Cosmic Accelerators

2. Pulsars, Black Holes and Shock Waves

Roger Blandford
KIPAC
Stanford
Particle Acceleration

Unipolar Induction

\[ V \sim \Omega \Phi \]
\[ I \sim V / Z_0 \]
\[ Z_0 \sim 100 \Omega \]
\[ P \sim V I \sim V^2 / Z_0 \]

Stochastic Acceleration

\[ \Delta E / E \sim +/- u / c \]
\[ \ln(E) \sim u / c (Rt)^{1/2} \]

SSI10 Cosmic Accelerators II
Cosmic Accelerators

- Stochastic acceleration
- Unipolar induction

Shocks transmit power law distribution
\[ f(p) \sim p^{-3r/(r-1)} \]
Also second order processes; efficient when relativistic

\[ V \sim \Omega \Phi \rightarrow 1ZV \]
\[ I \sim V / Z_0 \rightarrow 10EA \]
\[ P \sim V I \sim V^2 / Z_0 \]
\[ Z_0 \sim 100\Omega \]

Neutron stars (> PeV)
Black holes (< ZeV)

UHECR?
Particle acceleration in SNR

- ~ 100 TeV gamma rays
  - ~0.3 PeV cosmic rays
  - Hadronic vs leptonic (Fermi)

- Variable X-rays
  - 100 TeV electrons
  - ~0.3 mG magnetic field

- Shocks also amplify magnetic field
  - Details controversial
Convection-Diffusion Equation

- Consider nearly isotropic df in medium containing scatterers moving with fluid velocity $u(x,t)$
  - eg Alfven waves with speed $<<u$
  - Stationary 1D flow

\[
  u \frac{\partial f}{\partial x} - \frac{\partial}{\partial x} D_{xx} \frac{\partial f}{\partial x} = \frac{1}{3} \frac{du}{dx} \frac{\partial f}{\partial \ln p}
\]

- Spatial diffusion, $p \sim L^{-1}$ De Broglie…
- Much generalization
Diffusive Shock Acceleration

- Non-relativistic shock front
  - Protons scattered by magnetic inhomogeneities on either side of a velocity discontinuity
  - Describe using distribution function $f(p,x)$

\[
uf - D \frac{\partial f}{\partial x} = uf_-
\]

\[
[f] = \left[ -u \frac{\partial f}{\partial \ln p^3} - D \frac{\partial f}{\partial x} \right] = 0
\]
Transmitted Distribution Function

\[ f = f_- + (f_+ - f_-) \exp\left[ \int_0^x dx' u / D \right]; x < 0 \]

\[ f = f_+; x > 0 \]

\[ f_+(p) = qp^{-q} \int_0^p dp' p'^{q-1} f_-(p'); q = 3r / (r - 1) \]

- For strong shock with Mach number and monatomic gas (plasma),
  \( q=4M^2/(M^2-1) \Rightarrow r=4 \Rightarrow N(E) \sim E^{-2} \)
- Consistent with Galactic cosmic ray spectrum allowing for energy-dependent propagation
Too good to be true!

- **Diffusion**: CR create their own magnetic irregularities ahead of shock through instability if $\langle v \rangle \sim a$
  - Instability likely to become nonlinear - Bohm limit
  - What happens in practice?
  - Parallel vs perpendicular diffusion?

- **Cosmic rays are not test particles**
  - Include in Rankine-Hugoniot conditions
  - $u = u(x)$
  - Include magnetic stress too?

- **Acceleration controlled by injection**
  - Cosmic rays are part of the shock

- **What happens when $v \sim u$?**
  - Relativistic shocks

- **Energy cutoff?**
  - $E < euBR \sim \text{PeV}$ for mG magnetic field
Magnetic Bootstrap

- Alfven waves scatter cosmic rays at supernova remnants
  - $\lambda \sim$ several $r_L(E)$
  - $D \sim c\lambda/3; L \sim D/u > 100 E_{\text{PeV}} B_{\mu G}^{-1}Z^{-1}\text{pc}$
  - Requires magnetic amplification; $B > 100 \mu G$
  - Highest energy cosmic rays stream furthest ahead of shock
  - Distribution function is highly anisotropic and unstable
  - Conjecture that magnetic field created at radii $\sim 2R$ by highest energy escaping particles
  - Cosmic ray pressure dominates magnetic pressure upstream
  - Lower energy particles transmitted downstream and decompress!
  - Magnetic field created upstream and locally isotropic

