Electromagnetic cascades in magnetic fields

Leonardo J. Pellizza[1], **Mariana Orellana**[2,3], **Gustavo E. Romero**[2,4]

[1] Instituto de Astronomía y Física del Espacio (CONICET/UBA), Argentina
[2]Facultad de Ciencias Astronómicas y Geofísicas, Universidad de La Plata, Argentina
[3]Universidad de Valparaíso, Chile
[4]Instituto Argentino de Radioastronomía (CONICET), Argentina

High Energy Phenomena in Relativistic Outflows II, Buenos Aires, 26–30/10/2009

Summary

Motivation

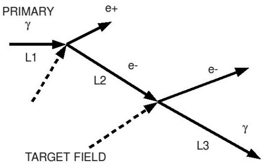
- Since the first γ-ray observatories, many sources emitting EM radiation with energies from MeV to TeV have been discovered.
- Many of these sources have been identified with systems already known at lower energies (X-ray binaries, microquasars, etc.), and there are still many unidentified ones.
- The origin of γ-rays 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 matter in, or radiation from, disks or winds to produce TeV energy photons (e.g., Benaglia & Romero 2003; Romero 2004; Paredes 2005).
- The predictions of these models must be tested against the observed γ-ray spectrum.

Motivation

- Primary γ-rays are produced in environments with non-negligible opacity, hence their propagation inside the system must be considered to model the observable spectrum.
- At low optical depths simple absorption calculations are accurate.
- At larger optical depths EM cascades can develop through IC scattering and e^+e^- pair creation, decreasing effective opacity.
- The correct computation of EM cascades is crucial to compare the predictions of different γ-ray production models to observations, and many efforts have been devoted to this issue using both numerical (Protheroe 1986, Bednarek 2007; Orellana et al. 2007) or semi-analytical (Aharonian et al. 2006; Khangulyan et al. 2008; Cerutti & Dubus 2009) techniques.

Previous work

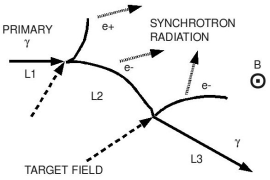
- Numerical methods use Monte Carlo techniques.



- Basic outline:
    - Sample a primary particle according to primary model.
    - Compute mean free path and sample a free path for next interaction.
    - Sample a target particle from proper distribution.
    - Compute interaction products.
    - Follow up energetic particles until they reach the system boundaries.
    - Compute the spectrum of the outgoing radiation.
- Usually assumed to be 1D.

Previous work

- Most systems have non-negligible magnetic fields.



  - Change the direction on motion of leptons → 3D.
  - Synchrotron losses drain energy, eventually supressing the cascade (Khangulyan et al. 2008).
- Few attempts to include magnetic field in numerical simulations
  - Isotropisation of lepton directions of motion (Bednarek 2000)
  - Approximations to particle motion, no synchrotron losses (Sierpowska & Bednarek 2005)
- A full, self-consistent numerical treatment of the development of cascades in magnetic fields would be desirable to better understand the γ-ray production in many systems.

Simulations

- Our goal is to devise a code for simulating EM cascades in magnetic fields from an ab-initio point of view, versatile enough to apply it to many different systems.
- Features of our code:
  - Full numerical time-integration of relativistic equations of motion for both leptons and photons for arbitrary magnetic field configurations.

$$\frac{d\vec{r}_{\rm e}}{dt} = v_{\rm e}(t), \ \ \frac{d\vec{r}_{\gamma}}{dt} = c, \ \ \frac{d\vec{v}_{\rm e}}{dt} = \pm e \frac{\vec{v} \times \vec{B}}{\gamma_{\rm e}}$$

  - Compute interaction rates for IC (leptons) and pair production (photons) at each timestep for arbitrary target photon fields using exact cross-sections.

$$r_{\rm int} = c \int_0^{\infty} \int_0^{\pi} \int_0^{2\pi} n(\epsilon, \theta, \phi) \sigma(\epsilon, \theta)(1 - \beta \cos\theta) d\epsilon d\theta d\phi \qquad (1)$$

  - Use Monte Carlo techniques to decide the occurrence of an interaction and sample the target properties.

