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Gamma-ray induced cascades in cosmic environments

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Abstract. The new generation of gamma-ray telescopes has revealed a rich sky at very high photon energies. The unveiling of the nature of these sources and the understanding of the physical processes that give rise to the gamma-ray emission are among the most important present challenges of high-energy astrophysics. To investigate these issues, the propagation and interaction of the emitted electromagnetic radiation, both within the source and during its journey to the observer, must be understood. In this work we describe the development of a tool to provide an accurate, *ab-initio* description of the propagation of gamma rays in astrophysical environments. We expect this tool to contribute to the understanding of the physics of cosmic gamma-ray emitters.

1. Introduction

During the last decades, the development of new instruments to collect radiation at very high photon energies (MeV–TeV) has provided a wealth of information on sources emitting in this spectral range (e.g., Hartman et al. 1999; Cheng & Romero 2004; Abdo et al. 2009, Aharonian et al. 2009). Many sources were identified with objects detected at lower energies, while many others remain still unidentified. To unveil the nature of these emitters, their gamma-ray spectrum must be modeled to determine the physical processes that produce the observed photon distribution. However, the observed spectrum differs from the primary one emitted by the source, due to the interaction of gamma-ray photons with electromagnetic and matter fields present either within the source or between it and the observer. These fields modify the primary radiation, changing the spectrum and introducing temporal and spatial variations in it. A precise description of the modification is then crucial for a good comparison of the emission models with observations.

Tools for radiation modification calculation have been developed since long time ago, either using semi-analytical or numerical techniques (e.g., Protheroe 1986; Bednarek 2000; Aharonian et al. 2006; Bednarek 2007; Orellana et al. 2007; Khangulyan et al. 2008; Sierpowska & Bednarek 2005; Cerrutti et al. 2009; Kachelrieß et al. 2012). Numerical techniques based on Monte Carlo schemes are especially well suited for scenarios in which the optical depth of the intervening medium to the VHE radiation is large. In this case simple absorption calculations are inadequate, because the secondary particles produced by the interaction of primaries with background fields carry a large fraction of the energy, strongly modifying the spectrum. These particles continue to interact with background fields, developing cascades in which the spectrum is modified in several stages.

In spite of their increasing complexity, numerical Monte Carlo techniques are confronted with a series of common problems, among them the computation of photon cross sections, the computation of interaction products, or the treatment of charged particle deflections in magnetic fields. These problems were usually solved by simplifying assumptions such as the one-dimensional treatment of cascades (e.g., Protheroe 1986; Bednarek 2000), probably with semi-analytical corrections for the lateral development (Kachelrieß et al. 2012), the use of background field symmetries to simplify cross section computations, or the isotropization of charged-particle motion in magnetic fields (Sierpowska & Bednarek 2005). These simplifications prevent the use of these tools to investigate complex systems with non-symmetric background fields, magnetic fields not strong enough to fulfill the isotropization condition, or phenomena with short scale spatial or temporal variations.

In this paper we present an overview of an ongoing project by our group (Pellizza et al. 2010; Pellizza et al. 2015), whose purpose is to overcome the aforementioned problems and simplifications of numerical techniques. We aim at developing a high-performance, *ab initio* simulation tool for radiation modification computation with arbitrary sources and background fields. This tool, named PRINCE (PRopagation and INteraction in Cosmic Environments), is described in Sect. 2.. Sect. 3. shows some preliminary results, and Sect. 4. discusses some of our prospects to apply PRINCE to astrophysical problems.

2. The PRINCE project

The main goal of the PRINCE project is to create a tool versatile enough to describe the spectrum modification in almost any arbitrary environment. We focused in solving the main shortcomings of previous approaches. As nearly all numerical codes devised for this problem, PRINCE uses a Monte Carlo scheme to sample photons from the primary source spectrum, and computes their propagation through the background fields. The propagation of each particle is described as a set of continuous trajectories interspersed by interactions between the travelling particle and a background one. The interactions destroy the incoming particles, creating new ones. The propagation of the new particles is then computed in the same way as that of primaries, until they reach the observer or their energy falls below a specified threshold.

In the already mentioned previous works, the occurrence of an interaction of a particle is determined by Monte Carlo sampling of its free path, given the background density, the interaction cross section and the particle velocity. This scheme assumes that the background field is homogeneous and stationary, which is an important limitation for many astrophysical systems. To overcome this difficulty, we adopted a different scheme. Following techniques developed for other astrophysical areas, such as N-body gravitational codes, we compute the trajectories of the particles by dividing them into small timesteps. The integration is trivial within each timestep, and the ocurrence of an interaction can be Monte Carlo sampled from its probability, which is still related to the same properties of particles and background. Using individual and adaptive timesteps for each particle allows our code to adapt the interaction sampling to spatial and temporal variations of the background density.

