Acceleration mechanisms in Astrophysics

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Outlines

Preliminaries-I

Non-thermal processes in Astrophysics : A great variety of objects (see B.Giebbels, I.Grenier lectures).

1. Compact sources : Sources associated with residues of massive stars
   - Stellar size compact sources : black holes and X-ray binaries, pulsars, gamma-ray binaries, gamma-ray bursts.
   - Galactic size compact sources : Central black-hole (Sagitarus A^*), Active galactic nuclei.
2. Diffuse or extended sources : Sources linked with a compact object but spread over larger scales
   - Stellar size extended objects : Pulsar nebula, supernova remnants, massive star clusters.
   - Interstellar medium.
   - Galactic size extended objects : Galaxy starburst, Clusters of galaxy.
3. Special effects associated with relativity (special or general)

All share a common property : to emit a large fraction of their bolometric luminosity into non-thermal radiation.

Preliminaries-II

Necessity for particle acceleration

1. Relativistic particles energies are observed : Efficient processes are required.
   - Radio radiation are produced by GeV electrons (e.g. interstellar medium, supernova remnants, jets ...)
   - High energy radiation (gamma rays) are produced by TeV particles.
   - Cosmic Ray spectrum extend up to 10^{20} eV.
2. Out of equilibrium particle distribution to be maintained with respect to fast cooling processes (see A.Neronov lecture)- Fast processes are required.
   - Leptons (electron/positron) : Coulomb/ionization-Bremsstrahlung-Synchrotron-Inverse Compton
   - Hadrons : Coulomb/ionization-Bremsstrahlung-Synchrotron-Pion production (matter interaction, radiation interaction)
3. Acceleration is the way nature has found to transfer energy from fast flows/ magnetic fields into fast particles and hence into radiation.

Preliminaries -III

Three main types of acceleration mechanisms. All based on the interplay of electric fields (EF) :

1. Microscopic EF associated with turbulent fluctuations (stochastic Fermi acceleration).
2. Macro-Mesoscopic EF associated with shocks.
    - Shock drift (SDA) and shock surfing acceleration (SSA)
    - Diffusive stock acceleration (DSA)
3. EF parallel to magnetic fields :
    - Magnetic reconnection (MR).
    - (a word about) Magnetospheres.

• Magnetic field ensures the particle's confinement and transport.

Bibliography

- Books
  - Kirk, J.G., Melrose D.B. & Priest E.R., 1994, Plasma Astrophysics, Springer (KMP94).
  - Longair, M.S., 1981, High energy Astrophysics, vol 1. and 2., Cambridge university press. (L81)
  - Melrose, D.B., 1980, Plasma Astrophysics vol 1. and 2., Gordon & Breach. (M80)
  - Schlickeiser R., 2002, Cosmic Ray Astrophysics, Springer. (S02)
- Articles-Reviews
  - Blandford, R.D., 1990, ApJ suppl. series, 90, 515.

Some recurrent notations

See NRL plasma formulary

- These lectures are given in CGS units.
- For a particle we define $\beta = v/c$ and its Lorentz factor $\gamma = (1-\beta^2)^{-1/2}$.
- Energy units 1erg =1/1.60 TeV

Generic spectrum produced by an acceleration mechanism

- Consider a volume V where 1) particles can be accelerated with a gain G at each cycle 2) have an escape probability at each cycle $1-P$
- We start with N_0 particles with energy E_0 at t_0. We have $N = P^m N_0$ particles with energy $E = G^m E_0$ at $t = m \times t_0$.

$$\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{ln(P)/ln(G)} . \tag{1}$$

- Some of these N will be further accelerated before escaping. The number of particles with an energy above E is :

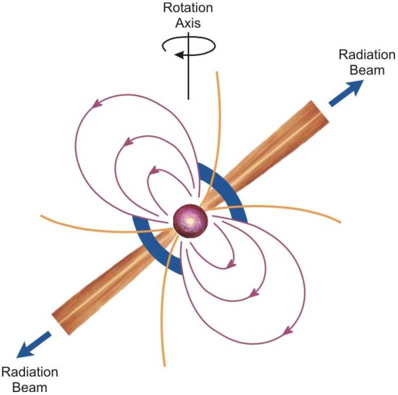
$$N(>E) \propto \left(\frac{E}{E_0}\right)^{-1+ln(P)/ln(G)} . \tag{2}$$

Outlines

Lecture 1

Outlines

Short description



Sketch of a non-aligned pulsar.

- Fast rotator (angular velocity $\Omega = 1/P$, P=33 ms for the Crab pulsar) with a dipolar magnetic field B ($B \sim 10^{12}$ G).
- Particle acceleration is associated with electric fields that develop parallel to the (dipolar) magnetic field.

Inside the neutron star the magnetic field is supposed to be a dipole with a moment M. In spherical coordinates (r, θ, ϕ) with θ is the angle with respect to the pole.

$$\vec{M} = M \left(\cos(\theta)\vec{r} - \sin(\theta)\vec{\theta} \right) \ , \tag{3}$$

and

$$\vec{B} = \frac{2M}{r^3}\cos(\theta)\vec{r} + \frac{M}{r^3}\sin(\theta)\vec{\theta} \, . \tag{4}$$

$B_\phi = 0$ due to the axial symmetry.

Electric field

- Stellar interior : The star interior is supposed to be a perfect conductor.

$$\vec{E} = -(\vec{v}_{rot}/c) \wedge \vec{B} = -\left(\vec{\Omega} \wedge \vec{r}\right)/c \wedge \vec{B} \to \perp \vec{B} \,. \tag{5}$$

- Stellar surface : We note R_* the radius of the stellar surface and $M(R_*) = B(R_*)R_*^3/2$

$$\vec{E}(R_*) = \frac{\Omega B_* R_*}{3c} \left((1 - P_2(\cos(\theta)))\vec{r} + \partial_\theta P_2(\cos(\theta))\vec{\theta}\right) \,, \tag{6}$$

with $P_2(x) = (3x^2 - 1)/2$.

- Stellar atmosphere = magnetosphere. We apply the continuity conditions.

$$\begin{aligned} E_{int,\theta} &= E_{ext,\theta} \,, \\ E_{int,r} - E_{ext,r} &= \frac{\sigma}{\epsilon} r \,, \end{aligned} \tag{7}$$

σ is the surface charge density.
The discontinuity of the radial component induces the existence of an electric field parallel to the magnetic field. The electric field is quadrupolar.

The Goldreich-Julian solution

From Eq.7

$$|E_{\parallel}(r > R_*)| = \Omega R_* B_* \frac{R_*^4}{cr^4} \cos(\theta) \ , \tag{8}$$

Typical values gives : $E(R_*) = 10^6 - 10^8$ V/cm.
The parallel component will strip charges out the stellar surface (EF > Gravitationnal force) : a pulsar magnetosphere cannot be void [1].

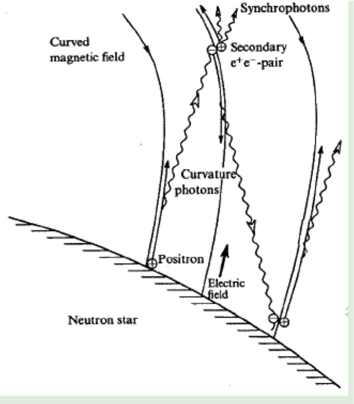
- The Goldreich-Julian charge density is :

$$n_{GJ} = \frac{\vec{\Omega}.\vec{B}}{4\pi ec(1 - v_{rot}^2/c^2)} \sim [3 \times 10^{11}\ \mathrm{cm}^{-3}] \times \frac{\mathrm{B}}{10^{13}\ \mathrm{G}} \mathrm{P}_{\mathrm{s}}^{-1} \ . \tag{9}$$

1. c.f. P. Goldreich & W.H. Julian 1969, ApJ, 157, 859

Particle acceleration-pair cascades-pulsar wind

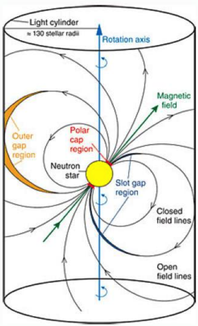
- The stripped electrons will follow the MF lines. The leptons can reach multi-TeV energies, emit synchrotron and curvature radiation and hence gamma-rays. Gamma-rays interacting will low energy photons from the environment induce electron/positron pair cascade [2] $\rightarrow$ relativistic pair wind.



