Extreme regimes of emission in relativistic outflows

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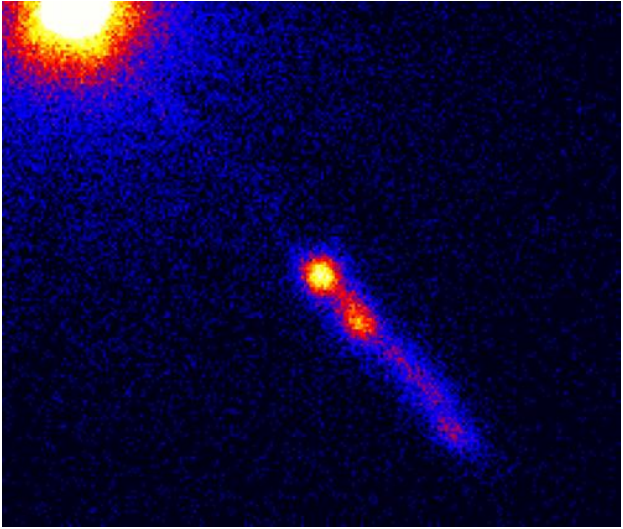
in collaboration with Felix Aharonian and Tsvi Piran

High Energy Phenomena in Relativistic Outflows, Barcelona 2019

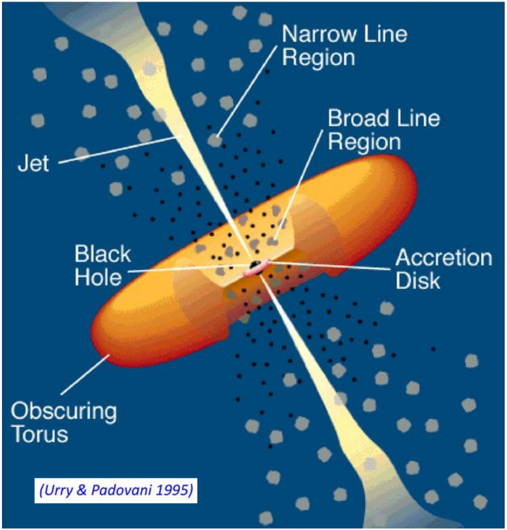
Outline

Blazar as seen from far away.

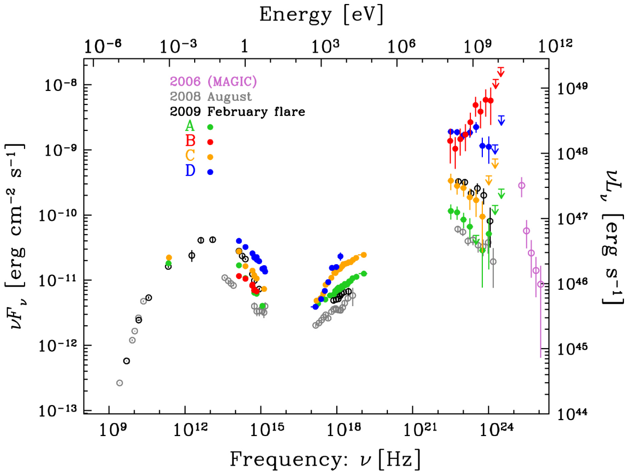


Picture of 3C273 (Chandra). Inner jet is not seen.

Blazar. Possible near view.



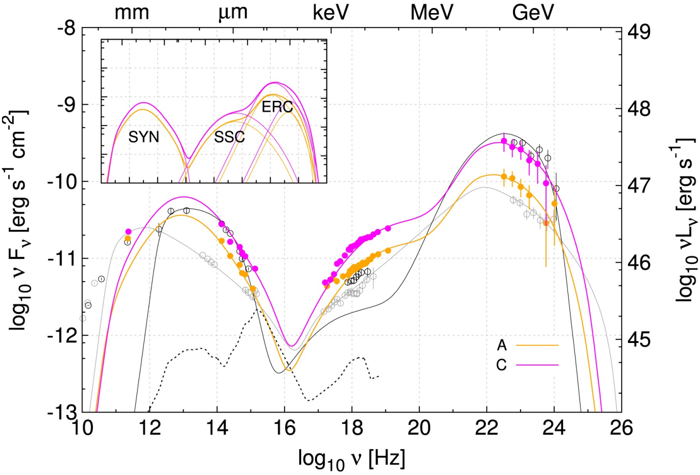
GeV blazar



Broadband SEDs of 3C 279 for the four observational periods.