The calculation of interaction probabilities (or mean free paths in previous works) leads to the problem of computing total cross sections. In previous works usually this computation is done in an analytical way, using different assumptions such as the isotropy of background fields (e.g., Protheroe 1986; Bednarek 2000). Once again, this prevents the use of these schemes for systems in which the assumptions are not fulfilled, such as highly anisotropic photon fields near the companion of compact objects in binary systems. To avoid this limitation, PRINCE computes the total cross sections through numerical integration, allowing the use of any well behaved background field, without any assumption at all. The sampling of the interaction products is also done numerically through a third Monte Carlo algorithm, and requiring strict momentum and energy conservation.

The trajectories themselves are easy to integrate. For neutral particles they are straight lines traversed at constant velocity, while for charged particles only magnetic fields (if present) are important to deflect them. As the code uses timesteps adapted to the field variations (either temporal or spatial), the evolution of the particles within each timestep can be assumed as occurring in a constant field, and the trajectories have analytical solutions. The energy loss by synchrotron emission of charged particles in magnetic fields is also computed.

The time variations of the spectra have never been computed self-consistently, the only attempts were done assuming that this variation has a timescale much greater than that of the cascade, and hence independent computations at different times were used (e.g., Cerrutti et al. 2009). The spatial (or angular, in the plane of the sky) dependence has been approached semianalytically for non-magnetic simulations, or through simplifying hypotheses when magnetic fields are present, such as the isotropization of lepton directions in strong magnetic fields (Khangulyan et al. 2008; Kachelrieß et al. 2012). This assumptions still leave many realistic astropysical scenarios unexplored. With the PRINCE scheme, the effects of magnetic fields are computed in a self-consistent way.

The PRINCE code implements the aforementioned physics, together with several administrative routines that allow the user to set up and run simulations of the cascades induced by VHE radiation in a large variety of astrophysical systems. The code is written in the C programming language and parallelized using both MPI and OpenMP to produce a high-performance tool. This tool is complemented with post-processing routines that allow the users to obtain observables from the simulation results.

3. Preliminary results

In this section we present a set of two preliminary results to show the sort of problems that can be explored with PRINCE. First, we simulated the electromagnetic cascade produced by a monoenergetic point source of 10 PeV photons against the Cosmic Microwave Background (CMB), and within a uniform magnetic field of intensity $B = 10^{-15}$ G. Fig. 1 depicts the trajectories of the cascading particles, showing the deflection from a straight line. This deflection is larger for lower energy particles. As a result, an extended source is observed, with a spectrum that varies with position in the plane of the sky (Fig. 2).

The second, more realistic simulation involves the cascade produced by gamma-ray photons from an extragalactic TeV source by two photon fields, the CMB and the Extragalactic Background Light (EBL), and a randomly oriented intergalactic magnetic field with a correlation length of 1 Mpc (Neronov et al. 2013). The CMB was modeled

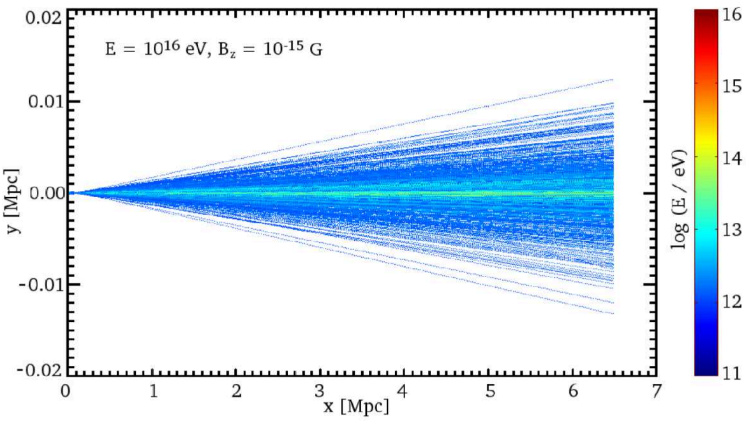

Figure 1. Electromagnetic cascade produced by a monoenergetic point source of 10 PeV photons against the CMB, in a uniform magnetic field with an intensity of 10^{-15} G. The trajectories of the particles involved in the cascade are shown; low energy particles suffer larger deflections from the primary motion direction than high energy ones.

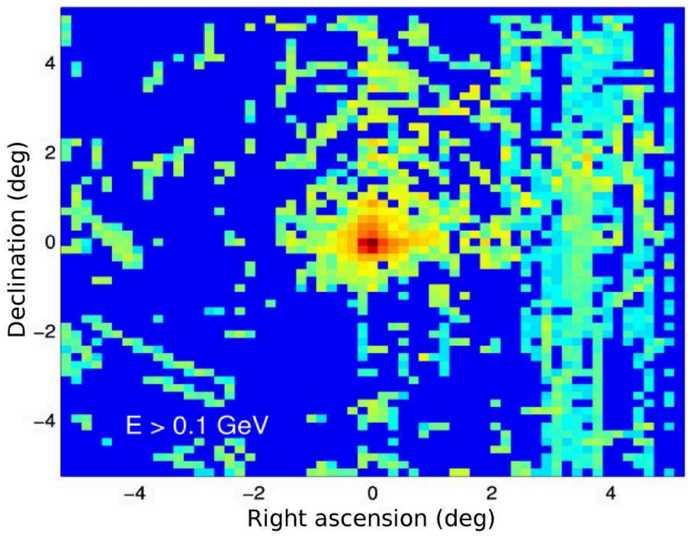

Figure 2. Electromagnetic cascade produced by a monoenergetic point source of 10 PeV photons against the CMB, in a uniform magnetic field with an intensity of 10^{-15} G. This simulated image of the source presents an angular extension in the plane of the sky that depends on energy.

