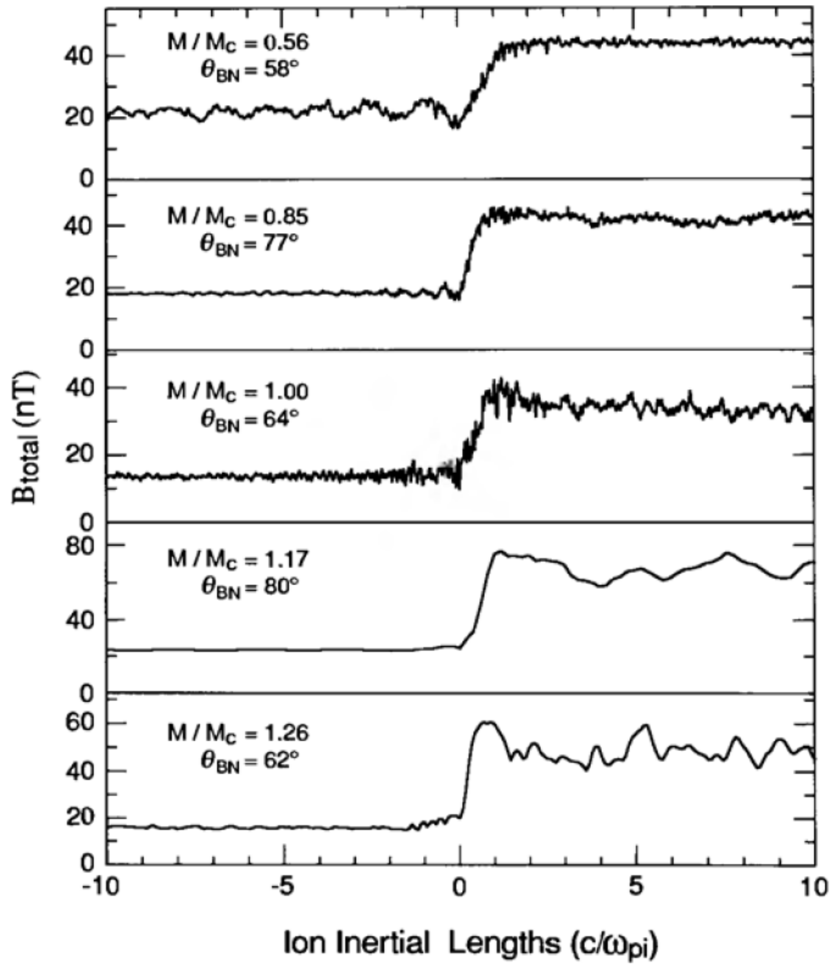


Figure after Baumjohann and Treumann. 1997
(not to scale)

Different types of Q$_\perp$ shock: the importance of Mach number

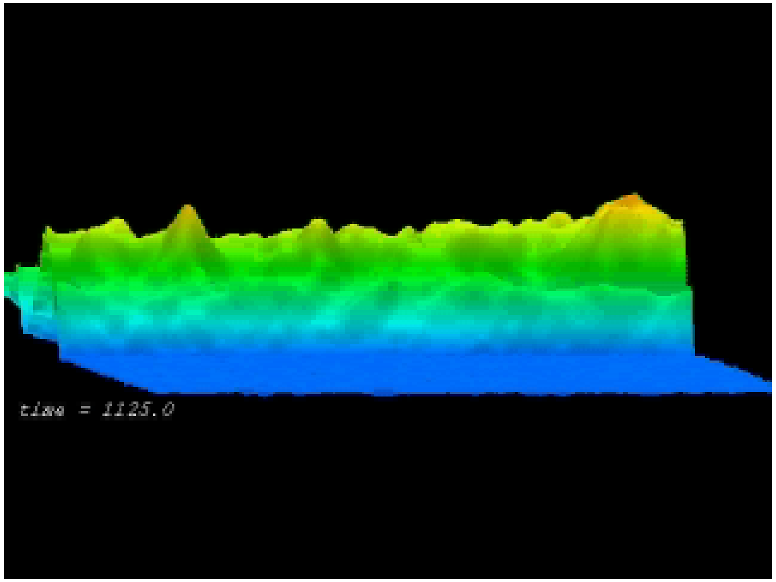
- Low Mach number: 1- 3 e.g. Interplanetary shocks:
  - Sharp transition; little overshoot
  - Sometimes see clear dispersive whistler leading shock ramp

