High energy aspects of Galactic and extragalactic jets

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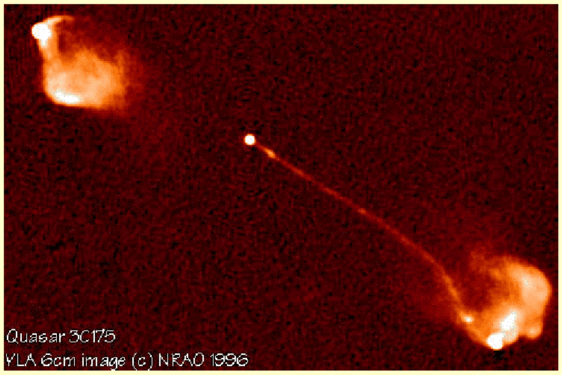
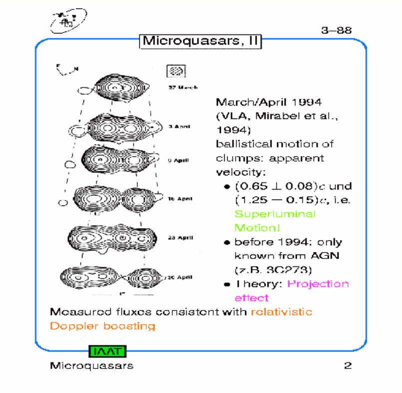

Quasar 3C175
VLA 6cm image (c) NRAO 1996



3–88

Microquasars, II

March/April 1994 (VLA, Mirabel et al., 1994) ballistical motion of clumps: apparent velocity:

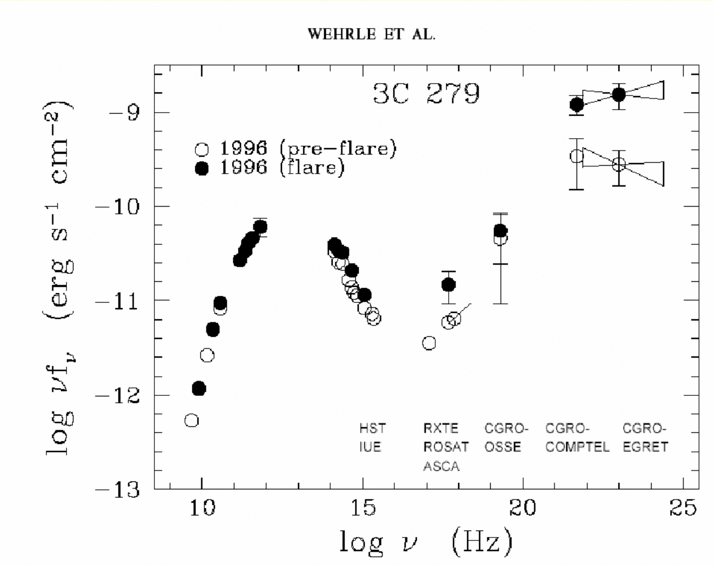
- $(0.65 \perp 0.08)c$ und $(1.25 - 0.15)c$, i.e. Superluminal Motion!
- before 1994: only known from AGN (z.B. 3C273)
- Theory: Projection effect

Measured fluxes consistent with relativistic Doppler boosting

IAAT

Microquasars 2

Characteristic blazar SED



$L_{\gamma,iso} \sim 10^{49}$ erg/s

$L_{\gamma} \sim 10^{46.5}$ erg/s

γ-ray power comparable to input into radio lobes; high radiative efficiency?

blazars

- ~ 100 γ-ray loud blazars are cataloged
- Apparent γ-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 γ-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 Γ ?
- 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?

