Astrophysical Particle Acceleration

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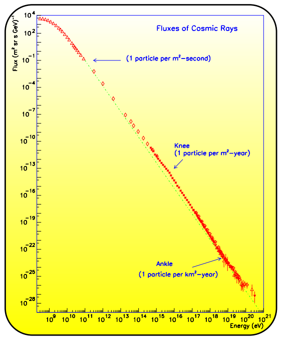
Lecture 1

General properties

- Non-thermal – far from thermodynamic equilibrium with surroundings e.g., cosmic rays, relativistic electrons in supernova remnants, AGN, jets...
- High energy, very low density, e.g., cosmic rays: particle energy 10^{10} eV up to 10^{20} eV (≈ 16 J) number density $10^{-10}\times$ interstellar medium.
- Interactions with background almost exclusively via electromagnetic fields

Cosmic Rays

Cosmic Ray Flux at Earth



Magnetic confinement?
Residence time $\sim 10^8$ years,
crossing time $\sim 10^3$ years.

Minimalistic electrodynamics

Lorentz boosts: three key properties of E-M fields

1. $f = \left(|\vec{E}|^2 - |\vec{B}|^2\right)/2$ is a Lorentz scalar
2. So is $g = \vec{E}\cdot\vec{B}$
3. The components of $\vec{E}$ and $\vec{B}$ parallel to the boost direction remain unchanged.

Consequences:

- Always possible to transform to a reference frame in which $\vec{E}\times\vec{B} = 0$ (i.e., either $E = 0$ or $B = 0$ or $\vec{E}\propto\vec{B}$)
- In the presence of a plasma, $g = 0$ and $f < 0$ for slowly varying fields.

Problem:

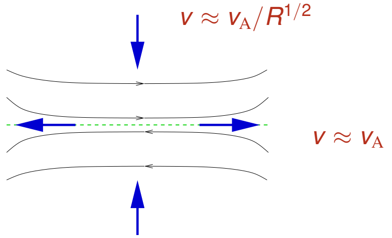
- usually lots of plasma around — MHD a good description
- trajectories are helical, with superimposed $\vec{E}\times\vec{B}$ drift: $\langle\gamma mc^2\rangle = \text{constant}$
- inhomogeneities and slow (quasi-neutral) variations lead to: additional drifts (grad-B, curvature...)
- and an electric field ($\vec{\nabla}\times\vec{E} = -\partial B/\partial t \Rightarrow E \sim BL_{\rm var}/t_{\rm var}$)
- but still no acceleration, $\oint \mathrm{d}t\left(\gamma mc^2 + qA^0\right) = \text{constant}$

Solutions:

- Ideal MHD not valid *everywhere* (boundary conditions require dissipation)
- Adiabatic invariance violated by high-frequency (compared to $eB/\gamma mc$) and/or short-wavelength fluctuations $\Rightarrow$ *scattering*.

Acceleration in a current sheet

Sweet-Parker reconnection model



Plasma ejected at approximately Alfvén speed.
Dissipation rate controlled by boundary conditions (R)

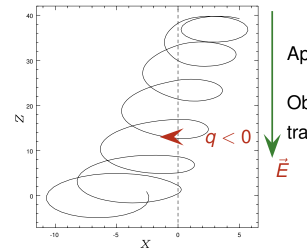
Recent application: Gamma-ray flares from the Crab Nebula, Cerutti et al, Phys Plasmas 21,6501 (2014)

Shock-drift acceleration

Classification of shocks:

1. Determine velocity $v_{\rm int}$ of an intersection point of $\vec{B}$ and the shock front
2. If $v_{\rm int} < c$ transform to De Hoffman-Teller frame:
   - $E = 0$ everywhere.
   - $\vec{U}$ and $\vec{B}$ parallel
   - No single-shot, non-stochastic acceleration.
   - Partial reflection of particles incident from upstream
3. If $v_{\rm int} > c$ transform to perpendicular shock frame:
   - $\vec{B}$ lies in shock plane
   - Acceleration can occur on crossing the shock
   - All particles transmitted

Perpendicular shock: $\vec{E} = -E\vec{z} = $constant; $\vec{B} = B_{\pm}\vec{y}$;
$B_{-} = B_{+}/r > E > 0$; $v_{\pm} = E\vec{x}/B_{\pm}$, $\vec{E} \times \vec{B}$ "drift"