2. M.A. Ruderman & P.G. Sutherland 1975 ApJ, 196, 51

Sites of particle acceleration and radiation

Several regions in a pulsar magnetosphere where it is difficult to sustain $\rho = \rho_{GJ}$. There a parallel electric can develop and accelerate particles. Favored sites are envelopes of zones where the magnetic field lines are closed (= do rotate at speed slower than c, see [3]). Polar cap likely not the site of gamma-ray production because of gamma-gamma absorption.



3. K.S. Cheng, C. Ho, M.A. Ruderman 1986, ApJ, 300, 500, J. Dyks & B. Rudak 2003, ApJ, 598, 1201.

Outlines

Transport : basis

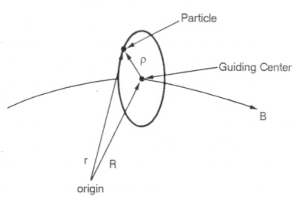
The transport of particle in space and energy is produced by the interaction with electromagnetic fluctuations that pervade the interstellar space.

- Spatial transport : interaction with magnetic fluctuations either parallel or perpendicular wrt to the mean field lines.
- Energy transport : interaction with electric fluctuations carried by the different waves (see section on Fermi stochastic acceleration).

Transport in regular magnetic fields

Integrating the trajectory produced by the Lorentz force

$$\frac{d\vec{p}}{dt} = q(\vec{v}/c \wedge \vec{B}) \tag{10}$$

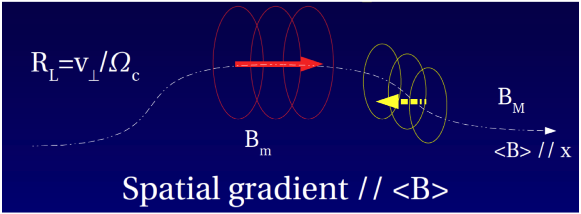


Trajectory of a charge q around the guiding-center.

The trajectory is helical with a radius $R_L = \gamma mc\, v \sin(\alpha)/qB$; $\alpha = (\vec{v}, \vec{B})$ is the particle pitch-angle. NB : one can define a guiding center if the magnetic field does not vary strongly over a scale $\sim R_L$. Hereafter we will note $\mu = \cos(\alpha)$, $R_g = R_L/\sin(\alpha)$ and $\Omega_c = qB/mc$, $\Omega_s = qB/\gamma mc$.

Magnetic mirroring

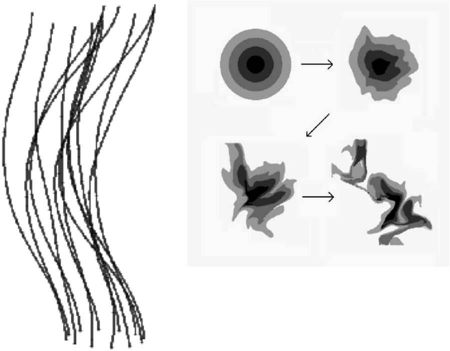
- If $L.\nabla.B/B \ll 1$ then $R_L^2 B$=cst. Also as no electric field is present v^2=cst.
- Particle is reflected at the mirror if $\sin(\alpha) > (B_m/B_M)^{1/2}$.



Trajectory of a charge q in a magnetic mirror. The maximum magnetic field is B_M and the minimum B_m.

Field line wandering process : perpendicular diffusion

- Two components : regular magnetic field $\vec{B}_{reg}$ (large scale magnetic field= size of the system), fluctuating (turbulent) magnetic field $\delta\vec{B}$.
- The turbulent component induces field line wandering $\rightarrow$ diffuse in the perpendicular direction of motion.



Effect of field line wandering : evolution of field lines perturbed by a wave traveling downward (left). Distorsion of a circular pattern following these lines (right) (see Maron & Goldreich (2001).

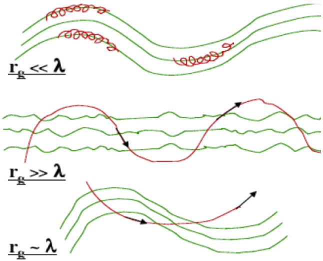
Wave-particle interactions

Two types of interactions.

1. Landau-synchrotron resonance (see figure) : $\omega - k_{\|} v_{\|} - s\Omega_s = 0$. In the case of MHD waves $\omega \ll k_{\|} v_{\|}$ and $\omega \ll \Omega_{cp}$

$$\boxed{k_{\|} r_g cos(\alpha) \simeq 1.} \tag{11}$$

2. Tcherenkov resonance :$s = 0, \omega = k_{\|} v_{\|}$. In the case of MHD waves $\omega = k_{\|} V_a$, no particular scales intervene $\rightarrow$ Transit-time damping process.



Principles of pitch-angle scattering process : parallel diffusion

- Parallel diffusion results from a random of the particle pitch-angle $\alpha(t)$ (now a random variable) due to δB.
- This permits to construct a diffusion coefficient

$$D_{\mu\mu} = \int_0^{\infty} \langle \dot{\mu}(t) \dot{\mu}(0) \rangle dt \ ,$$

$\dot{\mu}$ involves expression with $\delta B(t)$. Hence $D_{\mu\mu}$ can be finally expressed in terms of a Fourier space tensor $P(\vec{k}, t)_{i,j}$, (i,j)=(x,y,z). $P(\vec{k}, t)$ is the turbulent spectrum.

- The particle mean free path along the magnetic field is

$$\lambda_{mfp} = 3c \times \left[\int d\mu (1 - \mu^2)/D_{\mu\mu} \right]^{-1}$$

and the diffusion coefficient is $\kappa_{\parallel} = \lambda_{mfp} v/3$. With $\lambda_{mfp} = \eta r_g \times (r_g/\ell)^{1-\beta}$ (ℓ is the turbulence coherence length, $P(k) \propto k^{-\beta}$).

Streaming of cosmic rays

- Galactic CRs have a residence time of $\sim 10^7$ years in the galactic disc and have a small $< 0.1 - 1\%$ anisotropy. So they diffuse in our Galaxy.
- Resonant scattering is likely the process that produces such diffusion.
- CR have a distribution function $f(p, \alpha) = f_0(p) \times (1 + V_{CR}/v\mu)$ and $f_0(p) \propto p^{-4.7}$.
- CR can generate resonant ($kr_g = 1$) MHD waves (Alfvén, Magnetosonic) at a rate :

$$\gamma_{A,M} \propto p^{-1.6} \left(\eta/|\eta| V_{CR}/c - (4.7/3) v_A/c\right) \ , \eta = \cos(\theta) \ .$$

- The scattering of CR by the waves causes v_{CR} to be reduced at a rate (M80)

$$\frac{d \ln(V_{CR})}{dt} = \nu_s(p) \times \left(1 - \frac{(\zeta - 1)}{2} |\eta|/\eta (4.7/3) \frac{v_A}{V_{CR}}\right) \ .$$

$\zeta = F$+F$^-/(F^+ + F^-)$,$F^\pm$ are the fluxes of forward (backward) propagating waves respectively.

This rate is faster for low energy CRs as $\nu_s = c/\lambda_{\|}$ increase with the particle energy. High energy CRs are likely confine in the Galaxy because of other sources of turbulence.

Some remarks

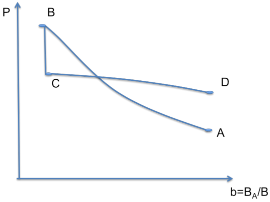
The above derivation should not let to think that the problem of transport is easy. It is very complicated task to calculate $D_{\mu\mu}$.

1. $P(\vec{k}, t)$ is not or very badly known, it can be time dependent (intermittency), anisotropic ....
2. The calculation itself is an integro-differential equation which involves the solution of the problem in the integral. One has to approximate the particle trajectory in ordre to find a solution.
   The most basic assumption is to suppose the particle trajectory unperturbed : Quasi-linear theory (QLT). QLT is known to have some drawbacks. It can be cured by invoking more orders in perturbation theory but no analytical calculations is fully reliable and can explain all the propagation domains [4].

4. A.Shalchi, 2009, Non-linear cosmic rays diffusion theories, Springer

Betatron acceleration

This process combines the mirror effect and particle scattering to produce an effective acceleration [5].



Betatron acceleration cycle. The compression may be produced by a shock wave (see next).

