Cosmic ray Acceleration by Magnetic Reconnection and the Non-thermal Emission from Accretion-Disk/Coronae of AGNs: an application to M 87

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Abstract: Very high energy observations of active galactic nuclei (AGNs) are challenging current theories of particle acceleration (mostly based on shock acceleration) which have to explain how particles are accelerated to energies above TeV in very compact regions compared to the characteristic scales of their sources. The identification of AGNs as sites of particle acceleration raises many fascinating and important questions. Recent magneto-hydrodynamical studies have revealed that cosmic ray acceleration by fast magnetic reconnection can be rather efficient because a first-order Fermi process may occur. In this work, we discuss this acceleration mechanism in the coronal region of the accretion disk around AGNs. In addition, the accelerated particles lose substantial amounts of their energy due to non-thermal interactions with the surrounding magnetic field, matter and radiation fields. Employing this model, we compute the corresponding acceleration rate and the relevant loss rates in order to reproduce the observed high energy spectrum of the AGN source M 87 which has strong gamma ray emission, considering both leptonic and hadronic processes.

Keywords: cosmic rays, magnetic reconnection, AGNs, non-thermal emission

1 Introduction

Very high energy observations of AGNs and GRBs, especially in recent years with the Fermi and Swift satellites and ground based gamma ray experiments (HESS, VERITAS and MAGIC) are challenging current theories of particle acceleration, which have to explain how particles with energies above Tev are produced within regions relatively small compared to the fiducial scale of their sources.

The mechanisms frequently discussed in the literature for accelerating energetic particles include varying magnetic fields in sources (e.g., [4],[5]), stochastic processes in turbulent environments [19], and acceleration behind shocks. In the latter mechanism, cosmic rays are accelerated when they cross a shock wave repeatedly gaining an enormous amount of energy through a first-order Fermi process.

An alternative, much less explored mechanism so far, involves particle acceleration within magnetic reconnection sites. This can be particularly important in sources or regions of sources where magnetic fields are dynamically dominating.

Magnetic reconnection occurs when two magnetic fluxes of opposite polarity encounter each other. Under finite magnetic resistivity, the converging magnetic field lines annihilate at the discontinuity surface also named current sheet.

de Gouveia Dal Pino & Lazarian (2005; henceforth GL05)[6] proposed that, similarly to shocks, charged particle trapped within a reconnection sheet may bounce back and forth several times and gain energy due to head-on collisions with magnetic fluctuations, thus undergoing a first-order Fermi process within a reconnection site. They found that after each round trip the particle gains energy $\Delta E/E \propto V_{rec}/c$. Similar processes were later explored by others ([10]; [11]; [24]see also [12] among others). The equation above suggests that in order to ensure an efficient acceleration process, the velocity at which the magnetic reconnection occurs, vrec, has to be fast. There are several processes in nature that may allow fast reconnection and the solar flares are a vivid example of it. Among the possible mechanisms, Lazarian & Vishniac (1999)[18] verified that the presence of turbulence makes magnetic reconnection fast with a velocity which is a substantial fraction of the Alfven speed, V_A, and nearly independent on the magnetic diffusivity. Besides, the presence of turbulence in the reconnection sheet makes it thicker and therefore, helps to retain charged particles for longer time to be accelerated. This model has been successfully tested numerically recently by Kowal, de Gouveia Dal Pino and Lazarian (2011, 2012)([16],[17]). In these works, thousands of charged particles were launched into 3D MHD domains of magnetic reconnection and their trajectories and energy spectrum have been computed. Figure 1 depicts one of these MHD domains of reconnection and the resulting energy growth of the particles with time. We note an exponential growth in their energy when they achieve the current sheet (Fig. 2).

In addition, the environment around an AGN is thick with visible, X-ray, and gamma-ray radiation. Charged particles are expected to lose considerable energy as they move out of the acceleration zone into these radiation fields. Interactions between cosmic rays and matter, magnetic and radiation fields will cause relevant losses such as Synchrotron, Bremsstrahlung, Inverse Compton, proton-proton inelastic collisions and photo meson production.

In this work, we consider the acceleration mechanism discussed above in the surroundings of the nuclear region of an AGN. As in GL05 and de Gouveia Dal Pino et al. ([7]), we assume that fast and powerful reconnection occurs between the lines arising from the accretion disk and the lines arising from the central source (see Figure 3). In such magnetically dominated environment, particles can be trapped and efficiently accelerated through a first-order

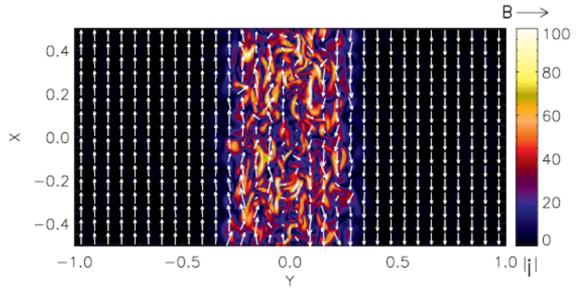

Figure 1: 3D MHD simulation of magnetic reconnection. 10,000 particles with an initial thermal spectrum were injected into this reconnection domain ([17]

