Particle Acceleration in Astrophysical Shocks

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Topics Covered

- Overview of shock acceleration and its cosmic sites;
- Achieving the energy for UHECRs;
- Population constraints: global energetics;
- Spectral issues: can acceleration models generate the right distributions?
- *If time permits*: Testing grounds for shock acceleration theory: the heliosphere.
Complete Cosmic Ray Spectrum

- Galactic CRs
- Extragalactic CRs
Galactic Cosmic Rays

- SNR origin?
- Solar modulation reduces flux below 1 GeV/nucleon;
- Instrumental data spread increases near CR knee;
- Non-linear models of acceleration required for SNRs: abundances are not solar;
- [Ellison et al. 1997]
Cassiopeia A Supernova Remnant
Spectral Modeling of SNR Shell Emission

Berezhko & Voelk (2006)
High Energy Cosmic Ray Spectrum

From Nagano & Watson (2000)
High Energy Cosmic Ray Accelerators: Radio Galaxies like Cygnus A
Multi-wavelength Flaring in the Blazar Markarian 421

$z=0.031$

Blazejowski et al. (2005)
Gamma-Ray Bursts: Relativistic Outflows
Magnetars - high B Neutron Stars

Good for UHECR production since high B guarantees very large induced E fields + small gyroradii.
Achieving the $10^{20}$ Energies of UHECRs

- **First criterion** for viability of bottom-up acceleration models:

- What conditions are required in sources in order to accelerate up to the observed UHECR energies?
Baring & Summerlin (2006)
For non-relativistic parallel (\(\Theta_{Bn1} = 0^\circ\)) shocks, in the diffusion approximation (= isotropy), the acceleration time is (e.g. Forman, Jokipii & Owens 1974)

\[
\tau_{acc}^{NR} = \frac{3}{u_1 - u_2} \int_{p_i}^{p} \left( \frac{\kappa_1}{u_1} + \frac{\kappa_2}{u_2} \right) \frac{dp'}{p'},
\]

so that

\[
\tau_{acc}^{NR} \approx \frac{0.1}{\beta_1^2} \frac{E_{\text{TeV}}}{B_{\text{Gauss}}} \text{ sec.}
\]

- Hence AGNs can accelerate to UHECRs energies in days if \(B \sim 100\) Gauss.
- For GRBs, the variability timescale is much shorter, thereby requiring much higher fields, \(B \sim 10^4\) Gauss.

Note: kappa is spatial diffusion coefficient

\[
\kappa = \frac{1}{3} \lambda \nu
\]
Cosmic Ray Acceleration: Fields and Spatial Scales

- B-R phase space - after Hillas (1984);
- Based on diffusion theory at non-rel. shock using Bohm limit ($mfp \sim c r_g / u$);
- **Gyroresonant interactions operate**;
- AGN jets, GRBs and magnetars are best candidates for UHECR production.
Acceleration Times:
Pitch Angle Diffusion

$\Theta_{B_1} = 0^\circ$, $r = 3$

$B = 1$ G

$\Gamma_r \beta_1 = 0.1$

$\Gamma_r \beta_1 = 10$

$\tau^{NR}(u_1 = c)$

(see Baring 2002)
Inferences of SNR B Fields using CHANDRA

- Spatially-resolved line and continuum spectroscopy by CHANDRA X-ray Observatory: probes B field amplification in SNRs;
- Case study: SN1006 (Long et al. 2003), a clean system, i.e. early Sedov-phase (deduced from radio proper motions), simple environment (high latitude source), with well-defined shell;
- Spatial mapping of non-thermal synchrotron emission details magnetic field contrast across quasi-perpendicular shock.
- Thermal interior (red) and non-thermal shell (blue).

SN1006

Red: 0.5-0.8 keV; 
Green: 0.8-1.2 keV; 
Blue: 1.2-2.0 keV.
Spatial Brightness Profiles in SN1006

- Brightness profiles are much broader for thermal X-rays and radio synchrotron than for non-thermal X-rays;
- Narrowsness of profiles along scans argues for shocks ⊥ to sky, i.e. no projectional smearing;
- Flux contrast ratio (< 1.5%) for upstream to downstream 1.2-2.0 keV suggests $B_\parallel / B_\perp \gg 4$, i.e. greater than standard MHD compression in high $M_\Sigma$ shocks (Cas A offers similar picture: Vink & Laming 2003);
- Non-thermal X-ray width implies connection between cosmic rays and B-field amplification.

