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Automatic quenching of power-law gamma-ray spectra from compact sources

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Abstract: We study a non linear mechanism for producing intrinsic broken power-law spectra in the GeV-TeV energy range in AGN SEDs, based on the principles of automatic photon quenching according to which, γ rays are being absorbed on spontaneously produced soft photons, whenever the injected luminosity in γ rays lies above a certain critical value. More specifically, we derive an analytical expression for the critical γ ray compactness in the monoenergetic case of γ ray injection and we generalize in the case of injection in two and finally N discrete energies in γ rays. Passing on to the continuous case, we discuss our results which are currently leading to interesting suggestions about the observational features of the mechanism.

1 Introduction

The non linear mechanism treated here, was first discussed by Stawarz & Kirk (2007)who showed that there is a theoretical limit to the γ ray luminosity escaping from a source, that depends on parameters such as the source radius and its magnetic field strength and does not rely on the existing photon population. Violation of this limit leads to automatic photon quenching of the γ rays, which involves photon-photon annihilation and lepton synchrotron radiation, with the synchrotron soft photons serving as targets for furthermore γ ray absorption.

2 Basic assumptions and considerations

We consider a spherical region of radius R and magnetic field strength B and we assume that γ rays are being uniformly produced by an unspecified emission mechanism throughout the volume of the source, injected with a compactness $l_\gamma^{inj} = L_\gamma^{inj}\sigma_\tau/4\pi R m_e c^3$.
There are two conditions that should be satisfied simultaneously in order for the non linear loop described above to function: i)**Feedback Criterion:** $b\varepsilon_\gamma^3 \geq 8$, or $\varepsilon_\star = 2/b^{1/3}$, derived by combining the energy threshold condition for $\gamma\gamma$ absorption $\varepsilon_\gamma x \geq 2$, the equipartition of energy among the created pairs $\gamma_\pm = \varepsilon_\gamma/2$ and the assumption that the pairs radiate only at $x = b\gamma^2$ (i.e. the soft photons required for the loop are the synchrotron photons radiated by the pairs) and ii) **Critical Condition**: $N_s(\frac{\varepsilon_\gamma}{2})n(\varepsilon_\gamma)\sigma_{\gamma\gamma}R \geq 1$, which is related to the fact that the optical depth must be larger than one in order to grow the instability.
Our work is based on the following assumptions:

1. Only photon-photon absorption and Synchrotron radiation of the pairs are taken into account. Inverse Compton Scattering (ICS) is safely neglected due to the strong magnetic field that is typically required for our loop to function ($B \sim 40G$) and the large Lorentz factors of the produced pairs (Klein-Nishina regime).

2. The equation for the pairs is neglected since these have synchrotron cooling timescales much smaller than the crossing time of the source and the Synchrotron energy losses are considered as catastrophic, i.e. an electron with Lorentz factor γ radiates photons at energy $b\varepsilon_\gamma^2/4$.

3. Synchrotron emissivity is approximated as a δ function i.e. $j_{syn}(x) = j_0\delta(x - b\gamma^2)$ and photon-photon absorption cross section as $\sigma_{\gamma\gamma} \approx \frac{\sigma_0\Theta(x\varepsilon_\gamma-2)}{x\varepsilon_\gamma}$, in units of σ_τ .

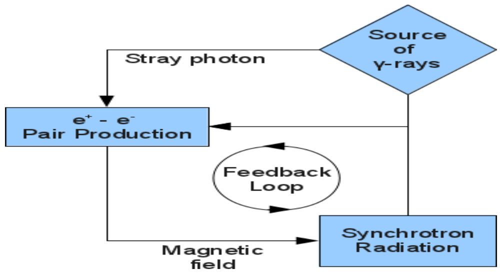

Figure 1: An outline of the non linear loop discussed in the present work

3 Equations and marginal Stability Criterion

Using all of the above, the kinetic equations that describe the system of the soft and the hard photons injected in two, discrete energies, are:

