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THE TIME-DEPENDENT ONE-ZONE HADRONIC MODEL: FIRST PRINCIPLES

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We present some results on the radiative signatures of the one zone hadronic model. For this we have solved five spatially averaged, time-dependent coupled kinetic equations which describe the evolution of relativistic protons, electrons, photons, neutrons and neutrinos in a spherical volume containing a magnetic field. Protons are injected and lose energy by synchrotron, photopair and photopion production. We model photopair and photopion using the results of relevant MC codes, like the SOPHIA code in the case of photopion, which give accurate description for the injection of secondaries which then become source functions in their respective equations. This approach allows us to calculate the expected photon and neutrino spectra simultaneously in addition to examining questions like the efficiency and the temporal behaviour of the hadronic models.

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1. Introduction

Hadronic models for the high energy emission of Active Galactic Nuclei and other astrophysical non-thermal objects postulate that protons are accelerated by some process in the relativistic outflows connected with these objects. The high energy photon emission comes then either from proton synchrotron radiation [1] or as a result of secondary particles produced in photopion collisions – for example, π^0 decay produces very high energy γ-rays, while it is possible that these high energy photons will be absorbed by soft photons, initiating thus intense electromagnetic cascades before escaping from the source [2].

In the present paper we revisit the hadronic model by carefully modeling photopion production which is one of its key processes. Furthermore we do not adopt the usual approach which is to assume an *ad hoc* proton distribution in the source but we go one step back and derive this as a solution of an equation which includes proton injection, losses and escape. This approach allows self consistency and in addition it can adress some important points as is the efficiency of the hadronic models and their expected time variability.

2. Key assumptions of the model

We adopt here the standard picture of an one zone radiation model. We assume that high energy protons are injected monoenergetically at some characteristic energy $\gamma_0 m_p c^2$ in a spherical source of radius R which contains a tangled magnetic field of strength B. We specify the rate of proton injection through the compactness ℓ_p which is related to the proton luminosity L_p through the relation

$$\ell_p = \frac{L_p \sigma_T}{4\pi R m_p c^3}$$

where σ_T the Thomson cross section and we also introduce a proton escape timescale $t_{p,esc}$ which denotes the removal of protons from the source due to physical escape. Finally, in order to keep the free parameters as few as possible, we assume that there is no injection of primary electrons.

Relativistic protons in the source lose their energy by photopair, photopion and synchrotron radiation. The stable and long-lived products of these interactions include electron/positron pairs, photons, neutrinos and neutrons. Electron/positron pairs radiate predominantly by synchrotron and inverse Compton radiation, so they become sources of photons. High energy photons can be absorbed by photon-photon annihilation producing electron-positron pairs. Low energy photons, produced through e.g. electron synchrotron radiation, become targets for protons, electrons and $\gamma-$rays. Neutrons, not being confined by the magnetic fields in the source can either escape or interact with the photons before decaying back to protons. Finally, neutrinos are the most uncomplicated component as they will escape from the source essentially with their production spectrum.

It is clear from this description that the hadronic model can be a highly non-linear system in the sense that its key components (i.e. protons, electrons and photons) are strongly coupled. In order to study it, one needs to use the kinetic equation approach where the evolution of protons, electrons, photons, neutrons and neutrinos are described through time-dependent partial integro-differential equations. Each species is coupled with the others through suitably modeled, energy conserving reaction rates representing the various important to the problem radiative processes. This approach has been used extensively in leptonic models[3], however in hadronic models it has thus far limited applications. One important reason for this was the difficulty in modeling the production rates of the secondaries in photopair and photopion interactions.

A step towards this direction was taken by Ref. 4 who have modeled photopair interactions by using the MC results of Ref. 5; however they used simple $\delta-$function approximations for the photopion reaction rates [6]. In the present treatment we relax this assumption by modeling photopion using the full results of the SOPHIA code [7] – details will appear in Dimitrakoudis et al. in preparation.

2.1. *Radiative signatures*

In addition to the above five parameters (i.e. R, B, γ_0, ℓ_p, $t_{p,esc}$) one needs to specify initial conditions for the five unknown distribution functions to fully determine the system. Without loss of generality, we can set them equal to zero for $t = 0$. Then we can integrate the equations forward in time. Therefore, for $t > 0$ protons will start accumulating in the source. At the same time they will lose energy by synchrotron, photopair and photopion, while a fraction will physically escape at a rate $t_{p,esc}^{-1}$ from the source region.