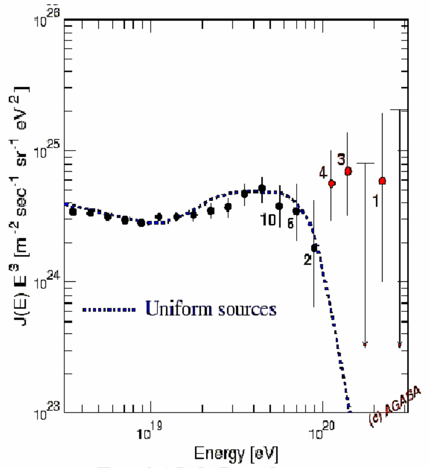
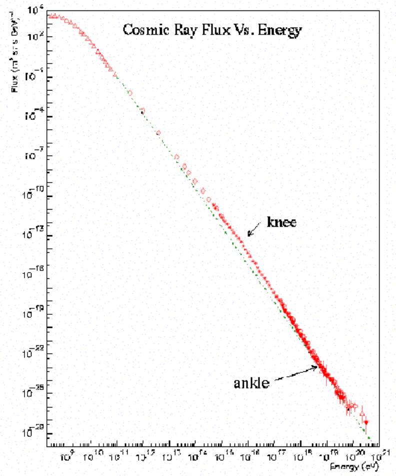


Figure 2: AGASA Energy Spectrum



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

Source / parameter	GRBs	AGN	Micro-Q	TypeII SN
Γ	10^2 - 10^3	5 – 20	2 – 5 ?	~ 1
Power (L_j) (erg/s)	10^{50}	10^{44} -10^{47}	10^{38} Minimum p analysis	10^{41} Effective
Timescale	Seconds	Hours to years	Days	Hours

B fields inside jets

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

$$\boxed{\text{AGNs:} \quad B \approx 10^3 \frac{(\xi L_{j46})^{1/2}}{(\theta\Gamma) r_{15}} \text{G}}$$

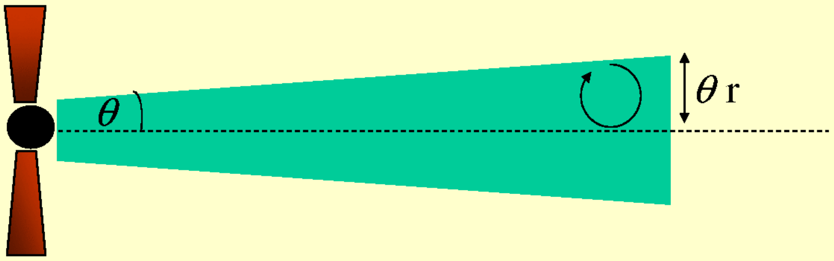
$$\boxed{\text{MQs:} \quad B \approx 10^6 \frac{(\xi L_{j38})^{1/2}}{(\theta\Gamma) r_8} \text{G}}$$

Limits on proton energy

ε_p - comoving proton energy

Confinement: $\lambda_L = \frac{\varepsilon_p}{eB} < r\theta$

$$\Rightarrow \boxed{\varepsilon_p \le 5\times10^{16}\xi^{1/2}L_{j38}^{1/2}\Gamma^{-1}\ \text{eV}}$$

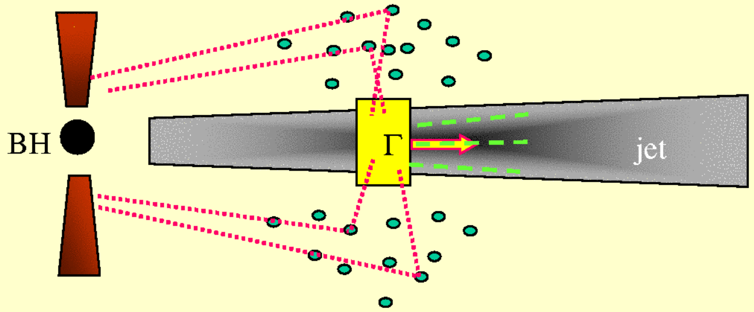


Limits on max proton energy in jets

	GRBs	AGN	Micro-Q
Γ	10^2	10	3
L_j (erg/s)	10^{50}	10^{46}	10^{38}
ε_p (eV) / $\xi^{1/2}$ (in rest frame)	5×10^{20}	5×10^{19}	2×10^{16}
$\varepsilon_p\,\Gamma$ (eV) Observed: ξ=0.01	$\sim10^{22}$	$\sim10^{20}$	$\sim10^{16}$