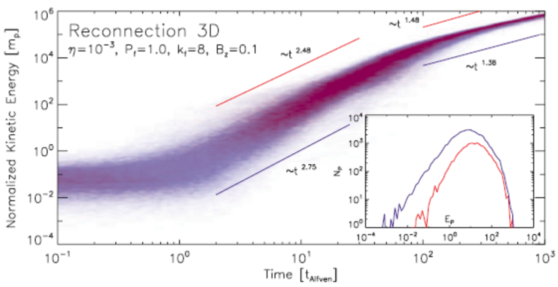

Figure 2: Evolution of the kinetic energy of the particles (red corresponds to parallel and blue to perpendicular acceleration). The bottom right panel depicts the accelerated particle spectrum ([17]).

Fermi process, as described above. We have calculated the corresponding acceleration rate by magnetic reconnection directly from the numerical MHD simulations of Kowal et al. ([17]; see Figure 2) and the cooling rates for both electrons and protons, in order to reconstruct the spectrum energy distribution (SED) of the AGN M 87.

2 Particle acceleration and losses

We consider the interaction of the relativistic particles that were accelerated within the magnetic reconnection site with the matter, photons and magnetic fields of the surrounding region of the accretion disk of the AGN. There are three proper processes of interaction of relativistic electrons with these fields which include synchrotron radiation, inverse Compton and relativistic Bremsstrahlung. For protons there are also three relevant loss mechanisms: synchrotron radiation, proton-proton inelastic collisions and photohadronic interactions. Particles emit synchrotron radiation at a rate

$$t_{synch}^{-1} = 4/3(m_e/m)^3 \sigma_T B^2/m_e y \quad (1)$$

where σ_T is Tompson cross section.
Relativistic protons in the surrounds of the source undergo pp collisions with the cold protons at a rate

$$t_{pp}^{-1} = n_c c \sigma_{pp} k_{pp} \quad (2)$$

Here the inelasticity coefficient is $k_{pp} = 1/2$, the corresponding cross section for inelastic pp interactions can be approximated by ([14],[15])

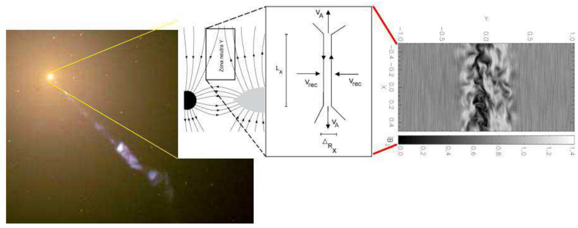

Figure 3: From left to right the figure shows: the HST image ofM87 AGN; a schematic representation of the expected magnetic field structure around the accretion disk and the central black hole, a schematic representation of the reconnection zone with the two converging magnetic fluxes of opposite polarity as in a Sweet-Parker configuration; and a 3D MHD simulation of magnetic reconnection with turbulence injected within the current sheet to make reconnection fast. Extracted from [8]

$$\sigma_{pp} = (34.3 + 1.88L + 0.25L^2)[1-(E_{th}/E_p)^4]^2 \times 10^{-27} \quad (3)$$

Where L=ln($E_p/1000GeV$), $E_{th} = 1.2GeV$. In both Thomson and Klein-Nishina regimes, the IC cooling rate for an electron is given by [1]

$$t_{IC}^{-1} = 1/E_e \int_{\varepsilon_{min}}^{\varepsilon_{max}} \int_{\varepsilon}^{\gamma E_e/1+\gamma} (\varepsilon_1 - \varepsilon) dN/(dt d\varepsilon_1)\, dx \quad (4)$$

Here $\varepsilon_1, \varepsilon$ are the energy of the incident photon, and the energy of the scattered photon respectively, and

$$\frac{dN}{dt d\varepsilon_1} = \frac{2\pi r_0^2 m_e^2 c^5}{E_e^2} \frac{n_{ph}(\varepsilon) d\varepsilon}{\varepsilon} F(q) \quad (5)$$

where $n_{ph}(\varepsilon), r_0$ are the number density of target photons, and the classical radius of the electron respectively, and

$$F(q) = 2q\ln(q) + (1+2q)(1-q) + 0.5(1-q)\frac{(\gamma q)^2}{1+\gamma q} \quad (6)$$

where $\gamma = \frac{4\varepsilon E_e}{m_e^2 c^4}$, $q = \frac{\varepsilon_1}{\gamma(E_e - \varepsilon_1)}$.
We consider both black body radiation (thermal photon field) and synchrotron self Compton (SSC) as photon fields. Proton interaction with photons can be also important cooling processes. In order to obtain the acceleration rate $t_{acc}^{-1} = \frac{\frac{dE}{dt}}{E}$ as function of the particle energy we used the results of the numerical numerical simulations [17] (Fig. 2). We note that all values in Fig. 2 are in code units and we must convert them into physical units. We obtain $t_{acc}^{-1} \sim E^{-a}$, where $a \sim 0.36 - 0.4$.
As an example, below, we present the results for M 87. The acceleration and cooling rates for high energy electrons and protons are shown in Figs. 4 and 5, respectively. Using typical values of M 87 parameters (see table 1), we assumed a coronal particle density $n_c \sim 5 \times 10^8 cm^{-3}$, a length scale of the reconnection site of the order of the emission radius (R) which is $R \sim 3 \times 10^{15} cm$, and a strength for the magnetic field in the inner disk region $B \sim 5 \times 10^5 G$ (the magnetic energy density in this case is in equipartition with the inner disk accretion energy). In this table there are values for another parameters such as magnetic reconnection power (W), fraction of this power which is assumed to accelerate the particles (f), α_1, α_2 are power law indexes in

