Effects of Non-Continuous Inverse-Compton Cooling in Blazars

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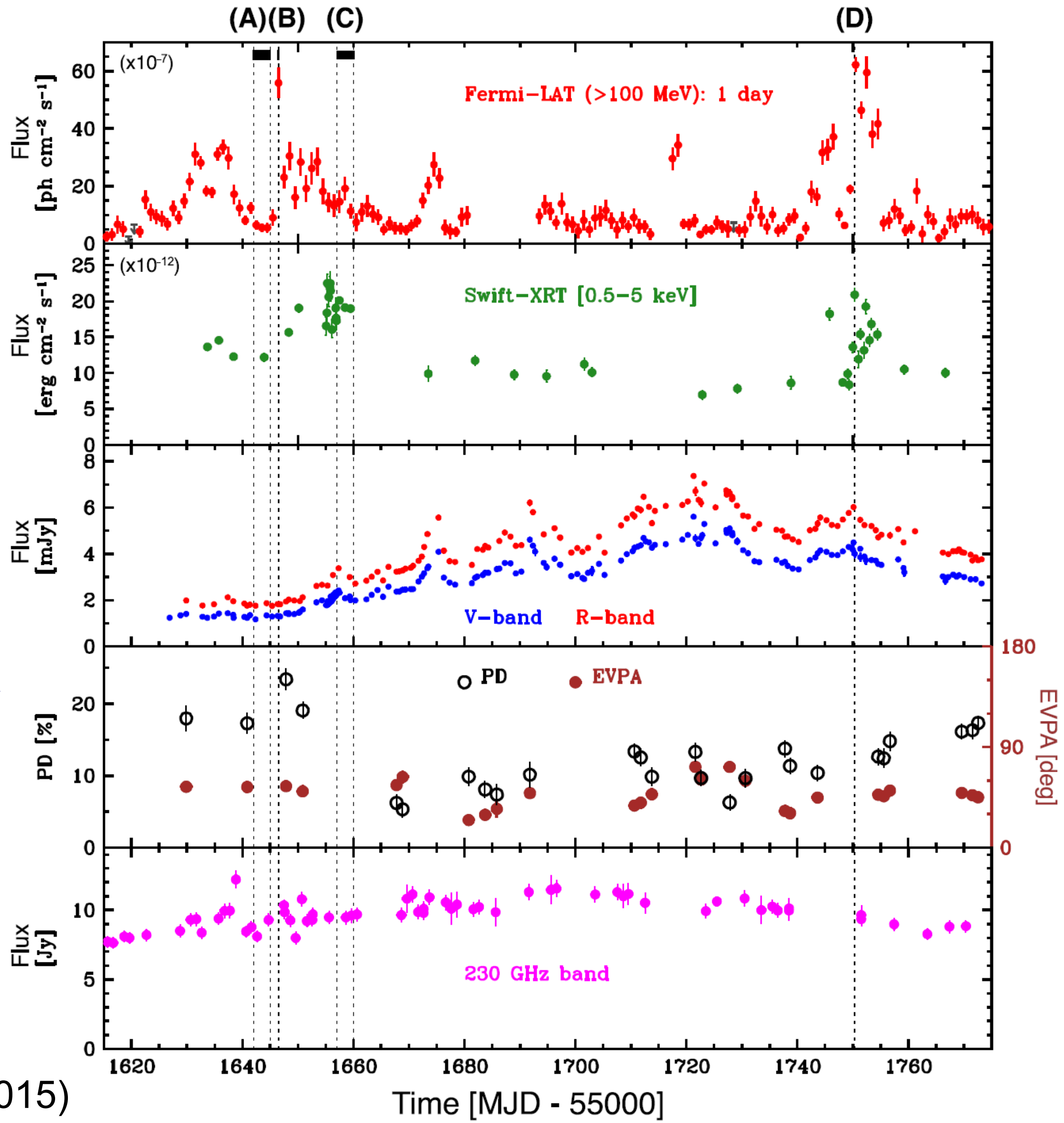
Blazar Variability

Flux, spectral, and polarization variability on time scales from years to minutes

Variability in different frequency regimes sometimes correlated, sometimes not.