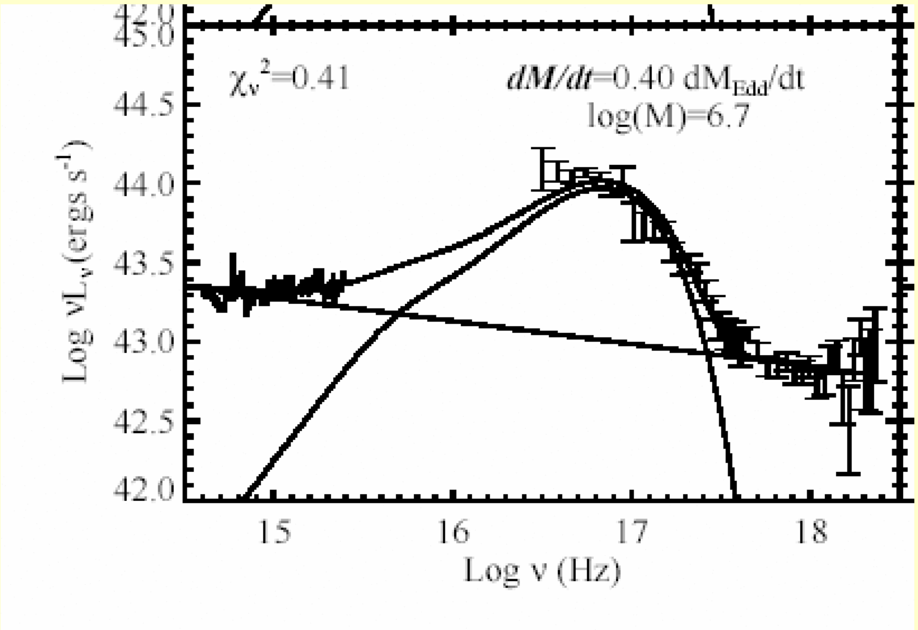
- For AGNs (FSRQs only) the proton energy is limited by losses due to photo-pion production, and is well below the confinement limit.

The basic picture

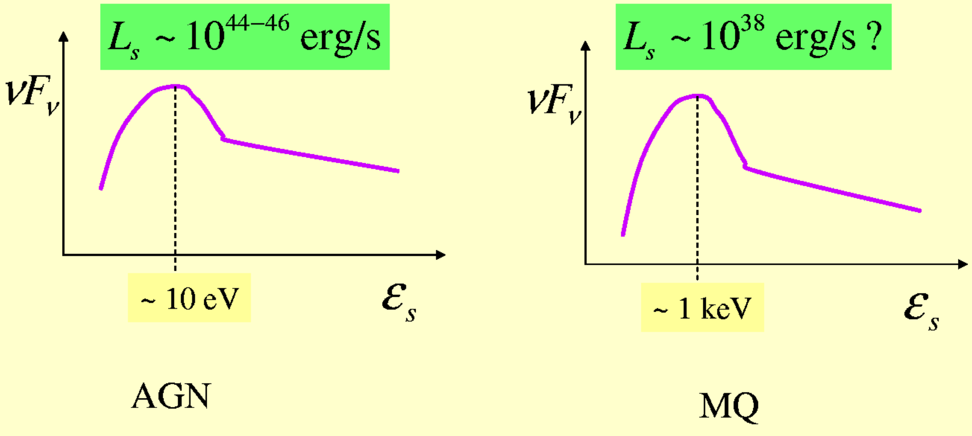


- ➢ **Target photons: synchrotron and /or external**
- ➢ **Composition: $e^\pm$ or e-p ?**
- ➢ **Electromagnetic: synchrotron, IC, pair production**
- ➢ **Hadronic: photopion production, nuclear collisions**

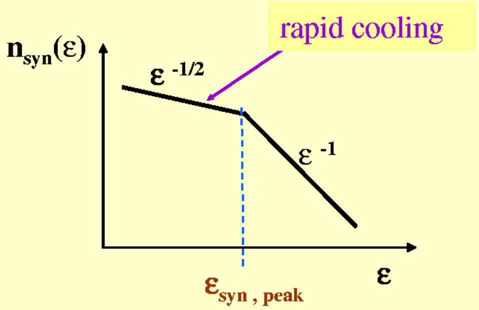
External radiation field



External component – a comparison



Spectrum of synchrotron photons



- **Energy distribution of injected electrons: thermal + power law tail**
- **Comoving energy of thermal electrons $mc^2\gamma_s$: $\gamma_s \sim 0.5(\Gamma_s - 1)(m_p/m_e)$**
- **$\varepsilon_{syn,peak} = (eB/m_e c)\,\gamma_s^2 = 50\,(\xi_{-1}\,L_{j38})^{1/2}\,(r_8\,\Gamma)^{-1}\,(\theta/0.1)^{-1}$ keV**