Approx. conservation of $p_{\perp}{}^2/B$

Oblique shock:
transmission *and* reflection

Magnetic pumping

Let $\vec{B} = B(t)\vec{z}$ (e.g., very long wavelength (compressional) magnetosonic wave)

$$\frac{\dot{p}_{\perp}}{p_{\perp}} = \frac{\dot{B}}{2B} \qquad \dot{p}_z = 0$$

The distribution function satisfies Liouville's eq:

$$\frac{\partial f}{\partial t} + \dot{p}_{\perp}\frac{\partial f}{\partial p_{\perp}} + \dot{p}_z\frac{\partial f}{\partial p_z} = 0$$

so that

$$\frac{\partial f}{\partial t} + \frac{\dot{B}}{2B}p_{\perp}\frac{\partial f}{\partial p_{\perp}} = 0$$

The pressure is

$$P = \frac{1}{3}\int \frac{\mathrm{d}^3 p}{E} p^2 f$$

If $\langle p_z^2\rangle \ll \langle p_{\perp}{}^2\rangle$, and assuming relativistic particles

$$\Rightarrow PB^{-3/2} = \text{constant}$$

Adiabat for 4 degrees of freedom
($B \propto$ density)

In spherical polars:

$$\frac{\dot{p}}{p} = \frac{(1-\mu^2)}{2}\frac{\dot{B}}{B} \qquad \frac{\dot{\mu}}{\mu} = -\frac{(1-\mu^2)}{2}\frac{\dot{B}}{B}$$

So that Liouville's eq. is

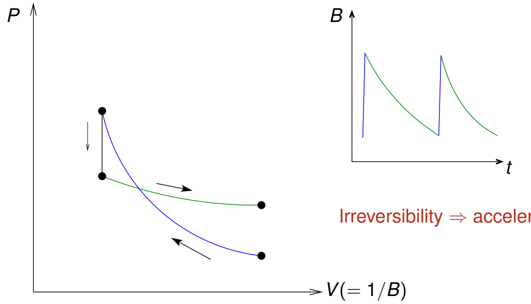
$$\frac{\partial f}{\partial t} + \frac{\dot{B}}{2B}(1-\mu^2)\left(p\frac{\partial f}{\partial p} - \mu\frac{\partial f}{\partial \mu}\right) = 0$$

Introducing strong isotropization:

$$\Rightarrow PB^{-4/3} = \text{constant}$$

Adiabat for 6 degrees of freedom

Adiabats for no scattering and isotropization



Irreversibility ⇒ acceleration

details: Saas Fee lectures, http://www.mpi-hd.mpg.de/~kirk/publications/saasfee.pdf

Fokker-Planck approach

Stochastic interactions with $\Delta p/p \ll 1$.
Evolution of an isotropic distribution on timescale long compared to that between individual interactions:

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left[-Fp^2 f + \frac{\partial}{\partial p}\left(Dp^2 f\right)\right]$$

$$\text{dynamical friction: } F = \frac{\langle \Delta p\rangle}{\Delta t} \qquad \text{diffusion: } D = \frac{\left\langle (\Delta p)^2\right\rangle}{2\Delta t}$$

Computation of F and D:
turbulent waves *two-body collisions*

Fermi acceleration

Two-body collisions:

$$\begin{aligned} \vec{p} + \vec{P} &= \vec{p}\,' + \vec{P}' \\ \sqrt{p^2+m^2} + \sqrt{P^2+M^2} &= \sqrt{p'^2+m^2} + \sqrt{P'^2+M^2} \end{aligned}$$

For non-relativistic targets, and $|p'-p| \ll p$

$$\begin{aligned} \frac{p'-p}{p} &\approx \frac{\sqrt{p^2+m^2}}{p^2 M}\left[\vec{P}\cdot\Delta\vec{p} + \text{second-order terms}\right] \\ \sim \frac{V}{v} &\ll 1 \end{aligned}$$

Head-on collisions ($\vec{P}\cdot\Delta\vec{p} > 0$) ⇒ energy gain
Tail-on collisions ($\vec{P}\cdot\Delta\vec{p} < 0$) ⇒ energy loss

Fokker-Planck coefficients:

$$\begin{pmatrix} \frac{\langle p'-p\rangle}{p\Delta t} \\ \frac{\left\langle (p'-p)^2\right\rangle}{p^2\Delta t} \end{pmatrix} = \int \mathrm{d}^3 P f_{\mathrm{T}}(\vec{P}) \int \mathrm{d}\Omega' \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega'} v_{\mathrm{rel}} \begin{pmatrix} \frac{V}{v}\hat{\vec{P}}\cdot\Delta\hat{\vec{p}} \\ \left(\frac{V}{v}\right)^2\left(\hat{\vec{P}}\cdot\Delta\hat{\vec{p}}\right)^2 \end{pmatrix}$$

