Particle Acceleration
GeV-TeV Astrophysics in the GLAST era

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Direct Evidence for SNR Acceleration

- Electron acceleration to TeV energies
- TeV gamma rays sometimes observed
  - Model-dependent evidence for ion acceleration
  - Efficient acceleration but not to knee
- EGRET, GLAST (GeV)
- Hess, VERITAS (TeV)
- pion decay
Proton spectrum

~MWB Energy Density

E ~ 50 J
c ~ 1 fm s⁻¹
c ~ 1 km H₀
~ GRB Energy Density

Aug 12-04
GeV–TeV electron emission

- $T_{\text{gyro}} < T_{\text{synchrotron}} \Rightarrow E < \alpha_f^{-1} \sim 100 \text{ MeV}$
- $\Rightarrow C^{-1}$ emission
- If electrons radiate efficiently on time of flight and $\alpha < 1$
- $\Rightarrow$ Modest electron energies in KN regime
- $\Rightarrow n(E^{-1}) \sigma_T R < 10$, $P^2$, relativistic sources quite likely
- Not a great challenge!
- Must beat radiative loss
- Protons?
Particle Acceleration

- Stochastic
- Shocks
- Reconnection
- Electrostatic
- Currents
Traditional Fermi Acceleration

- Magnetic field lazy-electric field does the work!
  - Frame change creates electric field and changes energy
- CR bounce off magnetic disturbances moving with speed $\beta c$
- $|\Delta E/E| \sim \beta$
  - Second order process
- $dE/dt \sim \beta^2 (c/\lambda)E - E/t_{esc}$
  - $t_{acc} > r/L/c\beta^2$
- $\Rightarrow$ Power law distribution function
  - IF $\lambda, t_{esc}$ do not depend upon energy
  - THEY DO!
Shock Acceleration

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

$$f = f_- \quad uf - D \frac{\partial f}{\partial x} = uf_-$$

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

\[ f_+(p) = q p^{-q} \int_0^p dp' p'^{q-1} f_-(p') \]

where

\[ q = \frac{3r}{r-1} \]

\[ \Rightarrow N(E) \sim E^{-2} \text{ for strong shock with } r=4 \]

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 \( \langle v \rangle > V_A \)
  - Instability likely to become nonlinear - Bohm limit

- **Cosmic rays are not test particles**
  - Include in Rankine-Hugoniot conditions
  - \( u=u(x) \)

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

- **What mediates the shock,**
  - Parallel vs Perpendicular
  - Firehose? Weibel when low field? Ion skin depth
Relativistic Shock Waves

- Not clear that they exist as thin discontinuities
  - May not be time to establish subshock, magnetic scattering
  - Weibel instability => large scale field???

- Returning particles have energy $\times \Gamma^2$ if elastically scattered

- Spectrum $N(E) \sim E^{-2.3}$

\[ \frac{2^{-1/2}}{\Gamma} \quad \Gamma \quad \text{eg Keshet & Waxman} \]
Flares and Reconnection

- May be intermittent not steady
- Strong, inductive EMF?
- Hall effects important
- Most energy -> heat
- Create high energy tail
- Theories are highly controversial!
- Relativistic reconnection barely studied at all
Unipolar Induction

\[ V \sim \nu \Phi \sim I Z_0; \quad P \sim V^2 / Z_0 \]

- **Crab Pulsar**
  - \( B \sim 100 \text{ MT}, \quad \nu \sim 30 \text{ Hz}, \quad R \sim 10 \text{ km} \)
  - \( V \sim 30 \text{ PV}; \quad I \sim 3 \times 10^{14} \text{ A}; \quad P \sim 10^{31} \text{ W} \)

- **Massive Black Hole in AGN**
  - \( B \sim 1 \text{ T}, \quad \nu \sim 10 \mu\text{Hz}, \quad R \sim 1 \text{ Pm} \)
  - \( V \sim 300 \text{ EV}; \quad I \sim 3 \text{ EA}, \quad P \sim 10^{39} \text{ W} \)

- **GRB**
  - \( B \sim 1 \text{ TT}, \quad \nu \sim 1 \text{ kHz}, \quad R \sim 10 \text{ km} \)
  - \( V \sim 30 \text{ ZV}, \quad I \sim 300 \text{ EA}, \quad P \sim 10^{43} \text{ W} \)

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Pictor A

Active collimation?
(Implicit) conventional view is that electromagnetic energy dissipated close to source and outflow is fluid dynamical. Perhaps the transport is primarily electromagnetic.