- In any case two invariants are obtained : $p_\perp^2/B = \text{cst}$, $p_\parallel$= cst'. This gives for a relativistic gas that a compression/decompression gives $p_\perp B^{-4/3}$ = cst".
- Point A : Isotropic distribution with small amount of pitch-angle scattering.
- Point B : Fast compression (no pitch-angle scattering) due to a long wavelength wave B so $P_\perp$ increases.
- Point C : Isotropization through pitch angle scattering. The pressure is redistributed from $\perp$ to $\parallel$.
- Point D : Slow decompression (pitch-angle scattering maintains isotropy). $E_D^2 \simeq (p_{\perp,A}^2 (B_B/B_A)^2 + p_{\parallel,A}^2)c^2 > E_A^2$: acceleration

5. A. Schlutter 1957, Zeit.Natur., 12a, 822, E.N. Parker 1958, Phys Rev., 109, 1328

Numerical techniques for turbulent flows and particle acceleration

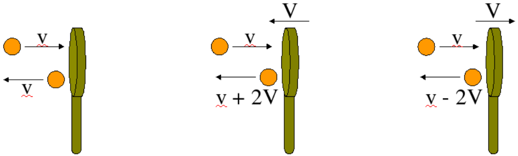
One basic major difficulty is the simulations have to cover several orders of magnitude in length, time, energy, wave-number .... scales.

1. Microscopic simulations : Particle-In-Cell (electron and ions (+neutrals) as kinetic, electromagnetic fields solved using Maxwell equations), Vlasov-Maxwell (electron/ions distributions solved with a kinetic equation, electromagnetic fields solved using Maxwell equations).
2. Mesoscopic simulations : Hybrid simulations (electron as fluid, ions as kinetic), or di-Hydrid (electron as fluid, thermal and supra-thermal ions as kinetic), electro-magnetic fields solved using Maxwell equations.
3. Macroscopic simulations : Magneto-hydrodynamics (2-3D) solving the electromagnetic fields and thermal fluid (electron, ions, neutrals) evolution. Add kinetic equation or Monte-Carlo methods for supra-thermal particles.

Outlines

Overview

- Primary introduced by Enrico Fermi in late 40s.
- A particle interacting with a random distribution of scatterers. It gains energy in head-on collisions. It losses energy in rear-on collisions. As the particle is moving faster than the scatterers more h.o. collisions occur and a mean energy gain.



court. E.Parizot, Ecole de Goutelas 2003

- The process is called Fermi second order acceleration (FII) or stochastic Fermi acceleration (SFA).

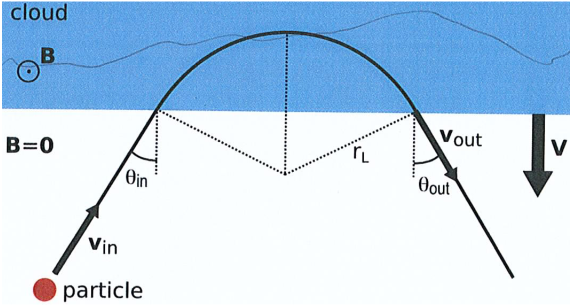
Fermi's ideas

- E.Fermi [6] did proposed a mechanism to accelerate cosmic particles to high energies. He argued for the interplay of magnetic fields through two different processes :
  - Moving (magnetic) walls : zones of strong magnetic field that deflect the particles along their trajectory - collision of type a.
  - Curved magnetic field regions : zones that progressively modify the particle pitch-angle - collision of type b
  - In paper 1 he derived a power-law solution comparing acceleration and losses over nuclear collisions
  - In paper 2 he introduced the possibility for a particle escape out of the Galaxy and focused on collision of type a, possibly related to shocks.

6. E.Fermi, Phys.Rev., 1949, 75, 1169 ; 1954, ApJ, 119, 1, see also Morrison P. et al, Phys.Rev., 1954, 94, 440.

Deflection by a magnetic mirror

- Hypothesis :
  - The ISM is pervaded by many magnetic fluctuations in form of magnetic mirrors.
  - Each mirror is moving at a velocity $V \ll v$.
  - The mirror motions are oriented randomly.



Energy gain : double Lorentz transform

1. Lab frame $\to$ wall frame : $(E_{in}, p_{in}) \to (E'_{in}, p'_{in})$:

$$\begin{aligned} E'_{in} &= \gamma(E_{in} - \beta c p_{in||}) && (12) \\ p'_{in||} &= \gamma(p_{in||} - \beta E_{in}/c) && (13) \end{aligned}$$

2. Elastic reflexion in the wall rest frame :

$$E'_{out} = E'_{in} \ , \ p'_{out||} = -p'_{in||} \qquad (14)$$

3. Wall frame $\to$ lab frame : $(E'_{out}, p'_{out}) \to (E_{out}, p_{out})$:

$$\begin{aligned} E_{out} &= \gamma(E'_{out} + \beta c p'_{out||}) && (15) \\ p_{out||} &= \gamma(p'_{out||} + \beta E'_{out}/c) && (16) \end{aligned}$$

Mean energy gain

- Energy gained or lost in one collision :

$$\Rightarrow \frac{E_{out} - E_{in}}{E_{in}} \equiv \frac{\Delta E}{E_{in}} = -2\frac{\mathbf{v} \cdot \mathbf{V}}{c^2} + 2\left(\frac{V^2}{c^2}\right) \tag{17}$$

  head-on collision : gain - overtaking collision : loss.

- Averaging over all encounters gives an energy gain as the number of head-on collisions is larger than the number of overtaking collisions.

$$\boxed{\langle \Delta E/E \rangle = 8/3(V/c)^2} . \tag{18}$$

  This is a second order $(V/c)^2$, Fermi $\Delta E \propto E$, process.

- A direct calculation in the lab frame invoking the work of electromotive force $\vec{V} \wedge \vec{B}$ gives the same result.
- If the out going angle is isotropic (isotropization in the magnetic loud) the normalization factor is $4/3$.

Particle distribution

- First let us drive the acceleration timescale. If the mean free path between two scattering centers is L and α is the particle's pitch-angle. the collision time is $t_{coll} = L/c\langle\cos(\alpha)\rangle = 2L/c$. The typical acceleration timescale is :

$$t_{acc} = t_{coll}\langle\frac{\Delta E}{E}\rangle^{-1} = \frac{3}{4} \times \frac{cL}{V^2} = \alpha^{-1} \ . \tag{19}$$

- Stationary Eq. (conservation Eq.) as we balance energy gain (α^{-1}) and escape (τ_{esc}) is :

$$-\frac{\mathrm{d}[\alpha E N(E)]}{\mathrm{d}E} - \frac{N(E)}{\tau_{esc}} = 0 \Leftrightarrow \frac{\mathrm{d}N(E)}{\mathrm{d}E} = -\left\{1 + \frac{1}{\alpha\tau_{esc}}\right\}\frac{N(E)}{E} \tag{20}$$

$\Rightarrow$ Power-law of index $x = 1 + (\alpha\tau_{esc})^{-1}$ (see solution in Eq.1) if both α and τ_{esc} do not depend on energy.

Fokker-Planck formulation

Fermi acceleration includes in fact *two effects* : a mean energy gain and a diffusion in the E space. Hence the equation is :

$$\frac{-\mathrm{d}[d\langle\Delta E\rangle/dt\, N(E)]}{\mathrm{d}E} - \frac{N(E)}{\tau_{esc}} + \frac{1}{2}\frac{\partial^2}{\partial E^2}(d\langle\Delta E\rangle^2/dt\, N(E)) = 0 \tag{21}$$

$\langle\Delta E\rangle^2 = 4E^2(V/c)^2(1/2)\int_{-1}^{1}\cos(\theta)^2 d\cos(\theta)$=$4/3E^2(V/c)^2$ hence $d\langle\Delta E\rangle^2/dt = \alpha E^2/2$ still $d\langle\Delta E\rangle/dt = \alpha E$.

• Looking for a power-law solution $N(E) \propto E^{-x}$:

$$\boxed{x^2 + x - (\frac{4}{\alpha\tau_{esc}} + 2) = 0}\,. \tag{22}$$

The solution $x_2 = [3/2(1 + 16/9(\alpha\tau_{esc}))^{1/2} - 1/2]$ is to be compared with $x_1 = [1 + (\alpha\tau_{esc})^{-1}]$ as obtained only retaining the energy gain.