($\hat{\vec{P}} = \vec{P}/P$, $\Delta\hat{\vec{p}} = \Delta\vec{p}/p$.)
If head-on and tail-on collisions equally probable (to lowest order in $|p'-p|/p$) then $F \sim (p'-p)^2/p^2 \sim D$
⇒ *second order Fermi process*
Under special conditions (e.g., anisotropic f_{T}) $F \sim |p'-p|/p$
⇒ *first order Fermi process*

Diffusion in energy

Maxwellian targets, density n_{T}, temperature $T = MV_{\mathrm{th}}^2$ ($k_{\mathrm{B}} = c = 1$):

$$\frac{\left\langle (\Delta p)^2\right\rangle}{p^2\Delta t} = 2n_{\mathrm{T}}\frac{\sigma V_{\mathrm{th}}^2}{v}\left(1 + \frac{1}{2}\langle\cos\theta\rangle\right) \qquad \theta = \text{scattering angle}$$

Requiring the equilibrium solution $f \propto \mathrm{e}^{-\sqrt{p^2+m^2}/T}$ to be stationary gives (specialising to relativistic particles, $v = 1$):

$$F = -n_{\mathrm{T}}\bar{\sigma}p^2/M + n_{\mathrm{T}}V_{\mathrm{th}}^2\frac{1}{p^2}\frac{\partial}{\partial p}\left(\bar{\sigma}p^4\right) \qquad \bar{\sigma} = \sigma(1 + \langle\cos\theta\rangle/2)$$

second derivative of D cancels!
Kinematical effect, true for all distributions, not just equilibrium

Diffusion in energy

recoil *Doppler*

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left[n_{\mathrm{T}}\bar{\sigma}p^4\left(\frac{1}{M}f + V_{\mathrm{th}}^2\frac{\partial f}{\partial p}\right)\right]$$

For heavy scatterers (T, $M \to \infty$, V_{th} finite)

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D\frac{\partial f}{\partial p}\right)$$

- Diffusion equation $\dot{f} = -\nabla_p\cdot\vec{F}$, with flux $\vec{F} = -D\nabla_p f$
- Applies also to wave turbulence ($\hbar k \gg \hbar\omega/v$, $v \gg v_{\mathrm{phase}}$)
- *Almost* always acceleration (e.g., for $D \propto p^q$, with $q > -2$)

Summary, first lecture

- Particle acceleration is associated with entropy production, either in the background plasma (e.g., during a single encounter with a shock front or a dissipative current sheet) or in the energetic particle distribution itself by a scattering process
- Single-shot mechanisms are important for relatively low energy accelerated particles, e.g., in the heliosphere, but not for acceleration over many order of magnitude in energy (cosmic rays)
- Second order Fermi mechanisms tend to be slow: $\sim$ scattering frequency $\times$ (wave speed/particle speed)^2

Lecture 2

Scale-free spectra

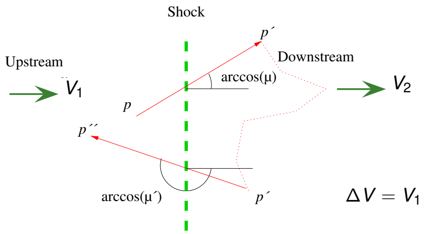
General case: acceleration events vs escape
If $\Delta E > 0$ in every event $\Rightarrow E(t)$
Let $P(p)$ be probability that a particle escapes with momentum $> p$ $\quad (p = \sqrt{E^2 - m^2c^4}/c)$

$$\begin{array}{ccc} \text{Acceleration } \dot{p} = ap & & \text{Escape rate } b \\ P(p+dp) & = & P(p)\,(1 - b\,dt) \\ \dot{P} = -bP & \Rightarrow & \dfrac{dP}{dp} = -\dfrac{bP}{ap} \end{array}$$

$$P \propto p^{-b/a}$$

Power-law (scale-free) provided b/a independent of p

Acceleration at shock



$\Delta V = V_1 - V_2$

$$p' = p\left(1 + \frac{\mu \Delta V}{v}\right) \qquad p'' = p'\left(1 - \frac{\mu' \Delta V}{v'}\right) \quad (\Delta V \ll c)$$

to first order in $\Delta V/v$: $\dfrac{\Delta p}{p} = \dfrac{\Delta V}{v}(\mu - \mu')$

