Flares with a Time-Dependent One-Zone Model

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Exploring the Physical Origin of Blazar Flares with a Time-Dependent One-Zone Model

Blazars are active galactic nuclei whose relativistic jets are collimated in the line of sight of the Earth. Multimode wavelength flux variability is a well-known signature of their emission. Rapid flares, with variability of the order of a few days and below, are frequently observed in high-energy bands, while many interpretations exist for individual flare events, based on radiative models with varying degrees of complexity, a unique picture of their physical origin is still lacking. Given the observed short variability timescales, a description based on a single compact emission region seems appropriate, if one focuses on rapid flares as isolated events. We have explored the parameter space of a one-zone synchrotron self-Compton model (Manzotti et al. 1992 \cite{1992ApJ...387..366M}, Bloom \\& Maierl 1996 \cite{1996ApJ...472L..77B}) for different scenarios leading to flares based on particle injection, diffusive shock acceleration, and adiabatic acceleration on turbulences (Matteucci et al. 2020 \cite{2020A&A...640A..64M}), taking into account adiabatic expansion. We use the time-dependent EMBLEM code (Dumitrescu 2021 \cite{2021A&A...640A..64D}) to solve the kinetic equation describing the evolution of the electron distribution, simulate broadband spectral distributions and multi-wavelength light curves and identify observable signatures to distinguish between these generic scenarios.

\section{Model and EMBLEM code}

The evolution of the electron distribution $N_e(\gamma, t)$ within the blob is governed by the Folkes-Plunk equation (Kardashev 1962 \cite{1962SvA....5...594K}, Tasinatto et al. 2011 \cite{2011ApJ...742..154T}, Tasinatto et al. 2021 \cite{2021CQGra..38q4001T})

\begin{equation}
\frac{\partial N_e(\gamma, t)}{\partial t} = \Gamma_p \phi_\gamma(\gamma) \left( N_e(\gamma, t) \right) - \frac{\partial}{\partial \gamma} \left( \frac{\gamma}{\Gamma_p} \frac{\partial}{\partial \gamma} N_e(\gamma, t) \right) - N_e(\gamma, t) \frac{\partial \phi_\gamma(\gamma)}{\partial \gamma}.
\end{equation}

\begin{table}
\begin{tabular}{|c|c|}
\hline
Cooling terms & Acceleration terms \\
\hline
- Synchrotron and Inverse Compton: & \\
\hline
- Adiabatic: & \\
\hline
- Escape: & \\
\hline
\end{tabular}
\end{table}

In all scenarios, the escape timescale $t_{\text{esc}}$ within the blob is given by the Folkes-Plunk equation

\begin{equation}
\frac{\partial N_e(\gamma, t)}{\partial t} = \frac{1}{\Gamma_p} \phi_\gamma(\gamma) \left( N_e(\gamma, t) \right) - \frac{\partial}{\partial \gamma} \left( \frac{\gamma}{\Gamma_p} \frac{\partial}{\partial \gamma} N_e(\gamma, t) \right) - N_e(\gamma, t) \frac{\partial \phi_\gamma(\gamma)}{\partial \gamma}.
\end{equation}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{LCs comparison of four different flaring types. The flux evolution is given in the radio band (top left), X-ray band (top right), $5\gamma$ band (bottom left), and VHE band (bottom right). The Fermi II acceleration scenario is implemented with $I_E = 1.5 \times \text{Fermi II}$ (intermediate CD regime).}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3}
\caption{SED obtained for the case of Fermi II acceleration with $I_E = 6 \times \text{Fermi II}$ (high CD regime). The shaded areas show the $1\sigma$ range and improve the limits on the parameters.}
\end{figure}

\section{Flare light curves}

We compared LCs for four flaring scenarios given a similar X-ray maximal amplitude. However, we cannot reach such an amplitude with Fermi II acceleration for an expected Compton dominance $C_D \lesssim 1$. We can reach larger X-ray amplitudes if $I_E$ is decreased, but the flattening enters a 'high CD regime' (Figure 3).

