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A FOKKER-PLANCK CODE FOR HIGH ENERGY PLASMAS

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Abstract. Particles in extreme objects such as X-ray binaries, AGN, or γ-ray bursters have often energies so high that they cannot be thermalized in the too rare particle-particle collisions by Coulomb interactions. They form high energy plasmas whose properties are not well understood yet. Not only are these plasmas responsible of the hard X- and γ-ray emission we observe but also they have a strong influence on the main dynamics and energetics of the astrophysical objects themselves.

We present a new kinetic code that solves the evolution equations for the distributions of particles and photons interacting by radiation processes such as self-absorbed synchrotron and Compton radiations. The code produces spectra that can be compared with observations X to constrain the radiation and acceleration processes in these objects. A first application is also presented that illustrates the thermalization of hot plasmas by self-absorbed synchrotron emission.

1 Introduction

Investigating the time evolution of a plasma of interacting particles and photons implies to deal with integro-differential equations that cannot be solved analytically, and numerical simulations are required. A few codes already exist that address the modeling of such high energy plasmas (see e.g. Nayakshin & Melia 1998; Coppi 1992), but they rarely include all the relevant physics, such as an accurate description of the particle distribution or a correct treatment of the self-absorbed synchrotron radiation. We have started the development of a new code that deals with particles from sub- to ultra-relativistic regime, and includes interactions with the photon distribution such as self-absorbed synchrotron and Comptonization. When the diffusion in the energy space is not to fast, the physical effect are treated with the Fokker-Planck limit, which allow a fast convergence. The code is time dependent and so is able to address the variability observed in the sources light curves and spectra. The numerical scheme we have developed conserves the number of particles and photons and the total energy to machine precision.

2 The code

The code solves simultaneously two identical equations that describe the time evolution of both the distribution of particles in the the momentum space ($x = p/mc$) and that of photons in the energy space ($x = h\nu/mc^2$) :

$$\partial_t N = \partial_x \left(A + \partial_x(DN)\right) + Q_{\rm inj} - \frac{N}{T_{\rm esc}}$$

The sink term $N/T_{\rm esc}$ represents the escape of particles/photons from the system. The source term $Q_{\rm inj}$ includes the direct injection of particles/photons in the system. It can model the seed photons from an accretion disc in X-ray binaries or the matter loading in an advection dominated accretion flow. This source term also includes contributions from highly non-linear interactions between the two populations (see hereafter). When possible/required, these interactions are rather treated in the Fokker-Planck approximation that leads to the

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first two terms corresponding to advection (A) (i.e. heating/cooling) and diffusion (D) in the momentum/energy space.

The distributions are discretized in bins. Since the Courant condition for explicit methods sets a very small time step when the energy range spans over several orders of magnitude, a semi-implicit method is used. The widely used Chang-Cooper method (CC) is known as one of the best implicit scheme (Chang & Cooper 1970; Park & Petrosian 19996). However, we have found it inaccurate when solving the FP equation with self-absorbed synchrotron: in the CC scheme, absorption and emission of photons appear in two different terms. When the synchrotron radiation is self-absorbed, these two terms are very large and must cancel, only leaving a small residual radiation field. This is hard to achieve numerically and it leads to a poor energy conservation. Rather, we use a scheme based on the equations written above where the coefficients A and B already include the contribution from absorption and emission in an exact manner. This guaranties number and energy conservation to machine precision.

3 Radiation processes

Particles and photons in high energy plasmas can interact in many different ways that must be taken into account when an accurate modeling is required. So far, two radiation processes have been implemented.

- Self-absorbed cyclo-synchrotron radiation:
  The gas in the corona of AGN and X-ray binaries and in γ-ray bursts is believed to be magnetized and to emit strong synchrotron radiation that is self-absorbed when particles are not too energetic ($\gamma < 10$). The power spectrum of a single electron is tabulated from a combination of asymptotic expressions to get a good accuracy in all energy regimes (Ghisellin & Svensson 1991; Ghisellini et al. 1998; Katarzyński et al. 2006). Contributions of the cyclo-synchrotron radiation to the FP coefficients in the equation for the particles are calculated from expressions given in Ghisellini et al. (1998) by assuming a given size for the emission region.