Hayashida et al., ApJ 807, 2015

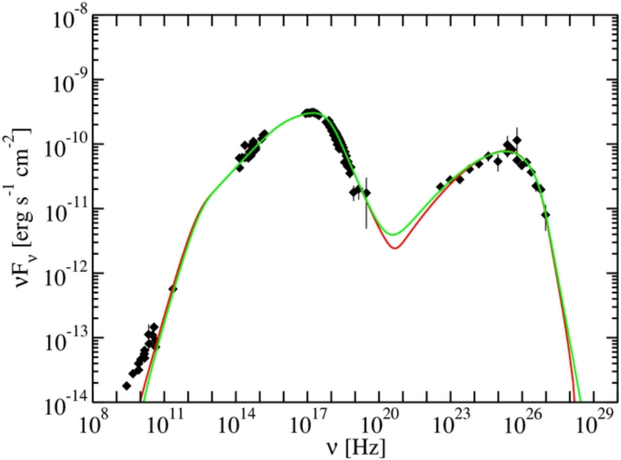
GeV blazar



Broadband SEDs of 3C 279 during two NuSTAR pointings.

Hayashida et al., ApJ 807, 2015

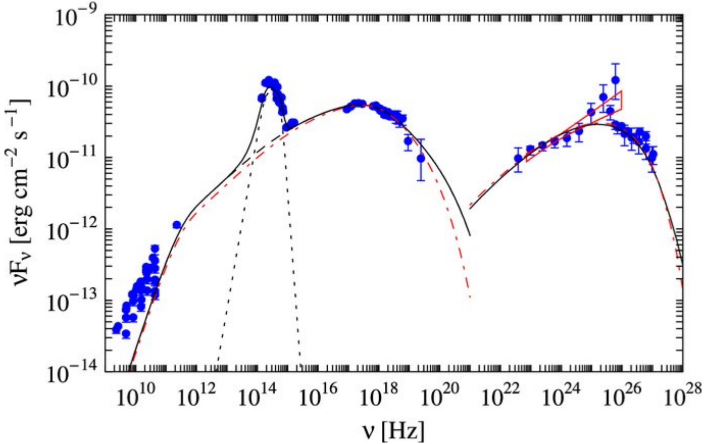
TeV blazar



SED of Mrk 421 with two one-zone SSC model fits.

Abdo et al., ApJ 736, 2011

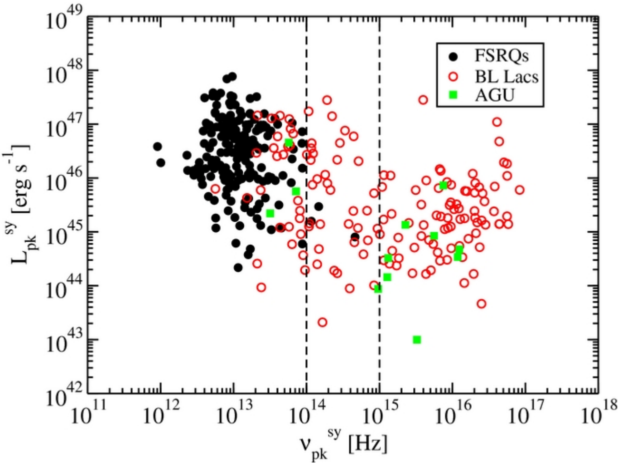
Another TeV blazar



SSC model fits to the broadband spectrum of Mrk 501. The dotted black curve is the starlight emission of the host galaxy.

