Abstract: We study the acceleration, transport, and emission of particles in relativistic jets. Localized stochastic particle acceleration, spatial diffusion, and synchrotron as well as synchrotron self-Compton (SSC) emission are considered in a leptonic model. To account for inhomogeneity, we use a 2D axi-symmetric cylindrical geometry for both relativistic electrons and magnetic field. In this first phase of our work, we focus on steady state spectra that develop from a time-dependent model. We demonstrate that small isolated acceleration regions in a much larger emission volume are sufficient to accelerate particles to high energy. Diffusive escape from these small regions provides a natural explanation for the spectral form of the jet emission. The location of the acceleration region within the jet is found to affect the cooling break of the spectrum in this diffusive model. Diffusion-caused energy-dependent inhomogeneity in the jets predicts that the SSC spectrum is harder than the synchrotron spectrum. There can also be a spectral hardening towards the high-energy section of the synchrotron spectrum, if particle escape is relatively slow. These two spectral hardening effects indicate that the jet inhomogeneity might be a natural explanation for the unexpected hard γ-ray spectra observed in some blazars.

Motivation

Ultra-fast flares in BL Lac – small emission region (~10^3 pc)

Very high energy (VHE) γ-ray light curve of PKS 2155-304 (HESS collaboration, 2007)

FSRQs detected above 100 GeV – far away emission site (~pc)

Spectral energy distribution (SED) of 3C279 above 50 GeV (MAGIC collaboration, 2008)

The fastest flares must originate from very small regions because of light crossing time effects. At the same time they should be located relatively far away from the central engine (presumably a black hole). The jet should have expanded considerably by then, therefore a small high energy region should reside in a relatively large jet. In order to model such an environment and account for emission on different scales and at different frequencies, an inhomogeneous jet model spanning different scales is necessary!

Closed Boundary Condition

The particles do not escape through the outer boundary. Initially particles have Lorentz factor of about 33, so at early times the combined electron energy distribution (EED) show two bumps representing the initial particles and the accelerated particles. At late times they reach a steady state with one power-law distribution. The SED shows harder inverse Compton spectrum compared to the synchrotron spectrum. This is caused by a preference of SSC scattering between high energy synchrotron photons and high energy electrons, both of which are concentrated in the central region. (See energy dependent inhomogeneity)

Energy Dependent Inhomogeneity

Particles distribute differently at different energy. Higher energy particles concentrate more in a small region. The consequences of this inhomogeneity include:

1) The SSC spectrum is harder than the synchrotron spectrum (see ‘Closed boundary condition – accelerator in the center’);

2) The internal γγ absorption opaqueness of the jet is lower than that of a homogeneous model.

The particle density maps correspond to the case in ‘Closed boundary condition – accelerator in the center’.

Open Boundary Condition

Particles escape through the outer boundaries. To compensate the loss of particles, there are continuous injection of new particles at small regions within the jet. The EEDs develop into typical broken power-law distributions in these cases.

Conclusions:

1) With acceleration region much smaller than the emission region, the electrons form power-law/broken power-law distribution that adequately reproduce blazar SEDs, with reasonable rate of particle escape;

2) The inhomogeneity developed in the jet is energy dependent, with higher energy particles concentrated in smaller regions;

3) The inclusion of particles both inside and outside of the acceleration region causes the EED/SED to have a feature of spectral hardening at high energy, when the particle diffusion is slow;

4) The energy dependent inhomogeneity causes the SSC spectrum to be harder than the synchrotron spectrum, and this might help to explain the very hard VHE spectra in several blazars.

5) If the acceleration region is not located at the center of the emission region in an open boundary escape scenario, the resulted EED forms an atypical broken power-law distribution with spectral break less than 1.

References


References


MAGIC collaboration, Science, 2008, 320, 1752


Sketch of the 2D Cylindrical Geometry

(Chen, Pohl & Böttcher, 2014)