Average over isotropic distribution (prob. of crossing proportional to relative speed $|\mu v|$):

$$\frac{\langle \Delta p \rangle}{p} = \int_0^{+1} d\mu \int_{-1}^{0} d\mu' |\mu\mu'| \Delta p/p \Big/ \int_0^{+1} d\mu \int_{-1}^{0} d\mu' |\mu\mu'|$$

$$\Rightarrow \langle \Delta p \rangle / p = 4\Delta V / 3v$$

Density $n = 2\pi p^2 \int_{-1}^{+1} d\mu f$

$$\begin{aligned} \text{N}^{\text{o.}}\ \text{entering/sec} &= 2\pi p^2 \int_0^{+1} d\mu (\mu v + V_2) f = nv/4 \\ \text{N}^{\text{o.}}\ \text{leaving/sec} &= 2\pi p^2 \int_{-1}^{+1} d\mu (\mu v + V_2) f = nV_2 \end{aligned}$$

$$\Rightarrow \text{Escape Prob.} = 4V_2/v$$

In terms of the phase-space density

$$f(p) \propto p^{-3 - P_{\rm esc}/\langle \Delta p/p \rangle} \equiv p^{-s},$$

$$s = \frac{3u}{\Delta u} = \frac{3r}{r-1}$$

where $r = V_1/V_2$ is the *compression ratio* of the shock.

A strong shock in a gas with $C_p/C_V = 5/3$, has $r = 4$, and $s = 4$.

Diffusion approximation $f(p,\mu)=f^{(0)}(p)+f^{(1)}(p,\mu)$

$$\frac{\partial}{\partial x}\left(\kappa\frac{\partial f^{(0)}}{\partial x}\right)-V\frac{\partial f^{(0)}}{\partial x} \;=\; 0$$

(constant $V=V_{1,2}$, *unmodified* shock). General solution:

$$f^{(0)}_{1,2} \;=\; A_{1,2}(p)+C_{1,2}(p)\exp\left(\int_0^x \mathrm{d}x' \, V_{1,2}/\kappa_{1,2}\right)$$

Exponential decay upstream and growth downstream
$\Rightarrow C_2=0$

No diffusive flux downstream $f_2^{(1)}=0$

Parallel shock (no change of $\vec{p}$ in shock frame)

$$p_2 \;\approx\; p_1\left(1+\Delta V\mu_1/v_1\right)$$

At shock front, Liouville's theorem gives

$$\begin{aligned} f_1(p_1,\mu_1) &= f_2(p_2,\mu_2)\\ &= f_2^{(0)}(p_2)\\ &\approx f_2^{(0)}(p_1)+\mu_1\frac{\Delta V}{v_1}p_1\left.\frac{\partial f_2^{(0)}}{\partial p}\right|_{p_1}\end{aligned}$$

Integrate over μ_1: $\Rightarrow A_1+C_1=A_2$

No density jump across shock

Fick's law just upstream:

$$-\kappa_1\frac{\partial f_1^{(0)}}{\partial x} \;=\; \frac{v_1}{2}\int_{-1}^{+1}\mathrm{d}\mu_1\mu_1 f_1$$

so that

$$-V_1C_1 \;\approx\; \frac{\Delta V}{3}p_1\left.\frac{\partial f_2^{(0)}}{\partial p}\right|_{p_1,x=0}$$

and the matching condition is

$$\frac{\Delta V}{3V_1}p\frac{\mathrm{d}f_2^{(0)}}{\mathrm{d}p}+f_2^{(0)} \;=\; A_1$$

General solution

$$f_2^{(0)}(p) \;=\; ap^{-s}+s\int_0^p\frac{\mathrm{d}p'}{p}\left(\frac{p'}{p}\right)^s A_1(p')$$

where

$$s \;=\; \frac{3V_1}{\Delta V} = \frac{3r}{r-1}$$

- a denotes particles *injected* at the shock
- $A_1(p)$ denotes incoming upstream particles, for $A_1=A_0p^{-q}$, $\quad f_2^{(0)}=\frac{s}{s-q}A_0p^{-q}$

Assumptions

1. There exist elastic scattering centres embedded in the plasma
2. The shock is a discontinuity in the (otherwise constant) flow velocity
3. The particle distribution is homogeneous and approximately isotropic at the shock

Result

A power-law (scale-free) spectrum

$$\frac{\mathrm{d}\ln n}{\mathrm{d}\ln p}\approx -2$$

Shock modification

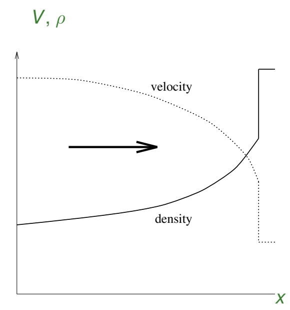
Energy density
$U=\int \mathrm{d}^3p\sqrt{p^2+m^2}f(p)$