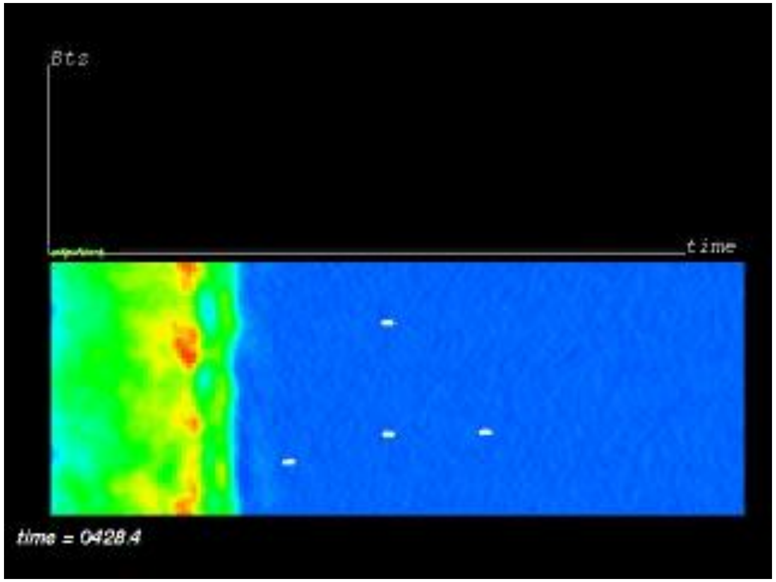


- Moderate to High Mach number:. 3-10 e.g.Terrestrial bow shock:
  - Foot; Ramp; Overshoot; Downstream wave decay
  - Ion reflection plays essential role

Shock variability

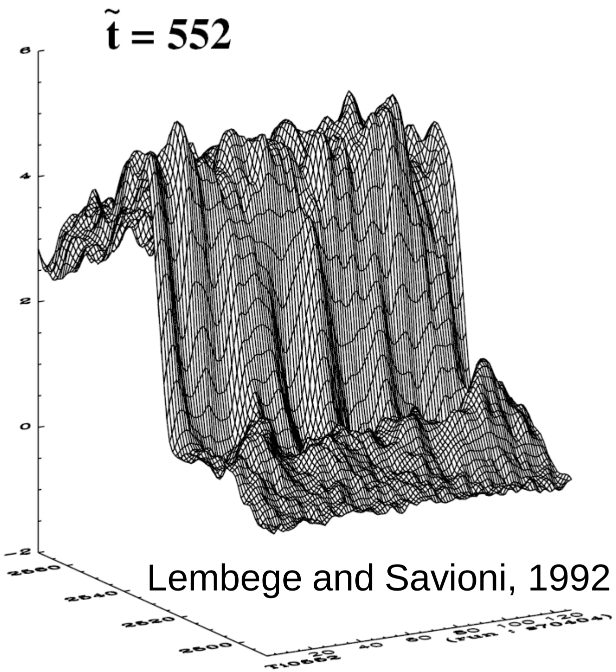
- Shocks are not planes
  - Ripples, waves
- Simulations cannot capture 3D dynamics
- This dynamics is fundamental to how the shock works, but it is poorly understood
- Need multiple spacecraft to measure variability
- Cluster provides this!



