UHECRs and Multiple Shock Acceleration in Active Galactic Nuclei Jets

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Outline

• Cosmic ray spectrum - sources

• AGN Jets and multiple shocks

• Shock acceleration mechanism – non relativistic/relativistic

• Simulation method and study results

• Summary and conclusions
Cosmic ray spectrum
Cosmic Ray Spectra of Various Experiments
Ankle \(1 \text{ part km}^{-2} \text{ yr}^{-1}\)

Knee \(1 \text{ part m}^{-2} \text{ yr}^{-1}\)

Toe \(1 \text{ part km}^2 \text{ cent}^{-1}\)

Non-relativistic sources

Galactic

Relativistic sources

Extragalactic
Ultra High Energy Cosmic Rays: At the ‘toe’
### Ultra High Energy Cosmic Rays: At the ‘toe’

<table>
<thead>
<tr>
<th></th>
<th>TA</th>
<th>Auger</th>
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</thead>
<tbody>
<tr>
<td>$\gamma_1$</td>
<td>$3.33 \pm 0.04$</td>
<td>$3.27 \pm 0.02$</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>$2.68 \pm 0.04$</td>
<td>$2.68 \pm 0.01$</td>
</tr>
<tr>
<td>$\gamma_3$</td>
<td>$4.2 \pm 0.7$</td>
<td>$4.2 \pm 0.1$</td>
</tr>
<tr>
<td>$\log(E_1/eV)$</td>
<td>$18.69 \pm 0.03$</td>
<td>$18.61 \pm 0.01$</td>
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<tr>
<td>$\log(E_2/eV)$</td>
<td>$19.68 \pm 0.09$</td>
<td>$19.41 \pm 0.02$</td>
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B. Stokes [TA Coll.], icrc1297

F. Salamida [Auger Coll.], icrc893
Relativistic sources
Active Galactic Nuclei

$\mathcal{L} \sim 10^{46} \text{ erg/s}$

$\Gamma \sim 10-50$

$E_{\text{max}} \sim 10^{19-21} \text{ eV}$

e.g. Lynden-Bell ’69,
Meier ’03, Georganopoulos ’05,
Marcher et al. ’08, ’10 etc.
AGN Jets
Individual or multiple shock acceleration

Sanders, 1983
Bridle&Perley, 1984
Melrose&Pope, 1993
Jones et al., 2001
Tregillis et al., 2004
Agudo et al. 2001
Marscher et al., 2008, 2010
Walker et al., 2008
Britzen et al., 2008
Keppens et al., 2008
Becker&Biermann, 2009
Nakamura et al., 2010
Diffusive shock acceleration

- Test particle - diffusion - $n$ acceleration shock cycles
  \[ E_n = (x + 1)^n \cdot E_0 \]
- Energy gain: fraction of initial energy
  \[ \Delta E = E - E_0 = x \cdot E_0 \]
- Average energy gain per collision:
  \[ \langle \Delta E / E \rangle \approx (2V / c) \]
- Leading to a power-law energy behaviour
  \[ N(>E) = \sum_{i=n}^{\infty} (1 - P_{esc})^n(E) = \ldots \propto E^{-\sigma} \]
  \[ \sigma = (r+2)/(r-1), \quad r = V_1/V_2 = (\gamma + 1) / (\gamma - 1) \]
  for mono-atomic gas:
  \[ \gamma = 5/3 \rightarrow r = 4 \rightarrow E^{-2} \]

Note: for non-relativistic shocks \( \rightarrow \sigma \) is ‘constant’, independent of scattering media or shock inclination

(e.g. Krymskii ‘77, Bell ’78, Drury ’83)
Shock-drift acceleration
What we know about individual relativistic shock acceleration

- Spectral index ($\sigma$) is not universal (observations confirm)
- $\sigma$ depends on: gamma flow speed, shock inclination
- $\sigma$ critically depends on the scattering modes (turbulence of the media)
- Relativistic shocks can generate a multitude of spectral forms (smooth, structured or concave)
- Faster shocks generate flatter distributions:
  - Subluminal (quasi-parallel) shocks efficient accelerators $\rightarrow \sim 10^{21}$ eV (UHECRs)
  - Superluminal (quasi-perpendicular) shocks not efficient $\rightarrow \sim 10^{15}$ eV
    - Large angle scattering ($\theta < \pi$): flatter distributions
    - Pitch angle diffusion ($\theta < \pi$): steeper distributions (but still flat)

(Meli & Quenby 2003a,b,2005; Meli et al. 2008,2009; Meli, 2011; etc)
Multiple relativistic shock acceleration
One can define a conical shock as a surface formed by a *sheaf of plane oblique shocks* all making the same angle $\eta$ to the upstream flow or jet axis (the flow upstream and downstream is always highly oblique on the surface of the shock).
Overlook

Facts: The best power-law fit to UHECRs suggests an $E^{-2.4} - E^{-2.7}$

(de Marco & Stanev, 2006; Berezinsky et al. 2009)

$\rightarrow$ Total power of: $10^{48.5} \times D^2$ erg/sec

$\rightarrow$ 1/3 of the total jet power can be supplied, then for UHECRs

max. power $10^{42.5}$ erg/sec ($\text{CenA}$) and $10^{44.5}$ erg/sec ($\text{M87}$)

(Whysong & Antonucci, 2003; Adbo et al. 2009) ...