- Compton scattering:
  Including the Compton contribution for all energy regimes requires to compute the exact distribution $P(p_0, \omega_0; \omega)$ of photons resulting from the interaction of particles of momentum p_0 with isotropic photons of energy ω_0. As computing this diffusion probability by successive numerical integrations is time consuming, and analytic expression has been derived, that can be numerically computed on a large range of energy (Belmont 2007, in preparation). In the small angle scattering limit, the contribution to the Fokker-Planck coefficients is computed from the first moments of the scattered distribution (Coppi & Blandford 1990). However, for the photon equation or for large angle scattering of particles, the FP approximation is not relevant and an exact treatment is used that integrates the scattering probability P over the two distributions (see Nayakshin & Melia 1998).

Tables for the synchrotron emission/absorption of one single electron and the Compton scattering probability are computed once. Then, they are used at each time step to compute the contribution to the evolution equations.

4 First results

Here we present a first use of the code. Several clues seem to indicate thermal plasmas in AGN and in X-ray binaries although acceleration processes rather produce power law distributions. Simple particle-particle collisions by Coulomb interactions are too rare to account for this thermalization. Ghisellini et al. (1988) suggested that exchange of energy between particles by exchanging synchrotron self-absorbed photons is much more efficient. We have run the code by constantly injecting mono-energetic particles in an empty corona. Fig. 4 shows the time evolution of the electron and photon distributions. The first electrons emit synchrotron photons and build the mean radiation field. Meanwhile, they strongly interact with these photons. We see that, as the the corona is filled by particles, their distribution evolves to a Maxwellian one on a few synchrotron times scales. Theses results very (similar to those of Ghisellini et al. (1998)) show that the exchange of photons is a very efficient thermalization process. In this run, the Comptonization of the synchrotron photons only play a secondary role by extending the photon distribution to higher energy.

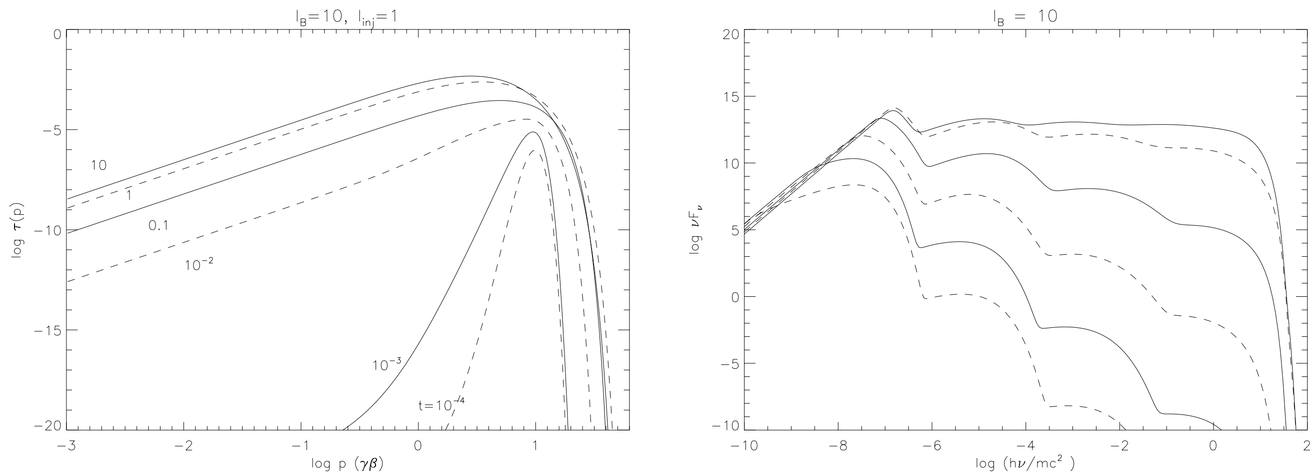

Fig. 1. Time evolution of the particle population (left panel) and photon distribution (right panel) when mono-energetic particles are constantly injected in an empty system (the time is normalized by the light crossing time of the system R/c and the distribution by $R\sigma_T$).

5 Conclusion

We have presented the basic properties of the code at its present stage and one first result that confirm previous studies. The code is still in development and new features will be added in order to give a complete modelling of high energy plasmas in microquasars, AGN, and γ-ray bursts... Among them: Coulomb interactions, non-absorbed cyclo-synchrotron coupled to other radiation processes, acceleration processes (e.g. Fermi), pair creation/anihilation...

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