Modelling Blazar emission with the time-dependent SSC cooling process

Michael Zacharias & Reinhard Schlickeiser

Institut für Theoretische Physik, Lehrstuhl IV: Weltraum- und Astrophysik,
Ruhr-Universität Bochum, Germany

March 19, 2013

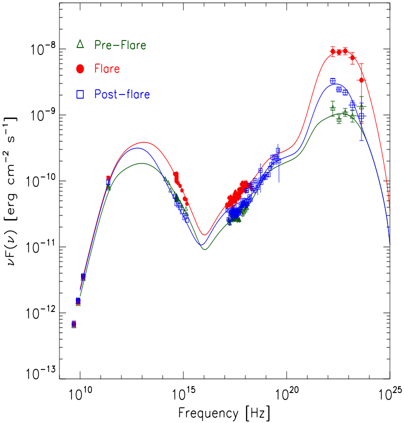

Figure 1: SED of 3C 454.3 during a large outburst in November 2010 (Vercellone et al. 2011)

- Numerical calculations of SEDs implement time-dependent nature of SSC cooling
- Most modeling attempts fail to recognize the important effects

- Electron kinetic equation:

$$\frac{\partial n(\gamma,t)}{\partial t} - \frac{\partial}{\partial \gamma}\left[|\dot{\gamma}|_{\mathrm{TOT}}\, n(\gamma,t)\right] = Q(\gamma,t)$$

- Source term:

$$Q(\gamma,t) = q_0 \delta(\gamma - \gamma_0)\delta(t)$$

  - Description of flares, i.e. single injection of relativistic ($\gamma_0 \gg 1$) particles
  - Not useful for steady-state sources

- Electron kinetic equation:

$$\frac{\partial n(\gamma,t)}{\partial t} - \frac{\partial}{\partial\gamma}\left[|\dot\gamma|_{\mathrm{TOT}}\, n(\gamma,t)\right] = Q(\gamma,t)$$

- Source term:

$$Q(\gamma,t) = q_0\delta(\gamma-\gamma_0)\delta(t)$$

  - Description of flares, i.e. single injection of relativistic ($\gamma_0 \gg 1$) particles
  - Not useful for steady-state sources
- Cooling rate:

$$|\dot\gamma|_{\mathrm{TOT}} = |\dot\gamma|_{\mathrm{SYN}} + |\dot\gamma|_{\mathrm{SSC}} = D_0\gamma^2 + A_0\gamma^2\int_0^\infty d\gamma\,\gamma^2 n(\gamma,t)$$

  - SSC cooling several orders of magnitude quicker than synchrotron cooling
  - SSC cooling depends on electron distribution (i.e. time-dependent) ⇒ synchrotron cooling dominates after some time

Kinetic equation

- Electron kinetic equation:

$$\frac{\partial n(\gamma,t)}{\partial t} - \frac{\partial}{\partial \gamma}\left[|\dot{\gamma}|_{\mathrm{TOT}}\, n(\gamma,t)\right] = Q(\gamma,t)$$

- Source term:

$$Q(\gamma,t) = q_0 \delta(\gamma-\gamma_0)\delta(t)$$

  - Description of flares, i.e. single injection of relativistic ($\gamma_0 \gg 1$) particles
  - Not useful for steady-state sources

- Cooling rate:

$$|\dot{\gamma}|_{\mathrm{TOT}} = |\dot{\gamma}|_{\mathrm{SYN}} + |\dot{\gamma}|_{\mathrm{SSC}} = D_0\gamma^2 + A_0\gamma^2 \int_0^\infty d\gamma\, \gamma^2 n(\gamma,t)$$

  - SSC cooling several orders of magnitude quicker than synchrotron cooling
  - SSC cooling depends on electron distribution (i.e. time-dependent) $\Rightarrow$ synchrotron cooling dominates after some time

Injection parameter α

- Defined as the ratio of the cooling terms at time of injection ($t = 0$)

$$\alpha = \left[\frac{|\dot{\gamma}(t=0)|_{\mathrm{SSC}}}{|\dot{\gamma}|_{\mathrm{SYN}}}\right]^{1/2} = \gamma_0 \left(\frac{q_0 A_0}{D_0}\right)^{1/2}$$

