Modeling Particle Acceleration in AGN's

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Abstract

The radiation from Active Galactic Nuclei of the Blazar class is commonly attributed to synchrotron emission and inverse Compton scattering of a population of relativistic electrons (and positrons) accelerated inside the jets of the source. In this work we discuss the ambiguities that are present in the determination of the parameters of the model such as the size the source region, its Doppler factor, the magnetic field and the maximum electron energy in the jet frame.

1. Introduction

The radiation from AGNs of the Blazar class is commonly attributed to the synchrotron emission and Inverse Compton (IC) scattering of a population of relativistic $e^{\mp}$ accelerated inside plasma regions (or "blobs") moving with ultra-relativistic velocity within jets aligned with the rotation axis of the central black hole [2]. As target for the IC scattering one can consider the synchrotron radiation (Self Synchrotron Compton (SSC) component), or externally produced photons (External Compton (EC) component). In the simplest and time integrated model the emitting region is described as a homogeneous sphere ("blob") of radius R containing a randomly oriented magnetic field of average value B. The "blob" moves in the galaxy frame with ultrarelativistic speed v and Lorentz factor Γ at an angle $\theta_{\rm view}$ with respect to the line of sight; all relativistic effects depend only on the Doppler factor $D = 1/(\Gamma(1 - \beta \cos\theta_{\rm view})$. The energy spectrum of the relativistic $e^{\mp}$ population can be approximately described as a power law: $n_e(\gamma) \simeq K\,\gamma^{-\alpha}$ with normalization K and slope α, up to a characteristic energy $\gamma_{\rm break}$, where the flux drops more rapidly. For example in [1] the $e^{\mp}$ spectrum is described with the form:

$$n_{\rm e}(\gamma) = K\,\gamma^{-\alpha}\,(1 + \gamma/\gamma_{\rm break})^{\alpha-\beta} \tag{1}$$

The external photon field can be modeled as isotropic in the galaxy frame, where the photons have average energy $\varepsilon_{\rm ext}$ and an energy density $u_{\rm ext}$. In summary the simplest homogeneous and time integrated model depends on the set of parameter $\{D, R, B, K, \gamma_{\rm break}, \alpha, \beta\}$ plus $\{\varepsilon_{\rm ext}, u_{\rm ext}\}$ to describe the external radiation fields. In general the Spectral Energy Distribution (SED) of a given source will appear

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as the combination of three "bumps" that can be attributed to the synchrotron, SSC and EC emission. The shapes of the three "bumps" clearly reflect the shape of the $e^{\mp}$ spectrum (or the values of the esponents α and β) and are very strongly correlated with each other, while the positions of the maxima ($\varepsilon_{\rm syn}$, $\varepsilon_{\rm ssc}$, $\varepsilon_{\rm ec}$) and the absolute values of the flux at the maxima depend on various parameter combinations. It is straightforward to obtain the following relations:

$$\begin{aligned}
\varepsilon_{\rm syn}\,(1+z) &= \varepsilon_0\, g\; D\; B\; (\gamma_{\rm break})^2 &(2)\\
\varepsilon_{\rm ssc}\,(1+z) &= \varepsilon_0\, g^2\; D\; B\; (\gamma_{\rm break})^4 &(3)\\
\varepsilon_{\rm ec}\,(1+z) &= \varepsilon_{\rm ext}\, g\; D^2\; (\gamma_{\rm break})^2 &(4)\\
(\nu F_\nu)^{\rm peak}_{\rm syn}\; d_L^2 &= A_{\rm syn}\; D^4\; B^2\; K\; R^3\, (\gamma_{\rm break})^{3-\alpha} &(5)\\
(\nu F_\nu)^{\rm peak}_{\rm ssc}\; d_L^2 &= A_{\rm ssc}\; D^4\; B^2\; K^2\; R^4\, (\gamma_{\rm break})^{2(3-\alpha)} &(6)\\
(\nu F_\nu)^{\rm peak}_{\rm ec}\; d_L^2 &= A_{\rm ec}\; D^6\; u_{\rm ext}\; K\; R^3\, (\gamma_{\rm break})^{3-\alpha} &(7)
\end{aligned}$$

where z and d_L are the redshift and luminosity distance of the source, $\varepsilon_0 \simeq q_e\hbar/m_e c \simeq 1.16\times 10^8$ eV/Gauss; g is an adimensional factor that depends on the shape of the electron spectrum [for example for a spectrum of form (1) $g \simeq (3-\alpha)/(\beta-3)$]; $A_{\rm syn} \simeq \sigma_T\, c \times f^{\rm syn}_{\rm shape}$, $A_{\rm ssc} \simeq \sigma_T^2\, c\times f^{\rm ec}_{\rm shape}$ and $A_{\rm ec} \simeq \sigma_T\, c\times f^{\rm ec}_{\rm shape}$; σ_T is the Thompson cross section, and three $f^{\rm comp}_{\rm shape}$ factors are other shape dependent adimensional constants. All these scaling laws can be checked with numerical calculations, but can also be understood with simple considerations. For example in (5) and (6) the dependence of the SED on D is the combined effect of angular beaming (D^2), energy boost (D) and time compression (D); the scaling of (5) on $\gamma_{\rm break}$ is due to the spectrum shape ($\gamma^{-\alpha}$), synchrotron emissivity (γ^2) and the energy weight (γ).

