High energy aspects of Galactic and extragalactic jets

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Characteristic blazar SED

\[ L_{\gamma,\text{iso}} \sim 10^{49} \text{ erg/s} \]

\[ L_{\gamma} \sim 10^{46.5} \text{ erg/s} \]

\( \gamma \)-ray power comparable to input into radio lobes; high radiative efficiency?
**blazars**

- ~ 100 $\gamma$-ray loud blazars are cataloged
- Apparent $\gamma$-ray luminosities exceed $10^{49}$ erg/s in the most powerful sources (dominate the bolometric luminosity)
- Lorentz factors inferred from SL motions > 10 (beaming factors >100)
- Highly variable (flare amplitudes > 10 have been observed over time scales of hours and even less): small size source
- Contribution to the $\gamma$-ray background?

**Micro-Q**

- One association with an EGRET source ??
- MQs may be unresolved at small viewing angles.
- Is there a subclass of MQs with higher $\Gamma$ ?
- What fraction of XRBs exhibit MQ features?
Some open questions

- jet composition?
- on which scales the bulk energy dissipates? (also relevant for collimation)
- acceleration mechanism? efficiency, max energy
- sources of UHECRs and neutrinos?

UHECR: top-down or bottom up?

If UHECRs are produced in astrophysical sites then emission of high energy neutrinos is expected
What can neutrinos tell us?

Neutrinos can probe the smallest scales that are opaque to most other bands

Electromagnetic radiation reflects mainly the leptonic component

- jet composition !!
- dissipation on very small scales
  - what fraction of the bulk energy dissipates?
  - mechanism?
- acceleration of protons
  - rate and efficiency

Source parameters

<table>
<thead>
<tr>
<th>Source parameter</th>
<th>GRBs</th>
<th>AGN</th>
<th>Micro-Q</th>
<th>TypeII SN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma$</td>
<td>$10^2 - 10^3$</td>
<td>5 – 20</td>
<td>2 – 5</td>
<td>?</td>
</tr>
<tr>
<td>Power ($L_j$) (erg/s)</td>
<td>$10^{50}$</td>
<td>$10^{44} - 10^{47}$</td>
<td>$10^{38}$ Minimum p analysis</td>
<td>$10^{41}$ Effective</td>
</tr>
<tr>
<td>Timescale</td>
<td>Seconds</td>
<td>Hours to years</td>
<td>Days</td>
<td>Hours</td>
</tr>
</tbody>
</table>
B fields inside jets

\[ \frac{c(\Gamma B)^2}{4\pi} \pi (\theta r)^2 = \xi L_j \]

AGNs: \[ B \approx 10^3 \frac{(\xi L_{j46})^{1/2}}{(\theta \Gamma) r_{i5}} \text{ G} \]

MQs: \[ B \approx 10^6 \frac{(\xi L_{j38})^{1/2}}{(\theta \Gamma) r_8} \text{ G} \]

Limits on proton energy

\( \varepsilon_p \) - comoving proton energy

Confinement: \[ \lambda_r = \frac{\varepsilon_p}{eB} < r \theta \]

\[ \Rightarrow \varepsilon_p \leq 5 \times 10^{16} \xi^{1/2} L_{j38}^{1/2} \Gamma^{-1} \text{ eV} \]
### Limits on max proton energy in jets

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<tbody>
<tr>
<td>$\Gamma$</td>
<td>$10^2$</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>$L_j$ (erg/s)</td>
<td>$10^{50}$</td>
<td>$10^{46}$</td>
<td>$10^{38}$</td>
</tr>
<tr>
<td>$\frac{\epsilon_p (eV)}{\xi^{1/2}}$ (in rest frame)</td>
<td>$5 \times 10^{20}$</td>
<td>$5 \times 10^{19}$</td>
<td>$2 \times 10^{16}$</td>
</tr>
<tr>
<td>$\epsilon_p \Gamma$ (eV)</td>
<td>$\sim 10^{22}$</td>
<td>$\sim 10^{20}$</td>
<td>$\sim 10^{16}$</td>
</tr>
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</table>

- For AGNs (FSRQs only) the proton energy is limited by losses due to photopion production, and is well below the confinement limit.