For $f\propto p^{-s}$, U diverges at large p if $s\leq 4$, (i.e., $r>4$)

Strong shock:

$$r \;=\; \frac{\hat{\gamma}+1}{\hat{\gamma}-1}$$

divergence for $\hat{\gamma}\leq 5/3$



Shock modification

Two feedback effects important for the spectrum in nonlinear case:

- Relativistic particles have $\hat{\gamma} = 4/3$, and so soften the equation of state
  - overall compression ratio increases
  - high energy particles (with long mean free path) get a harder spectrum
- Pressure gradient decelerates and heats incoming plasma
  - Mach number (strength) of sub-shock reduced
  - low energy particles (with short mean free path) get a softer spectrum

$\Rightarrow$ concave spectrum

Ways around excessive feedback:

- Allow for a steady state with escape of high energy particles
- Follow the time dependence explicitly

Problems:

- A delicate balance with the *injection* mechanism needed
- Possible feedback effect of magnetic amplification not fully understood
- Transport properties in driven turbulence uncertain

Review article: Malkov & Drury, *Rep. Prog. Phys.* 64, 429 (2001)

Modelling of SNR: Berezhko & Völk, *Astroparticle Phys.* 14, 201 (2000)

Cycle time

Total number of particles upstream

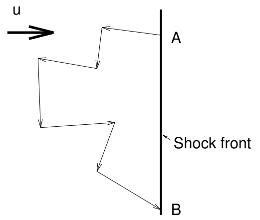
$$\begin{aligned} \int dx\, n_1 &= n_1(0) \int_{-\infty}^{0} dx \exp\left(xV_1/\kappa_1\right) \\ &= n_1(0)\kappa_1/V_1 \end{aligned}$$

Rate at which particles cross into upstream $= vN_1(0)/4$.
Average residence time upstream

$$t_1 = \frac{4\kappa_1}{vV_1}$$

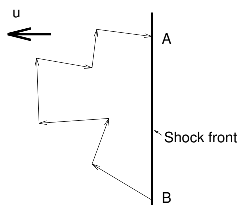
Downstream?

Upstream trajectory



$$t = \frac{\kappa}{vu}$$

Downstream trajectory



$$t = \frac{\kappa}{vu}$$

Acceleration timescale

$$\langle \text{cycle time} \rangle = \frac{4}{v}\left(\frac{\kappa_1}{V_1} + \frac{\kappa_2}{V_2}\right)$$

$$\begin{aligned} \langle \text{acceleration timescale} \rangle &= \frac{\langle \text{cycle time} \rangle}{\frac{\langle \Delta p \rangle}{p}} \\ &= \frac{3}{\Delta V}\left(\frac{\kappa_1}{V_1} + \frac{\kappa_2}{V_2}\right) \\ &\sim \kappa/V_1^2 > r_{\text{gyro}} c/V_1^2 \end{aligned}$$

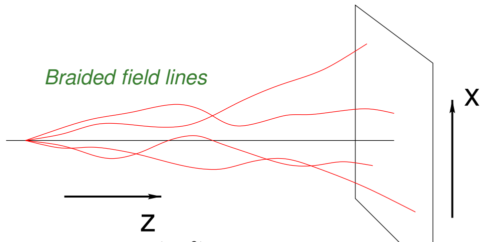
Too slow for SNR to make cosmic rays?
$\Rightarrow$ magnetic field amplification

Review: Bell Astroparticle Physics 43, 56 (2013)

Non-diffusive transport

- Small anisotropy $f = f^{(0)}(p) + \epsilon f^{(1)}(\vec{p})$
  $\Rightarrow$ Fick's law, the *diffusion approximation*
- Parallel shock: anisotropy driven by relative motion of scattering centres $\epsilon \sim \Delta V/v$
  - Small for fast particles (at nonrelativistic shock).
  - $\Rightarrow$ Random walk in x: $\langle \Delta x^2 \rangle \propto t$.
- Oblique shock: additional anisotropy/inhomogeneity driven by compression of B-field.
  - Anisotropy in the gyro-phase distribution for weak scattering
  - Density inhomogeneities from compressed magnetic fluctuations
  - Diffusion approximation fails

Wandering field lines



diffusion along B: $\langle \Delta z^2 \rangle \propto t$

diffusion of field lines $\langle \Delta x^2 \rangle \propto \Delta z$

$\Rightarrow \langle \Delta x^2 \rangle \propto \sqrt{t}$ *sub-diffusion*

Propagators

In terms of propagators,
Diffusion:

$$P(x,t) = \frac{1}{\sqrt{4\pi\kappa t}} \exp\left[-\frac{x^2}{4\kappa t}\right]$$