Problems in the context of Cosmic Rays origin

1. The acceleration timescale is too long :
   The typical speed of the magnetized clouds in the ISM is $V/v \leq 10^{-4}$ with a typical distance $L = 1$ parsec $\Rightarrow \sim 1$ Gyr to multiply the energy by 3.
2. How to inject particles ? :
   Strong Coulomb losses at low energy. How to inject particles directly beyond GeV energies ?
3. The index of the particle distribution is not universal :
   No strong arguments for $\alpha\tau_{esc}$ to take a universal value.
4. As we will see shock acceleration supersedes Fermi second order acceleration.

That does not mean that FII is not relevant in astrophysics (see some cases discussed here).

Further developments

One may ask the question about the nature of magnetic fluctuations that pervade the interstellar medium ? (see M80 and references therein).

- Davis (1956)[7] : betatron effect over magnetic inhomogeneities.
- Parker (1955)[8] : interaction with (strong) MHD waves that pervades the ISM. But the scattering process were not defined.
- A modern view of interaction with MHD waves is provided by Kulsrud & Ferrari[9] where the scattering rate is calculated including wave-particle resonance in the weak turbulence limit.

7. Davis L., Phys.Rev., 1956, 101, 351
8. Parker E.N., Phys Rev., 1955, 99, 241, also Phys Rev., 1958, 109, 1328.
9. R.M. Kulsrud & A. Ferrari 1971, Astr. Space Science, 12, 302.

Lecture 2

Summary of lecture 1

We you need to retain for this second part.

1. Particle are transported due to their interaction with EM fluctuations.
2. The electric field accelerates particles
3. The magnetic field confines and ensures a spatial transport.
    - Parallel transport : wave-particle resonant interaction + magnetic mirrors
    - Perpendicular transport : Field line wandering.

Outlines

Overview-I

Shocks are ubiquitous in astrophysics :

1. Non-relativistic shocks ($V < 0.1$-0.3 c) : magnetospheres, supernova remnants, stellar winds, accretion columns, shocks in the interstellar medium, galactic winds, galactic spiral shocks, shocks in galaxy clusters.
2. Mildly relativistic shocks ($\Gamma = 1.1$-10) : shocks in some trans-relativistic gamma-ray bursts, internal shocks (relative velocities), jets (galactic sources and active galactic nuclei).
3. Highly-relativistic shocks ($\Gamma > 10$ up to 10^6) : active galactic nuclei, external shocks in gamma-ray burst fireball scenario, pulsar winds.

Overview-II

We can distinguish among three main acceleration mechanisms at shocks :

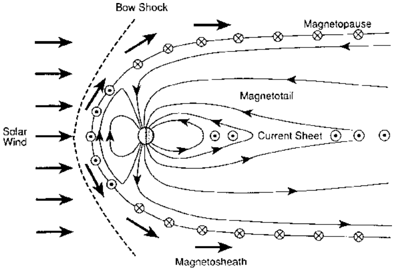
1. Diffusive stock acceleration (DSA) : acceleration through repeated shock crossings by successive head-on interaction with up- and downstream disturbances.
2. Shock drift acceleration (SDA) : acceleration by the convective electric field produced by shock curvature or magnetic field gradients.
3. Shock surfing acceleration (SSA) : acceleration of trapped particles by convective electric field at the shock front.

General properties and definitions

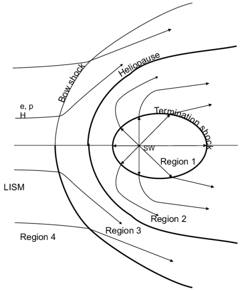
Conditions for shock formation.

- A fluid with a velocity larger than the local sound speed $c_s = [9.79 \times 10^5] \times \sqrt{\gamma_{ad} k T_{e,eV}/m_p}\ cm/s$. γ_{ad} and m_p are the adiabatic index and the proton rest-mass respectively. For typical ISM conditions $c_s \sim 10\ km/s$. One defines the shock Mach number as $M_s = V_s/c_s$.
- If the medium is magnetized, MHD waves velocities have to be accounted. One defines the Alfvén Mach number as $M_s = V_s/V_a$. Remind $V_a = [2.18 \times 10^5] \times B_{\mu G} n_{p,cm^{-3}}^{-1/2}\ cm/s$.
- On microscopic (ion, electron) levels a shock form as the particles are reflected by an electromagnetic barrier.

Close examples

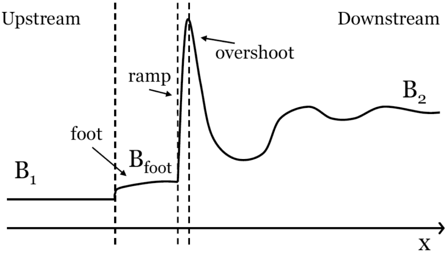


Sketch of the Earth magnetospheric shock

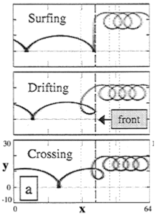


Sketch of the heliospheric shocks

Microscopic structures



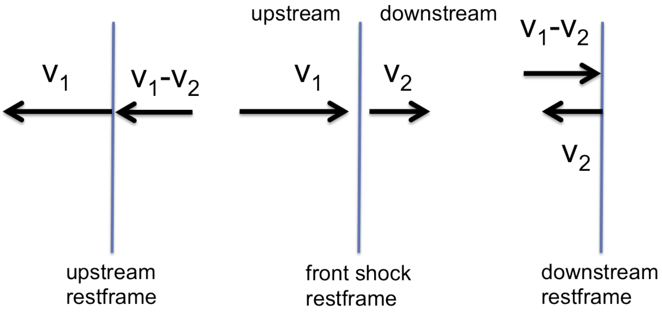
Structures in a perpendicular supercritical shock.



Sketch the three shock acceleration mechanisms (Lever et al 2001).

Rest-frames

- 1 and 2 are the up- and downstream medium respectively in the shock front rest-frame, hence $v_1 = -V_{shock}$.

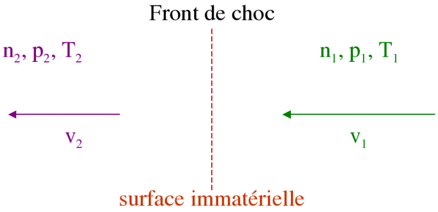


Three different rest frames

Hydrodynamic shocks

Rankine-Hugoniot relations

- Conservation of mass, momentum and energy through the shock discontinuity.

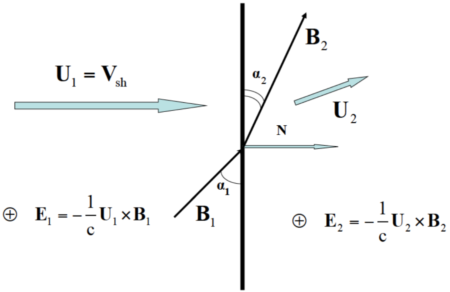


$$\rho_2 v_2 = \rho_1 v_1$$
$$p_2 + \rho_2 v_2^2 = p_1 + \rho_1 v_1^2$$
$$\rho_2 v_2 (v_2^2/2 + p_2/\rho_2 + e_2) = \rho_1 v_1 (v_1^2/2 + p_1/\rho_1 + e_1)$$

$$\Rightarrow \frac{v_2}{v_1} = \frac{\gamma_{ad} + M_{s1}^{-2} \pm (1 - M_{s1}^{-2})}{\gamma_{ad} + 1} \qquad M_{s1} \equiv \frac{v_1}{c_{s,1}}$$ Sonic Mach number.

- For $v_1 \neq v_2 : r \equiv \frac{\rho_2}{\rho_1} = \frac{\gamma_{ad} + 1}{\gamma_{ad} - 1 + 2M_{s1}^{-2}} \xrightarrow{M_{s1} \to \infty} \frac{\gamma_{ad} + 1}{\gamma_{ad} - 1} = 4$ for monoatomic non-relativistic gas.

Magneto-hydrodynamic shocks and shock obliquity



Geometry of MHD shocks in the shock front rest-frame.

- Parallel shocks : $\alpha_1 = 90^o$. No convective electric field upstream.
- Perpendicular shocks : $\alpha_1 = 0^o$.
- It is almost always possible to find a frame that cancels the electric fields up- and downstream : de Hoffmann-Teller frame. These shocks are called sub-luminal. (On the contrary the shocks are called super-luminal).