Abdo et al., ApJ 727, 2011

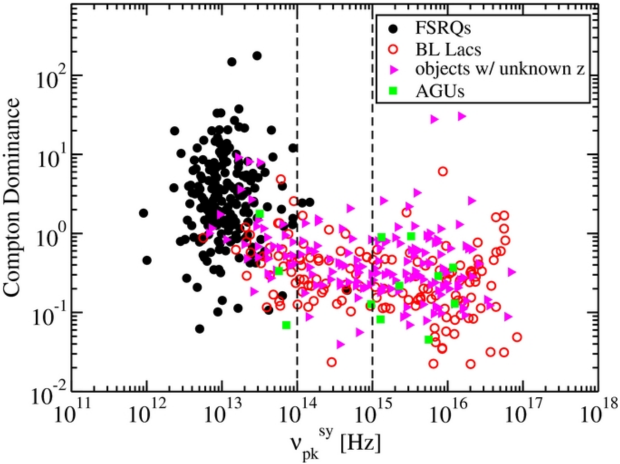
Position of low-frequency peak



Peak synchrotron luminosity vs. peak synchrotron frequency.

Finke, ApJ 763, 2013

Compton dominance



Compton dominance (i.e., L^{C}_{pk}/L^{sy}_{pk}) vs. peak synchrotron frequency.

Finke, ApJ 763, 2013

Typical blazar parameters

Known from observations:

- Jets' Lorentz factors $\Gamma \sim 10$
- Variability timescale:

  GeV blazars $\delta t \sim 1$ day (up to minutes)
  TeV blazars $\delta t \sim 1$ hour (up to minutes)
- Apparent (isotropic equivalent) luminosity:

  GeV blazars $L \sim 3 \times 10^{47}$ erg/s
  TeV blazars $L \sim 10^{45}$ erg/s

We can calculate

- Size of emitting region $R \sim \Gamma^2 \, c \, \delta t$:

  GeV blazars $R \sim 3 \times 10^{17}$ cm
  TeV blazars $R \sim 10^{16}$ cm
- Radiation energy density:

  GeV blazars $w_{rad} \sim 0.3$ erg/cm^3 ($B_{eq} \sim 3$ G)
  TeV blazars $w_{rad} \sim 1$ erg/cm^3 ($B_{eq} \sim 5$ G)

Required magnetic field strength

$$\epsilon_{sy} = \Gamma \gamma_e^2 \frac{\hbar e}{m_e c} B$$

Synchrotron-self-Compton (SSC) model

- TeV blazars (Klein-Nishina regime)

$$\gamma_e = \frac{\epsilon_{IC}}{\Gamma m_e c^2} \sim 10^5 \quad \Rightarrow \quad B \sim 1 \text{ G}$$

$$w_B \sim 0.01 \div 0.1 w_{rad} \quad - \quad \text{small, but acceptable}$$

- GeV blazars (Thomson regime)

$$\gamma_e = \sqrt{\epsilon_{IC}/\epsilon_{sy}} \sim 3 \times 10^4 \quad \Rightarrow \quad B \sim 10^{-3} \text{ G}$$

$$w_B \sim 10^{-7} w_{rad} \quad ?!$$

Required magnetic field strength

$$\epsilon_{sy} = \Gamma \gamma_e^2 \frac{\hbar e}{m_e c} B$$

External Compton (EC) models

- GeV blazars (Thomson regime)

$$\gamma_e = \frac{1}{\Gamma}\sqrt{\epsilon_{peak}/\epsilon_{disk,BLR}} \sim 3 \times 10^2 \Rightarrow B \sim 10 \text{ G}$$

$$w_B \sim 10 w_{rad} \qquad \checkmark$$

Hadronic models

- GeV, TeV blazars

$$B \sim B_{eq}, \qquad w_B \sim w_{rad}$$

- No radiation from accelerated electrons ?!

