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# Effect of Particle Acceleration Process on the Flare Characteristics of Blazars

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**Abstract.** Following the kinetic equation approach, we study the flare processes in blazars in the optical-to-X-ray region, considering energy dependent acceleration time-scale of electrons and synchrotron and adiabatic cooling as their dominant energy loss processes.

## 1. Introduction

Blazars are characterised by a non-thermal photon spectrum ranging from radio-to-gamma-ray region and a high degree of optical polarisation (Maraschi 1992). Their spectral energy distribution shows two prominent peaks – a low energy peak in the optical/soft X-ray region, and the high energy peak in the GeV/Tev gamma-ray region (Kataoka *et al.* 1999). It is generally accepted that the radio-to-soft X-ray emission arises due to synchrotron cooling of relativistic electrons in the blazar jet, and that the hard X-ray to gamma-ray photons are produced by the inverse Compton scattering of low-energy photons (Kusunose *et al.*).

Blazar emissions also show large and rapid time-variability. Many models exist in the literature (Kirk *et al.* 1998) which attempt to understand the origin of some of the observed features of these flares, such as the rise and the decay times of fluxes, time-lag at different energies, etc., in the frame work of the kinetic equation approach. Following such a general approach and restricting our study to the optical to soft X-ray energy region of blazar spectra, we here study the effect of particle acceleration process on the variability features.

## 2. Model

It is necessary to first study the time-evolution of electron energy spectrum and in the model presented here we, therefore, consider two zones, namely, an acceleration zone (AR) around a shock front and a cooling zone (CR), the two being spatially separated within the blazar jet. Monoenergetic electrons of Lorentz factor $\gamma_o$ are continously fed into AR at a rate $Q_o s^{-1}$ (consistent with the source bolometric luminosity) where they are accelerated at a rate $1/t_{\rm acc}$ in a diffusive shock acceleration process (Drury 1983), while simultaneously **(i)** losing energy due to synchrotron emission in the ambient magnetic field and **(ii)** escaping the AR at a rate $1/t_{\rm esc}$. The time-evolution of electron spectrum in AR is given by

$$\frac{\partial Q(\gamma, t)}{\partial t} + \frac{\partial}{\partial \gamma}[(\frac{\gamma}{t_{\rm acc}} - \beta\gamma^2)Q(\gamma, t)] + \frac{Q(\gamma, t)}{t_{\rm esc}} = Q_o\delta(\gamma - \gamma_o) \qquad (1)$$

where $t_{\rm acc} = \frac{20 m_e c^2 \xi \gamma}{3 v_s^2 e B_{\rm acc}}$, $v_s$ is the velocity of the shock, $B_{\rm acc}$ is the ambient magnetic field in the AR and $\xi$ is a parameter connected to Larmor radius. $\beta$ is a function of $B_{\rm acc}$.

After leaving the AR at a rate $1/t_{\rm esc}$, particles enter into the CR which we consider here to be a spherical blob expanding adiabatically with expansion speed $v_{\rm exp}$, while moving down the jet relativistically with a Doppler factor $\delta$. The relativistic electrons in the CR lose energy adiabatically and also emit electromagnetic radiation by synchrotron process in the *in situ* magnetic field $B$. The evolution of spectrum in CR is obtained by solving the kinetic equation

$$\frac{\partial N(\gamma,t)}{\partial t} + \frac{\partial}{\partial \gamma}[P(\gamma,t)N(\gamma,t)] + \frac{N(\gamma,t)}{\tau} = \frac{Q(\gamma,t)}{t_{\rm esc}} \qquad (2)$$

$$P(\gamma,t) = -\frac{v_{\rm exp}\gamma}{R} - \frac{4}{3}\frac{\sigma_T c}{m_e c^2}\frac{B^2}{8\pi}\gamma^2 \qquad (3)$$

where $R = R_o + v_{\rm exp} t$ and $B = B_o(\frac{R_o}{R})^m$ are the instantaneous radius and the magnetic field of the CR respectively and $R_o$, $B_o$ their initial values. $\tau$ is the escape timescale of particles from the CR. The emitted synchrotron photon flux is next calculated by convoluting $N(\gamma,t)$ with the single particle emissivity $P(\nu,\gamma) = \frac{\sqrt{2}e^3 B}{m_e c^2} F(\nu/\nu_c)$, where $\nu_c = \frac{3eB}{4\pi mc}\sqrt{\frac{2}{3}}\gamma^2$ and $F(x) = x\int_x^\infty K_{\frac{5}{3}}(\xi)d\xi$. It is to be noted that the emission of radiation from energetic electrons in AR is not included in this study because of the smaller volume of AR compared to that of CR.