Simulations

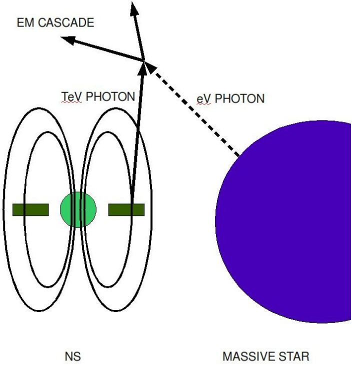
- Features of our code:
  - Compute interaction products sampling from exact differential cross sections and ensuring strict conservation of energy and momentum.
  - Use adaptive timesteps to account for gradients of target field density and magnetic fields.
  - Accurately compute (classical) synchrotron losses at each timestep

$$\frac{dE}{dt}_{\rm sync} \propto \gamma^2 B^2$$

- Can be applied to any γ-ray production model for which the distribution of position, energy and momentum of the primary photons is given, with arbitrary target photon fields and magnetic field configuration.
- Compute 3D cascades that give information on the SED of photons leaving the system, and its dependence with time, position and propagation direction.
- Provides a self-consistent treatment of synchrotron emission, and its dependence with position within the system and time.

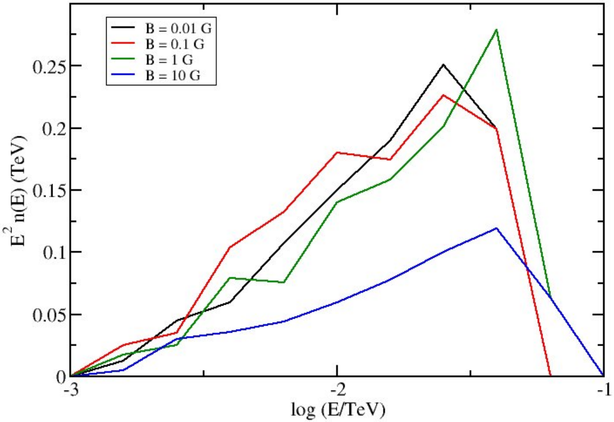
Results

- Toy model:

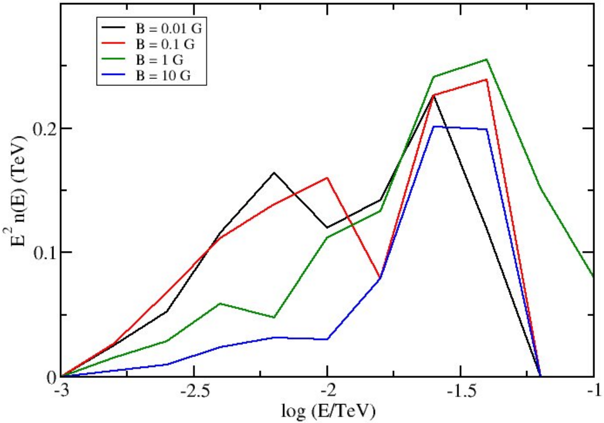


  - NS + massive star binary
  - Primary TeV photons produced in the interaction of relativistic particles with accretion disk (monoenergetic, $E = 1,\ 100$ TeV)
  - Target photon field: stellar radiation field
  - Dipole magnetic field of NS

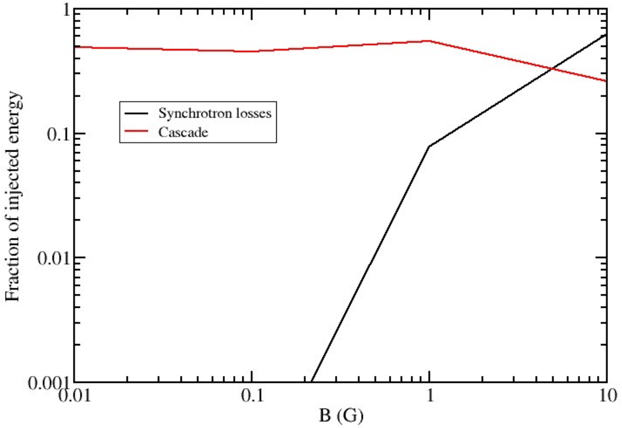
Results: E = 1 TeV



Results: E = 100 TeV



Results: Synchrotron losses - 1 TeV



Conclusions

- 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 distributions (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 model, the code reproduces the basic features of cascade supression by synchrotron losses.