2. Self Synchrotron Compton Emission

For many sources (in particular for the TeV Blazars such as Mrk 421 and Mrk 501) [3], the emission is modeled as only due to the synchrotron and SSC components. It can be shown that in this case the determination of the parameters in the model is ambiguous (see fig. 1.). The esponents of the $e^{\mp}$ distribution can be extracted from the shape of any one of the two bumps; in particular the slope p of the SED before the maximum is related to α with: $p = (3-\alpha)/2$. The break energy $\gamma_{\rm break}$ can be unambiguously obtained as: $\gamma^2_{\rm break} \simeq \varepsilon_{\rm ssc}/(\varepsilon_{\rm syn}\, g)$. For the other parameters one can find the solution:

$$\begin{aligned}
K &= \eta^{-\frac{1}{3}}\; (L_{\rm syn})^{-\frac{4}{3}}\; L_{\rm ssc}\; (\varepsilon_{\rm syn}/\varepsilon_0\, g)^{\frac{4}{3}}\; (\gamma_{\rm break})^{\frac{2}{3}(\alpha-7)} &(8)\\
D &= \eta^{-\frac{1}{3}}\; (L_{\rm syn})^{+\frac{2}{3}}\; (L_{\rm ssc})^{-\frac{1}{2}}\; (\varepsilon_{\rm syn}/\varepsilon_0\, g)^{\frac{1}{3}} (\gamma_{\rm break})^{\frac{(1-\alpha)}{3}} &(9)\\
B &= \eta^{+\frac{1}{3}}\; (L_{\rm syn})^{-\frac{2}{3}}\; (L_{\rm ssc})^{\frac{1}{2}}\; (\varepsilon_{\rm syn}/\varepsilon_0\, g)^{\frac{2}{3}}\; (\gamma_{\rm break})^{\frac{1}{3}(\alpha-7)} &(10)\\
R &= \eta^{+\frac{1}{3}}\; (L_{\rm syn})^{+\frac{1}{3}}\; (\varepsilon_{\rm syn}/\varepsilon_0\, g)^{-\frac{4}{3}}\; (\gamma_{\rm break})^{\frac{(5+\alpha)}{3}} &(11)
\end{aligned}$$

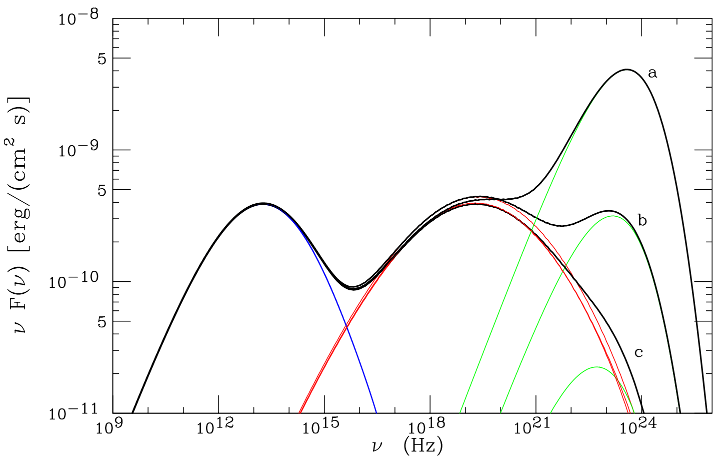

Fig. 1. Three calculations of the SED of a blazar at $z = 0.5$. The parameters of the model are chosen so that the synchrotron and SSC contributions remain approximately equal. For curve b the parameters are: $R = 5 \times 10^{16}$ cm, $D = 30$, $B = 0.4$ Gauss, $K = 5000$ cm^{-3}, $\alpha = 1.6$, $\beta = 4.7$, $\gamma_{\rm break} = 10^3$. For curve a (c) R and B are modified by the factor 2 (1/2), while D and K are modified by the inverse factor 1/2 (2). The external photon field is described with $\varepsilon_{\rm ext} = 10$ eV and an energy density $u_{\rm ext} = 1.9 \times 10^7$ eV/cm^3

where we have introduced the notations $L_{\rm comp} = (\nu F_\nu)^{\rm peak}_{\rm comp}\; d_L^2/A_{\rm comp}$. The quantity η has the physical meaning: $\eta = B^2/K$. This set of equations indicate that there are infinite solutions that can be obtained varying η. If one set of parameters gives a good description of an observed SED, the new parameter set obtained multiplying B and R by an arbitrary factor f and K and D by the inverse factor $1/f$ gives essentially identical synchrotron and SSC contributions to the SED. A possible method to solve the ambiguity is to assume energy equipartition, equating the energy density in magnetic field $(B^2/(8\pi))$ to the energy density in relativistic electrons $(\propto K m_e \gamma_{\rm break})$ to fix the value of B^2/K.