Magneto-Hydrodynamic shocks

In the particular case of perpendicular magnetic field (magnetic field perpendicular to the shock normal) [10].

$$\rho_2 v_2 = \rho_1 v_1$$

$$(p_2 + B_2^2/2\mu_0) + \rho_2 v_2^2 = (p_1 + B_1^2/2\mu_0) + \rho_1 v_1^2$$

$$\rho_2 v_2 (v_2^2/2 + (p_2 + B_2^2/\mu_0)/\rho_2 + e_2) =$$
$$\rho_1 v_1 (v_1^2/2 + (p_1 + B_1^2/\mu_0)/\rho_1 + e_1)$$

$$B_2 v_2 = B_1 v_1$$

$B_2/B_1 = \rho_2/\rho_1 = r = \frac{\gamma_a+1}{\gamma_a-1+2M_1^{-2}}$.

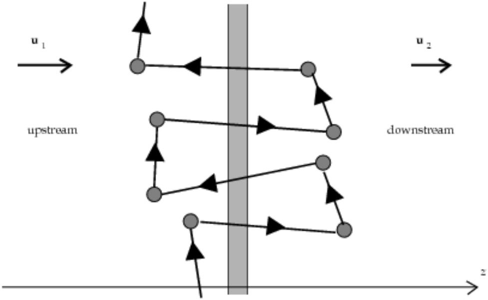
10. see e.g. S02 chapter 16 for more general cases

Questions about particle acceleration

- DSA mechanism is thought to be the main mechanism to produce high energy particles (cosmic rays), see next slides.
- However, DSA does work only if $v_{part} \gg V_{flow}$. So there are two regimes where DSA faces difficulties : Low energy particles in non-relativistic shocks, this is the injection problem and acceleration in ultra-relativistic shocks.
- DSA with a perpendicular magnetic field is more difficult since the magnetic field inhibits the particle return upstream. The two above problems are stronger in that case.
- SDA and SSA mechanisms can help injecting particles in the perpendicular shock acceleration configuration.

Principles of diffusive shock acceleration

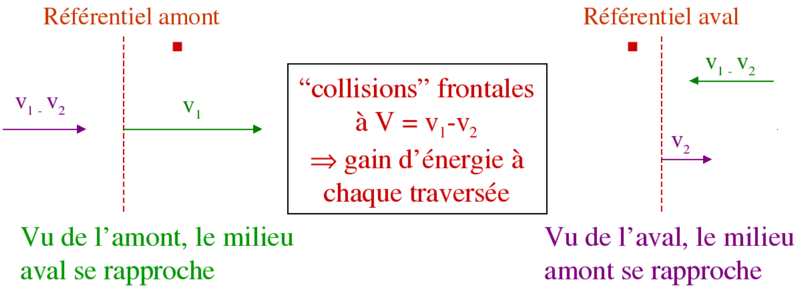
- Particles are assumed to have $r_g \gg \Delta x_{shock} \sim r_{L,thp}$.
- Up- and downstream media are assumed to carry electro-magnetic disturbances (magnetic clouds)



Sketch of DSA mechanism.

We will consider the energy gain during a cycle (e.g.) up-/down-/up-stream.

Rest frames views



Scattering centers views from up- and downstream rest frames

At each crossing a particle isotropized in the up- (down-) stream medium has a first head-on interaction with scattering centers moving at a velocity $V_1 - V_2$: this produces a systematic energy gain (see eq. 17).

Energy gain at each cycle

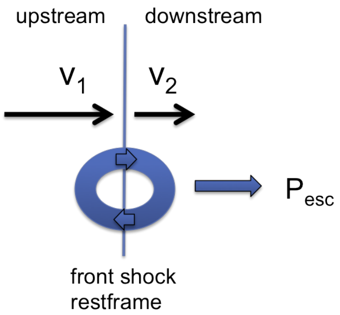
Using Eq. 17 and averaging over the crossing angles ($\theta_{1\to 2}$ and $\theta_{2\to 1}$) one finds in terms of the shock compression ratio $r = V_1/V_2$ [11].

$$\boxed{\langle \frac{\Delta E}{E} \rangle = \frac{4}{3}\frac{r-1}{r}\frac{V_{sh}}{c}}. \tag{23}$$

The gain is of Fermi type and to the first order in terms of V/c.

11. see L. Drury, 1983, Rep. Prog. Phys., Vol. 46, pp. 973.

Escape at each cycle



Escapes downstream at each shock cycle.

$$\boxed{P_{esc} = 4\frac{V_2}{c}}\ . \qquad (24)$$

see again Drury 1983.

Particle distribution solution in the test-particle case

To build the particle distribution we account for two effects :

1. Energy gain per cycle : $\Delta E/E = \chi$. We have $G = 1 + \chi$ in Eq.1.
2. The probability to stay around the shock : $(1 - P_{esc})$ where P_{esc} is given by Eq. 24.

Using the arguments advanced in Eq. 1 and 2 :

$$N(>E) \propto \frac{1}{P_{esc}} \left(\frac{E}{E_0}\right)^{\delta}, \delta = \frac{log(1 - P_{esc})}{log(1 + \chi)} . \tag{25}$$

The solution is a power-law with an index which depends only on the compression ratio : $\delta = -(r+2)/(r-1) = -2$ for a strong non-relativistic shock.

Acceleration timescale

Residence timescales up- and downstream ($\kappa_{1,2}$ are the diffusion coefficients up- and downstream respectively), see Drury 1983 :

$$t_{res,1/2} = \frac{4\kappa_{1/2}}{V_1 v} \ . \tag{26}$$

The time duration of a complete cycle is hence : $t_{cyc} = t_{res,1} + t_{res,2}$ and the acceleration timescale is $t_{acc} = t_{cyc} \times \langle E/\Delta E \rangle$. We finally obtain :

$$\boxed{t_{acc} = \frac{3}{V_1 - V_2} \times \left(\frac{\kappa_1}{V_1} + \frac{\kappa_2}{V_2}\right) = \frac{\kappa_1}{V_1^2} f(r, \kappa_1, \kappa_2)} \ . \tag{27}$$

Application to supernova remnants : Lagage & Cesarsky model

A SNR pervading standard ISM ($n = 1$ cc, $T = 10^4$ K) at a velocity $V_{sh} = 3000$ km/s in a magnetic field of $B_{ISM} = 3\mu$ Gauss. The diffusion coefficients are supposed to follow a Bohm law ($\eta = 1$, see slide 24). In case $r = 4$:

1. Acceleration timescale :
$$t_{acc} \simeq [70] \text{ years} \times \mathrm{g(r=4)} \times \mathrm{E_{TeV} B_{3\mu G}^{-1}} , \mathrm{g(r=4)} = \frac{\mathrm{(1 + 4B_1/B_2)}}{5} ,$$
$g(r = 4) = 1$ for a parallel shock and $g(r = 4) = 2/5$ for a perpendicular shock.
2. Comparing with the SNR age at the end of the Sedov phase $t_{acc} = t = t_{Sedov} \sim 300$ yrs : $E_{max} = Z \times 4.3$ TeV (11 TeV) [12]
3. The maximum particle energy may be fixed by escape upstream $t_{acc} = min(t, t_{esc})$
$$t_{esc} = \xi \frac{\kappa_1(E_{max})}{V_1^2} \simeq 0.1t ,$$
giving even lower values.

12. see the analysis in P.O. Lagage & C.J. Cesarsky, 1983, A&A, 125, 249 which leads to equivalent results although with a different modeling.

So how to reach higher energies ?

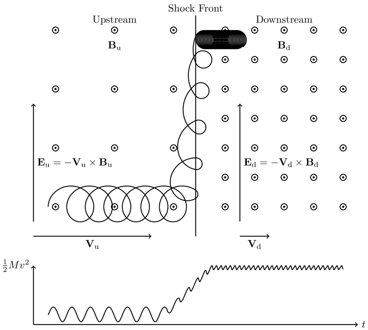
- Acceleration in perpendicular shocks [13]
- Propagation in stellar winds [14] : here B is the MF from the star ($B_* = 50$ G). B is higher than in the ISM hence E_{max} increases.
- Amplify the magnetic field to improve particle confinement around the shock [15]
- Produces the highest energies earlier whence V_{sh} can reach 0.1c (Radio SNR) (Bell, 2004)

What about injection ? SDA/SSA may contribute to it.

13. R.L. Jokipii, 1987, ApJ, 313, 842
14. H.J. Voelk & P.L. Bierman, 1988 ApJ, 333, L65.
15. see next, and A.R. Bell, 2004 MNRAS.