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4}
\caption{Flare light curves for our domains of study: radio, optical, X-rays, $\gamma$-rays and VHE-\gamma-rays.}
\end{figure}

\section{Flare scenarios}

- Particle injection: corning corresponds to an additional particle injection in the blob for a duration $t_{\text{inj}} = 3$ observer days $< \approx 8 R/c$, with fixed escape timescale $t_{\text{esc}} = \text{Fermi II}$. There is no acceleration, no blob expansion.
- Injection and adiabatic expansion: same as above including adiabatic expansion for an initial opening angle $\alpha = 0.4^\circ \approx 0.44^\circ$ with $\beta = 0.26$ (Pushkarev et al. 2009 \cite{2009ApJ...696..130P}).
- Fermi II acceleration: during corning to stochastic acceleration of blob particles for a duration $t_{\text{inj}} = 8 \times \text{Fermi II}$. With time-dependent escape timescale $t_{\text{esc}}$. We consider only the hard-\gamma-emissions scenario for $q = 2$ and vary the turbulence level $0 < \delta B/B < 1$ and maximum width $0 < \Lambda_{\text{tur}} < \infty$. There is no additional particle injection, no blob expansion.
- Fermi I acceleration: during corning to diffusive shock acceleration during $t_{\text{inj}} = 8 \times \text{Fermi II}$. Timescale $t_{\text{shock}} = 1.3 \times \text{Fermi II}$, which dominates the stochastic acceleration of particles $I_E/B = 1$ and $t_{\text{esc}} = 1$. There is no additional particle injection, no blob expansion.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5}
\caption{SED obtained for the case of Fermi II acceleration with $I_E = 6 \times \text{Fermi II}$ (high CD regime). The shaded areas show the $1\sigma$ range and improve the limits on the parameters.}
\end{figure}

\section{Stochastic acceleration regimes}

We compare the LCs for three cases of Fermi II acceleration: low ($I_E = 15 \approx \text{Fermi I}$), intermediate ($I_E = 6 \approx \text{Fermi II}$), and high ($I_E = 6 \times \text{Fermi II}$) CD regimes, presenting different behaviours due to the pile-up and cooling of high-energy electrons, as visible in the shift of the SED synchrotron and SSC bumps in Figure 1.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure6}
\caption{Stochastic acceleration regimes. The high CD Fermi II regime is implemented with $I_E = 3 < \text{Fermi II}$ and $t_{\text{esc}} = 1.3 \times \text{Fermi II}$, the intermediate with $I_E = 6 < \text{Fermi II}$ and $t_{\text{esc}} = 1.3 \times \text{Fermi II}$, and the low with $I_E = 15 < \text{Fermi II}$ and $t_{\text{esc}} = 1.3 \times \text{Fermi II}$.}
\end{figure}

\section{Conclusions}

Exploiting the parameter space, we identify LC signature corresponding to different flaring scenarios:
- Particle injection: concave rise, positive half-flux asymmetry; $C_D \lesssim 1$, the reaching of a plateau phase (flaring nearly static) depends on the duration $t_{\text{inj}}$.
- Injection and adiabatic expansion: decreasing quiescent emission, decreasing plateau (when reached) and negative asymmetry.
- Low CD Fermi II acceleration: concave rise, positive asymmetry; $C_D \lesssim 1$, larger variability amplitudes (VA) of radio and $\gamma$-ray bands compared to injection.
- High CD Fermi II acceleration: concave/rise in radio, optical and $\gamma$-ray bands, convex in X-rays and VHE-\gamma-rays; $C_D > 1$, larger VA (2-3 orders of magnitude) of (V)HE $\gamma$-ray bands compared to the other domains, fast rise (negative asymmetry) and early decay in X-rays and VHE-\gamma-rays. This result indicates the possibility of describing high CD flares without including external photon fields.
- Fermi I acceleration: CD value $\approx 4 \times 10^3$ affected by the stochastic acceleration contribution, larger VA of (V)HE $\gamma$-ray bands compared to the other domains and scenarios. If $C_D \lesssim 1$, plateau phases reached at different times depending on the band and shift of the SED bumps to higher frequencies during the flaring phase. In all scenarios, the escape timescale $t_{\text{esc}}$ and the effect of radiative cooling determine the decay time and decay shapes of the fluxes between energy bands.

\section{References}