3. External Compton Emission

For other sources (for example for 3C279) one finds that very likely the EC emission dominates the high energy radiation [1], while the SSC component is poorly determined. Also the combination of the information from the synchrotron and EC components does *not* allow to determine unambiguously the parameters of our simple homogeneous model (see fig. 2). The solution for the case of synchrotron–EC emission can be written as:

$$\gamma_{\rm break} = (K\,R^3)^{+\frac{1}{3+\alpha}}\; (L_{\rm syn})^{-\frac{1}{3+\alpha}}\; (\varepsilon_{\rm ec}/\varepsilon_{\rm ext}\,g)^{+\frac{1}{3+\alpha}}\; (\varepsilon_{\rm syn}/\varepsilon_0\,g)^{\frac{2}{3+\alpha}} \tag{12}$$

$$B = (K\,R^3)^{-\frac{1}{3+\alpha}}\; (L_{\rm syn})^{+\frac{1}{3+\alpha}}\; (\varepsilon_{\rm ec}/\varepsilon_{\rm ext}\,g)^{-\frac{5+\alpha}{6+2\alpha}}\; (\varepsilon_{\rm syn}/\varepsilon_0\,g)^{\frac{1+\alpha}{3+\alpha}} \tag{13}$$

$$D = (K\,R^3)^{-\frac{1}{3+\alpha}}\; (L_{\rm syn})^{+\frac{1}{3+\alpha}}\; (\varepsilon_{\rm ec}/\varepsilon_{\rm ext}\,g)^{+\frac{1+\alpha}{6+2\alpha}}\; (\varepsilon_{\rm syn}/\varepsilon_0\,g)^{-\frac{2}{3+\alpha}} \tag{14}$$

It can be seen that if the set of the parameters $\{D, B, \gamma_{\rm break}, (K\,R^3)\}$ is found to describe the SED of a source, all other sets of parameters obtained from this

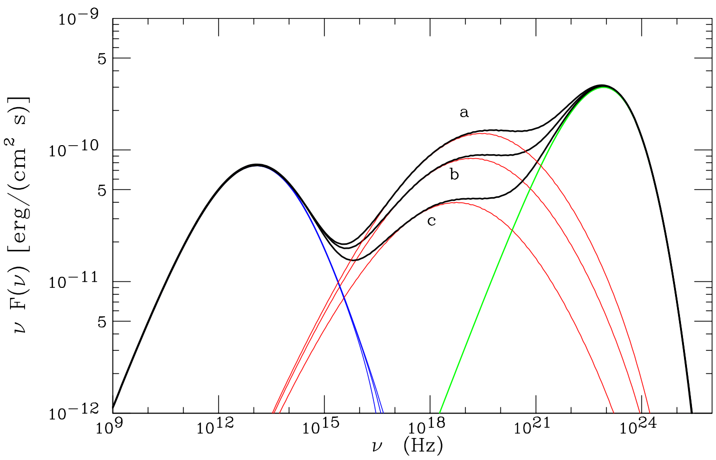

Fig. 2. Three calculations of the SED of a blazar at $z = 0.5$. The parameters of the model are chosen so that the synchrotron and EC contributions remain approximately equal. For curve b the parameters are: $R = 5 \times 10^{16}$ cm, $D = 30$, $B = 0.4$ Gauss, $K = 5000$ cm^{-3}, $\alpha = 1.6$, $\beta = 4.7$, $\gamma_{\rm break} = 10^3$, $\varepsilon_{\rm ext} = 10$ eV and $u_{\rm ext} = 1.9 \times 10^8$ eV/cm^3. For curve a (c) $\gamma_{\rm break}$ is modified by a factor f=2/3 (3/2), B and D by the inverse factor $1/f$ and $K\,R^3$ by a factor $f^{3+\alpha} = 0.155$ (6.45).

solution rescaling D and B by an arbitrary factor f, $\gamma_{\rm break}$ by f^{-1} and the combination $(K\,R^3)$ by $f^{-(3+\alpha)}$ give essentially identical synchrotron and EC emission. Only the combination (KR^3) can be determined. Note that in our solution the quantities $L_{\rm ec}$ and $u_{\rm ext}$ do not appear. This may appear surprising, however it is simple to see that in general one has the relation:

$$u_{\rm ext} = (L_{\rm ec}\ \varepsilon_{\rm ext}^2\ \varepsilon_{\rm syn}^2)\ /\ (L_{\rm syn}\ \varepsilon_{\rm ec}^2\ \varepsilon_0^2) \tag{15}$$

therefore the equation involving $(\nu F_\nu)_{\rm ec}^{\rm peak}$ can be used to determine $u_{\rm ext}$ if it is not known, or becomes an identity that can only be used as a consistency check. The assumption of energy equipartition condition can again resolve this ambiguity.

The ambiguities in parameter determination are resolved if all three components (synchrotron, SSC and EC) are well measured. More in general, additional constraints can be used to define the parameters. For example the (non) observation of synchrotron self–absorption gives additional information on the combination of R and K, and the observation of superluminal motions and time variations gives constraints on D and R.

References

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