Sub-diffusion:

$$P_{\rm sub}(x,t) = \frac{1}{4\pi\sqrt{\kappa_B \kappa_\| t}} \int_{-\infty}^{+\infty} \mathrm{d}s \frac{1}{\sqrt{|s|}} \exp\left(-\frac{x^2}{4\kappa_B|s|} - \frac{s^2}{4\kappa_\| t}\right)$$

Spectral index

Sub-diffusive flux finite at shock

$$\frac{\text{density far downstream}}{\text{density at shock front}} = \frac{1}{u\int \mathrm{d}t P(ut,t)} = \frac{3}{2} \quad \text{for sub-diffusion}$$

So, escape probability is

$$P_{\rm esc} = \frac{3}{2} \times \frac{4V_2}{v}$$

Modified index:

$$s = \frac{3r}{r-1}\left(1 + \frac{1}{2r}\right)$$

Recent work on anomalous transport and CR acceleration: Lazarain & Yan ApJ (2014)

Diffusive shock acceleration – summary

- Robust mechanism, can amplify magnetic field and produce its own scattering waves. Predicts a power-law spectrum with slope independent of scattering details
- May be too efficient for its own good, leading to nonlinear modification of the shock structure and sensitivity to the (unknown) properties of the injection mechanism
- Needs modification if the transport properties are non-diffusive e.g., at perpendicular shocks if cross-field transport weak, or if magnetic field lines are braided

Lecture 3

9. Bulk relativistic motion
10. First-order Fermi mechanism at relativistic shocks
11. Pulsar winds

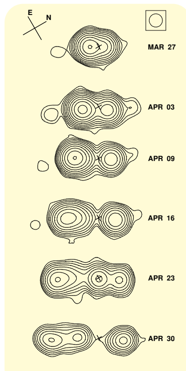
Micro-Quasars

GRS 1915+105

Jet and counter-jet
speeds and flux measured
$\Rightarrow$ full solution of kinematics:

$$\Gamma = 2.6$$
$$\text{inclination} = 70^{\rm o}$$

Mirabel & Rodriguez (1994)



Relativistic bulk motion

Object	*Evidence*	*Lorentz factor*	*Radiation mechanism*
Radio Galaxies	direct	10	synchrotron
Micro-Quasars	direct	3	synchrotron
γ-ray Bursts	indirect	250	synchrotron/IC
γ-ray Blazars	indirect	50	synchrotron/IC
Pulsar Winds	theory	10^5	synchrotron

In all cases $\gamma(\text{particle}) \gg \Gamma(\text{bulk})$

$\Rightarrow$ *Particle Acceleration*

Upstream	Downstream
$x < 0$	$x > 0$
$u = u_-$	$u = u_+$
$f \to 0$ as $x \to -\infty$	f regular at $x \to +\infty$

Mixed coordinates: t, x in shock frame, p, μ in plasma frame

$$\frac{\partial}{\partial\mu}\left(D_{\mu\mu}\frac{\partial f}{\partial\mu}\right) - (u+\mu)\frac{\partial f}{\partial x} \quad = \quad 0$$

- No momentum scale $\Rightarrow$ $f = g(\mu, x)p^{-s}$
- Well-defined kinematical problem: given u_+ and u_-, find s

Solve using methods developed for neutron/radiation transfer:

- Attempt to find an analytical solution
  No consistent analytic treatment available
- Expansion in suitably chosen eigenfunctions
  Converges rapidly for well-behaved $D_{\mu\mu}$
- Convert to integral equation and solve numerically
  Might be better for finite-angle scattering
- Monte-Carlo Flexible: allows e.g., prescribed turbulence, regular magnetic field, escape boundaries, etc.
- 3D relativistic, electron proton, particle-in-cell simulation
  Still out of reach

Best bet: use methods as a check on each other

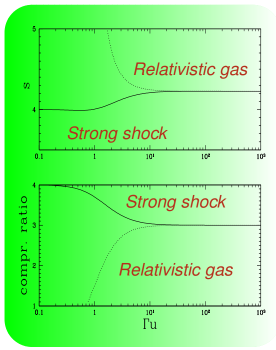
Nonrelativistic (DSA) vs. Relativistic

Nonrelativistic (DSA)	Relativistic
pitch-angle diffusion $\Rightarrow$ near-isotropy $\Rightarrow$ spatial diffusion	pitch-angle diffusion, particles in narrow, forward directed cone
solution of PDE in x, p required	solution of PDE in μ, x, p required
small escape probability, small $\langle\Delta p\rangle/p$ per cycle	escape probability $\sim$ 0.5, $\langle\Delta p\rangle/p \sim \Gamma^2$ for first cycle, then ~ 2
power-law of index $s = 3r/(r-1)$, independent of scattering law	asymptotically, $s = 4.23$, weakly dependent on scattering law