(Hayashida et al. 2015)

Numerical approach to modeling blazar variability

In almost all time-dependent (leptonic) models for blazar variability:

Solve Fokker-Planck equation for the evolution of the electron distribution $N_e(\gamma,t)$:

$$\boxed{\frac{\partial N_e}{\partial t} = \frac{\partial}{\partial \gamma}\left(\left[\underbrace{b_{cool}\gamma^2}_{\text{cooling}} - \underbrace{a\gamma}_{\text{Fermi-I}} - \underbrace{2D_0\gamma}_{\substack{\text{Fermi-II} \\ \text{(system.} \\ \text{en. gain)}}}\right] N_e\right) + \underbrace{\frac{\partial}{\partial \gamma}\left(D_0\gamma^2 \frac{\partial N_e}{\partial \gamma}\right)}_{\substack{\text{Fermi-II} \\ \text{(diffusion in} \\ \text{momentum} \\ \text{space)}}} - \underbrace{\frac{N_e}{t_{esc}}}_{\text{escape}} + \underbrace{Q_{inj}}_{\text{injection}}}$$

Term $\gamma = b_{cool}\,\gamma^2$ describes continuous energy loss, with $\Delta\gamma/\gamma << 1$ for one individual interaction.

O.k. for synchrotron (with $B << B_{crit}$) and inverse-Compton (IC) in the Thomson regime

Inverse-Compton cooling

$\varepsilon = E_{ph}/(m_e c^2)$

- Thomson regime ($\varepsilon\gamma << 1$):

$\varepsilon_s \sim \gamma^2 \varepsilon \Rightarrow \Delta\gamma \sim \varepsilon_s - \varepsilon \sim \varepsilon (\gamma^2 - 1) << \gamma$

=> Continuous-loss approximation o.k.

- Klein-Nishina (KN) regime ($\varepsilon\gamma \gtrsim 1$):

$\varepsilon_s \sim \gamma \Rightarrow \Delta\gamma \sim \varepsilon_s - \varepsilon \sim \gamma - \varepsilon \sim \gamma$

=> Electron loses most of its energy in 1 interaction

=> Non-continuous cooling!

Numerical approach to modeling IC cooling in blazars

In almost all time-dependent (leptonic) models for blazar variability:

KN effects accounted for through the suppression of the KN cross section and reduced fractional energy loss (compared to $\varepsilon[\gamma^2-1]$), but still adopting a continuous-cooling approach, e.g., Moderski et al. (2005):

$$\dot{\gamma}_{\rm cool,IC} = -\frac{4\sigma_T}{3m_e c}\gamma^2 \int_{\epsilon'_{\rm min}}^{\epsilon'_{\rm max}} f_{\rm KN}(4\gamma\epsilon')\, u'_{\rm rad}(\epsilon')\, d\epsilon'$$

$$f_{\rm KN}(x) = \begin{cases} (1+x)^{-1.5}, & \text{for } x < 10^4 \\ \frac{9}{2x^2}\left(\ln(x) - \frac{11}{6}\right) & \text{for } x \geq 10^4 \end{cases}$$

with $x = 4\gamma\varepsilon'$.

Reasonably approximates KN throughout most of the spectrum, but does not reproduce large energy jumps.

Numerical approach to full IC cooling (incl. large energy jumps)

Integro-differential equation for electron evolution with full IC scattering kernel (Blumenthal & Gould 1970; Zdziarski 1988):

$$\frac{\partial N_e(\gamma,t)}{\partial t} = -N_e(\gamma,t)\int_1^{\gamma} C(\gamma,\gamma')d\gamma' + \int_{\gamma}^{\infty} N(\gamma',t)C(\gamma',\gamma)d\gamma' +$$

$$+\frac{\partial}{\partial\gamma}\left[-\dot{\gamma}_{\rm cool,syn}N_e(\gamma,t)\right] - \frac{N_e(\gamma,t)}{t_{\rm esc}} + Q_{\rm inj}(\gamma,t)$$

where $$C(\gamma,\gamma') = \int_{E_*/\gamma}^{\infty} dx\, n_0'(\varepsilon)\,\frac{3\sigma_{\rm T}c}{4E\gamma}\left[r + (2-r)\chi - 2\chi^2 + 2\chi\ln\chi\right]$$

and $\chi = E_*/E$, $E = \gamma\varepsilon$, $E_* = (\gamma/\gamma' - 1)/4$, $r = (\gamma/\gamma' + \gamma'/\gamma)/2$

C is sharply peaked around $\gamma = \gamma'$.