## 3. Results and discussion

Choosing the parameter space, with $\gamma_o = 2$, $\delta = 10$, $Q_o = 10^{46} s^{-1}$, $B_{\rm acc} = 0.1G$, $B_o = 0.2G$, $m = 1$, $R_o = 10^{13}$cm and $v_s = 0.4c$, together with the initial condition $Q(\gamma,0) = N(\gamma,0) = 0$ to reproduce the usually observed spectrum of blazars, we seek solutions of equations (1) and (2) for **(a)** energy-independent and **(b)** energy-dependent acceleration process cases. Using $t_{\rm esc} = t_{\rm acc}$, $\tau = 2R/c$ for both (a) and (b) cases, we replace $\gamma$ (in the expression for $t_{\rm acc}$) by a constant value $\gamma_{\rm eff}(= 10^7)$ and obtain $t_{\rm acc} = 2 \times 10^4$s, $0.0418\gamma\ s$ in the source-frame in case (a) and case (b) respectively. For $t \geq 0$, the electron energy distribution and the photon spectrum evolve into a steady state when the flux values at different energies do not change with time. The maximum frequency of emitted radiation depends on the maximum value of the Lorentz factor of electrons, $\gamma_{\rm max}$ with the parameter values chosen here, for case (a), $\gamma_{\rm max} = \frac{1}{\beta t_{\rm acc}} = 8.89 \times 10^5$ and for case (b) $\gamma_{\rm max} = \frac{1}{\sqrt{t_{a,o}\beta}} = 2.98 \times 10^6$.

We represent a flare by a sudden increase in the injection rate, driven by source instability in the jet flow, into the AR for a small duration, once the system attains a steady state. In Fig. 1(a), we show the flare patterns at frequencies of $10^{17}$, $10^{16}$ and $10^{15}$ for case (a) when $Q_o$ increases from $10^{46} s^{-1}$ to $1.5 \times 10^{46}\ s^{-1}$ for 0.2 days (in observer's frame) after a steady state is already reached on the second day. It is seen that not only do low energy flares manifest themselves earlier in time than the higher energy flares but the time-lag between their respective peak positions also increases with increase in $t_{\rm acc}$ (not shown here). We also find that the hysterisis loop (a plot of X-ray flux vs spectral index) is traced anticlockwise (not shown here). These observations suggest the presence of the oft-quoted 'hard-lag' in the blazar spectra. In Fig. 1(b),

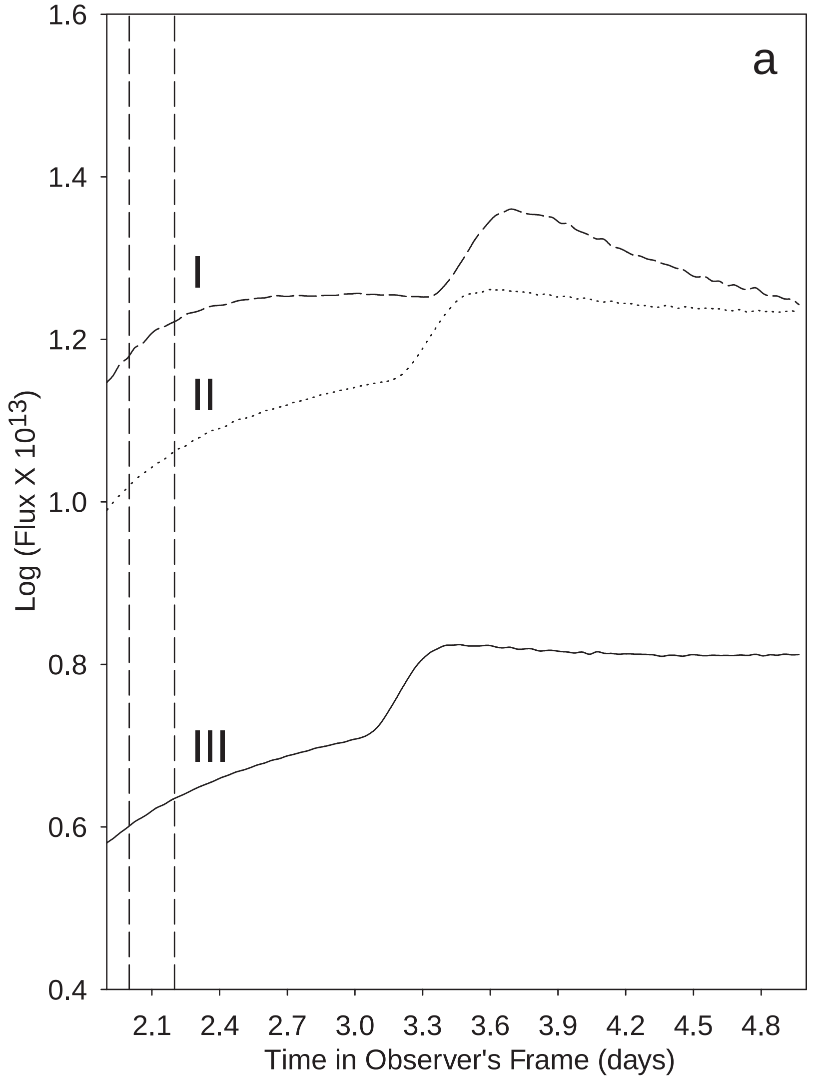


**Figure 1.** Flares at different frequencies **(I)** $10^{17}$ Hz, **(II)** $10^{16}$ Hz and **(III)** $10^{15}$ Hz: **(a)** energy-independent and **(b)** energy-dependent acceleration process. Vertical dashed lines show the duration of excess injection of particles in the AR.

