A Physical Model for the Revised Blazar Sequence

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Blazar Sequence - synchrotron component

Synchrotron peak luminosity vs synchrotron peak frequency

5 GHz luminosity vs synchrotron peak frequency

Fossati et al. (1998)
Previous work

Peaks from fit to Swift / Planck data by Giommi et al. (2011).

“L” shape seen.

Note: y-axis is synchrotron peak + Compton peak.

But upper right may be filled in with BL Lacs with unknown redshift.

“L” (or “V”) shape also seen by Nieppola et al. (2006), Meyer et al. (2011)

Giommi et al. (2011) arXiv:1108.1114
External radiation field for Compton scattering correlates with power injected into electrons.

As power increases, greater external radiation field leads to greater Compton scattering, and hence more Compton dominance.

At the same time, the greater scattering cools the electrons more, leading to a lower cooling break energy.

\[
\gamma_c = \frac{3m_e c^2}{4c \sigma_T (u_B' + u_{sy}' + u'_{ext}) t_{esc}}
\]

The peak frequency is directly related to this cooling break energy.

Ghisellini et al. (1998)
Calculating the synchrotron peak

Abdo et al. (2010; CA: P. Giommi; M. Mazziotta; A. Tramacere) fit LBAS blazars to determine peak frequencies and luminosities:

\[ \nu F_\nu = a \cdot \nu^3 + b \cdot \nu^2 + c \cdot \nu + d. \]

They provided empirical formulae for finding the peak frequency based on optical, radio, and X-ray data (\( \alpha_{ro} \), \( \alpha_{ox} \)).

The 2LAC provides peak synchrotron frequency for sources with enough data using these formulae.

Can also use Abdo et al. (2010) empirical formula to calculate peak flux (normalized to 5 GHz flux density):

\[ \log(\nu_{peaks} F(\nu_{peaks})) = 0.5 \cdot \log(\nu_{peaks}) - 20.4 + 0.9 \cdot \log(R_{5GHz}), \]

Can use this to create the blazar sequence from the 2LAC.
Lack of a “V” shape, anti-correlation is more clear. Explanation?
Simple explanation: as synchrotron bump moves to higher frequencies, radio flux will decrease (e.g., Lister et al. 2011).

A physical effect, or a result of the way the peak frequency is calculated?
Gamma-ray selected sample 2LAC “Clean sample” with:
• known redshifts
• enough measurements for well-defined synch peak.
• ~ 350 sources
• “V” shape seen
Correlations

Spearman and Kendall Rank Coefficients

Can objects with unknown $z$ ruin this anti-correlation?

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\rho$</th>
<th>PNC($\rho$)</th>
<th>$\tau$</th>
<th>PNC($\tau$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{pk}^{ay}$ versus $\nu_{pk}^{ay}$</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>BL Lacs</td>
<td>-0.19</td>
<td>0.019</td>
<td>-0.12</td>
<td>0.032</td>
</tr>
<tr>
<td>FSRQs</td>
<td>-0.12</td>
<td>0.073</td>
<td>-0.088</td>
<td>0.066</td>
</tr>
<tr>
<td>All sources with known $z$</td>
<td>-0.56</td>
<td>$2.1 \times 10^{-30}$</td>
<td>-0.37</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Fitting the high-energy components of blazars in the LBAS sample, Abdo et al. (2010) found a relationship between the LAT spectral index and peak frequency of the Compton component:

\[ \log(\nu_{\text{peak}}^{IC}) = -4.0 \cdot \Gamma + 31.6 \]

This can be used to calculate the peak Compton frequency for the 2LAC sample.
Once the peak frequency is known, the power law can be extrapolated to find the peak Compton luminosity.

~10% of the 350 sources in our sample are also in the 58 month Swift-BAT catalog. For these objects their BAT spectra were also used to constrain the Compton peak.

For the LBAS, $L_{pk}^C$ from the fit (Abdo et al. 2010) and from the extrapolation:

![Graph showing the relationship between $\log (L_{C,est} / \text{erg s}^{-1})$ and $\log (L_{C,fit} / \text{erg s}^{-1})$.](image)
Compton dominance does not depend on redshift. Sources with unknown redshifts are also plotted.
Correlations