Numerical approach to full IC cooling (incl. large energy jumps)

Integro-differential equation for electron evolution with full IC scattering kernel (Blumenthal & Gould 1970; Zdziarski 1988):

$\gamma/(1+\delta)$

$$\frac{\partial N_e(\gamma,t)}{\partial t} = -N_e(\gamma,t)\int_1^{\gamma} C(\gamma,\gamma')d\gamma' + \int_{\gamma}^{\infty} N(\gamma',t)C(\gamma',\gamma)d\gamma' +$$

$\gamma(1+\delta)$

$+\ b_{cont}\gamma^2$

$$+\frac{\partial}{\partial\gamma}\left[-\dot{\gamma}_{\rm cool,syn}N_e(\gamma,t)\right] - \frac{N_e(\gamma,t)}{t_{\rm esc}} + Q_{\rm inj}(\gamma,t)$$

where $$C(\gamma,\gamma') = \int_{E_*/\gamma}^{\infty} dx\, n_0'(\varepsilon)\,\frac{3\sigma_{\rm T}c}{4E\gamma}\left[r + (2-r)\chi - 2\chi^2 + 2\chi\ln\chi\right]$$

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C is sharply peaked around $\gamma = \gamma'$.

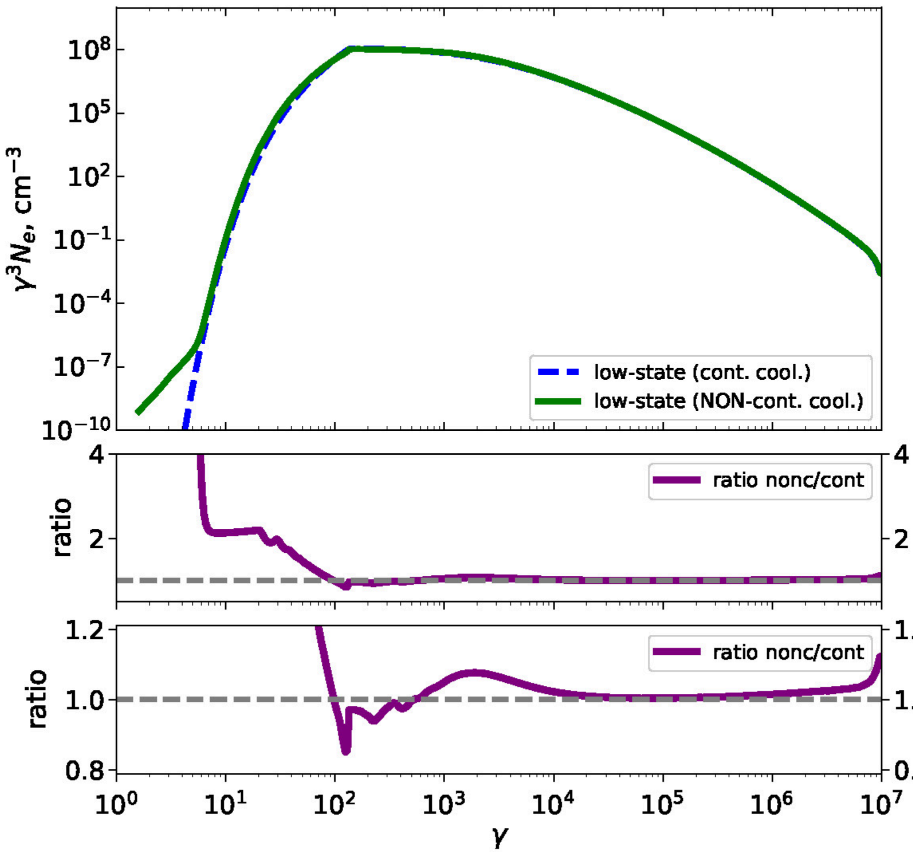
=> In practice: Treat an interval $\gamma/(1+\delta)$ to $\gamma(1+\delta)$, with $\delta \ll 1$, as continuous-cooling term.

