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On the origin of very-high-energy photons in astrophysics: A short introduction to acceleration and radiation physics

De l'origine des photons de très haute énergie en astrophysique : une brève introduction aux mécanismes d'accélération et de rayonnement

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A B S T R A C T

Powerful astrophysical sources produce non-thermal spectra of very-high-energy photons, with generic power-law distributions, through various radiative processes of charged particles, e.g., synchrotron radiation, inverse Compton processes, and hadronic interactions. Those charged particles have themselves been accelerated to ultra-relativistic energies in intense electromagnetic fields in the source. In many cases, the exact acceleration scheme is not known, but standard scenarios, such as Fermi mechanisms and reconnection processes are generally considered as prime suspects for the conversion of bulk kinetic or electromagnetic energy into a power law of supra-thermal particles. This paper proposes a short introduction to the various acceleration and radiative processes which shape the distributions of very-high-energy photons ($\epsilon_\gamma \gtrsim 100$ MeV) in astrophysics.

R É S U M É

Les sources astrophysiques puissantes sont à l'origine de spectres non thermiques de photons de très haute énergie, généralement caractérisés par des distributions en loi de puissance. Ces photons sont le fruit de processus radiatifs divers de particules chargées primaires, qui interagissent, par exemple, par rayonnement synchrotron, processus Compton inverse ou par des interactions hadroniques. Ces particules chargées ont, quant à elles, été accélérées à des énergies ultra-relativistes dans les champs électromagnétiques intenses des sources. Le mécanisme exact de l'accélération est bien souvent inconnu, mais les processus de Fermi, ou de reconnexion, sont généralement considérés comme des agents idéaux d'une conversion d'énergie d'ensemble, cinétique ou electromagnétique, en énergie de particules supra-thermiques. Cet article propose une brève introduction à la physique de ces processus d'accélération et de rayonnement, à la source des spectres de photons de très haute énergie ($\epsilon_\gamma \gtrsim 100$ MeV) en astrophysique.

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1. Introduction

The pioneering detections of high-energy photons from cosmic sources in the seventies have opened a whole new way of studying the Universe, through the non-thermal radiation produced by the most violent particle accelerators. One understands those manifestations through an apparently simple universal scheme: powerful sources accelerate charged particles in intense electromagnetic fields, and those particles then radiate non-thermal electromagnetic radiations via various electrodynamical processes.

In the past decades, high-energy-photon astronomy has thus become an unvaluable tool to study the physics of acceleration and radiation in the core of powerful astrophysical sources. Thanks to the development of large collecting area and high resolution detectors [1,2], we have reached now a stage in which modellers and theorists alike strive to understand a wealth of high-energy data from various sources, such as active galactic nuclei, compact objects, gamma-ray bursts, and supernovae.

However, as the devil lies in the details, an in-depth description of the non-thermal radiation of a source involves highly complex phenomena acting on different scales, combining hydrodynamics, relativity, electrodynamics, plasma physics in extreme conditions, and even particle physics at large. Accelerating particles in cosmic sources turns out to be a complex task, mostly because the high conductivity of astrophysical plasmas screens efficiently any electric field in the rest frame of the plasma. The physics of particle acceleration in astrophysical sources has thus become a field of study it its own right.

In contrast, radiation physics is well known, but accurate calculations of the emitted spectra are often fraught with approximations made in the description of the source on scales that are not accessible to observation. Characteristic examples include the detailed description of magnetized turbulence, which determine the synchrotron spectra, or that of radiative backgrounds with which the accelerated particles interact. A careful comparison of a model to the data thus requires to bridge, in one way or another, the gap between the microphysical scales of acceleration and radiation and the macrophysical scales of the source. These source models are discussed in the subsequent articles, while the present paper proposes a short introduction to the physics of acceleration and radiation inside high energy astrophysical sources.

General features of acceleration processes are discussed first (Section 2) and radiative processes next (Section 3). Section 4 provides a summary of the notions introduced with some perspectives. Two warnings are in order. One should first of all make a distinction between microphysical acceleration processes and bulk plasma acceleration mechanisms such as jet and wind launching: the acceleration processes that we are interested in give a possibly large fraction of the available energy to a minority of the plasma constituents, e.g., a power-law distribution in Lorentz factor γ, $\mathrm{d}N/\mathrm{d}\gamma \propto \gamma^{-p}$ with index $p > 1$, while the latter accelerate the bulk of the plasma. Although fascinating by itself, the topic of bulk plasma acceleration is not discussed here. Furthermore, given the breadth of the topics discussed here, it is of course impossible to do justice to either of these; hence, emphasis has been put on the fundamental physical processes, on modern developments and on some applications in high-energy astrophysics. The subsequent articles offer multiple examples of applications of the various processes that are discussed in the following.

2. Acceleration mechanisms

There exist a number of reviews discussing the physics of particle acceleration in astrophysical sources, e.g., [3–9]. Particles can be accelerated in electromagnetic fields through the Lorentz force

$$\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = q\left(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}\right) \tag{1}$$

This fundamental equation is rich in useful lessons: the transverse character of the magnetic Lorentz force implies that the magnetic field does not exert work on the particle, so that acceleration requires an electric field. However, in a rest frame $\mathcal{R}_{\mathrm{b}}$ in which the ions of the background plasma are at rest, i.e. no bulk velocity, electric fields are generally screened on a microphysical timescale due to the large mobility of the electrons, implying[1] $\boldsymbol{E}_{|\mathbf{b}} = 0$. In the laboratory frame, in which Eq. (1) is written, in which the plasma moves at velocity $\boldsymbol{v}_{\mathbf{p}}$, there exists a motional electric field, $\boldsymbol{E} = -\boldsymbol{v}_{\mathbf{p}} \times \boldsymbol{B}$, associated with the Lorentz transform of the magnetic field; note that $\boldsymbol{B}$ is written here in the laboratory frame, which explains why no bulk Lorentz factor appears in this transform.

Therefore, in order to accelerate the particle in a general astrophysical setting, where ideal magneto-hydrodynamics (MHD) conditions apply, one must exploit the motional electric fields. This tells us that the acceleration timescale, in this laboratory frame, is at most of the order

$$t_{\mathrm{acc}} \lesssim \left|\frac{1}{p}\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t}\right|^{-1} \sim \frac{t_{\mathrm{g}}}{\beta_p} \tag{2}$$

where $t_{\mathrm{g}} = p/(eB)$ denotes the gyration time of the accelerated particle in the magnetic field, and $\beta_p = v_p/c$. This upper limit saturates if motion along $\boldsymbol{E}$ is regular; however, the above $\boldsymbol{E}$ is transverse to $\boldsymbol{B}$ (see further below for the possibility of a parallel component $\boldsymbol{E}_{\parallel}$), therefore one also needs an agent, e.g., a force or scattering events, to push the particles

[1] Throughout this article, we use the index notation, e.g., $_{|\mathrm{b}}$, to indicate that the quantity is expressed in a given frame, here $\mathcal{R}_{\mathrm{b}}$.