- $\alpha \ll 1$: linear cooling $\Rightarrow$ dominance of the synchrotron peak
- $\alpha \gg 1$: initial nonlinear cooling $\Rightarrow$ dominance of the IC peak

Injection parameter α

- Defined as the ratio of the cooling terms at time of injection ($t = 0$)

$$\alpha = \left[\frac{|\dot{\gamma}(t=0)|_{\mathrm{SSC}}}{|\dot{\gamma}|_{\mathrm{SYN}}} \right]^{1/2} = \gamma_0 \left(\frac{q_0 A_0}{D_0} \right)^{1/2}$$

- $\alpha \ll 1$: linear cooling $\Rightarrow$ dominance of the synchrotron peak
- $\alpha \gg 1$: initial nonlinear cooling $\Rightarrow$ dominance of the IC peak

- *The higher the density q_0 of electrons in the source, the higher the probability of (initial) nonlinear cooling.*

Injection parameter α

- Defined as the ratio of the cooling terms at time of injection $(t = 0)$

$$\alpha = \left[\frac{|\dot{\gamma}(t=0)|_{\mathrm{SSC}}}{|\dot{\gamma}|_{\mathrm{SYN}}} \right]^{1/2} = \gamma_0 \left(\frac{q_0 A_0}{D_0} \right)^{1/2}$$

- $\alpha \ll 1$: linear cooling $\Rightarrow$ dominance of the synchrotron peak
- $\alpha \gg 1$: initial nonlinear cooling $\Rightarrow$ dominance of the IC peak

- *The higher the density q_0 of electrons in the source, the higher the probability of (initial) nonlinear cooling.*

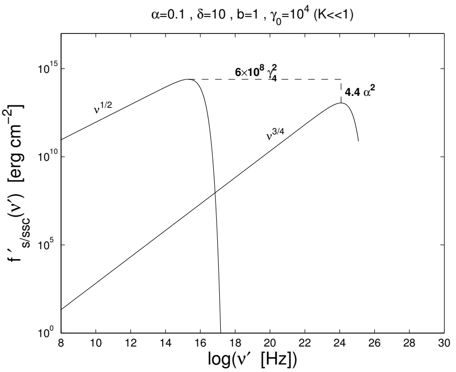

Figure 2: Model-SED for $\alpha \ll 1$ in the Thomson-limit

- Compton dominance depends strongly on α as predicted

RUHR UNIVERSITÄT BOCHUM RUB

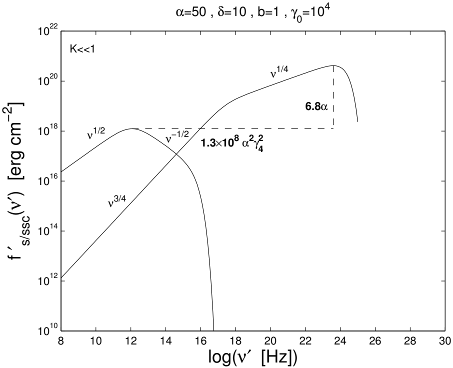

Figure 3: Model-SED for $\alpha \gg 1$ in the Thomson-limit

- Compton dominance depends strongly on α as predicted
- The peaks exhibit characteristic breaks for $\alpha \gg 1$ (without the need for fancy electron distributions)
- Different electron distributions affect only the high-energy end of the (synchrotron) peak

(MZ & RS 2010)

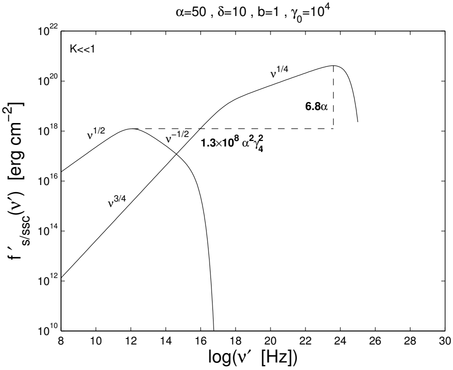

Figure 3: Model-SED for $\alpha \gg 1$ in the Thomson-limit

- Compton dominance depends strongly on α as predicted
- The peaks exhibit characteristic breaks for $\alpha \gg 1$ (without the need for fancy electron distributions)
- Different electron distributions affect only the high-energy end of the (synchrotron) peak