Application to 3C279

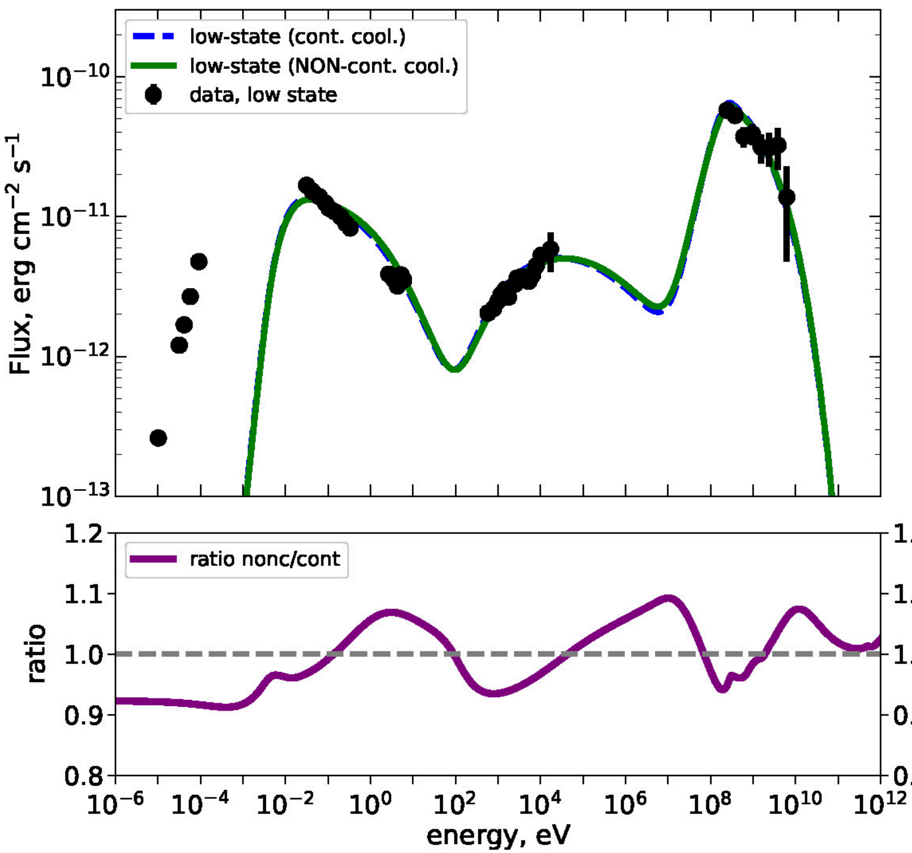
- Prominent, γ-ray bright FSRQ at $z = 0.536$
- Strongly Compton-dominated SED
- In leptonic models, γ-ray emission believed to be external-IC (BLR?) dominated
- => KN effects expected to be important at the highest energies.
- Model both quiescent state (Hayashida et al. 2012) and flare in June 2015 (H.E.S.S. collaboration et al. 2019).
- Using the EMBLEM (Evolutionary Modeling of BLob EMission) code (Dmytriiev et al. 2021), extended for applications to FSRQs, and including non-continuous IC cooling effects.