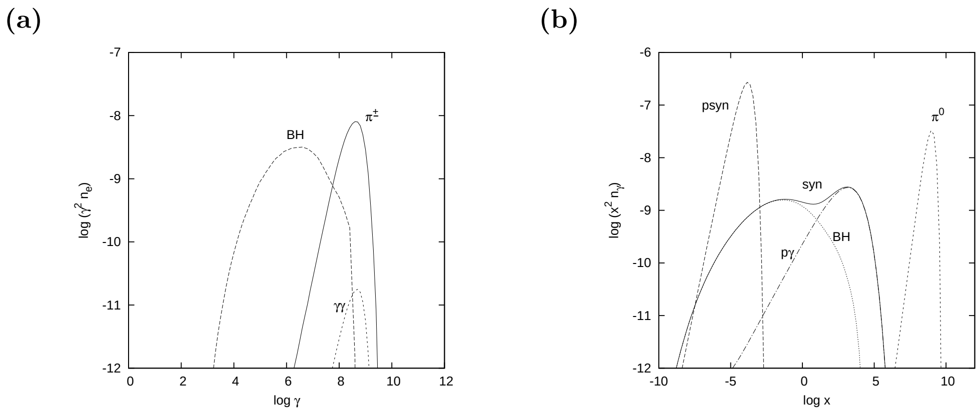

Fig. 1. (a) Production rate of secondary electrons for $R = 3 \times 10^{16}$ cm, $B = 1$ G, $\ell_p = 0.4$, $t_{p,esc} = t_{cr} = R/c$ and $\gamma_0 = 2.5 \times 10^6$. '$\pi^\pm$' denotes the injection resulting from charged pion decay, 'BH' the photopair (Bethe-Heitler) injection, while '$\gamma\gamma$' the injection resulting from photon-photon annihilation which is negligible for the particular set of the initial parameters chosen. (b) The corresponding steady state multiwavelength spectrum of photons resulting from the monoenergetic proton injection considered in (a). The '$p\gamma$' and 'BH' curves are the synchrotron spectra of the pairs injected by the photopion and photopair processes respectively– see (a). 'psyn' is the proton synchrotron component while 'π^0' denotes the $\gamma-$rays resulting from the corresponding decay

Figure 1 shows a typical example where the parameters were chosen in such a way, so that the photons radiated cause minimal losses on the protons. Secondary electron/positron pairs are injected in the system mainly through photopair and photopion. (At higher compactness photon-photon pair production becomes important but we can neglect this for the time being.) These two processes are in direct competition with each other and their relative importance depends on γ_0 and on the soft photons which serve as targets. Fig. 1a plots the injection functions of these two processes for the initial parameters given above. We note that the two distributions have different characteristics. The injection function of photopair electrons is broader and has a peak at energies $\gamma_e \simeq \gamma_p$. The injection function of photopion electrons, on the other hand, is flatter and peaks at much higher energies, of the order of $\gamma_e = \eta_{\pi e}\gamma_p$, with $\eta_{\pi e} \simeq 150$.

In the case we are considering here, the photon spectrum will show four distinctive features (see Fig. 1b). Two of them are conncected to the synchrotron radiation of the injected pairs populations discussed above while the other two features are connected to proton synchrotron and π^0-decay respectively. Classifying them in ascending order with respect to frequency we have:

(1) *Proton synchrotron radiation:* Since the proton distribution function is a $\delta-$function at γ_0, the radiated photon spectrum will have a peak at $\epsilon \simeq \frac{m_e}{m_p} b\gamma_0^2$.
(2) *Synchrotron radiation from photopair electrons:* As stated above, the electron injection function resulting from photopair interactions is rather broad with a peak at $\gamma_e \simeq \gamma_p$. Synchrotron cooling of electrons and consequent radiation results in a photon spectrum with peak at $\epsilon \simeq b\gamma_0^2$.
(3) *Synchrotron radiation from photopion electrons:* In complete analogy to the photopair, the peak of this distribution will be at $\epsilon \simeq b(\eta_{\pi e}\gamma_0)^2$.
(4) *γ-rays from π^0-decay:* A monoenergetic proton distribution produces a well defined peak at $\epsilon \simeq \eta_{\pi\gamma}\gamma_0$, with $\eta_{\pi\gamma} \simeq 350$.

2.2. *Increasing the injected proton compactness: From linear to non-linear proton cooling*

We turn next to investigate the effects that the injected proton compactness has on the photon spectra. In the case of pure proton injection as the one we are considering here, there are – up to a degree, profound analogies to the synchrotron - SSC relationship of a leptonic system. There the electrons radiate synchrotron photons and consequently upscatter them through inverse compton scattering interactions. As long as the magnetic energy density dominates the synchrotron photon density, then the system can be considered to be in the linear regime. This situation changes when the synchrotron photon density dominates and the system becomes non-linear leading to the well-known Compton catastrophe.