$$\begin{aligned} \frac{\partial n_i(\varepsilon_{\gamma,i},\tau)}{\partial \tau} &= -n_i(\varepsilon_{\gamma,i},\tau) + \frac{3l^{inj}_{\gamma,i}}{\varepsilon^2_{\gamma,i}} - \frac{\sigma_0}{\varepsilon_{\gamma,i}x_i} n_i n_{0,j} \\ \frac{\partial n_{0,i}(x_i,\tau)}{\partial \tau} &= -n_{0,i}(x_i,\tau) + \frac{\sigma_0}{x_j^2} n_i n_{0,j} \end{aligned} \quad (1)$$

(for i,j= 1,2), where $n_i(\varepsilon_{\gamma,i},\tau)$, $n_{0,i}(x_i,\tau)$ are the dimensionless photon number densities of the hard and soft photons respectively. We introduce perturbations to all photon number densities and linearize the set of equations around the trivial solution $(\bar{n}_1 = \frac{3l^{inj}_{\gamma,1}}{\varepsilon^2_{\gamma,1}}, \bar{n}_2 = \frac{3l^{inj}_{\gamma,2}}{\varepsilon^2_{\gamma,2}}, 0, 0)$.
By demanding positive eigenvalues (in order to build a finite number of soft photons in the source), we derive the following condition: $\frac{l^{inj}_{\gamma,1}}{\varepsilon^6_{\gamma,1}} + \frac{l^{inj}_{\gamma,2}}{\varepsilon^6_{\gamma,2}} \geq \frac{b^2}{48\sigma_0}$ (2) , which keeps its form and in the case of injection in N discrete energies becomes : $\sum_{i=1}^{N} \frac{l^{inj}_{\gamma,i}}{\varepsilon^6_{\gamma,i}} \geq \frac{b^2}{48\sigma_0}$ (3). If the injection can be modeled by a power law i.e. $n_i = n_0(\frac{\varepsilon_i}{\varepsilon_1})^{-\Gamma}$, $\varepsilon_1 \equiv \varepsilon_{min} \leq \varepsilon_i \leq \varepsilon_N \equiv \varepsilon_{max}$, and we use that in the continuous case $l^{inj}_{\gamma} = \frac{1}{3}\int_{\varepsilon_{min}}^{\varepsilon_{max}} \varepsilon n(\varepsilon) d\varepsilon$, then
the *critical compactness* becomes :
$l^{inj}_{\gamma,cr} = \frac{b^2}{48\sigma_0} \begin{cases} \frac{(\Gamma+3)}{(\Gamma-2)} \frac{(\varepsilon_{min}^{-\Gamma+2} - \varepsilon_{max}^{-\Gamma+2})}{(\varepsilon_M^{-\Gamma-3} - \varepsilon_{max}^{-\Gamma-3})}, & \Gamma \neq 2 \\ \frac{(\Gamma+3)}{(\varepsilon_M^{-\Gamma-3} - \varepsilon_{max}^{-\Gamma-3})} \ln(\frac{\varepsilon_{max}}{\varepsilon_{min}}), & \Gamma = 2 \end{cases}$ (4) , where $\varepsilon_M = max[\varepsilon_{min}, \varepsilon_\star]$ and Γ the photon index.

4 Validity of the results -Conclusion

By comparing the expression (4) with the derived values using a numerical code including the physical processes of Synchrotron self absorption and ICS, we can conclude that the analytical solution fails in the energy range $\varepsilon_{min} \geq \varepsilon_\star$(in this regime the approximation of catastrophic energy losses proves to be crude). The present work leaves room for an interesting discussion including i) the steady-state solution of the system if $l^{inj}_{\gamma} \geq l^{inj}_{\gamma,cr}$, ii) the effects of a primary soft photon component and iii) the observational features of the mechanism in AGN SEDs (For a complete analysis see "Spontaneously quenched γ ray spectra from compact sources" , M. Petropoulou, D. Arfani & A. Mastichiadis, A & A 557, A48 (2013).

References

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