we show the flare patterns for the same energies for case (b). We note that in this case the system attains a steady state much faster than in case (a) and the peak values at different frequencies are attained simultaneously. Contrary to case (a), the hysterisis loop is traced clockwise in this case (not shown here).

The light curves (Fig. 1a,b) are asymmetrical, with a shorter rise time and a longer decay time. It cannot obviously arise due to effects of light crossing time alone. Effects due to different acceleration and emission time-scales are folded in here. For one, the decay times depend upon energy loss time-scales which are known to be energy-dependent.

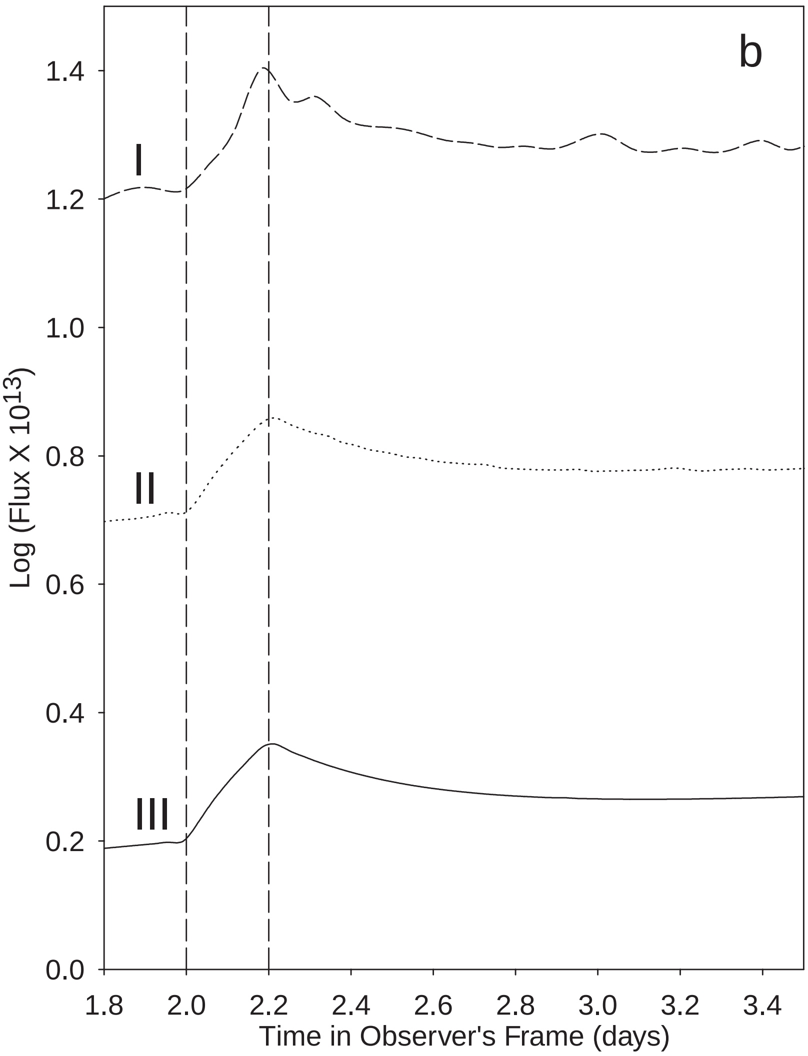


**Figure 1.** (*Continued*).

We also find that the inclusion of adiabatic cooling process merely stretches the decay part of the light curves slightly.

## 4. Conclusion

The model reproduces, though only qualitatively, the observed hard-lag in flare spectra from blazars in the optical-soft X-ray region. A detailed comparison of our model with observation is not warranted at this stage as correlated flux variations in the optical and X-ray remain as yet poorly established, although BeppoSax observations of Mrk421 do show flare spectra which have features somewhat similar to those presented here

(Fossati *et al.* 2000). Moreover, we are still in the process of fine-tuning our parameter space so as to be able to reproduce observations as closely as possible. The results will be presented elsewhere (Bhattacharyya *et al.*).

The absence of the hard-lag effect in case $t_{acc}$ is energy-dependent suggesting that the hard-lag effect, if observed unequivocally may provide useful inputs in understanding the dynamics of particle acceleration in blazars.

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