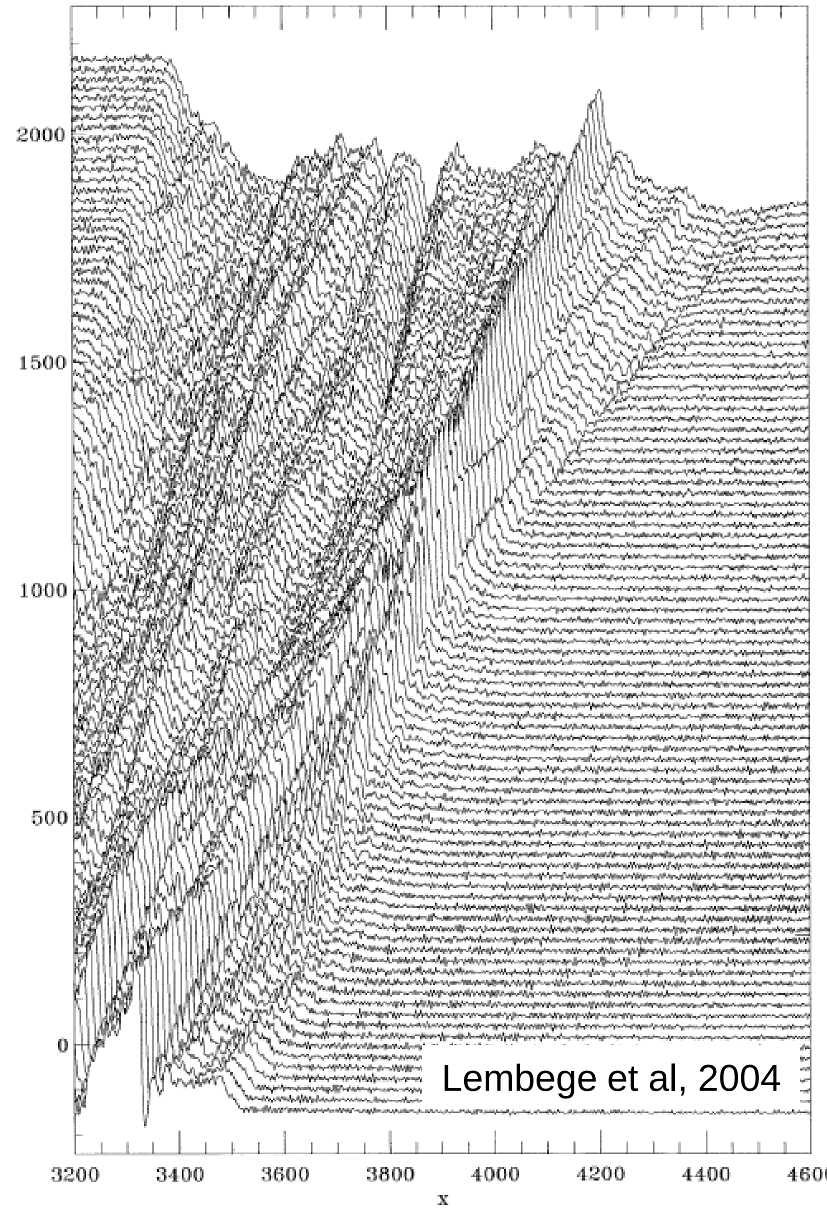


Shock variability

- Simulations show non-stationary structure
  - Important for particle heating?
  - Reformation of the ramp
  - Rippling of the shock front