MQ: 20 –50 KeV

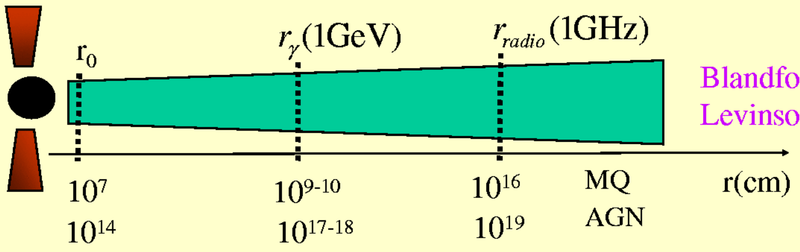
AGN: 1- 5 eV

Gamma-ray emission region

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

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

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



Blandford & Levinson `95
Levinson & Blandford ‘96

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

Neutrino emission: processes

Photomeson production

$$\left.\begin{array}{l} \mathrm{p}+\gamma\rightarrow\ \pi^{+}+\mathrm{n}\rightarrow\mu^{+}+\nu_{\mu}\ \rightarrow\ \mathrm{e}^{+}+\nu_{e}+\nu_{\mu}+\nu_{\mu} \\ \mathrm{p}+\gamma\rightarrow\ \pi^{0}+\mathrm{p}\rightarrow\gamma+\gamma \end{array}\right\}\ \begin{array}{l}\sigma\sim 0.1\,\mathrm{mbn}\\ \varepsilon_{\pi}\approx 0.2\varepsilon_{p}\end{array}$$

Inelastic nuclear collisions

$$\left.\begin{array}{l} \mathrm{p}+\mathrm{n}\rightarrow\ \mathrm{p}+\mathrm{p}+\pi^{-}\rightarrow\mu^{-}+\nu_{\mu}\ \rightarrow\ \mathrm{e}^{-}+\nu_{e}+\nu_{\mu}+\nu_{\mu} \\ \mathrm{p}+\mathrm{n}\rightarrow\ \mathrm{n}+\mathrm{n}+\pi^{+}\rightarrow\mu^{+}+\nu_{\mu}\ \rightarrow\ \mathrm{e}^{+}+\nu_{e}+\nu_{\mu}+\nu_{\mu} \\ \mathrm{p}+\mathrm{n}\rightarrow\ \mathrm{p}+\mathrm{n}+\pi^{0}\ \rightarrow\ \gamma+\gamma \\ \mathrm{p}+\mathrm{p}\rightarrow\ \ldots \\ \mathrm{n}+\mathrm{n}\rightarrow\ \ldots \end{array}\right\}\ \sigma\sim 50\,\mathrm{mbn}$$

Photo π production: threshold

- Threshold photon energy for photopion production in the nucleon rest frame:

$$\varepsilon_{\gamma}^{\mathrm{rest,thr}}=m_{\pi}(1+m_{\pi}/2m_{N})\approx 160\,\mathrm{MeV}\qquad \gamma\longrightarrow\bullet\mathrm{N}$$

- For a background radiation field with photon energy ε, the corresponding thrshold energy of the nucleon measured in the Lab frame is

$$\varepsilon_{p,thr}=\frac{m_{\pi}(m_{N}+m_{\pi}/2)}{\varepsilon_{s}}\approx 10^{17}\left(\frac{\varepsilon_{s}}{1\,\mathrm{eV}}\right)^{-1}\mathrm{eV}\qquad \gamma\longleftarrow\circ\mathrm{N}$$

Note: typical CMB photon energies are ε ~ 10^{-3} eV ⇒ GZK “cutoff” at ~ 10^{20} eV

Photo π production: relevant timescales

decay time: $t_\pi = 2\times10^{-8}\gamma_\pi$ sec

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

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

Conclusion: if protons are accelerated to energies in excess of $5\times10^{18}(\theta/0.1)^{1/2}r_{15}^{1/4}$ eV, then the charged pions will lose their energy before decaying. (Levinson & Waxman)

Relations between photo- π production and pair production

Same target photons for both processes.