### The basic picture

- **Target photons:** synchrotron and/or external
- **Composition:** $e^\pm$ or $e-p$?
- **Electromagnetic:** synchrotron, IC, pair production
- **Hadronic:** photopion production, nuclear collisions
External radiation field

\[ \frac{dM}{dt} = 0.4 \frac{dM_{\text{rad}}}{dt} \]

\[ \log(M) = 6.7 \]

\[ \chi^2 = 0.41 \]

\[ \log(V) \text{ (Hz)} \]

\[ 45.0 \]

\[ 44.5 \]

\[ 44.0 \]

\[ 43.5 \]

\[ 43.0 \]

\[ 42.5 \]

\[ 42.0 \]

\[ 15 \]

\[ 16 \]

\[ 17 \]

\[ 18 \]

External component – a comparison

\[ L_s \sim 10^{38} \text{ erg/s} \]

\[ vF_{\nu} \]

\[ \epsilon_s \]

\[ \sim 1 \text{ keV} \]

MQ

\[ \sim 10 \text{ eV} \]

AGN

\[ vF_{\nu} \]
**Spectrum of synchrotron photons**

- Energy distribution of injected electrons: thermal + power law tail
- Comoving energy of thermal electrons $m c^2 \gamma_s$: $\gamma_s \sim 0.5 (\Gamma_s - 1) (m_p / m_e)$
- $\varepsilon_{\text{syn, peak}} = (eB / m_e c) \gamma_s^2 = 50 (\xi_{-1} L_{38})^{1/2} (r_{8 \Gamma})^{-1} (\theta / 0.1)^{-1} \text{keV}$

MQ: 20 –50 KeV  
AGN: 1–5 eV

**Gamma-ray emission region**

$\gamma$ threshold: $\varepsilon_{\text{thr}} = 0.25 (\varepsilon_\gamma / 1 \text{GeV})^{-1} \text{keV}$

Target photon field: $\varepsilon_s \frac{dn}{d\varepsilon_s} \propto r^{-2} \varepsilon_s^{-\alpha}$

Gamma-sphere: $r_\gamma (\varepsilon_\gamma) \propto \varepsilon_\gamma^\alpha$

Not applies to BL-LAC – consistent with rapid variability of TeV emission
Neutrino emission: processes

Photomeson production

\[ p + \gamma \rightarrow \pi^+ + n \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \nu_\mu \]
\[ p + \gamma \rightarrow \pi^0 + p \rightarrow \gamma + \gamma \]
\[ \sigma \sim 0.1 \text{ mbn} \]
\[ \epsilon_\pi \approx 0.2 \epsilon_\rho \]

Inelastic nuclear collisions

\[ p + n \rightarrow p + p + \pi \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \nu_\mu \]
\[ p + n \rightarrow n + n + \pi^\pi \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \nu_\mu \]
\[ p + n \rightarrow p + n + \pi^0 \rightarrow \gamma + \gamma \]
\[ \sigma \sim 50 \text{ mbn} \]

Photo \( \pi \) production: threshold

- Threshold photon energy for photopion production in the nucleon rest frame:
  \[ \epsilon_\gamma^{\text{rest,thr}} = m_\pi (1 + m_\pi / 2m_N) \approx 160 \text{ MeV} \quad \gamma \rightarrow \nu_N \]

- For a background radiation field with photon energy \( \epsilon_\gamma \), the corresponding threshold energy of the nucleon measured in the Lab frame is
  \[ \epsilon_{p,thr} = \frac{m_\pi (m_N + m_\pi / 2)}{\epsilon_s} \approx 10^{17} \left( \frac{\epsilon_s}{1 \text{ eV}} \right)^{-1} \text{ eV} \quad \gamma \rightarrow \nu_N \]

Note: typical CMB photon energies are \( \epsilon \sim 10^{-3} \text{ eV} \Rightarrow \text{GZK “cutoff” at } \sim 10^{20} \text{ eV} \)
Photo $\pi$ production: relevant timescales

decay time: $t_\pi = 2 \times 10^{-8} \gamma_\pi$ sec

For: $\varepsilon_\pi \approx 0.2 \varepsilon_p$, $\varepsilon_{p,max} = eBr\theta$

cooling time: $\frac{t_{syn}}{t_\pi} \approx 10^{-7} \frac{\theta^2 r_{15}}{(\varepsilon_{p,max}/10^{21} \text{ eV})^4}$