Nonthermal emission is ohmic dissipation of current flow? $10^{17}$ or $10^{18}$ A?
Is particle acceleration ohmic dissipation of electrical current?

- Jets delineate the current flow?
- Organized dominant electromagnetic field
- Shocks weak and ineffectual
- Tap electromagnetic reservoir
  - Poynting flux along jet and towards jet
- Jet core has equipartition automatically
- Unlikely to be direct electrostatic acceleration above GeV-TeV
Let there be Light

- Faraday
- Maxwell
- Initial Condition
- Definition

\[ \frac{\partial B}{\partial t} = -\nabla \times E \]
\[ \frac{\partial E}{\partial t} = \nabla \times B - j \]
\[ \nabla \cdot B = 0 \]
\[ \nabla \cdot E = \rho \]

=> Maxwell Tensor, Poynting Flux

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**Force-Free Condition**

\[ \rho E + j \times B = 0 \Rightarrow E \cdot B = E \cdot j = 0 \]

\[ j = \frac{(\nabla \cdot E) E \times B + (B \cdot \nabla \times B - E \cdot \nabla \times E)B}{B^2} \]

- Ignore inertia of matter \( \sigma = \frac{U_M}{U_P} >> \Gamma^2, 1 \)
- Electromagnetic stress acts on electromagnetic energy density
- Fast and Alfven wave modes
- \( B^2 - E^2 > 0, \) normally
Surfing

- Relativistic wind eg from pulsar
- $V = E \times B / B^2$, $E \rightarrow B$, $V \rightarrow c$
- More generally force-free electrodynamics, limit of MHD when inertia ignorable evolves to give regions where $E/B$ increases to, and sometimes through, unity
- cf wake-field acceleration
Stochastic acceleration

- Line and sheet currents break up due to instabilities like filamentation?
- Create electromagnetic wave spectrum
- Nonlinear wave-wave interactions give electrons stochastic kicks
  - Inner scale where waves are damped by particles
  - Are there local power laws?
Summary

- GeV-TeV emission - inverse Compton scattering by relativistic electrons
  - Protons?
- Shock acceleration likely to be dominant in gas-dominated regions - eg SNR
- Ultrarelativistic outflows may be electromagnetically dominated and require different acceleration mechanisms
  - Stochastic acceleration, Surfing, shear drift acceleration
Abundances

- \((\text{Li, Be, B})/(\text{C, N, O})\)
- \(\lambda \sim 10 \ (E/1\text{GeV})^{-0.6} \ \text{g cm}^{-2}\)
- \(S(E) \sim E^{-2.2}\)
- \(L \sim U_{\text{CR}} M_{\text{gas}} c \lambda^{-1}\)
  \(~ 3 \times 10^{40} \ \text{erg s}^{-1}\)
  \(~ 0.03 \ L_{\text{SNR}}\)
  \(~ 0.001L_{\text{gal}}\)
Sources

- $t \sim 15 \text{ Myr} \ (\text{eg } ^{10}\text{Be etc})$
- $\Delta t > 10^5 \text{ yr} \ (\text{eg } ^{59}\text{Ni/Co})$

Heavy element injection

Ionization Potential

Volatility

Injected as grains?
UHE Cosmic Rays

- Range ~30 Mpc (GZK)
  - luminosity density ~ GCR
- Probably not $\gamma$, Fe?
- Probably not "top down"
- Excess $\gamma$ -ray background
- Sources
  - Isotropy, clustering?
    - permanent not transient? Limits on B
- Need better statistics
- => Auger(S)…
Cosmic Ray Propagation