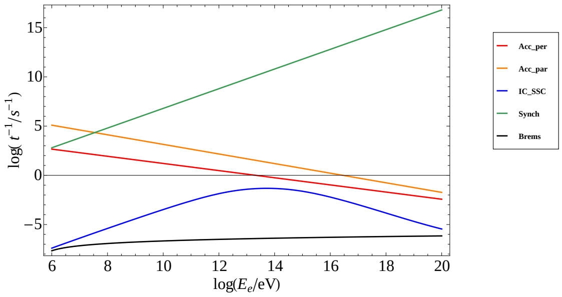

Figure 4: Acceleration by magnetic reconnection and cooling rates for electrons

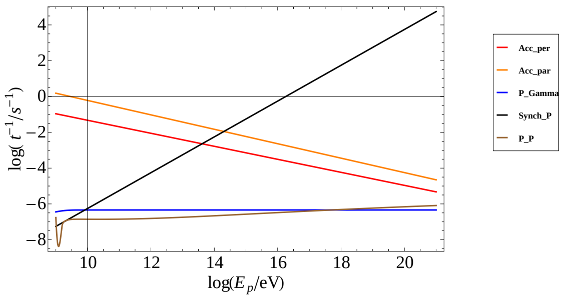

Figure 5: Acceleration by magnetic reconnection and cooling rates for protons

lower energies and higher energies respectively and "D" is the distance of the source which is 16 Mpc.
As remarked, the main loss mechanism for electrons is Synchrotron radiation which is probably all lost in situ, i.e., still in the acceleration region. Other relevant loss mechanisms are Synchrotron-self Compton (SSC) ([22]; [13]) and Bremsstrahlung. The maximum energy for the electrons is obtained equating the loss rates with the acceleration rate. The result is ∼1 GeV.
The loss mechanisms for protons are p-p inelastic collisions, synchrotron and p- γ interactions due to SSC process. The maximum energy of these particles is $\sim 10^{15} eV$, which is much larger than the maximum energy of the electrons, as expected. Figure 6 shows the computed spectral energy distribution (SED) combining the acceleration rate due to magnetic reconnection with the loss mechanisms above. The energy cut-off both for electrons and protons was determined from Figures 4 and 5. Then, we computed the SED as in [20] see also [25]; [21]; [9]). We note that the non-thermal emission at frequencies $10^{12} - 10^18Hz$ is

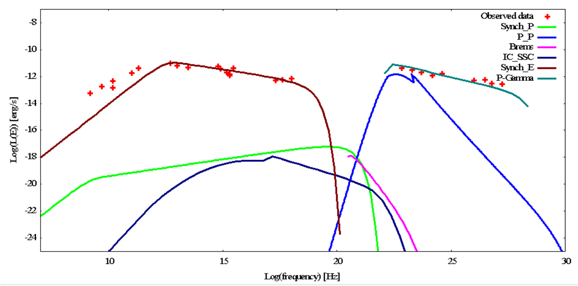

Figure 6: Computed non thermal spectral energy distribution

B (Gauss)	5×10^5
$n_c(cm^{-3})$	5×10^8
R (cm)	3×10^{15}
W (erg s^{-1})	10^{41}
f	0.1
α_1	1.8
α_2	2.4
D(cm)	4.8×10^{25}

Table 1: Typical values for M 87.

dominated by Synchrotron and for frequencies between $10^{22} - 10^{27} Hz$, is dominated by the p-γ interactions due to SSC process is the most effective. In this system, the IC-SSC and Bremsstrahlung mechanisms are not effective.

3 Conclusions

We used the theory proposed by GL05 [6] and [7] and successfully tested numerically by Kowal et al. ([16] and [17]) for relativistic particle acceleration in a 1st order Fermi process within magnetic reconnection zones at the corona of accretion disks around the gamma ray emitter AGN M 87. Comparing the computed acceleration rate with relevant radiative losses for both relativistic electrons and protons, we have found that the magnetically dominated model above is plausible to explain the observed high energy spectrum of this AGN source. Similar studies must still be performed considering other gamma ray sources. In particular, the recent detection of gamma-ray emission in the surrounds of the nuclear region of the pulsar Crab [23] suggests that mechanism here studied may be a promising one in several class of collisional cosmic ray accelerators (see also de Gouveia Dal Pino; and Kadowaki de Gouveia Dal Pino in this meeting)and [26],[27], [2] and [3].

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