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ELECTROMAGNETIC CASCADES IN MAGNETIZED MEDIA

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The investigation of the astrophysical nature of gamma-ray sources and the processes responsible for their broad-band emission requires a detailed modeling of their observable spectrum, in which electromagnetic cascades can play an important role. An open issue in this modeling is the effect of magnetic fields in the development of cascades. In this paper we present a novel numerical scheme to compute this effect in a self-consistent way. Applied to a toy model, our scheme reproduces the features expected for cascades in the strong and weak magnetic field regimes.

Keywords: Gamma-rays; cascades; magnetic fields.

1. Introduction

Many sources emitting electromagnetic radiation in the range from MeVs to TeVs have been discovered in recent years.[1–3] Some of these sources have been identified with systems already known at lower energies (e.g. X-ray binaries, microquasars, AGNs, pulsar wind nebulae, star forming regions, etc.), while there are still many unidentified ones. The origin of the high-energy radiation in each system is still under debate. Many models have been proposed, in which relativistic particles accelerated in different environments (jets, pulsar wind shocks, colliding stellar winds) interact with ambient matter, radiation, or magnetic fields to produce high-energy photons.[4,5] Model predictions for such kind of sources must be tested against their observed high-energy spectra. The primary energetic photons in many astrophysical systems are probably produced in environments with non-negligible opacity, hence their propagation inside the source must be considered to model the observable spectrum. At low optical depths simple absorption calculations are accurate enough, as secondary photons produced in the interaction of primary ones are few, and do not affect the spectrum in a significant way. At larger optical depths, electromagnetic cascades can develop through a combination of pair creation and inverse Compton scattering, decreasing the effective opacity and considerably changing the spectrum. Hence, the correct computation of electromagnetic cascades is crucial to compare the predictions of different high-energy production models with observations. Many efforts have been devoted to this issue using both numerical [6–8] or semi-analytical [9–11] techniques.

The basic scheme of numerical methods relies on the use of Monte Carlo techniques. A set of primary, high-energy photons, is sampled from a proposed primary spectrum and propagation field. For each particle in the set, the free path traveled up to the next interaction with a target background of photons is numerically sampled according to the density and motion of this background. The properties of the photon with which the primary photon interacts are also sampled accordingly, and the properties of the interaction products (energy, motion direction) are computed. The products (electrons or positrons) are then followed in the same way as the primary, producing new energetic photons through inverse Compton scattering, and giving rise to the cascade. Each particle is followed until it leaves the system or its energy is low enough to be neglected. In this way, the full set of escaping photons provides a representation of the observable spectrum of the source.

This basic outline has been used by several authors in the past, usually assuming that the development of the cascade is one-dimensional, given the large momenta of the primary photons. This hypothesis is a reasonable one if the effect of magnetic fields is neglected. However, most systems are thought to have non-negligible magnetic fields. Accordingly, some attempts to include their effects in cascades have been made, through simplifying hypotheses like the local isotropization of lepton directions of motion [12] or approximations to particle motion neglecting synchrotron losses. [13] **However, the latter hypothesis can be applied only to weak fields, and the assumption of local isotropization is valid only for fields with an important random component. It seems that there are many interesting cases in which none of these approximations can be applied.**

Given the aforementioned arguments it is clear that a full, self-consistent numerical treatment of the development of electromagnetic cascades in magnetic fields would be desirable to better understand the production of high energy radiation in many astrophysical systems. In this work we present a novel scheme for the computation of electromagnetic cascades, which allows to treat the motion of leptons in magnetic fields in an *ab initio* way. Our method combines the integration of the relativistic equations of motion of leptons and photons, with classical Monte Carlo methods to describe the interactions between particles. We present our scheme in Section 2, apply it to a simple toy model in Section 3, and discuss the results and the potential uses of the method in Section 4.

2. Simulation scheme

Our goal is to devise a scheme for the simulation of electromagnetic cascades in magnetic fields from an *ab initio* point of view, and versatile enough as to be applied to many different systems. The cascades to be discussed comprise leptons and photons. The main effects of magnetic fields are to curve lepton trajectories, rendering the problem three dimensional, and to take out energy of the system in the form of synchrotron radiation. In order to achieve a reliable estimate of all these effects, we sample a set of primary photons, and accurately follow their trajectories, compute their interactions with background photons, and iterate the procedure for each particle created in the computed interactions, until they leave the system or their energy goes below a certain threshold.

The values of the properties of the primary photons are given by the chosen production model, while a model for the background density, propagation direction and spectrum is used to compute the interactions. At the top of our scheme there is an accurate integrator of the relativistic equations of motion of every particle, which uses a leap-frog algorithm for electrons and positrons and assumes rectilinear paths with constant energy for photons, similar to that of Ref. 14. The integrator divides particle trajectories in time steps much smaller than both the inverse of the local gyro-frequency and the inverse of the local interaction rate. Exact cross-sections are used to compute the latter. The probability of interaction is computed at each time-step, and a Monte Carlo scheme used to decide whether the interaction actually takes place. If so, the properties of the target particle are sampled and the interaction products are computed. If not, the particle position, momentum and energy at the end of the time-step are estimated. Synchrotron losses are taken into account by decreasing the particle energy according to the classical formula [15], and modifying its momentum accordingly. The position and momentum of the particle are stored, which allows a posteriori the computation of the synchrotron spectrum of the source in arbitrary directions. The time step is adaptive to take into account variations in both the magnetic field and the density of targets as the particles move.