Lembege and Savioni, 1992



Lembege et al, 2004

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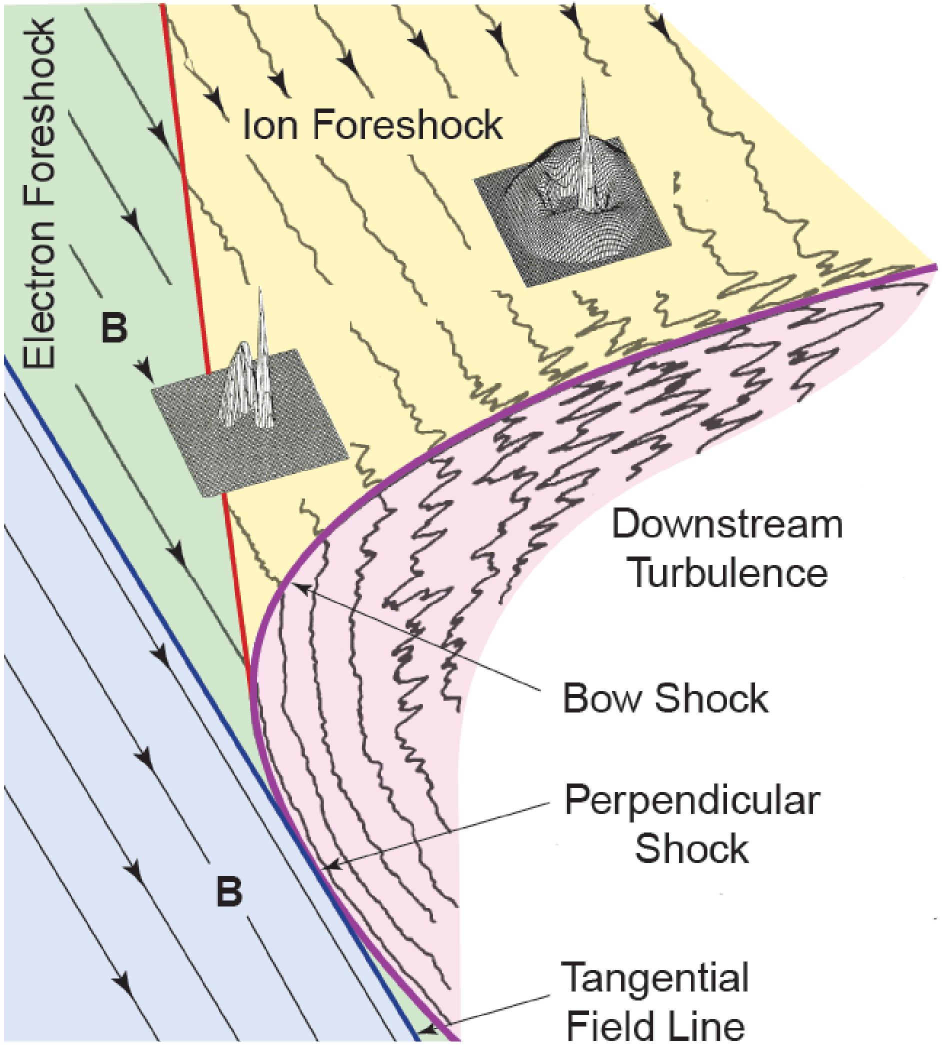
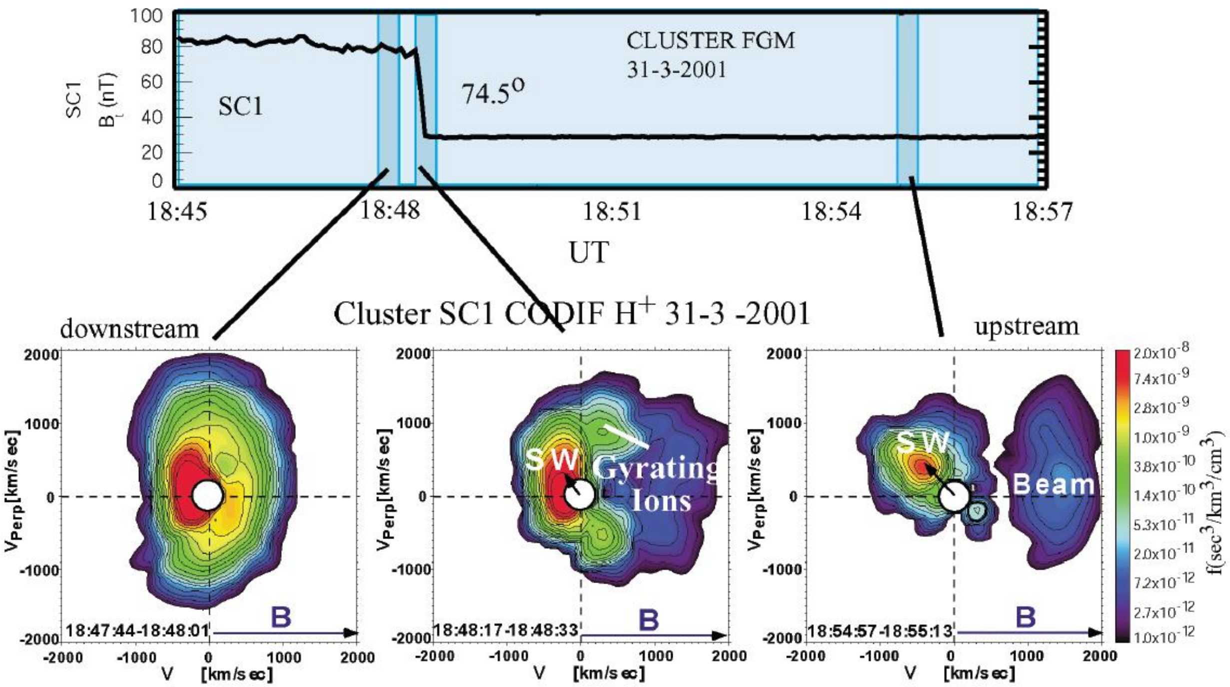
Generation of ion beams