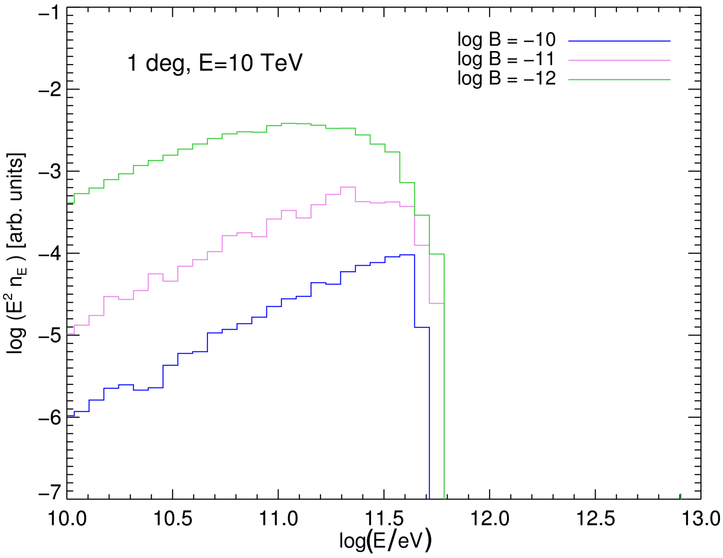

Figure 3. Spectra of a 10 TeV jet with an opening angle of 1 deg, after traversing 600 Mpc of intergalactic medium, for different values of the magnetic field strength. The magnetic field coherence length is fixed at 1 Mpc.

as a 2.73 K blackbody, while for the EBL we used the model of Finke et al. (2010). The source is a monoenergetic ($E = 10\,\text{TeV}$) jet spreading with an opening angle of 1 deg, located at 600 Mpc from the observer. Fig. 3 shows the spectrum of the source as a function of the intensity of the intergalactic magnetic field. The absorption of TeV photons is due mainly to the EBL. The absorbed radiation is converted into lower energy (10–100 GeV) photons through leptons produced by pair creation, giving rise to the bump seen at these energies. The cooling of leptons through synchrotron radiation is responsible for the variation of the spectral intensity at GeV energies with the magnetic field intensity.

4. Discussion

PRINCE is an ongoing project devoted to the development of a high-performance computing tool for the investigation of VHE radiation cascades. The tool allows the simulation of the spectrum of gamma-ray sources in arbitrary environments, using *ab initio* computations of the physical processes involved in radiation modification, and eliminating as many simplifying assumptions as possible. The basis of the tool is a computing code that uses three Monte Carlo schemes to solve the propagation of individual photons emitted by the source through background electromagnetic and matter fields, until it reaches the observer.

PRINCE has been successfully tested in simple astrophysical situations, such as the cascades produced by TeV–PeV gamma-ray photons against extragalactic photon fields, and with ambient magnetic fields. In the future, we plan to use this tool to simulate different astrophysical sources, including microquasars, active galactic nuclei, and dark-matter annihilation signals. We expect that the comparison of our numerical experiments with observations will allow us to provide clues to answer relevant astrophysical questions, such as the nature of dark matter or the intensity and origin of intergalactic magnetic fields.

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References

Abdo, A. A. et al. 2009, ApJ Suppl., 183, 46

Aharonian, F. et al. 2006, J. Phys. Conf. Ser., 39, 408

Aharonian, F. et al. 2009, ApJ Lett., 695, L40

Bednarek, W. 2000, A&A, 362, 646

Bednarek, W. 2007, A&A, 464, 259

Cerutti, B. et al. 2009, A&A, 507, 1217

Cheng, K. S. & Romero, G. E. 2004, "Cosmic Gamma-Ray Sources", Kluwer Academic Publishers, The Netherlands

Finke, J. D. et al. 2010, ApJ, 712, 238

Hartman R. C., et al. 1999, ApJ Suppl., 123, 79

Kachelrieß, M. et al. 2012, CoPhC, 183, 1036

Khangulyan, D. et al. 2008, MNRAS, 383, 467

Neronov, A. et al. 2013, A&A, 554, A31

Orellana, M. et al. 2007, A&A, 465, 703

Pellizza, L. J. et al. 2010, IJMPD, 19, 671

Pellizza, L. J. et al. 2015, in prep.

Protheroe, R. J. 1986, MNRAS, 221, 769

Sierpowska A. & Bednarek, W. 2005, MNRAS, 356, 711