- Larmor radius: $r_L \sim E_{21}/B$ pc
- Larmor period: $t_L \sim 20 E_{21}/B$ yr
- Resonant scattering by magnetic disturbances (wave modes) with $k \sim r_L^{-1}$
  - Random walk in pitch angle
  - Mean free path: $\lambda \sim (B/\delta B_{res})^2 r_L > r_L$
  - Non-resonant scattering: $\lambda \sim k r_L^2 > r_L$
- Diffusion coefficient: $D \sim \lambda c/3$
  - Bohm Diffusion: $D \sim 0.1 r_L c$
Local Cosmic Ray Sources

- Magnetosphere, Jupiter, Sun
- Interplanetary traveling and standing shocks
- Solar Wind Termination Shock
- Galaxy (SNR, hot stars?)
UHE Cosmic Rays

- $L > r_L/\beta; \beta = u/c$
  - $BL > E_{21}G pc \Rightarrow I > 3 \times 10^{18} E_{21} A!$
  - Lateral diffusion

- $P > P_{EM} \sim B^2 L^2 \beta c/4\pi > 3 \times 10^{39} E_{21}^2 \beta^{-1} W$
  - Powerful extragalactic radio sources, $\beta \sim 1$

- Relativistic motion eg gamma ray bursts
  - $P_{EM} \sim \Gamma^2 (E/e\Gamma)^2/Z_0 \sim (E/e)^2/Z_0$

- Radiative losses; remote acceleration site
  - $P_{mw} < 10^{36}(L/1pc)W$

- Adiabatic losses
  - $E \sim \Gamma/L$

- Observational association with dormant AGN?
"Relativistic Jets"
Pictor A
Wilson et al
UHE Cosmic Rays

- $L > r_L / \beta$; $\beta = u/c$
  - $B L > E_{21} G pc \Rightarrow I > 3 \times 10^{18} E_{21} A!$
  - Lateral diffusion

- $P > P_{EM} \sim B^2 L^2 \beta c / 4 \pi > 3 \times 10^{39} E_{21}^2 \beta^{-1} W$
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Second order acceleration

- $N \sim \beta^{-2}
- L \sim N^{1/2}\lambda \sim \lambda/\beta$
- Similar requirements to shock model
Electrostatic Acceleration

- Establish static potential difference
- Gaps
- Double Layers
- Aurorae
- Pulsars
- $P_{EM} > (E/e)^2/Z_0$
Pulsar Wind Nebulae

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
Problems

- Unlikely to make full potential difference available for electrostatic acceleration
  - 1TV creates pair discharge in pulsars
  - 1GV is all that is needed in AGN
  - The larger the EMF the harder it is to dissipate the current
Solar Flares

Magnetic instability and reconnection

SOHO YOHKOH Trace

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
Magnetars

- Neutron stars with $10^{14-15}$G field
- Repeating gamma ray sources
- Magnetically powered
- Radiative and adiabatic losses severe?
- Galactic source as extragalactic, magnetar luminosity density too low
- Fe?
Magnetars

- Slowly spinning, high field neutron star
- May spin rapidly at birth.

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Shear Layer

- \( E_z = \sinh kz; \quad B_y = \cosh kz; \quad V_x = -c \tanh kz \)
- \( \rho E + j \times B = 0 \)
- Analytic solutions
- eg \( u_x = -(1-k^2)^{1/2}t; \quad u_z = (1-k^2)^{1/2}/k \)
- Electric, gradient, polarization drifts
- Energy bounded by electrostatic potential difference
- \( P_{em} > (E/e)^2/Z_0 \)
Relativistic Outflows

- Enormous particle energies possible in principle through “magnetic slingshot”
- Can particles slide smoothly along field lines?
- Radiative losses
Summary

- Basic astrophysical accelerators - shocks, holes, magnetars, winds - not ruled out
- All pose serious problems
- New idea or top down solution (also hard)
- Auger should rule out many possibilities
General References

- Ong (2003) SSI03 vugrafs
Acceleration Mechanisms

- **Statistical Acceleration**
  - Shock Waves
- **Electrostatic Acceleration**
  - Unipolar Induction
- **Flares**
  - Magnetars
- **Surfing**
  - Relativistic Outflows