- What is the source of ion beams?
  - Magnetosheath leakage?
  - Shock generated?
- Compare ion distributions made
  - Downstream
  - In ramp
  - Upstream
- Some multi-spacecraft, simultaneous observations



Generation of ion beams **Kucharek et al, *Ann. Geophys.*, 2004**

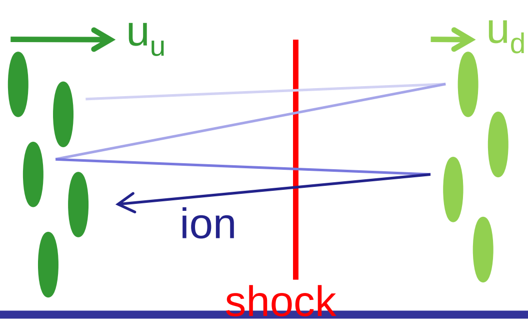


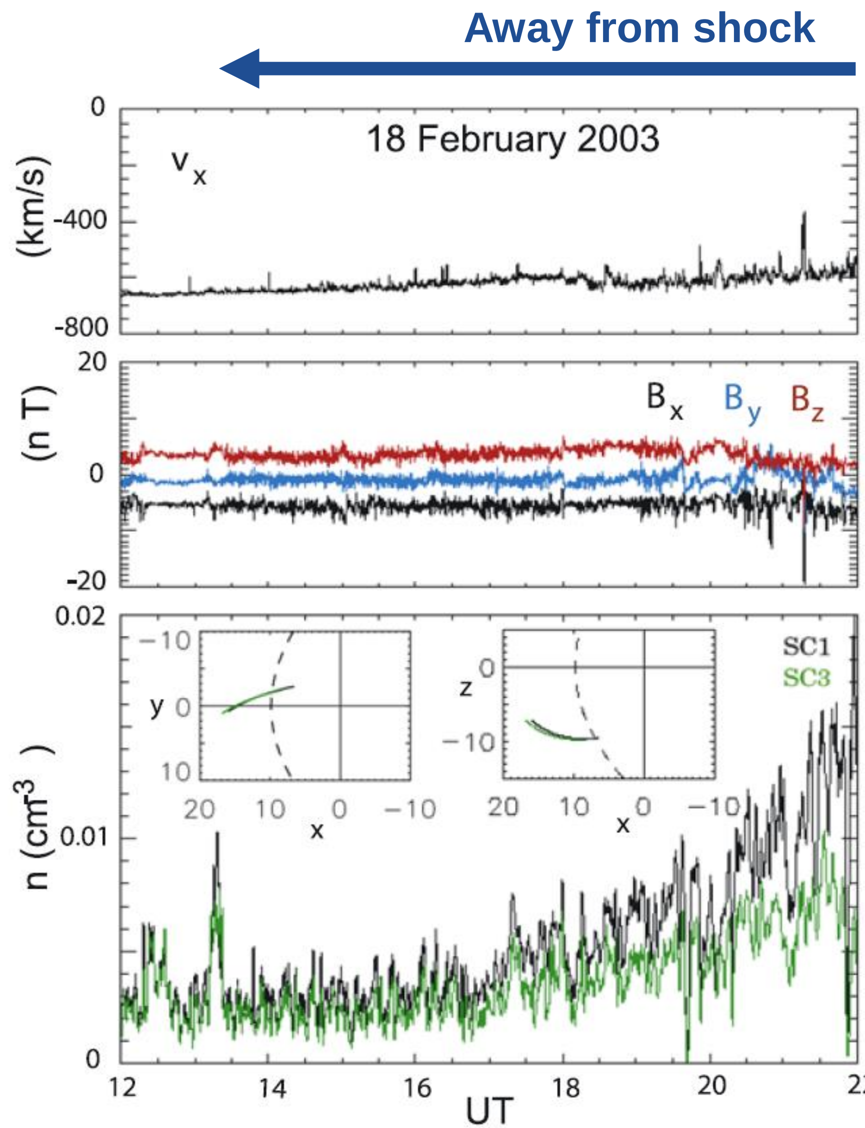
- Ion beams originate in the shock ramp – they do not leak from the magnetosheath
- The density of the ion beam is higher for high Mach number shocks
- Gyrating ions and ion beams come from same population
  - Specular reflection not sufficient for ions to escape
    - scattering/multiple shock interactions?
  - Predicted by simulations [Burgess, Ann. Geophys., 1987]

Hot ions upstream of the bow shock

First order Fermi-acceleration:

- Particle history:
  1. Crosses shock
  2. Scatters off density irregularities (waves, tubulence) in sheath
  3. Moves upstream
  4. Scatters again… from pulsations…?
  5. Sees upstream and downstream irregularities are converging at u_u-u_d
  6. Gains energy