Spearman and Kendall Rank Coefficients

Objects with unknown redshift do not destroy the correlation!
A Little Theory

Inject electrons as power law between two electron energies:

$$Q_e(\gamma) = Q_0 \gamma^{-q} H(\gamma; \gamma_1, \gamma_2).$$

Equilibrium solution, injection balanced with escape and injection
slow cooling solution, \(\gamma_1 < \gamma_c\):

$$N_e(\gamma) \approx Q_0 t_{esc} \begin{cases} (\gamma/\gamma_c)^{-q} & \gamma_1 < \gamma < \gamma_c \\ (\gamma/\gamma_c)^{-q-1} & \gamma_c < \gamma < \gamma_2 \end{cases}$$

$$\gamma_c = \frac{3m_e c^2}{4c\sigma_T(u'_B + u'_s y + u'_e x)t_{esc}}$$

Fast cooling solution, \(\gamma_c < \gamma_1\):

$$N_e(\gamma) \approx Q_0 t_{esc} \begin{cases} (\gamma/\gamma_1)^{-2} & \gamma_c < \gamma < \gamma_1 \\ (\gamma/\gamma_1)^{-q-1} & \gamma_1 < \gamma < \gamma_2 \end{cases}$$

See, e.g., Boettcher & Dermer (2002)
Peak frequency is associated with $\max(\gamma_c, \gamma_1)$.

$\gamma_c$ depends on power, but $\gamma_1$ does not, presumably.

Once $\gamma_c$ is less than $\gamma_1$, synchrotron peak luminosity will be roughly independent of peak frequency.

$$\epsilon_{pk} = \frac{h \nu_{pk}}{m_e c^2} = \delta_D \epsilon_B \left\{ \begin{array}{cc} \gamma_c^2 & \gamma_1 < \gamma_c \\ \gamma_1^2 & \gamma_c < \gamma_1 \end{array} \right\}$$

$$L_{pk}^{sy} = L_{\epsilon_{pk}}^{sy} = \frac{2\delta_D^4}{3} \sigma_T u_B Q_0 t_{esc} \left\{ \begin{array}{cc} \gamma_c^3 & \gamma_1 < \gamma_c \\ \gamma_1^3 & \gamma_c < \gamma_1 \end{array} \right\}$$

Scale injected electrons:

$$Q_0 = Q_{00} \ell$$

Scale injected Lorentz factor with power:

$$\Gamma = \Gamma_0 \ell^g$$

Scale injected magnetic field with power:

$$B = B_0 \ell^b$$

Scale external radiation field with power:

$$u_{ext} = u_0 \ell^a$$

So we assume blazars are two parameter engines: $\theta, \ell$
A clever choice of parameters can reproduce the “V” shape in the $L_{\text{pk}}$-$\nu_{\text{pk}}$ diagram.
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$\Gamma^2 u_{\text{ext}} < u_B$
A clever choice of parameters can reproduce the “V” shape in the $L_{pk}$-$\nu_{pk}$ diagram. Possible change in $\gamma_1$ could explain more sources.
Reproducing Blazar Sequence

It can also reproduce the “L” shape on the $A_C-\nu_{pk}$ diagram.
Reproducing Blazar Sequence

It can also reproduce the “L” shape on the $A_C$-$\nu_{pk}$ diagram.
• Blazar sequence generated from the 2LAC ($L_{pk}$-$\nu_{pk}$ and $A_C$-$\nu_{pk}$).

• Largest sample yet for Compton Dominance plot.

• Blazars with unknown $z$ could ruin $L_{pk}$-$\nu_{pk}$ anti-correlation, but not $A_C$-$\nu_{pk}$ anti-correlation.

• Standard cooling scenario seems to explain “V” and “L” shapes on $L_{pk}$-$\nu_{pk}$ and $A_C$-$\nu_{pk}$ diagrams if $\nu_{pk}$ is associated with the maximum of $\gamma_c$ and $\gamma_1$. 
Extra slides
Compton dominance = $\gamma$-ray dominance = $L_{\text{pk,C}} / L_{\text{pk,sy}}$

Compton dominance vs synchrotron peak frequency
EGRET era, ~ 30 sources

Fossati et al. (1998)
Other works

Meyer et al. (2011)
“V” shape (or “L” shape)

Intermediate SED shapes don’t appear common.

Meyer et al. explain this as due to viewing angle effects in stratified jets.

Other recent works have similar “V” or “L” shape: e.g., Nieppola et al. (2006), Giommi et al. (2011).

But upper right may be filled in with BL Lacs with unknown redshift (Giommi et al. 2011).
Nieppola et al. (2006) fit BL Lacs with log-parabola to locate synchrotron peaks. They also found “V” or “L” shape.

Problems with fitting with log-parabola versus third-order polynomial?

Also, no FSRQs included.

Nieppola et al. (2006)
2FGL J0059.2-0151
(1RXS 005916.3-015030)
and
2FGL J0912.5+2758
(1RXS J091211.9+27595)

Hardest sources in 2LAC, also large error bars. When propagating errors in spectral index, $A_C$ is consistent with 1, within error bars.