In the case of hadronic systems one can find also parameter values that make the system operate in the linear regime. Such is the case shown in Fig. 1: Protons radiate by synchrotron and the radiated photons are used as targets for photopair and photopion production. As can be seen from Fig. 1b, the proton synchrotron luminosity dominates which means that the cooling, however small, is regulated by this process. Therefore the question which becomes relevant is what happens to the system if the proton injection luminosity is increased further while the magnetic field value is kept constant. This essentially would mean that the photon density of the system increases over the magnetic one, and as a result the photopair and

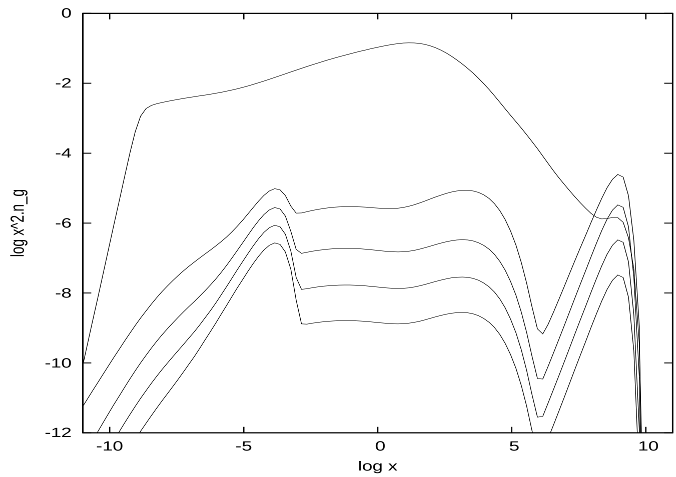

Fig. 2. Steady state MW photon spectra for $\delta-$function proton injection at energy $\gamma_0 = 2.5 \times 10^6$ and different injection compactnesses ℓ_p =0.4, 1.3, 4, 13 and 40 (bottom to top). The other parameters are $R = 3 \times 10^{16}$ cm, $B = 1$ G, $t_{p,esc} = t_{cr}$.

photopion losses/injection increase more than the proton synchrotron ones. This occurs because while the synchrotron luminosity depends only on the proton density, the photopair and photopion luminosities depend on both the proton and photon density. Since the latter depends on the former, we conclude that the above processes depend quadratically on the proton density.

The above situation can be exemplified in Fig. 2 which depicts the steady state multiwavelength spectra in the case where the injection proton compactness is increased by a factor of 3 over its previous value, while all the other parameters are kept constant. One notices that as the injection compactness increases, the synchrotron component increases linearly while the photopair and photopion increase quadratically. However for the last adopted value of ℓ_p the system undergoes a transition and the photon luminosity increases by a factor of 10^4. This type of abrupt transitions are caused by various feedbacks [8,9,10,11] which operate in hadronic systems and are an indication that the protons become supercritical inside the source. As it was shown in the references given above in that case electrons and photons increase in an autoregulatory manner causing the protons to lose energy by photopair and photopion and forcing them to move back to the subcritical regime. The system then can either reach a steady state, as in the example shown above, or show limit cycles[4].

Fig. 3 shows the locus separating the subcritical and supercritical proton regimes for various monoenergetic proton energies γ_0. The concept is that once the proton energy density crosses this boundary, protons become supercritical and therefore cannot be stable for this value. It is interesting to note that, as preliminary calculations show, depending on the value of γ_0, different types of feedback operate on

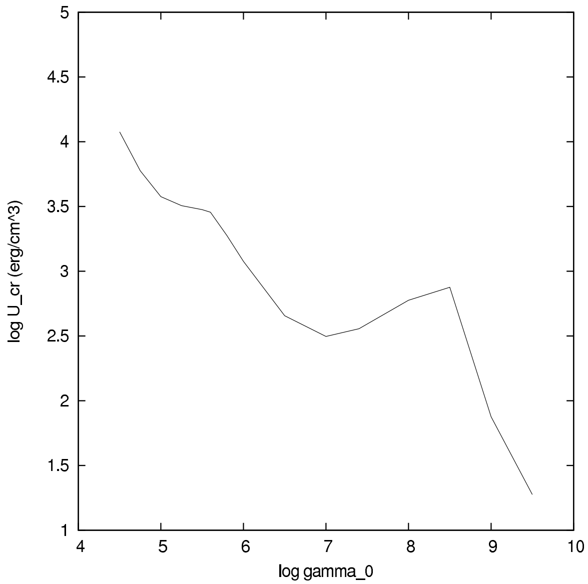

Fig. 3. Plot of the locus which separates the subcritical (lower part) and supercritical (upper part) proton regimes as a function of the proton energy γ_0 in the case where $R = 3 \times 10^{16}$ cm and $B = 10$ G.

the hadronic system. This explains the shape of the locus. We will deal fully with the implications of the hadronic non-linearities in a forthcoming publication.

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