(MZ & RS 2010)

A new chain of reasoning

Standard scenario:

- Efficient accretion disk
- $\Rightarrow$ Strong BLR and torus
- $\Rightarrow$ Lots of seed photons
- $\Rightarrow$ Strong EC cooling of the electrons
- $\Rightarrow$ Dominance of the IC peak

A new chain of reasoning

Standard scenario:

- Efficient accretion disk
- $\Rightarrow$ Strong BLR and torus
- $\Rightarrow$ Lots of seed photons
- $\Rightarrow$ Strong EC cooling of the electrons
- $\Rightarrow$ Dominance of the IC peak

A new chain of reasoning

Standard scenario:

- Efficient accretion disk
- $\Rightarrow$ Strong BLR and torus
- $\Rightarrow$ Lots of seed photons
- $\Rightarrow$ Strong EC cooling of the electrons
- $\Rightarrow$ Dominance of the IC peak

A new chain of reasoning

Standard scenario:

- Efficient accretion disk
- $\Rightarrow$ Strong BLR and torus
- $\Rightarrow$ Lots of seed photons
- $\Rightarrow$ Strong EC cooling of the electrons
- $\Rightarrow$ Dominance of the IC peak

A new chain of reasoning

Standard scenario:

- Efficient accretion disk
- ⇒ Strong BLR and torus
- ⇒ Lots of seed photons
- ⇒ Strong EC cooling of the electrons
- ⇒ Dominance of the IC peak

New scenario:

- Efficient accretion disk
- ⇒ High electron density in the jet
- ⇒ Strong nonlinear SSC cooling of the electrons
- ⇒ Dominance of the IC peak

A new chain of reasoning

Standard scenario:

- Efficient accretion disk
- $\Rightarrow$ Strong BLR and torus
- $\Rightarrow$ Lots of seed photons
- $\Rightarrow$ Strong EC cooling of the electrons
- $\Rightarrow$ Dominance of the IC peak

New scenario:

- Efficient accretion disk
- $\Rightarrow$ High electron density in the jet
- $\Rightarrow$ Strong nonlinear SSC cooling of the electrons
- $\Rightarrow$ Dominance of the IC peak

A new chain of reasoning

Standard scenario:

- Efficient accretion disk
- ⇒ Strong BLR and torus
- ⇒ Lots of seed photons
- ⇒ Strong EC cooling of the electrons
- ⇒ Dominance of the IC peak

New scenario:

- Efficient accretion disk
- ⇒ High electron density in the jet
- ⇒ Strong nonlinear SSC cooling of the electrons
- ⇒ Dominance of the IC peak

A new chain of reasoning

Standard scenario:

- Efficient accretion disk
- $\Rightarrow$ Strong BLR and torus
- $\Rightarrow$ Lots of seed photons
- $\Rightarrow$ Strong EC cooling of the electrons
- $\Rightarrow$ Dominance of the IC peak

New scenario:

- Efficient accretion disk
- $\Rightarrow$ High electron density in the jet
- $\Rightarrow$ Strong nonlinear SSC cooling of the electrons
- $\Rightarrow$ Dominance of the IC peak

A new chain of reasoning

Standard scenario:

- Efficient accretion disk
- ⇒ Strong BLR and torus
- ⇒ Lots of seed photons
- ⇒ Strong EC cooling of the electrons
- ⇒ Dominance of the IC peak

New scenario:

- Efficient accretion disk
- ⇒ High electron density in the jet
- ⇒ Strong nonlinear SSC cooling of the electrons
- ⇒ Dominance of the IC peak