Conclusion: if protons are accelerated to energies in excess of $5 \times 10^{18} (\theta/0.1)^{1/2} r_{15}^{1/4} \text{ eV}$, then the charged pions will lose their energy before decaying. (Levinson & Waxman)

Relations between photo-$\pi$ production and pair production

Same target photons for both processes.

$$\frac{\tau_{p\gamma}(\varepsilon_p)}{\tau_{\gamma\gamma}(\varepsilon_\gamma)} = \left(\frac{\varepsilon_p}{1.2 \times 10^6 \varepsilon_\gamma}\right)^{\alpha} \frac{\sigma_{p\gamma}}{\sigma_{\gamma\gamma}} \approx 10^{-3}$$

Conclusion: regions of significant photo-$\pi$ opacity are opaque to emission of high-energy gamma rays.

BL-Lac: $\varepsilon_\gamma > 1 \text{ TeV}$ + rapid variability of the Tev emission implies very small photo-pion opacity.

Not good candidates for neutrino astronomy!
Threshold energy and opacity: external photons

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<td>$\varepsilon_{p,\text{thr}}$ (eV)</td>
<td>$10^{14}$</td>
<td>$10^{15} - 10^{16}$</td>
</tr>
<tr>
<td>$\tau_{p\gamma}$</td>
<td>$&lt; 1 , r_g^{-1}$</td>
<td>$\sim 1 - 100 , r_{15}^{-1}$</td>
</tr>
<tr>
<td>$\varepsilon_\nu$</td>
<td>$\sim 1 \text{ TeV}$</td>
<td>$\sim 50 \text{ TeV}$</td>
</tr>
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</table>

Contribution of the target synchrotron field

MQ: \[ \tau_{p\gamma} \approx 1 \left( \varepsilon_p / \varepsilon_{p,\text{peak}} \right)^{1/2} \leq 30; \varepsilon_p > \varepsilon_{p,\text{peak}} \]

AGN: \[ \tau_{p\gamma} \approx 10^3 \left( \varepsilon_p / \varepsilon_{p,\text{peak}} \right); \varepsilon_p < \varepsilon_{p,\text{peak}} \]
Dr. Amir Levinson, Tel Aviv University (KITP Jets & Disks Program 5-09-05) High-Energy Aspects of Astrophysical Jets

Characteristic scales

- $r_0^2 = \frac{v_0^2}{c^2} \Delta t = r_0^2$ - smallest radius of shock formation
- $r_\gamma$ - Edge of pi interaction region
- $r_\gamma(1 \text{ GHz})$ - photosphere of GHz emission

Neutrino production region

Spectrum: $d\nu/d\nu \propto \nu^{-2}$ (thick target)

$\nu \sim 5\% \nu_p \Rightarrow \begin{cases} \text{MQ: } 1 \text{ TeV} < \nu_p < 100 \text{ TeV} \\ \text{AGN: } 10 \text{ TeV} < \nu_p < 1000 \text{ TeV} \end{cases}$

Flux: $F_\nu \approx 10^{-9} \left(\frac{\nu}{1 \text{ GeV}}\right)^{3/2} L_{28} (D/3 \text{ kpc})^{2/3} \text{ erg/cm}^2/\text{s}$

Number of events in a km$^3$ detector:

$N_\nu \approx 0.2 \left(\frac{\nu}{1 \text{ GeV}}\right) (\delta^2/\Gamma) (D/3 \text{ kpc})^2 (E/10^{15} \text{ erg})/A/1 \text{ km}^2$
Detection ?

Blazars: ~ 1 event per year at Z~1 for the most powerful sources (e.g, 3C279) (Atoyan & Dermer 2002)

MQ: a few events from a powerful flare like the 1994 event seen in GRS 1915 (Levinson & Waxman 2000; Distefano et al. 2002)

Perhaps somewhat optimistic?
But !! recall that the large gamma-ray fluxes detected from blazars by EGRET came as surprise

THE END