Thin black line: 0.5-0.8 keV; Black line: 1.2-2.0 keV; Grey line: 1.4 GHz radio.

Long et al. 2003
Modeling Field Amplification

- **Lucek & Bell (2000)** proposed that high energy cosmic rays (CRs) in strong shocks could non-linearly amplify $B$ when streaming upstream;

- Work done on Alfven turbulence scales as the CR pressure gradient: $\frac{dU_A}{dt}=v_A \frac{dP_{CR}}{dx}$;

- Field amplification should then scale as $(dB/B)^2\sim M_A P_{CR}/\rho u^2$; works for high $M_A$ strong shocks that generate large $P_{CR}$;

- Idea needs simulational vindication. Bell has been working on this, but progress is needed.
Population Constraints: Global Energetics

- **Second criterion** for viability of bottom-up acceleration models:
  - Can the putative sources/sites for acceleration provide UHECRs in sufficient numbers?
  - And within the GZK horizon, if needed?
High Energy Cosmic Ray Spectrum

From Nagano & Watson (2000)
Gamma-Ray Bursts and UHECRs

- Possibility of GRBs generating UHECRs was raised by Milgrom & Usov (1995), Waxman (1995) and explored in later papers;

- Need to match the UHECR flux at $10^{20}$ eV
  - $E^3 \, dn/dE \sim 1.2 \times 10^{21} \, \text{eV}^3 \, \text{cm}^{-2} \, \text{s}^{-1}$;

- UHECR energy density is:
  - $U_{\text{CR}} = 2 \times 10^{-21} \, \text{ergs cm}^{-3}$;

- GRBs liberate $L_{\text{ph}} \sim 10^{51} \, \text{ergs}$ in photons, and perhaps $L_{\text{CR}} \sim f_{\text{CR}} \, L_{\text{ph}}$ in UHE cosmic rays;

- Since $f_{\text{CR}} = f(E_{\text{CR}})$, both $f<1$ and $f>1$ are possible;

- GRBs occur at rate of $1/\text{galaxy}/10^7 \, \text{years}$;
Gamma-Ray Burst Redshift Distribution

BeppoSax, HETE, INTEGRAL + Swift

October 2005

XRFs, XRRs & GRBs
XRFs only
Swift bursts only
Gamma-Ray Bursts and UHECRs (ctd.)

- Redshift distribution sets spatial density of GRB hosts; short bursts are fewer, but on average nearer;
- In the GRB volume of ~\((10 \text{ Gpc})^3\) in a Hubble time, the produced cosmic ray energy
  \[ U_{\text{CR,GRB}} = 4.7 \times 10^{-21} f_{\text{CR}} \text{ ergs cm}^{-3} \];
- \( \Rightarrow \) GRBs can populate UHECRs at the required rate if their luminosity in each source is comparable to \( L_{\text{ph}} \)
  i.e. 0.1% of total explosion energy budget;
- Very reasonable constraint: \( L_{\text{CR}} > L_{\text{ph}} \) follows from radiation if \( n_{\text{CR}} \sim n_e \), and then UHECR budget
  depends on acceleration spectrum;
- GLAST will probe energetics of GRB population.
Active Galaxies and UHECRs

- AGNs (Seyferts, blazars, radio galaxies, quasars) have $L_{ph} \sim 10^{42} - 10^{47} \text{ erg/sec}$; [$10^{44} \text{ erg/sec}$ now assumed]
- In the GZK volume of $\sim(30 \text{ Mpc})^3$ in a Hubble time, the AGN-produced cosmic ray energy density is
  - $U_{CR,AGN} = 1.7 \times 10^{-24} f_{CR} \text{ ergs cm}^{-3} \text{ per AGN}$;
- $\Rightarrow$ need at least $10^3$ AGNs per GZK volume ($z=0.01)^3$ for them to populate UHECRs if $L_{CR} \sim 10^{44} \text{ erg/sec}$;
- N.B. flaring duty cycle reduces $f_{CR}$;
- Less than Hubble time available? Higher $z$ quasars generally have higher $L_{ph}$;
- Energetic AGN populations (blazars and quasars), their number densities and duty cycles will be surveyed by GLAST after launch, late 2007.
Spectral Issues for UHECR Generation