There are three main advantages of our scheme. First, the code can be applied to any γ-ray production model for which the density, energy and momentum of the primary photons are given, with arbitrary target photon fields and magnetic field configurations. Second, it computes three dimensional cascades that give information on the spectral energy distribution of photons leaving the system, and its dependence with time, position and propagation direction. Finally, it provides a self-consistent treatment of synchrotron emission, and its dependence with position within the physical system and time. In the following section we show some preliminary results obtained by applying our scheme to a high-mass X-ray binary toy model.

3. Results

In order to test our code with a simple model, we computed the cascade produced in a high-mass X-ray binary composed by a neutron star plus an O-type star (Fig. 1). We assumed that primary TeV photons are produced in the interaction of relativistic particles with the accretion disk, and that they propagate against the background stellar radiation field. Primary photons were assumed to be monoenergetic, with an energy $E = 1\,\mathrm{TeV}$. The neutron star has a dipole magnetic field whose intensity B_0 is a free parameter, in order to explore the dependence of the spectrum on it. Primary photons were injected along the orbit of the system, at a distance of 10^9 cm from the neutron star, where the magnetic field is $B = B_0\ f(\vec{r})$. The O-type star, with a radius of 10^{12} cm, is located at a distance of 10^{13} cm from the neutron star. Its radiation field is assumed to have a blackbody spectrum, with an effective temperature of 3×10^4 K and a luminosity of $1.5 \times 10^5 L_\odot$.

The resulting observable spectra, averaged over all directions and normalized to the total energy injected by primary particles, are shown in Fig. 2 for different magnetic field intensities in the range $B = 0.01 - 100\,\mathrm{G}$ at the point of injection

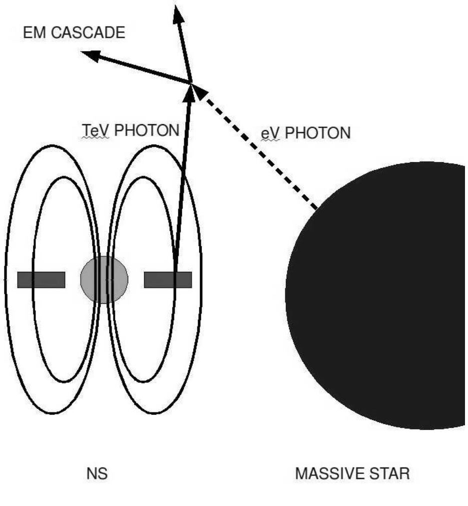

Fig. 1. Toy model used for testing our simulation scheme: a high-mass X-ray binary harboring a neutron star with a dipole magnetic field. Primary TeV photons, injected as a result of the interaction of particles accelerated in the magnetic field with the accretion disk, produce a cascade because of the interaction with the radiation field of the companion, assumed to have a blackbody spectrum and to be propagating radially outwards from it.

of the particles. It is clearly seen that the cascade is essentially not affected by the magnetic field for $B < 1\,\mathrm{G}$, but is strongly suppressed when $B = 10\,\mathrm{G}$. At $B = 100\,\mathrm{G}$ (not shown in Fig. 2), no cascade develops. This result is consistent with that of Ref. 10, who found that inverse Compton cascades are completely suppressed for fields of $\sim 100 - 1000\,\mathrm{G}$.

Fig. 3 shows the fraction of the injected energy drained by synchrotron losses, together with that remaining in the cascade, for different magnetic field intensities. As expected, synchrotron losses are negligible for weak fields, and grow abruptly for fields $B > 1\,\mathrm{G}$, taking energy off the cascade.

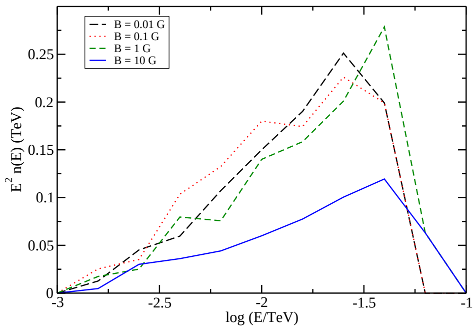

Fig. 2. Observable spectra produced by 1 TeV primary photons for different magnetic field intensities.

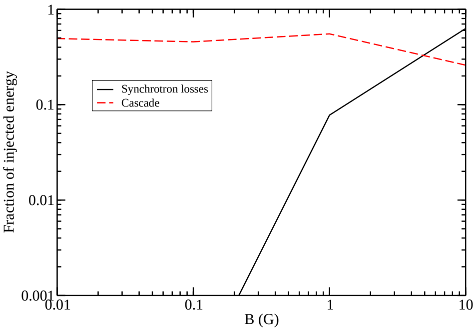

Fig. 3. Fraction of injected energy remaining in the cascade apectrum and lost as synchrotron radiation, as a function of magnetic field intensity at the point of injection.

4. Discussion

We developed a numerical code that computes electromagnetic cascades in magnetic fields, including synchrotron losses, in a self-consistent way. The code can simulate cascades produced by different distributions of primary particles (in space, time, momentum and energy), hence it can be used to test different γ-ray production models. Different target photon fields can be simulated as well, allowing to describe many types of systems (microquasars, pulsar binaries, massive star binaries, etc.). Applied to our toy X-ray binary model, the code reproduces the basic features of cascade suppression by synchrotron losses.

The main advantages of our code are the self-consistent *ab initio* treatment of the interaction of leptons with magnetic fields, its capability to predict not only the spectrum but any possible spatial or time variation of the high-energy emission, and its flexibility that allows to apply it to a wide range of astrophysical systems.

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