Acceleration rate

Balance of acceleration and radiative losses

- Electron acceleration rate $\dot{\epsilon}_{acc} = eE_{eff}\,c \equiv \eta eBc$

  (in case of shock acceleration $\eta \simeq U_{sh}^2/c^2$)
- Power of synchrotron radiation $\dot{\epsilon}_{loss} = \frac{4}{9}\gamma_e^2 \left(\frac{e^2}{m_e c^2}\right)^2 B^2 c$
- balance $\dot{\epsilon}_{loss} = \dot{\epsilon}_{acc} \quad \Rightarrow \quad \epsilon_{sy} \simeq \eta \frac{m_e c^2}{\alpha}$

Acceleration efficiency:

	expected	actual
• Crab (plerion)	~ 1	~ 1
• Supernova remnants	$\sim 10^{-5} \div 10^{-4}$	$\sim 10^{-5} \div 10^{-4}$
• Blazars	~ 1	$\sim 10^{-9} \div 10^{-6}$

The slowest possible acceleration

Derishev, ApSS 309, 2007

To reduce acceleration rate we increase particles' scattering length

- the magnetic field changes its direction on scales $\sim \lambda_B$ much smaller than the gyroradius r_g
- acceleration efficiency $\eta \sim \dfrac{\lambda_B}{r_g} \ll 1$
- for GeV blazars, the required scale $\lambda_B < r_g/\gamma$
- $\Rightarrow$ transition to undulator regime with $\omega \propto \lambda_B^{-1}$

We may choose: blazars are

extremely bad accelerators

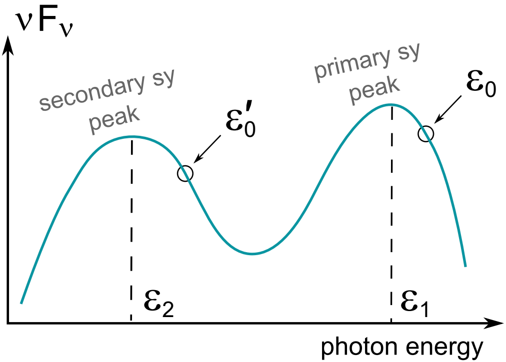
- either velocities of internal motions
  $\sim \sqrt{\eta}\, c$ up to $10^{-5}c$ (!) for GeV blazars
- or spatial scale of the magnetic field
  $\sim \eta r_g \ll r_g/\gamma_e$ – transition to undulator radiation

extremely efficient accelerators

- velocities of internal motions $\sim c$
  $\Rightarrow$ acceleration efficiency $\eta \sim 1$
- *high-frequency* peak in the spectra is synchrotron

  $\Gamma m_e c^2/\alpha \sim 1$ GeV for electrons
  $\Gamma m_p c^2/\alpha \sim 1$ TeV for protons

Top-down model for GeV blazars



$$\varepsilon_0 = \left(\frac{B_{cr}}{B}\right)^{\frac{1}{3}} m_e c^2$$

$\Gamma\varepsilon_0 \sim 100$ GeV

$\Gamma\varepsilon'_0 \sim 200$ eV

Photons with energy ε_0 produce $e^{\pm}$-pairs, whose synchrotron radiation (with typical photon energy ε'_0) is most efficient absorber for photons with exactly the energy ε_0

$B_{cr} \simeq 4.4 \times 10^{13}$ G – the Schwinger field strength

High-frequency asymptotics for primary synchrotron radiation

- Gaussian distribution of local magnetic field strength

$$F_\omega(\gamma) \propto B_0 \left(\frac{\omega}{\omega_0} + \left(\frac{\omega}{\omega_0} \right)^{1/3} \right) \exp\left(-2 \left(\frac{\omega}{\omega_0} \right)^{2/3} \right)$$