Eigenfunction expansion
$\Rightarrow$ angular dependence:

$$\frac{\exp\left(-\frac{1+\mu_s}{1-\mu_s u/c}\right)}{(1-\mu_s u/c)^s}$$

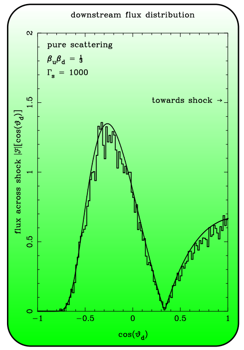
As $\Gamma \to \infty$, $s \to 4.23$
Universal index?



Monte-Carlo

Comparison of MC/analytic angular distributions

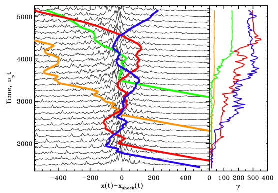
Achterberg et al MNRAS 328, 393 (2001)



2D PIC simulations, pair plasma

Spitkovsky (2008)
Martins et al (2009)

- Unmagnetized e^+e^- plasma
- Bulk $\Gamma \approx 30$
- Field generated by Weibel instability
- *Ab initio* demonstration of 1st order Fermi process at a shock front?

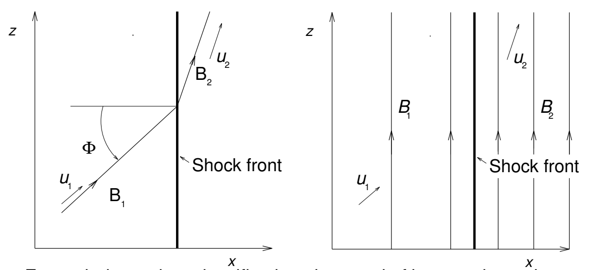


- 1% of particles in power-law tail
- Cut off at $\sim 100\times$ peak, growing in time
- $\mathrm{d}\ln N/\mathrm{d}\ln\gamma = -2.4 \pm 0.1$

Sub- and superluminal shocks

De Hoffmann/Teller frame

Perpendicular shock frame



Frame-independent classification via speed of intersection point of B and shock: $v_{\mathrm{inter}} < c$ subluminal, $v_{\mathrm{inter}} > c$ superluminal

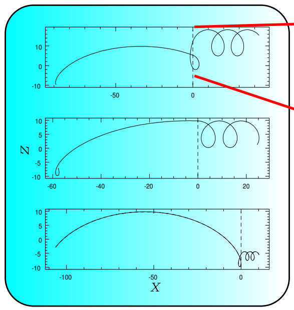
MHD+ test particles

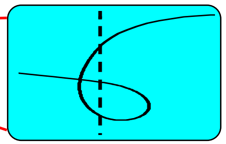
If particles tied to field lines, then

- only *subluminal* shocks can accelerate by the 1st order Fermi process
- oblique shocks $\rightarrow$ provide particles with a higher effective compression

Small length-scale magnetic fluctuations needed at superluminal shocks

Average field orientation: $B_{\parallel} = B'_{\parallel}$, $B_{\perp} = \Gamma_{\mathrm{shock}} B'_{\perp}$.
Large $\Gamma \Rightarrow$ perpendicular shocks. Begelman & Kirk 1990





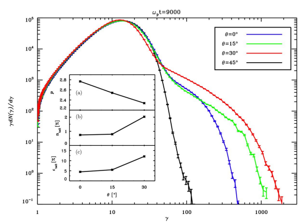
Particle overtaken in small fraction of a gyration
$N_{\mathrm{cross}} \lesssim 3$ for $\Gamma \rightarrow \infty$
Lemoine et al 2006

Short-wavelength turbulence needed

Oblique shocks

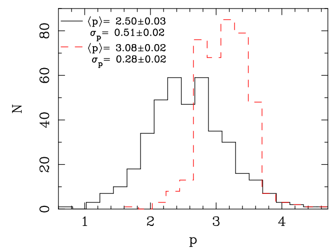
Sironi & Spitkovsky (2009)

- Magnetized e^+e^- plasma
- Shock generated by magnetic reflection
- Qualitative agreement with test-particle picture