![Graph showing energy distributions](image)
Magnetic Field Amplification

Weibel
- Unmagnetized plasma
- Short wavelength - ion skin depth
- Saturates when magnetized

Bell-Lucek
- GeV cosmic rays
- Cosmic ray and return current respond differently to perturbations
- Riquelme & Spitkovsky

Magnetic Bootstrap
- Operates far ahead of shock front and enables PeV acceleration
**Why does a collisionless shock exist?**

Particles are slowed down either by instability (two-stream-like) or by magnetic reflection. Unmagnetized shocks are mediated by Weibel instability, which generates magnetic field:

*Spitkovsky*
Magnetic Bootlaces

- How can a small magnetic pressure mediate the interaction between two particle “fluids”?

\[ \nabla P_P = j_P B \]
\[ \nabla P_{CR} = j_{CR} B \]
\[ \frac{dB}{dX} = j_P + j_{CR} \]
Solar system shocks

• Observations of planetary bow shocks
• Voyager observations of solar wind termination shock
• Numerical simulations
Cluster of Galaxies

- eg Perseus Cluster
- Observe using X-rays, lensing, CMB, simulations and gamma rays
- High entropy gas in outer regions. Requires ~10Mpc strong accretion shock
  - Simulations concur
- Accelerate UHECR if Fe!
- Unlikely to make observable neutrinos
GeV $\gamma$-rays from Clusters of Galaxies

Upper limits are interesting!

- Active Galactic Nuclei
- Primordial cosmic rays
- Dark Matter Annihilation

Keith Bechtol
Unipolar Inductors

- Neutron star magnetospheres
  - Mapping of pulsar magnetospheres
  - Plerions and relativistic shocks
  - Force-free models
  - Typically $B \sim 10^{12}$ G, $P \sim 100$ms, $\Phi \sim PV$
  - Millisecond magnetars
  - $B \sim 10^{15}$ G, $P \sim 3$ms, $\Phi \sim ZV$
Pulsar Wind Nebulae

- Common sources especially at TeV
- Displaced from pulsar
- Synchrotron nebulae
- Compton -CMB/synchrotron
- Accelerating >10PeV electrons
- Larmor radius – ~0.1pc
  - Cooling length - ~0.01pc
  - Requires E>~B!!
- Pulsar wind – relativistic beaming?
- Pulsar magnetosphere – ground-states of gyration

\[
\text{Pulsar Wind Nebulae} \quad \text{synchrotron} \quad \text{Crab Nebula} \quad \text{Compton}
\]
Black Hole Accelerators

- **$10^9 \, M_\odot$ AGN hole**
  - $B \sim 1T$; $\Omega \sim 10^{-3}$ rad s$^{-1}$
  - $V \sim 1ZV$; $I \sim 10^{EA}$
  - $P \sim 10^{39}W$

- **$10 \, M_\odot$ GRB hole**
  - $P \sim 10^{44}W$

Co-ax or hosepipe?

Coaxial Accelerator?
Losses

- **Radiative losses**
  - Synchrotron, Compton losses
  - $P \sim E^2 M^{-4}$; irrelevant for protons

- **Photo–pion production**
  - Dark accelerators

- **Collisional losses**
  - Source of gamma rays

Good for VHE neutrinos; bad for UHECR!
VHE Neutrinos

- Ice Cube deployed and working well
- No sources yet
- **Leptonic** vs hadronic jets
- GZK neutrinos (unless Fe)
- Cosmic ray detector
- Geophysics…
- Radio, sonic detection

PM will explain!
Summary

- Cosmic shocks are efficient accelerators
  - Solar system, SNR, clusters..
- Accelerate protons/electrons to higher energy than expected
- This implies that they also stretch magnetic field lines. Many competing plasma instabilities
- Unipolar induction associated with millisecond magnetars, black holes in AGN, GRB can induce ZV.
- Neutrino observations can distinguish leptonic from hadronic sources