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Automatic quenching of high energy γ-ray sources by synchrotron photons

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Abstract. We investigate a magnetized plasma in which injected high energy gamma-rays annihilate on a soft photon field, that is provided by the synchrotron radiation of the created pairs. For a very wide range of magnetic fields, this process involves gamma-rays between 0.3 GeV and 30 TeV. We derive a simple dynamical system for this process, analyze its stability to runaway production of soft photons and paris, and find conditions for it to automatically quench by reaching a steady state with an optical depth to photon-photon annihilation larger than unity.

Keywords: radiation mechanisms: non-thermal — gamma-rays: theory

INTRODUCTION

Here we analyze the conditions under which a magnetized system, with an embedded source of photons of energy $\mathscr{E} \equiv \varepsilon/m_{\rm e}c^2 \gg 1$ can sustain pair production autonomously. The nonlinear process that makes this possible is annihilation on soft photons with energies $\mathscr{E}_0 \equiv \varepsilon_0/m_{\rm e}c^2 \ll 1$, produced as the synchrotron emission of the created electron-positron pairs. To describe the dynamics of this process, we simplify the description to a system of three, first-order, ordinary differential equations for the evolution on timescales larger than the light-crossing time of the source, of the populations of hard photons, soft photons and electrons, as discussed in details in Stawarz & Kirk [2]. We assume an isotropic distribution of the photon fields and relativistic pairs in the source rest frame. The described process operates when the magnetic field B is such that $B = 6\,B_{\rm cr}\,\mathscr{E}^{-3}$, where $B_{\rm cr} = m_{\rm e}^2c^3/\hbar e \approx 4.4\times10^{13}$ G. This implies $B = 265\,\left(\mathscr{E}/10^6\right)^{-3}\,\mu{\rm G} = 35\,(\varepsilon/{\rm TeV})^{-3}\,\mu{\rm G}$. Such systems are important in high energy astrophysics, because for an extremely wide range of magnetic field strengths $B = 10^{-9}\,{\rm G}{-}10^{6}\,{\rm G}$ the above 'resonance' condition $B \propto \varepsilon^{-3}$is satisfied for photon energies between $\varepsilon \approx 0.3$ GeV and 30 TeV. This energy range is now, or will shortly, be accessible to the *AGILE* and *GLAST* satellites, together with the Cherenkov Telescopes *HESS*, *MAGIC*, and *VERITAS*.

We restrict our analysis to the high energy and soft photon populations that interact with ultrarelativistic pairs (henceforth "electrons") of characteristic Lorentz factor $\gamma = \mathscr{E}/2 = 1/\mathscr{E}_0$. In the systems of interest, the radiative cooling time scale of these electrons is much shorter than the light-crossing time of the emitting volume, and we assume that no other process such as acceleration, or interaction with background particles or waves competes with the cooling. We denote the total number of high energy photons, soft photons, and the created electrons in our source volume $\mathscr{V} = \pi R^3$ by N, N_0 and $N_{\rm e}$, and define the effective logarithmic number densities as $\mathscr{N}(\mathscr{E}) = N/\mathscr{E}\mathscr{V}$, $\mathscr{N}_0(\mathscr{E}_0) = N_0/\mathscr{E}_0\mathscr{V}$, $\mathscr{N}_{\rm e}(\gamma) = N_{\rm e}/\gamma\mathscr{V}$. With the high energy luminosity intrinsic to the source $L_{\rm inj}$ and magnetic field energy density $U_{\rm B} = B^2/8\pi$ we define the high-energy injection and the magnetic compactnesses as

$$\ell_{\rm inj} \equiv \frac{\mathscr{E}\,L_{\rm inj}\,\sigma_{\rm T}}{4\pi\,m_{\rm e}c^3\,R} \quad \text{and} \quad \ell_{\rm B} \equiv \frac{\mathscr{E}\,U_{\rm B}\,R\,\sigma_{\rm T}}{m_{\rm e}c^2}. \tag{1}$$

Instead of the soft photon number density we use the optical depth for photon-photon annihilation $n_0 \equiv \tau_{\gamma\gamma} = 2\,\sigma_{\rm T}\,R\,\mathscr{N}_0(\mathscr{E}_0)/(3\mathscr{E})$, and instead of the hard photon number density, we use the ratio of the hard photon energy density to the energy density of soft photons needed to give $\tau_{\gamma\gamma} = 1$: $n \equiv U/\,U_0|_{\tau_{\gamma\gamma}=1} = \mathscr{E}^3\sigma_{\rm T}R\mathscr{N}(\mathscr{E})/6$. Similarly, for the electron density we use the ratio of the energy densities required for $\tau_{\gamma\gamma} = 1$: $n_{\rm e} \equiv U_{\rm e}/\,U_0|_{\tau_{\gamma\gamma}=1} = \mathscr{E}^3\,\sigma_{\rm T}\,R\mathscr{N}_{\rm e}(\gamma)/24$, and measure time in units of the light crossing time $\tau \equiv ct/R$. This leads to the autonomous dynamical system:

$$\frac{{\rm d}n}{{\rm d}\tau} = -n\,n_0 - n + \frac{2}{3}\,\ell_{\rm inj} \quad , \quad \frac{{\rm d}n_0}{{\rm d}\tau} = -n_0 + \frac{1}{3}\,\ell_{\rm B}\,n_{\rm e} \quad , \quad \frac{{\rm d}n_{\rm e}}{{\rm d}\tau} = n\,n_0 - \frac{2}{3}\,\ell_{\rm B}\,n_{\rm e} - \frac{4}{\eta}\,n_{\rm e}\,n_0 \quad . \tag{2}$$

where $\eta = 5^{1.5}$.