$$\omega_0 = \frac{4}{3}\gamma^2 \frac{eB_0}{m_e c} \qquad (1)$$

Derishev & Aharonian, to appear soon

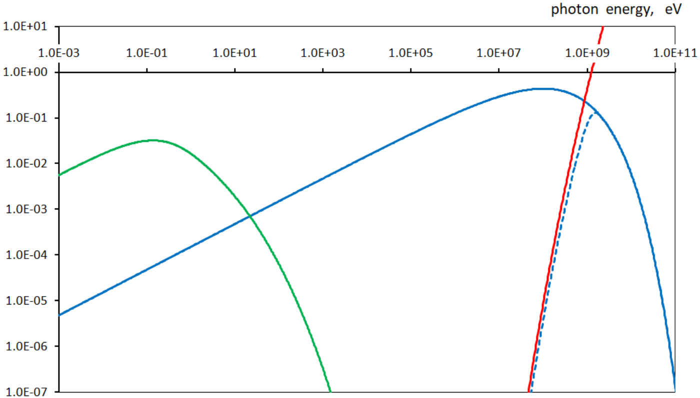
- distribution function of radiating particles
  has Gaussian cut-off at high energies.
  Using (1) and approach of Zirakashvili and Aharonian (A&A 465, 2007):

$$F_\nu \propto \exp\left[-\left(\nu/\nu_1 \right)^{2/5} \right]$$

Spectrum of secondary radiation

- Main term in the high-frequency asymptotics for secondary radiation – $F_\nu \propto \exp\left[-(\nu/\nu_2)^{1/5}\right]$
- optical depth is reduced by factor ~ 0.02 compared to absorption by photons at low-frequency peak

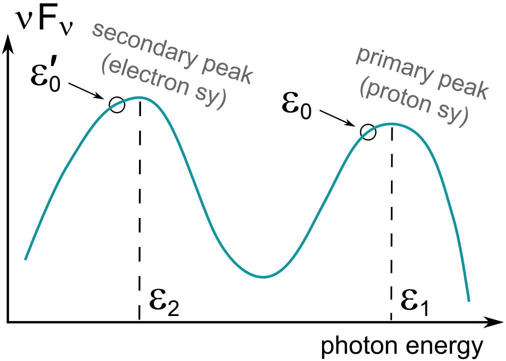
Example simulation



Vertical axis – νF_ν (arbitrary units) and optical depth for two-photon absorption,

solid blue – primary synchrotron radiation,
solid green – secondary synchrotron radiation,
solid red – optical depth,
dashed blue – absorbed radiation

Top-down model for TeV blazars



$$\varepsilon_0 = \left(\frac{B_{cr}}{B}\right)^{\frac{1}{3}} m_e c^2$$

$\Gamma\varepsilon_0 \sim 100$ GeV

$\Gamma\varepsilon_0' \sim 200$ eV

Energies ε_0 and ε_0' are close to the maxima in SED

$\Rightarrow$ two-photon absorption is much more efficient

Blazar jets are the most suitable sites for production of ultra-high energy cosmic rays

Advantages and disadvantages

Top-down model

- \+ Natural values for acceleration rate and the magnetic field strength
- − No explanation for difference between TeV and GeV blazars

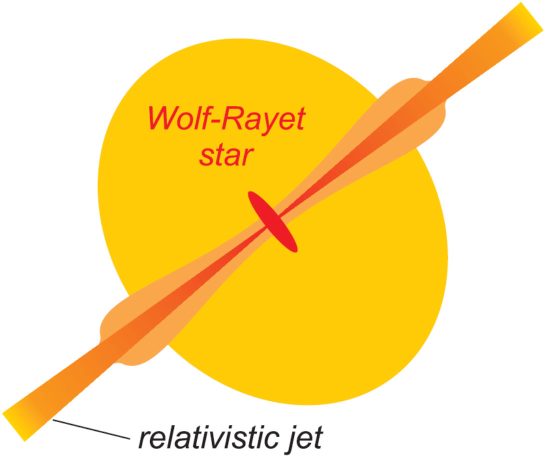
Standard model

- ± In some cases unreasonably weak magnetic field is required
- − Unreasonably low acceleration rate
- − No explanation for difference between TeV and GeV blazars

Top-down model is more complicated technically (but not physically!)