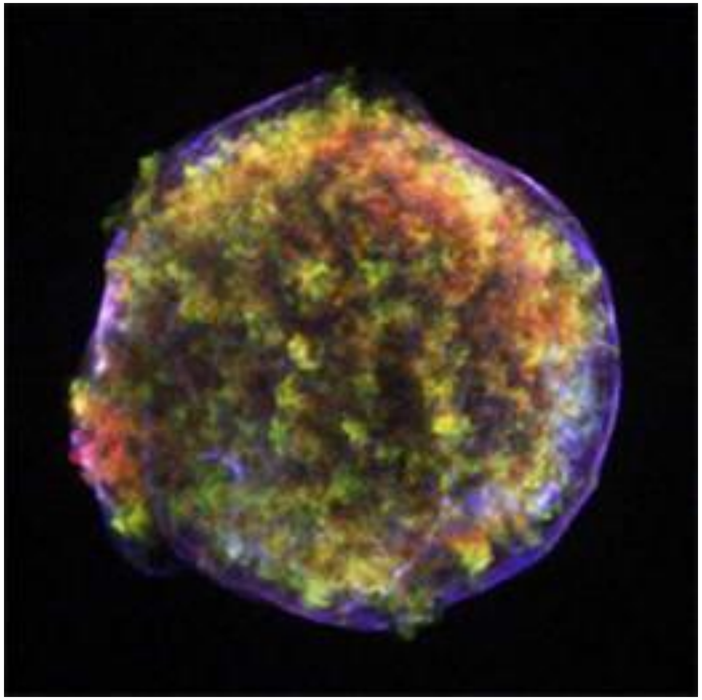




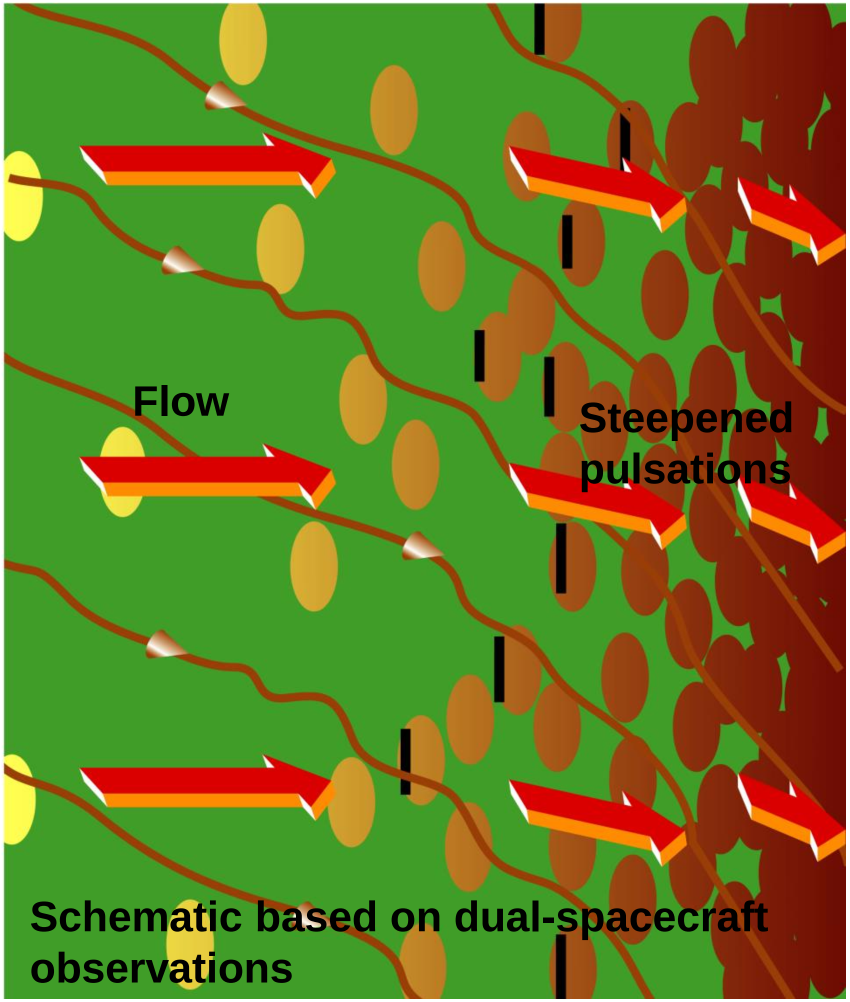
Energy partitioning

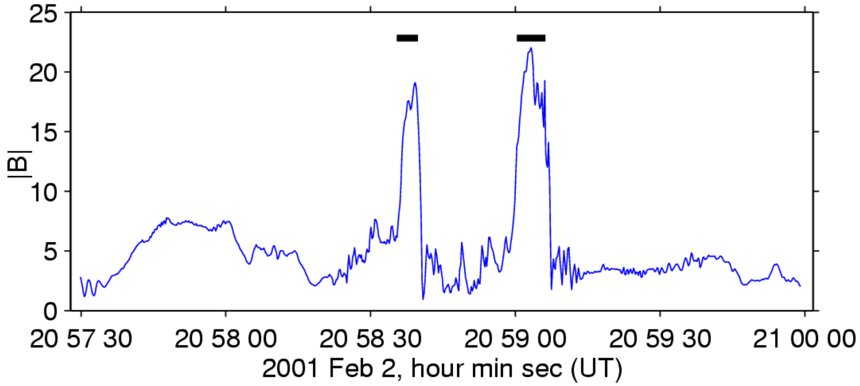
- Where does the energy go?
- Proton heating
  - Temperature anisotropy?
- Electron heating
  - Temperature anisotropy?
- Supra-thermal particles
- Heavy species: helium, …

- Can depend on θ_{BN}, Mach number, …



Parallel shock schematic
Schwartz and Burgess,1991





Parallel shock is a patchwork of small scale structures

- SLAMS: short, large amplitude magnetic strucures
- Pulsations are fast mode structures (correlated |B| and n_i)
- Pulsations grow from ULF waves in presence of hot ions
- Role in the shock itsef?