⇒ Potentially both processes are equally important

RUHR UNIVERSITÄT BOCHUM RUB

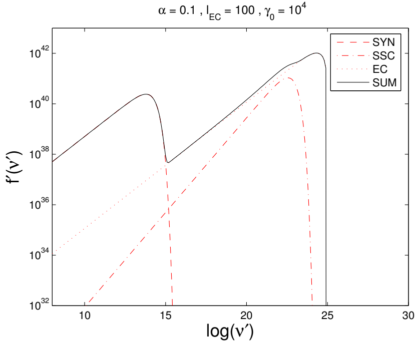

Figure 4: Model-SED for $\alpha_{ec} \ll 1$ and $l_{ec} \gg 1$ in the Thomson-limit

- Inclusion of external Compton requires new parameters:
  - Relative strengths $l_{ec} = u_{ec}\Gamma_b^2 / u_B$
  - Injection parameter $\alpha_{ec}^2 = \gamma_0^2 q_0 A_0 \,/\, D_0(1 + l_{ec})$
- In order to get large α_{ec}, more extreme q_0 is needed $\Rightarrow$ SSC luminosity increases with $(1 + l_{ec})$

External Compton

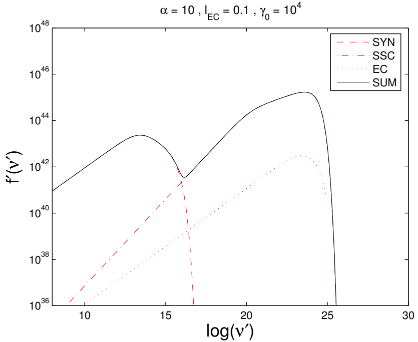

Figure 5: Model-SED for $\alpha_{ec} \gg 1$ and $l_{ec} \ll 1$ in the Thomson-limit

- Inclusion of external Compton requires new parameters:
  - Relative strengths $l_{ec} = u_{ec}\Gamma_b^2/u_B$
  - Injection parameter $\alpha_{ec}^2 = \gamma_0^2 q_0 A_0 \,/\, D_0(1 + l_{ec})$
- In order to get large α_{ec}, more extreme q_0 is needed $\Rightarrow$ SSC luminosity increases with $(1 + l_{ec})$

External Compton

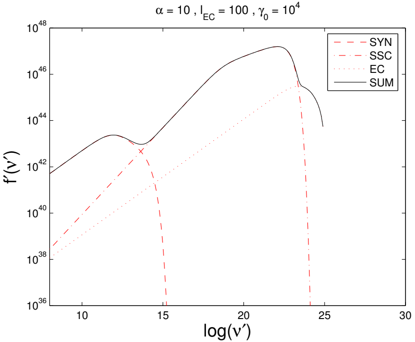

Figure 6: Model-SED for $\alpha_{ec} \gg 1$ and $l_{ec} \gg 1$ in the Thomson-limit

- Inclusion of external Compton requires new parameters:
  - Relative strengths $l_{ec} = u_{ec}\Gamma_b^2/u_B$
  - Injection parameter $\alpha_{ec}^2 = \gamma_0^2 q_0 A_0 \,/\, D_0(1 + l_{ec})$
- In order to get large α_{ec}, more extreme q_0 is needed $\Rightarrow$ SSC luminosity increases with $(1 + l_{ec})$

Summary & Outlook

- Dominating IC peak can be achieved by time-dependent SSC scenario (MZ & RS 2012a)
- Comparable with EC depending on parameters (MZ & RS 2012b)
- Follow-ups:
  - Lightcurves (paper in prep.)
  - Optical depth

Summary & Outlook

- Dominating IC peak can be achieved by time-dependent SSC scenario (MZ & RS 2012a)
- Comparable with EC depending on parameters (MZ & RS 2012b)
- Follow-ups:
  - Lightcurves (paper in prep.)
  - Optical depth

RUHR UNIVERSITÄT BOCHUM RUB

Thank you very much!

- Zacharias & Schlickeiser 2012b, *ApJ* 761, 110
- Zacharias & Schlickeiser 2012a, *MNRAS* 420, 84
- Zacharias & Schlickeiser 2010, *A&A* 524, A31
- Schlickeiser, Böttcher & Menzler 2010, *A&A* 519, A19
- Vercellone et al. 2011, *ApJ* 736, L38