- **Third criterion** for viability of bottom-up acceleration models:

- Can shock acceleration in putative sources generate particle distributions commensurate with the UHECR spectrum, *and in concord with radiation signatures for the sources?*
Distinguishing Properties of Relativistic Shocks

- For small angle scattering, ultra-relativistic, parallel shocks have a power-law index of 2.23 (Kirk et al. 2000);
- Result obtained from solution of diffusion/convection equation and also Monte Carlo simulations (Bednarz & Ostrowski 1996; Baring 1999; Ellison & Double 2004);
- Power-law index is not universal: scattering angles larger than Lorentz cone flatten distribution;
- Large angle scattering yields kinematic spectral structure;
- Spectral index is strongly increasing function of field obliquity.
Relativistic Shocks: Spectral Dependence on Scattering

- Deviations from "canonical" index of 2.23 (Bednarz & Ostrowski 1998; Kirk et al. 2000; Baring 1999) occur for scattering angles outside Lorentz cone;
- Large angle scattering yields kinematically structured distributions;
- (e.g., Baring 2005)
Oblique Shock Geometry

upstream flow velocity $u_0$

downstream flow velocity $u_2$

$\theta_{B2}$

$\theta_{u2}$

$B_0$

$B_2$

shock front

Gaussian volume
- Increasing upstream B-field obliquity and/or ratio of mean free path to gyroradius steepens the continuum (e.g. Bednarz & Ostrowski 1998; Ellison & Double 2004; see also Kirk & Heavens 1989).
High Energy Emission in EGRET Bursts

A Selection of EGRET Bursts

\[ \log_{10}[\text{Flux}(>E), \text{photons} \text{ cm}^{-2}\text{sec}^{-1}] \]

\[ \log_{10}[\text{Energy, MeV}] \]

Baring (2006)
Synchrotron radiation (preferred paradigm) fits most burst spectra - index below 100 keV is key (Preece et al. 1998 "line of death") issue;

But, underlying electron distribution is **predominantly non-thermal**, i.e. unlike a variety of shock acceleration predictions (e.g. PIC codes, hybrid codes, Monte Carlo simulations): see Baring & Braby (2004).
3D PIC Plasma Shock Simulations

- Nishikawa et al. (ApJ 2006): e-p (left panels) and pair shocks have great difficulty accelerating particles from thermal pool (green is Lorentz-boosted relativistic Maxwellian), dominated by electromagnetic thermal dissipation;
- Medvedev (priv. comm.): Weibel instability simulation with the upper energy cutoff continuously growing in time, i.e. no steady-state;
- In PIC simulations, non-thermal power-law is at best, not prominent.
Shock Acceleration, Sources & CRs: What do we know?

- **Maximum Energy**: the key parameter is the magnetic field strength in the (diffusive) shock environ - 
  - Active galaxies (jets and radio lobes), gamma-ray bursts and magnetars are best candidates;
- **Global Energetics**: population supply for UHECRs OK for gamma-ray bursts, a little harder for AGNs - 
  - Source space density and CR production efficiency relative to neutrinos and radiation are key unknowns;
- **Spectral Issues**: relativistic shocks in GRBs and AGN can only generate \( \sim E^{-3} \) CR distribution if either quasi-parallel or possessing strong field turbulence - 
  - GRB and AGN non-thermal radiation are consistent with \( \sim E^{-3} \) electron (and therefore CR?) distributions.
Shock Acceleration, Sources & CRs:
Where are we going next?

- Need to see evidence of ions in discrete sources, either SNRs, AGNs, GRBs or all;
- Need to fully understand relationship between electron acceleration (probed by radiation) and ion energization (i.e. injection);
- Need to understand character of relativistic shocks in more detail (e.g. do non-linear effects operate?);
- Need to ascertain under what conditions magnetic field amplification occurs;
- GLAST and TeV-band Cherenkov telescopes will provide huge advances on individual sources;
- Auger and other CR arrays will propel the UHECR database, while ICECUBE, etc probe neutrinos.
Shocks in the Heliosphere: Testing Grounds for Acceleration Theory

- Planetary bow shocks: usually strong, with nonlinear acceleration being important.
- Interplanetary travelling shocks: usually low Mach number, with a big contribution from interstellar pick-up ions;
- Solar wind termination shock: site of anomalous cosmic ray generation [Voyager I was there, 2005?].