$$\frac{\tau_{p\gamma}(\varepsilon_p)}{\tau_{\gamma\gamma}(\varepsilon_\gamma)} = \left(\frac{\varepsilon_p}{1.2\times10^6\varepsilon_\gamma}\right)^\alpha \frac{\sigma_{p\gamma}}{\sigma_{\gamma\gamma}} \qquad \frac{\sigma_{p\gamma}}{\sigma_{\gamma\gamma}} \approx 10^{-3}$$

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

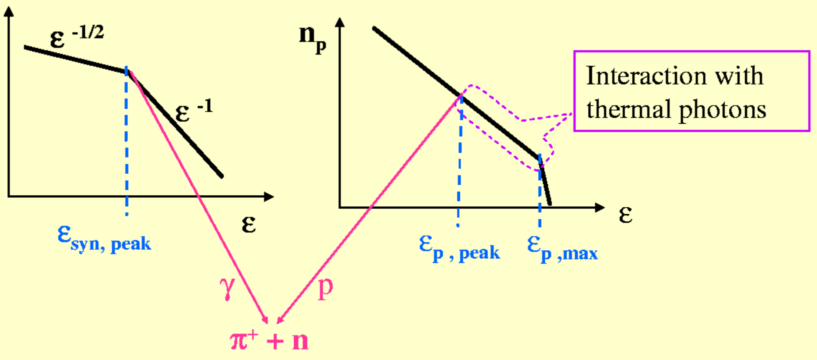
BL-Lac: $\varepsilon_\gamma > 1$ TeV + rapid variability of the Tev emission implies very small photo-pion opacity.

Not good candidates for neutrino astronomy !

Threshold energy and opacity: external photons

	MQ	AGN
$\varepsilon_{p,thr}$ (eV)	10^{14}	10^{15} - 10^{16}
$\tau_{p\gamma}$	$< 1\ r_8^{-1}$	~ 1 -100 r_{15}^{-1}
ε_ν	~ 1 TeV	~ 50 TeV

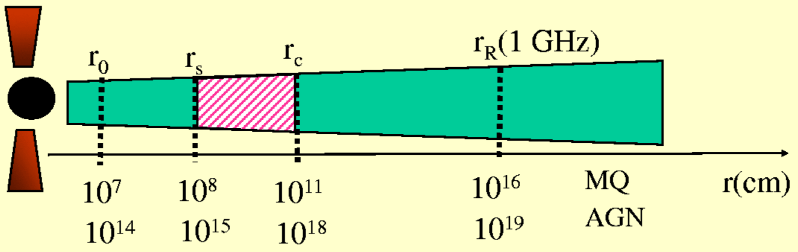
Contribution of the target synchrotron field



$$\text{MQ}: \quad \tau_{p\gamma} \approx 1\,(\varepsilon_p / \varepsilon_{p,peak})^{1/2} \le 30;\ \varepsilon_p > \varepsilon_{p,peak}$$

$$\text{AGN}: \quad \tau_{p\gamma} \approx 10^3\,(\varepsilon_p / \varepsilon_{p,peak});\quad \varepsilon_p < \varepsilon_{p,peak}$$

Characteristic scales



- r_0 - injection radius
- $r_s \approx \Gamma^2 c\, \delta t = \Gamma^2 r_0$ - smallest radius of shock formation
- r_c - Edge of $p\gamma$ interaction region
- r_R(1 GHz) - photosphere of GHz emission

▨ - Neutrino production region

Neutrino spectrum & flux

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

$\varepsilon_\nu \sim 5\%\ \varepsilon_p \Rightarrow$

MQ: $1\ \text{TeV} < \varepsilon_\nu < 100\ \text{TeV}$

AGN: $10\ \text{TeV} < \varepsilon_\nu < 1000\ \text{TeV}$

Flux: $F_\nu \approx 10^{-9}\ (\eta/0.1)\ \delta^4\ L_{j38}\ (D/3\ \text{kpc})^{-2}$ erg/ cm²/s

Acceleration efficiency

Doppler factor

Number of events in a km³ detector:

$N_\nu \approx 0.2\ (\eta/0.1)\ (\delta^3/\ \Gamma\ )\ (D/3\ \text{kpc})^{-2}\ (E/10^{43}\ \text{erg})(A/1\ \text{km}^2)$

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

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THE END