Shock Drift Acceleration

Use the adiabatic invariant up- and downstream $p_\perp^2/B$=cst (correct at the order of v_{sh}/v), but a variation of B at the shock discontinuity : the particle guiding-center drifts across the shock. $B_\perp$ hence $p_\perp$ increases : Shock drift acceleration [16] In the simplest case : perpendicular shock : $E_2 = E_1 \times \sqrt{B_2/B_1} = E_1 \times \sqrt{r}$.

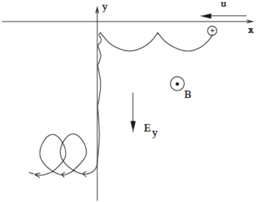


Trajectory from up- to downstream of a particle undertaking SDA in a perpendicular shock configuration (see in the shock rest frame,e.g. case of superluminal shock) : see KMP94.

16. G.M. Webb et al, 1983, ApJ, 270, 537.

Shock Surfing Acceleration

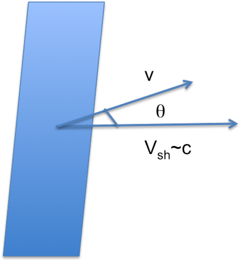
In this process the particle has a velocity $v < v_{sh}$ and is reflected at the shock front by the potential barrier towards up-stream where it is convected back to shock front and accelerated by the convective electric field. A trajectory that can be seen as a surfing over the shock front [17]

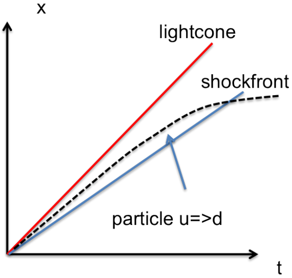


Trajectory from up- to downstream of a particle undertaking SSA in a perpendicular shock configuration.

17. R.Z. Sagdeev 1966, Rev. Plasma Phys, 4, 23, V.D. Shapiro & P. Ucer 2003, Rev Plan and Sp. Sci.,51, 665.

Basics





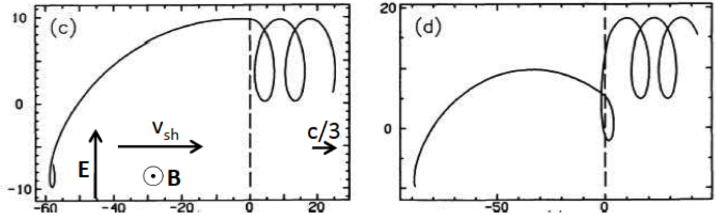
One particle upstream the shock is catcher back if $\theta > 1/\Gamma_{sh}$. Very anisotropic distribution upstream.

- Energy gain per cycle : If one assumes an elastic scattering at each side of the shock then :

$$E_f = E_i \times \Gamma_{sh}^2 (1 + \beta_{sh} \cos \theta_{out,d})(1 - \beta_{sh} \cos \theta_{out,u}) \ . \tag{28}$$

  This gives a gain in Γ_{sh}^2 for an isotropic upstream distribution at first cycle but hence only a factor ~ 2 because further cycles are anisotropic.

Kinematics



Particle trajectory in shock drift acceleration in a perpendicular shock.

- Tight to large scale magnetic field lines the particle can at most do one cycle and half [18] because the escape downstream is important (the flow has a speed of c/3) [19].
- If the turbulence is at scales $\geq r_g$ the conclusion is the same. Particle acceleration can only occur over microscopic turbulence scales $\ll r_g$. The solution in the test-particle limit for isotropic turbulence is $E^{-2.2}$, see [20].

18. M. Begelman & J.G. Kirk 1990, ApJ, 353, 66.
19. M. Lemoine et al 2006, ApJ, 645, L129.
20. M.Lemoine & G. Pelletier 2003, ApJ, 589, L73.

Comparison Relativistic/Non-relativistic shock acceleration

- (Relativistic) Anisotropy : high
- Energy gain per cycle : 2 (after the first cycle)
- Return Probability : $P \sim 0.43$
- Energy spectrum : $s \sim 2.2$
- Acceleration time : $t_{acc} \sim t_L$.

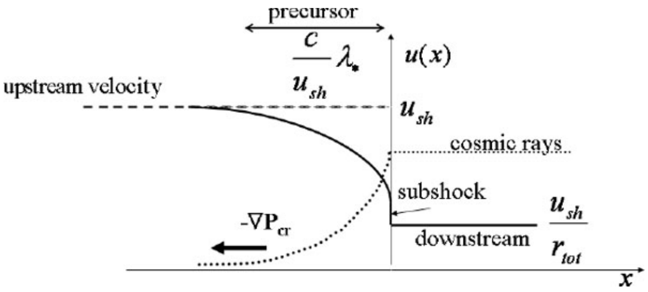
- (Non-relativistic) Anisotropy : small
- Energy gain per cycle : 4/3 $\Delta V/c < 1$.
- Return probability : $P = 1 - 4V_d/c$ close to 1
- Energy spectrum : $s = (r+2)/(r-1) = 2$ (r=4).
- Acceleration time : $t_{acc} > t_L/\beta_{sh}^2$.

Particle back-reaction

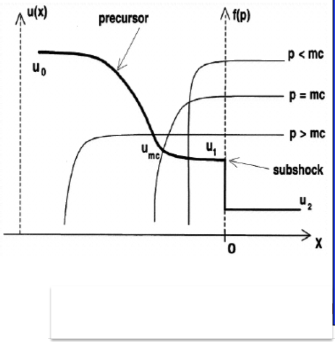
Energetic particle pressure in the test particle case gives :

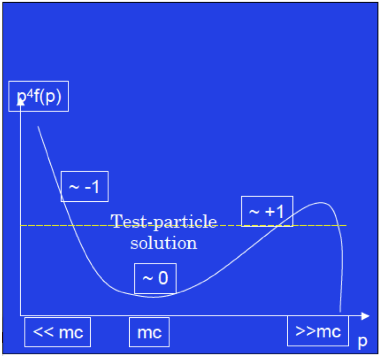
$$P_{CR} \simeq \eta \left(\frac{c}{V_{ch}}\right)^2 \ln(p_{max}/p_{inj}) \times \rho V_{ch}^2 \tag{29}$$

For $V_{ch} = 1/10$c, $\eta = 10^{-4}$ et $p_{max} = 10^6 p_{inj}$: $P_{CR} \simeq 0.14 \rho V_{ch}^2$ this is non negligible. This implies that the shock profile itself is modified by the particle pressure.



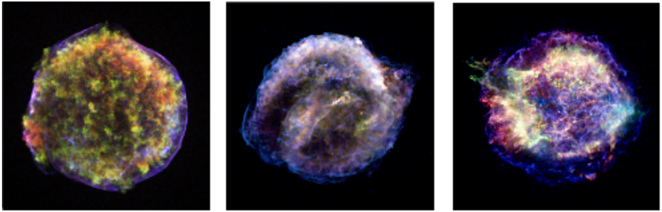
- Source spectrum:
  - CR backreaction over the flow => concave spectrum.





Magnetic field amplification : non-relativistic shocks

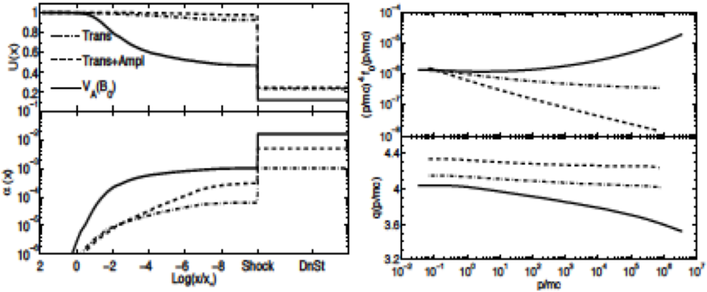
- It has been known this early 80's that waves and magnetic field necessary to scatter particles can be self-generated in the shock precursor [21]. But the fluctuations were thought to saturate at levels $\delta B/B_{ISM} \sim 1$, see [22].
- Since 2000 several mechanisms have been proposed to produce $\delta B/B_{ISM} > 10 - 100$, see [23] as it seems required from X-ray observations of filaments in several young and fast SNRs.