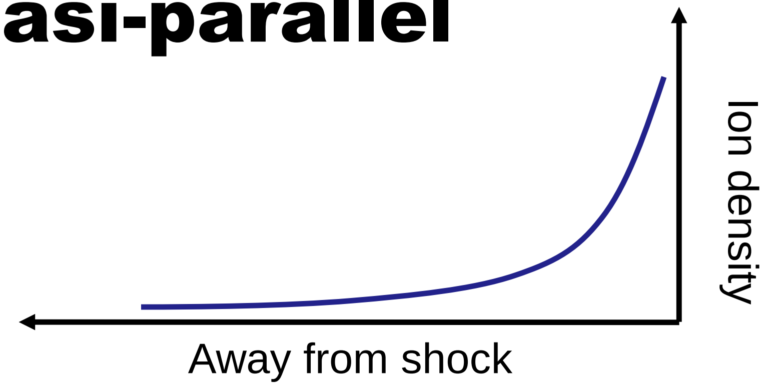
Evolving picture of the quasi-parallel shock

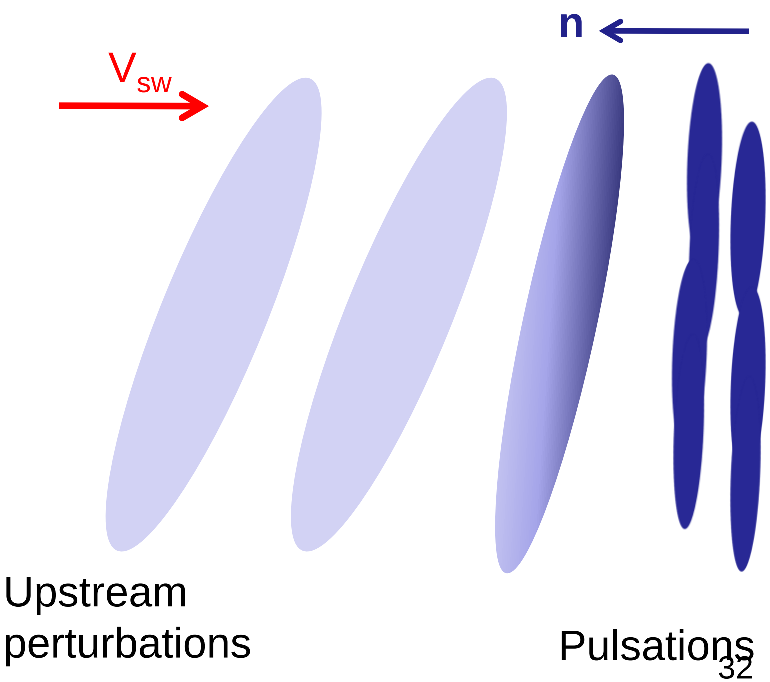
- Pulsation grow rapidly as convected Earthwards, gaining energy from hot ions

- As pulsations grow:
  - Become filamentary – shorter scale lengths
  - They become refracted to lie parallel to expected shock front
  - They start to reflect ions

  - Single or few pulsations form the shock, cause plasma thermalisation

  - How long before new pulsations replace old ones?
  - What is the 'filling factor' of SLAMS – important for ion acceleration





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Summary

- Basic concept of a shock: R-H relations
- Plasma shocks
  - θ_{BN}
  - Mach number
  - Earth's bowshock as an accessible example
  - Collisionless shocks
  - Particle reflection
  - Shock variability in space and time
  - Particle acceleration