Application to 3C279 – Quiescent State

Equilibrium electron distribution



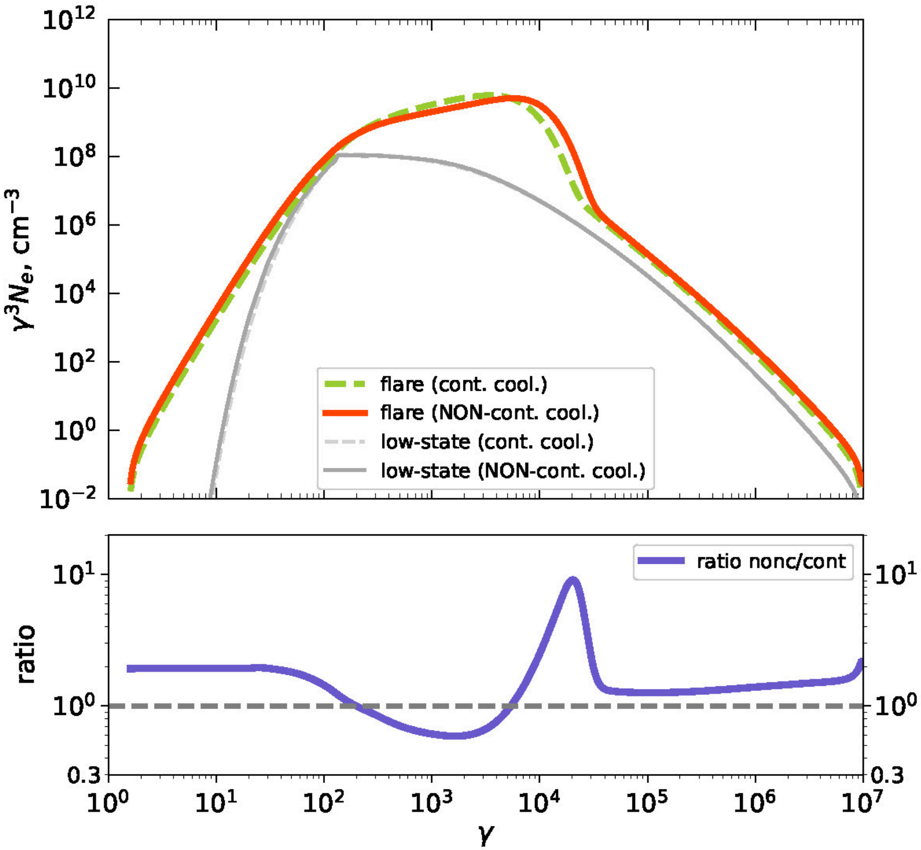
Equilibrium SED



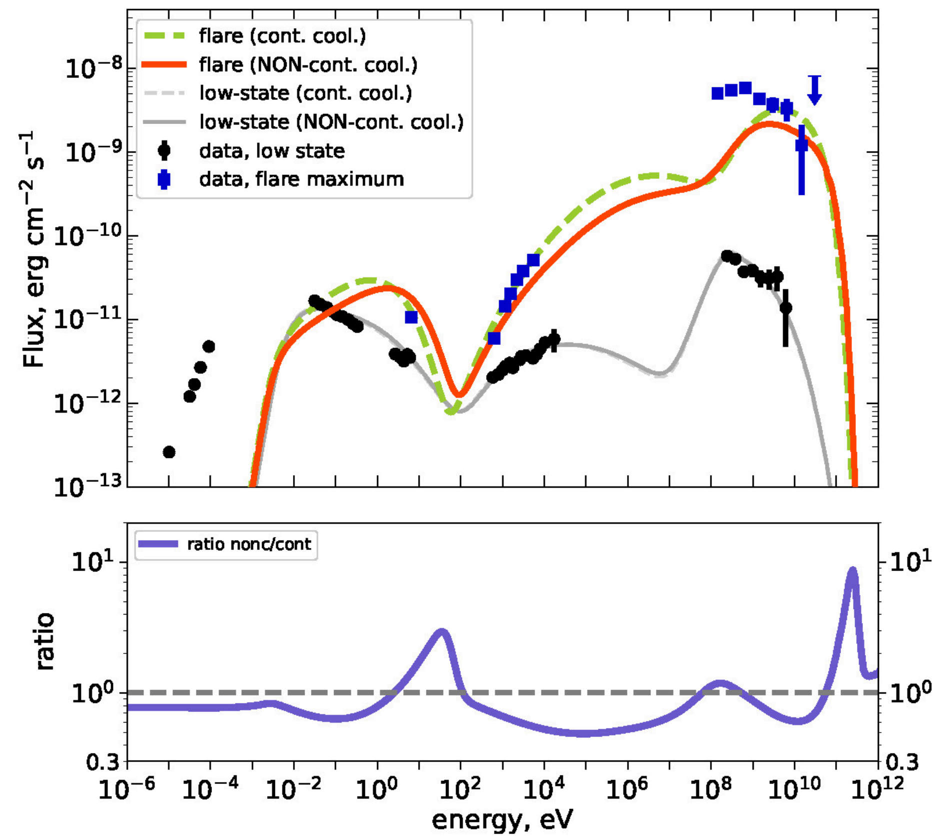
- Notable difference only at lowest energies (particles losing most of their energy in one scattering)
- Differences in the SED < 10 %.

Application to 3C279 – Flaring State

Flaring-state electron distribution



Flaring-State SED



- Significant (up to factor ~10) differences, especially near / beyond the peaks of the SED.
- Continuous-cooling approx. significantly over-estimating cooling at the highest energies.

Summary

1. Non-continuous Compton cooling effects can become significant in the case of high Compton-dominance, external-Compton dominated sources (FSRQs) in flaring states.

2. Steady-state emission is only negligibly affected.

3. Flaring-state emission exhibits significant excess emission at energies beyond the SED peaks when including non-continuous cooling effects.


Thank you