Tycho-Kepler and Cassiopeia A SNR observed by the Chandra satellite

21. Bell A.R. 1978, MNRAS, 182, 147 and 443
22. J.F. McKenzie & H.J. Voelk 1982 A&A, 116, 191
23. A. Marcowith et al 2006 A&A, 453, 193, K.M. Schure et al, 2012 SSR, 173, 491 and references therein

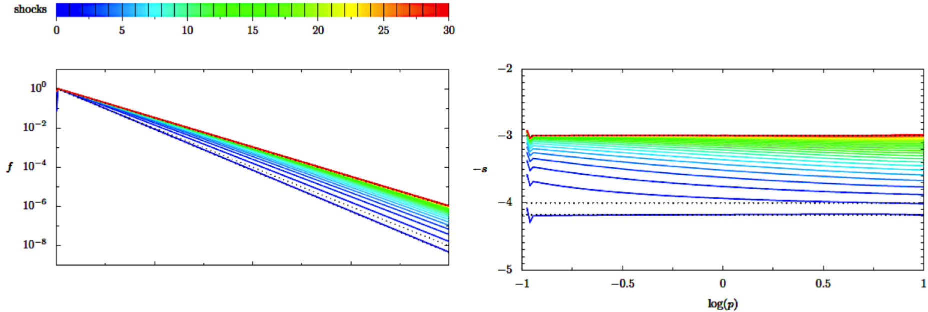
- It results from $\delta B/B_{ISM} > 10 - 100$ that the scattering centers velocity V_a increases with δB and that the CR drift with a reduced velocity $V_1 - V_a$. This reduces the plasma compressibility and produces solutions closer to the test-particle case or even softer $p^{-4.2/-4.4}$, see [24].



24. D. Caprioli et al, 2009 MNRAS, 395, 895

Multiple shock Fermi acceleration (M-DSA)

- The main effect of repeated shock acceleration is to produce spectra harder than p^{-4}, see [25].
- In the ISM : to be found is massive star clusters, binary star systems, SNR shock in interaction with turbulent molecular clouds, galaxy starbursts ...



Spectra produced by a succession of shocks in the test-particle limit (see Ferrand et al 2008).

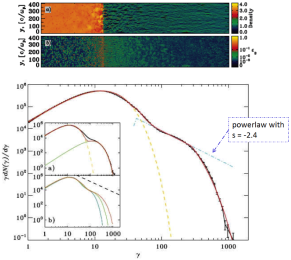
25. D.B. Melrose & M.H. Pope, 1993 PASAu, 10, 222 Bykov 2001 SSR, 99, 317, E. Parizot et al 2004, A&A, 484, 747, G. Ferrand et al 2008 MNRAS, 383, 41, G. Ferrand & A.Marcowith 2010 A&A, 510, 101.

Magnetic field amplification : relativistic shocks

Magnetic field amplification induced from observations and microphysics [26]. The conditions for efficient particle acceleration are :

1. Main turbulence scale $\ell \sim r_g/\Gamma_{sh}^3$ (small scale)
2. $\delta B/B_{background} \gg 1$.

This kind of solutions are found in simulations [27] micro-instabilities produced by accelerated particles, especially so-called Weibel instability.

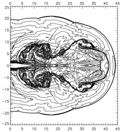


2D PIC simulations in a $\Gamma = 10$ shock.

26. G.Pelletier et al 2009, MNRAS, 393, 587.
27. A.Spitkovsky 2008, ApJ, 682, L5.

Non inertial flow acceleration

More generally impact over particle acceleration in the case the velocity of the fluid is varying over a large scale $L \leq \lambda$ (in a shock L varies over thermal ion Larmor radius), where λ is the particle mean free path [28] applied to relativistic case by Webb [29]. One particular interesting case is the once $\partial v / \partial x \neq 0$ for instance transversely to a jet. Different scenario have been considered in a jet [30].
Here the example of a transverse shear.



MHD simulations of a radio galaxy relativistic jet (A. Lucas-Serrano et al 2003)

Other possibilities : longitudinal shears along the jet, with or without discontinuities.

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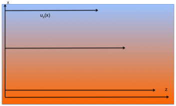
28. see J.A. Earl et al 1988, ApJ, 331, L91, R.L. Jokipii & G.E. Morfill 1990, ApJ, 356, 255.
29. G.M. Webb 1989, ApJ, 340, 1112.
30. F.Rieger, P.Duffy 2004, ApJ, 617, 155.

Principle of shear flow acceleration



Transverse shear flow with $u_z(x)$ (see Jokipii & Morfill 1990, Rieger & Duffy 2004)

- Considering a scattering time $\tau \propto p^a$ (time between two interactions).
- The particle momentum is randomized in an instantaneous comoving fluid frame.
- Transformed in the observer frame : Net energy gain

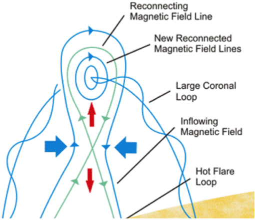
$$\left\langle \frac{dp}{dtp} \right\rangle = \frac{(4+a)}{15} \tau(p) \left(\frac{\partial u(x)}{\partial x} \right)^2 . \tag{30}$$

- Spectrum $N(p) \propto p^{-3-a}$. Scattering in the Bohm regime $a = 1$ leads to p^{-4}.
- Usually difficult to accelerate electrons due to losses. Protons acceleration is limited by transversal escapes. May explain multi EeV CRs in relativistic jets.

Outlines

Sites and principles

Reconnection is a quite widespread phenomenon : solar corona, magnetospheric and heliospheric shocks and likely present in astrophysical shocks especially downstream, in the interstellar medium (molecular clouds). Reconnection is also at the base of the galactic magnetic field dynamo process.



Equation of magneto-hydrodynamics

... including magnetic diffusivity.
NB : one approach of the (non-relativistic) reconnection process : describe the large scale structures.

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \vec{\nabla}.(\rho \vec{v}) &= 0 \ \text{ Mass continuity,} && (31)\\
\frac{\rho \partial \vec{v}}{\partial t} + \rho(\vec{v}.\vec{\nabla})\vec{v} &= -\vec{\nabla} p + \frac{1}{4\pi}(\vec{\nabla} \wedge \vec{B}) \wedge \vec{B} \\
&\quad + \rho \vec{g} + \rho \nu \nabla^2 \vec{v} \ \text{ Momentum,} && (32)\\
\frac{\partial \vec{B}}{\partial t} &= \vec{\nabla} \wedge (\vec{v} \wedge \vec{B}) + \eta \nabla^2 \vec{B} \ \text{ Induction .} && (33)
\end{aligned}
$$

ν = viscosity coefficient (collisions) (cm^2/s).η= magnetic diffusivity (cm^2/s).
Ohm's law :

$$\vec{E} = -\vec{v}/c \wedge \vec{B} + \vec{j}/\sigma. \quad (34)$$

σ is the electrical conductivity $(1/s)$. We have $\eta = c^2/4\pi\sigma$.

The ratio of the two RHS terms in the induction equation is :

$$\frac{[\vec{\nabla} \wedge (\vec{v} \wedge \vec{B})]}{[\eta \nabla^2 \vec{B}]} \equiv \frac{Lv}{\eta} = \mathcal{R}_m \;, \tag{35}$$

where L and v are the scale and velocity lengths respectively. In most of astrophysical situations $\mathcal{R}_m \ll 1$ except in places where $L.v$ becomes small. Here magnetic diffusivity can become important and induces reconnection. The reconnection speed is : $v_r = \eta/L$, the reconnection timescale is $\tau_r = L^2/\eta$.

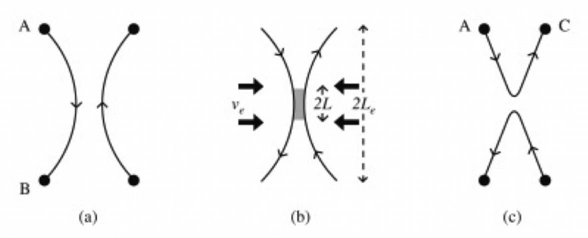
The qualitative effects are :

- Breaking the magnetic field lines and change of magnetic field topology.
- Creation of large electric field current, even shock waves.
- Transfer of the magnetic energy into : 1) heat 2) plasma acceleration and particle acceleration.