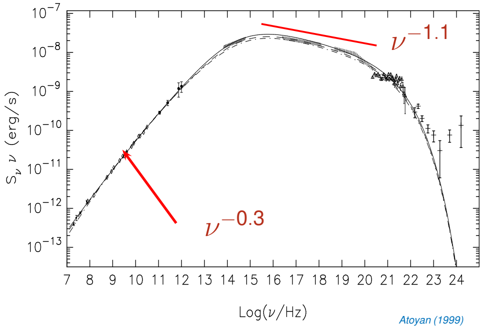
GRBs

- BATSE bursts
  Shen, Kumar & Robinson (2005)



Model dependent interpretation, $\Gamma \sim 10$
Narrow frequency band (100 keV – 2 MeV)

Crab Nebula



Bulk relativistic motion First-order Fermi mechanism at relativistic shocks Pulsar winds

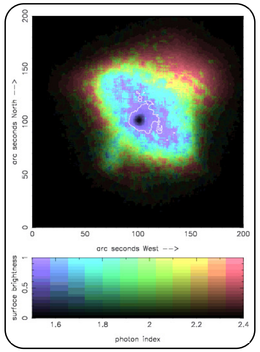
Crab Nebula

XMM-Newton
Willingale et al 2001

$$N(\gamma) \quad \propto \quad \gamma^{2-s}$$

Centre: $s \approx 4.2$

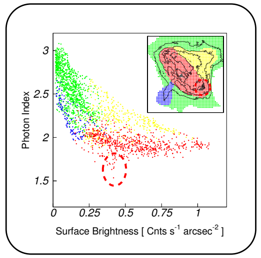
Edge: $s \approx 4.2 + 1$



Bulk relativistic motion First-order Fermi mechanism at relativistic shocks Pulsar winds

Crab Nebula

Chandra
Mori et al 2004



Bulk relativistic motion First-order Fermi mechanism at relativistic shocks Pulsar winds

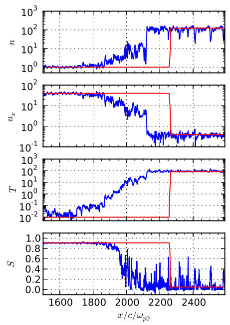
Eletromagnetically modified shock front

- Pulsar winds are modulated at the rotation frequency of the pulsar
- The wind density and local plasma frequency decrease with radius
- There exists a surface outside of which electromagnetic waves can propagate
- The termination shocks of isolated pulsars lie well outside this radius

Bulk relativistic motion First-order Fermi mechanism at relativistic shocks Pulsar winds

Shock structure

- Run A: $\omega/\omega_{p0} = 1.2$
  Run B: $\omega/\omega_{p0} = 0.4$
- Fluids maintain symmetry: $p_\parallel{}^+ = p_\parallel{}^-$, $n^+ = n^-$, $p^+_{y,z} = -p^-_{y,z}$.
- Langmuir wave activity remains at noise level



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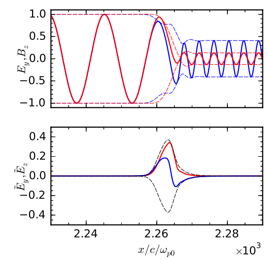
Non-MHD fields

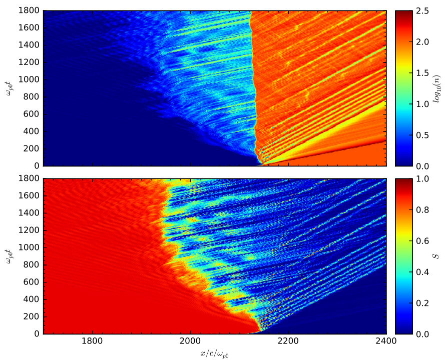
Raw fields

Non-MHD fields

$$\bar{E}_y \quad = \quad E_y - v_x B_z$$
$$\bar{E}_z \quad = \quad E_z + v_x B_y$$



Time evolution



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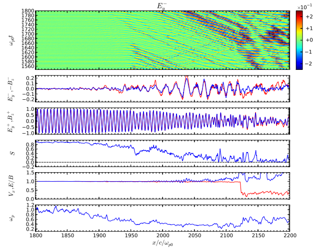
Wave helicity



Positive helicity injected wave (E^+, B^+).
Backwards propagating, negative helicity waves generated.

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Relativistic shocks – summary

- Kinematics $\Rightarrow$ spectral slope $s = 4.2 - 4.3$ for ultrarelativistic shock
- Soft spectrum $s > 4 \Rightarrow$ *linear* picture valid
- Mechanism supressed by non-zero average B-field — short wavelength turbulence required
- Highly relativisitic shocks in low density media may generate non-MHD precursor — properties as yet largely unexplored!