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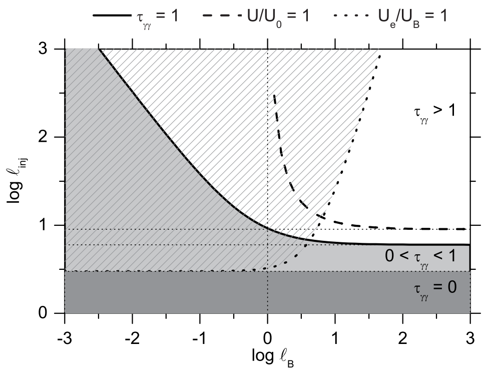

FIGURE 1. Properties of the stable solutions to the dynamical system of Eq. (2) as functions of the injection and magnetic compactnesses, Eq. (1).

STATIONARY SOLUTIONS AND THEIR STABILITY

For all $\ell_{inj} > 0$ and $\ell_B > 0$ there exists a trivial stationary solution of the system (2): $n = 2\ell_{inj}/3$, $n_0 = 0$, $n_e = 0$, corresponding to free propagation of the hard photons through a medium in which pairs and soft photons are completely absent. The eigenvalues of the Jacobian matrix evaluated for this solution are all real. For $\ell_{inj} < 3$ they are all negative, so that the solution is stable in this region. This means that the nonlinearity is not sufficient for the system to initiate and sustain a population of pairs if $\ell_{inj} < 3$. Furthermore, in this region, no other physically acceptable ($n_0 > 0$, $n_e > 0$) stationary solution exists. For $\ell_{inj} > 3$, at least one of the eigenvalues has a positive real part, so that the solution in which pairs are absent is unstable. However, in this region a second stationary solution emerges, with $n = 2\ell_{inj}/[3(1+n_0)]$, $n_e = 3n_0/\ell_B$ and $n_0 = \left[-6-\eta\ell_B+\sqrt{(\eta\ell_B-6)^2+8\eta\ell_B\ell_{inj}}\right]/12$. Using the Routh-Hurwitz conditions [1, 17.715], one can show that the real parts of the eigenvalues of the Jacobian matrix corresponding to this physical solution are negative, so that the solution is stable for all values of $\ell_B > 0$. All physically acceptable solutions appear to approach this stable one. We find no chaotic regime. We also have no physical grounds on which to expect such behavior within the current model.

Figure 1 illustrates the properties of the stable solutions of this system on the ℓ_B–ℓ_{inj} plane. The horizontal dotted line $\ell_{inj} = 3$ bounds from above the region (shaded dark gray) in which the stable solution contains neither pairs nor soft photons, so that $\tau_{\gamma\gamma} = 0$. The solid line, on which $\ell_{inj} = 6 + 36/(\eta\,\ell_B)$, is the locus of points at which the stable solution has unit optical depth to absorption of high energy photons: $n_0 = \tau_{\gamma\gamma} = 1$. Strictly speaking, our treatment of the escape probability of hard photons is valid only in the optically thin case $\tau_{\gamma\gamma} < 1$, which is shaded light gray. However, for $\ell_{inj} > 6 + 36/(\eta\,\ell_B)$, (white area) we expect on physical grounds that the system tends spontaneously to an optically thick state with almost total absorption of the hard photons. Stable solutions which have equal energy densities of soft and hard photons ($n = n_0$) occur formally when $\ell_{inj} = 3\eta\ell_B(3\eta\ell_B - 12)/(\eta\ell_B - 12)^2$, shown as a thick dashed line. This line lies entirely within the optically thick region. Thus, our system is valid only for solutions in which the energy density of soft photons is small compared to that in hard photons. Finally, stable solutions in which the electron and magnetic field energy densities are equal occur when $U_e/U_B \equiv 6n_e/\ell_B = 1$, shown as a thick dotted line. Solutions which are particle dominated lie above this line in the hatched region of Fig. 1. It is interesting to note that when the optical depth for photon-photon annihilation is less than unity, $\tau_{\gamma\gamma} < 1$, stable solutions can be found that are pair dominated, in the sense that the electron energy density exceeds that in the magnetic field. These solutions occur in the intersection of the hatched and light gray areas of Fig. 1. They imply efficient pair-loading of the system and are particularly relevant for $\ell_B \ll 1$, where they occur for all relevant injection compactnesses $\ell_{inj} > 3$.

REFERENCES

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