- Self-consistent calculation of spectrum is only possible in a model with nonlinear feedback
- Two-zone (at least) models

Gamma-Ray Burst source.
Possible near view.



GRB 190114C, observations

General characteristics

- Bright long burst, $E_{\rm rad}^{\rm iso} = 3 \times 10^{53}$ erg
- Redshift $z = 0.4245$

MAGIC observation (no official data released so far)

- ~ 300 GeV emission ~ 100 sec after the trigger
- most likely IC component of afterglow's SSC emission
- ratio of IC to synchrotron (~ 10 keV) fluxes is $\eta_{IC} \simeq 0.25$

GRB 190114C, parameters

Derishev & Piran arXiv:1905.08285

Estimate for the Lorentz factor of emitting electrons

- Klein-Nishina regime: $E_{\rm IC} \simeq \Gamma \gamma_{e,\rm KN} m_e c^2 \quad \Rightarrow \ \gamma_{e,\rm KN} \simeq \dfrac{10^6}{\Gamma}$
- Thomson regime: $E_{\rm IC} \simeq \Gamma \gamma_{e,\rm Th}^4 \dfrac{B}{B_{\rm cr}} m_e c^2$
$$\Rightarrow \ \gamma_{e,\rm Th} \simeq 1.2 \times 10^3 \left(\frac{\epsilon_r}{\epsilon_B}\right)^{1/8} \Gamma^{1/2}$$
- $\gamma_e = \max\left[\gamma_{e,\rm Th}, \gamma_{e,\rm KN}\right]$ – make choice and tell the regime

sub-TeV radiation of GRB 190114C: KN or Thomson?

- $\Gamma \gtrsim 100$ ($\gamma\gamma$ opacity) and $\Gamma \lesssim 150$ (shock deceleration)
- $\epsilon_r/\epsilon_B \sim \eta_{IC}$

$\gamma_{e,\rm Th} \simeq \gamma_{e,\rm KN} \simeq 1.5 \times 10^4$, i.e., the sub-TeV radiation is produced on the border between KN and Thomson regimes

GRB 190114C, parameters

Magnetization issue

- In Thomson regime $\epsilon_B \simeq \epsilon_r/\eta_{IC}$
- Too large magnetization ($\epsilon_B \sim 0.1$) unless η_{IC} is considerably larger
- Assume moderate internal absorption to rise estimate to $\eta_{IC} \sim$ a few; this fixes the problem

A coincidence?

- radiation at IC peak is produced on the border between KN and Thomson regimes
- a large fraction of high-energy IC radiation is absorbed upstream of the shock

Modified relativistic shock

Derishev & Piran MNRAS (2016)

Acceleration – radiation feedback

- Start with few IC photons absorbed in the upstream
- Secondary pairs are Lorentz-boosted to much higher energy
- IC peak goes up both in power and in photon energy
- More photons absorbed in the upstream
- Secondary pairs accelerate upstream fluid before the shock, reducing (or eliminating) velocity jump
- Lorentz boost for secondary pairs becomes smaller
- IC peak goes down both in power and in photon energy
- Few IC photons absorbed in the upstream
- repeat until a steady state reached

Modified relativistic shock

Steady state (GRB 190114C conforms with it)

- IC peak is at the border between KN and Thomson regime, barely making two-photon production possible
- A significant fraction of IC radiation is absorbed in the upstream and modifies the shock to reduce efficiency of converter acceleration

In this picture there is no room for diffusive shock acceleration. Acceleration and radiation are the two sides of one and the same cooperative process.

Instead of conclusion

In extreme environments, the ties between particle acceleration and radiation processes are so close, that they cannot be considered separately.

There are no clear answers yet,
but there is a hope to solve some of the issues.

Besides, it's a new physics. Have fun with it!