Motivation/Proposal: Multiple shock acceleration (e.g. Sanders 1983)

in jets (e.g. Marsher et al. 2008) with a single particle injection (e.g. Sunyaev 1970) $\rightarrow$ depleted and flatter spectra may solve the acquiring power problem, giving considerable insights on the resulted primary cosmic ray spectra and consequent radiation in AGN jets

Meli & Biermann (2011)
Repeated conical shocks with opening angles $a$, $b$, $c$, $d$, in an AGN jet

Meli & Biermann (2011)
Simulation method*

- Injection of relativistic particles upstream - scattering in respective fluid frames of four consecutive oblique shocks
  \[ L = - \lambda \cdot p \ln (r) \] (Cashwell & Everett, 1959)
- Random generation of phase:
  \[ \phi = 2 \pi \times r \]
- Probability to move a distance \( DL \) along the field lines at pitch angle \( \theta \) before it scatters: \( \text{Prob}(DL) = \exp \left( -\frac{DL}{\lambda} \right) \)
- Scattering can be treated via pitch angle diffusion approach
  (e.g. Kennel & Petscheck '66, Forman et al. '74, Jokipii '87, Quenby & Meli '05, Meli & Biermann '06)
  \[ \kappa_\perp = \kappa_\parallel \cdot (1 + (\lambda/r_I)^2)^{-1} \]
  \[ \lambda = 10r_I \]
  \[ \kappa = \kappa_\parallel \cos^2 \psi + \kappa_\perp \sin^2 \psi \]
  \[ 1/\Gamma \leq \delta \theta \leq 10/\Gamma, \phi \in (0, 2\pi) \]
- Fully relativistic Lorentzian transformations
- \( P_{\text{esc}} (p < p_0) \) (probability of escape) \( \text{Melrose & Pope (1993) - decompression effect} \)

*(based on the established relativistic numerical code of Meli & Quenby 2003)
An overall view of the proposed jet topology and geometries (not to scale) simulation framework ($\lambda$ denotes the distance traveled by a particle proportional to its energy).
Simulation results
\( \Gamma_{sh} = 45, 15 \)

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Summary - Conclusions I

• We performed simulations of multiple relativistic particle shock acceleration in AGN jets as an application to observations and theoretical claims

• The first two shocks from an assumed repetitive shock sequence in an AGN jet, establish power-law spectra with $\sigma \sim 2.7 - 2.2$ (subluminal) and $\sigma \sim 2.8 - 2.4$ (superluminal), reaching energies up to $\sim 10^{17}$ eV (assuming protons - no losses)

• The following two shocks of the sequence push the particle spectrum up in energy to $\sim 10^{20}$ eV, with flat distributions $\rightarrow$ flatter than individual shocks. We observe a flux depletion at lower energies, forming characteristic depleted spectra

• With a smaller number of particles (single injection) one can achieve very high energies, thus the puzzling power problem of AGN fed into the very high energy cosmic rays would not be necessary
Consequences - Conclusions II

• **A single source** (> $10^9$ GeV) within 50 Mpc: (Cen A is within 3-5 Mpc, M87 is within 16-17 Mpc) → additional losses to steepen the spectra (protons + heavier nuclei? (e.g. Aloisio et al. 2011))

• **Multiple sources** (> $10^9$ GeV) within 50Mpc: (which we do not see yet) → spectral superposition requirement over the different shock profiles shown in this work (note: there maybe many very high energy particle extragalactic sources, but it is hard to believe that they could all be sources of *only* heavy nuclei)

• The results could explain variabilities of gamma-ray or X-ray spectra observed in extragalactic sources (electrons accelerating and radiating), within different time frames (observation angle) during the acceleration sequence of more than one shocks

Thank you
Back up slides
Left: A conical shock as viewed in the normal-shock-frame (NSH), where the vector of the upstream flow velocity is parallel to the shock normal. The magnetic field is oblique to the shock surface by default, so here, in order to facilitate our view clearer on the geometry of a conical shock in a Cartesian system, we show the case of the magnetic field vector (B), perpendicular to the jet axis thus inclined to the shock normal. Right: The same conical shock as it viewed after the Lorentz transformation into the de Hoffmann-Teller frame. In this frame the velocity vector is placed parallel to the vector of the magnetic field as was viewed in the frame above. By this transformation there is no electric field E in this frame. Viewing closely the topology in NSH, one sees that $90^\circ = i + a$ and $90^\circ = \psi + i$, then $\psi = a$. 
One can define a conical shock as a surface formed by a sheaf of plane oblique shocks all making the same angle $\eta$ to the upstream flow or jet axis (the flow upstream and downstream is always highly oblique on the surface of the shock).
Fig. 2.—Emergent steady-state radiation spectra from a finite sphere with a central soft photon source. Parameters and units are as Fig. 1, except that curves are labeled by sphere radius in units of criticality radius $(\pi/2)(mc^2/3kT)^{1/2}$. 