X-type collapse : $B_x = y, B_y = \alpha^2 x$, $\alpha^2 > 1$ (see KMP94, sect 6.4 p59). Hence the Lorentz force in the Euler Eq. is

$$\vec{j} \wedge \vec{B} = -\frac{(\alpha^2 - 1)\alpha^2 x}{4\pi} c^2 \vec{x} + \frac{(\alpha^2 - 1) y}{4\pi} c^2 \vec{y} \qquad (36)$$

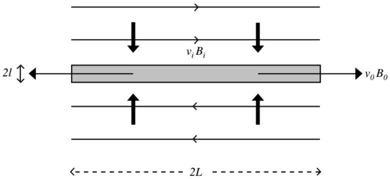
Magnetic pressure dominates over x axis/ Magnetic tension dominates over y axis.



The current sheet that appears has a size 2L (to be specified), and fields lines are inclined at the end of sheet by an angle of 60^o (KMP94).

Slow reconnection : Sweet-Parker model

Steady-state 2D reconnection process [31].



From magnetic flux and calculation of the Lorentz over the outflow :

$$\boxed{v_0 = \frac{B_i}{\sqrt{4\pi\rho}} = V_{ai}}\ , \tag{37}$$

the plasma is accelerated to the Alfvén inflow speed.
From the mass conservation we have $L/l = V_{Ai}/v_i \gg 1$ (quasi-steady). The reconnection rate is :

$$v_i = \sqrt{\eta V_{Ai}/L}\ , M_i = 1/\sqrt{\mathcal{R}_{mi}}\ . \tag{38}$$

The inflow EM energy is equally imparted into outflow kinetic energy and heat (KMP94).

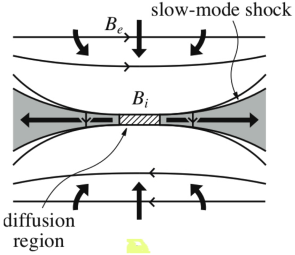
31. P.A. Sweet 1958 IAU sump 6, 123, E.N. Parker 1958, 128, 664.

Difficulties

- Typical solar flare timescales : (100-1000) s.
- Typical diffusion time for SP reconnection event : $t_d = l^2/\eta$, $\eta = 10^{13} T_K^{-3/2}$ cm^2/s. If we take $l \sim 10$ km a fraction of the granularities, hence t_d is about 10^8 s. Far too long.
- One solution is to decrease l.

Fast reconnection : Petschek model

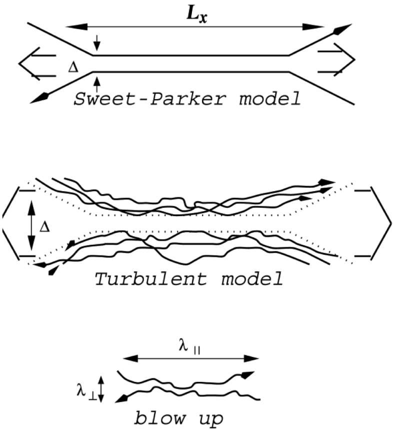
Fast (at rate faster than Sweet-Parker) steady model is due to Petschek [32]. This idea is to limit the reconnection to a small segment (of length $L \ll L_{ext}$) of the boundary between opposing fields. The diffusion region is thinner and the reconnection faster.



In this model the plasma is heated and accelerated at slow magnetosonic shocks. Now the fraction imparted into heat and kinetic energy is 2/5 and 3/5 respectively.
The maximum Petschek reconnection rate is : $M_e = \pi/(8\log(\mathcal{R}_{me}))$ larger than the Sweet-parker rate $M_i = 1/\sqrt{\mathcal{R}_{mi}}$.

32. H.E. Petschek 1964, AAS-NASA sump SP-50, 425.

Turbulent reconnection



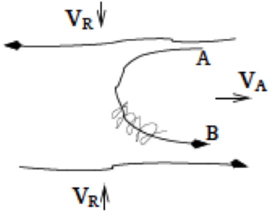
- Turbulent in the sense that the field lines are turbulent (see A.Lazarian, E. Vishniac 1999, ApJ, 517, 700).
- Reconnection happens along the tangled field lines over a scale $\lambda_{\parallel}$.
- Reconnection rate : $\mathcal{R}_m^{-3/16}(\delta V/V_a)^{3/4}$ faster than $1/\sqrt{\mathcal{R}_m}$.

see book E. Priest & T. Forbes 2000, Magnetic Reconnection for further reconnection models (3D models), Cambridge.

1. One-shot acceleration due to the electric field j/σ that develop in the current sheet : produces mono-energetic particles [33] and power-laws including losses.
2. Fermi-like processes : if turbulence is raised along the reconnecting magnetic field lines particles can be scattered and accelerated via second order process. But They also can scatter back and forth over the two converging magnetic field tubes giving a first order effect $\Delta E/E \propto V_r/c$ [34].

33. Y.E. Litvinenko 1996, ApJ, 462, 997
34. E. de Gouveia dal Pinto & G. Kowal 2013, arXiv1302.4374.

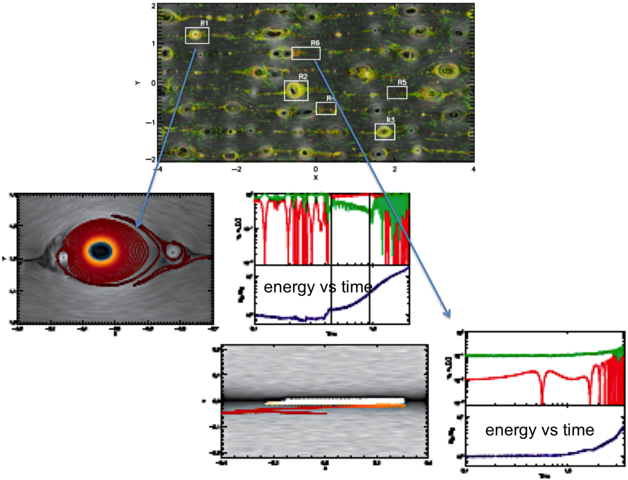
Fermi-like process



- It is easy using Eq. 1 to determine the index of the energy density particle distribution given by $ln(1 - P_{esc})/ln(G)$.
- It can be found that $G = 1 + 8/3V_r/c$.
- The escape probability depends on the properties of the medium. Using a shock analogy : $P_{esc} = 4V_r/c$ [35] (not really justified, see [36])
- Thus using Eq. 2 we have : $N(E) \propto E^{-5/2}$.

35. E. de Gouveia dal Pinto, A. Lazarian 2005, A&A, 441, 845.
36. L.O'C. Drury 2012, MNRAS, 422, 2474, which predicted even harder spectra.

Simulations

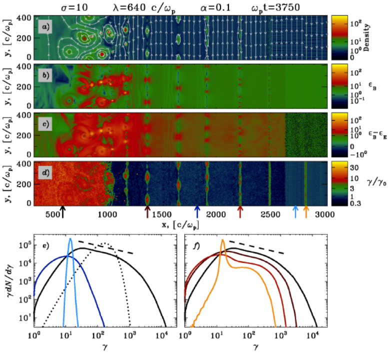


Particle (proton) acceleration in two configurations in 2D MHD simulations (see de Gouveia dal Pinto and Kowal, 2013)

3D simulations can be found

Pulsar nebula spectra ?

- Maybe a good illustration of the combine effect of shock and reconnection acceleration. Reconnection may happen in the striped pulsar wind compressed at the termination shock.



Particle (proton) acceleration in 2D PIC simulations (see L.Sironi, A. Spitkovsky 2011, ApJ, 741, 39). The dotted line shows a spectrum with an index s=1.4 ($EdN(E)/dE$). The article also presents some 3D results.

Outlines

General conclusions

- Particle acceleration is related to the action of electric fields. In most of the situation the EF are provided by fluctuations (of interest MHD scales).
- Acceleration due to parallel electric component is effective is magnetized rotating sources : pulsars (to produce high energies) but also planets.
- Diffusive stock acceleration is thought to be likely the most effective mechanism to accelerate CRs to the highest energies but require strong magnetic field amplification.
- Others mechanism may be important : Fermi second order, reconnection and shear flow acceleration.

Some perspectives

• With such a number of acceleration mechanisms it is essential to isolate in each sources the dominant process. It may depends on the energy range, source location and properties.

• Usually a full description of the acceleration process which is highly non-linear requires the advent of numerical simulations.

• Future : 1) we need to go to microphysics and a kinetic description of plasmas (MHD is not enough) 2) development of multiple-scale methods to link the acceleration chain process from microscopic to macroscopic scales. Need a better understanding of the magnetized turbulence properties, here again favored by heavy numerical calculations.

Thank you for your attention
and to the organizers : thank you for your invitation