ACTIVE GALACTIC NUCLEI AS HIGH ENERGY ENGINES

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Abstract

Active Galactic Nuclei are considered as possible sites of cosmic ray acceleration and some of them have been observed as high energy gamma ray emitters (Blazars). There naturally comes an appealing idea that the acceleration of the highest energy cosmic rays in the AGNs has a signature in the form of gamma ray emission and high energy neutrino emission through the collisions of very high energy protons with soft photons. Moreover it is often said that electrons cannot reach enough energy through Fermi acceleration to account for the highest energy photons observed with ground Cerenkov telescopes. In this paper, we discussed these points and show that the fast variability of the flares recently observed rules out the assumption of a Fermi acceleration of protons. We show that Fermi acceleration of electrons is enough to account for the gamma spectra, their shape, cut-off and their variability. Moreover the spectral break is nicely explained by invoking an gamma-ray photosphere. Nevertheless we give estimates of the high energy cosmic ray generation in AGNs and of the resultant neutrino flux, that turns out to be very sensitive to the spectral index of the proton distribution.

1 Introduction

Active Galactic Nuclei are particular among the high energy engines for they are both compact objects in a precise physical sense and the central power engine of the most extended non thermal sources of the Universe. As such they are sites of high energy electrodynamics with gamma ray and pair production, and particle accelerators that could generate high energy cosmic rays, that undergo hadronic processes and could emit high energy neutrinos as a signature of this generation.
They are compact objects because they display an intense X-radiation field that makes them optically thick to gamma-rays, at least within some radius of order $100r_G$ ($r_G = 2GM_*/c^2$ is the gravitational radius of the presumed black hole). This is measured by a number called "compactness" and defined for a spherical region of size $R$ by:

$$l \equiv \frac{\sigma_T L_X}{4\pi R m_e c^3}.$$  \hspace{1cm} (1)

where $L_X$ is the X-ray luminosity around 500 keV.

So when $l \gg 1$, every gamma-photon interacts with an X-photon to give a pair of electron-positron. There are several possible processes that produce gamma-photons and thus pairs in AGNs. They can be consequence of the Penrose mechanism, the effect of the gap electric field in the vicinity of the rotating black hole, of the Fermi processes that maintain hadronic collisions (proton-proton collisions and proton-soft photon collisions) and the Inverse Compton process.

The presumed central black holes are likely surrounded by an accretion disk that have been devised to explain the intense black body emission [27]. Later the standard model has been modified to explain the hard X emission (the so-called Comptonized disk model) and also to account for jet production [2,3] by assuming the existence of opened magnetic field lines threading the disk. In fact, no high energy physics can be figured out without a magnetic field having a pressure at least in rough equipartition with the particle pressure. This is another important aspect of the black hole accretion disk to concentrate a magnetic field in large volumes especially when the central mass is of order $10^8$ solar masses. Jets, and especially FR2 ones with their hot spots and extended lobes, are large magnetic structures revealed by their powerful synchrotron radiation. Fermi processes of first and second order need those large magnetized regions to accelerate particles to very high energy. Indeed the size of the accelerator determines the maximum energy through the maximum gyro-radius it can contain and the transit time of the particle flow in the acceleration region limits the acceleration period.

The purpose of the paper is to gathered the results we have obtained recently on the high energy emission of AGNs and on particle acceleration in order to explain why we prefer the electrodynamic explanation of the gamma-ray emission of blazars and BL-Lac and to compare our pair model with other electrodynamic models. Nevertheless we want to emphasize also the interesting hadronic physics of AGNs (as proposed by [22,15]) and to discuss the possibility for AGNs to produce high energy cosmic rays (between $10^6$ to $10^{11}$ GeV) and the consequent neutrino emission.

The paper is organized as follows. In section 2 we discuss the efficiency of
the Fermi processes. Section 3 is devoted to the discussion of the nature of the physics that underlines the gamma emission of blazars (hadronic or electrodynamic?) and the discussion of the various electrodynamical models. The generation of high energy protons and neutrinos in AGNs is examined in section 4.

2 The efficiency of the Fermi processes

It is often said that the first order Fermi process at shock is more efficient than the second one, and that the Fermi processes accelerate protons more efficiently. We will examine these issues. Then we will estimate the highest energy achieved by electrons and protons in Active Galactic Nuclei and their associated jets and extended regions.

2.1 1st and 2nd order Fermi acceleration

Fermi acceleration at shocks

A suprathermal particle that crosses a nonrelativistic shock front, comes back up stream through pitch angle scattering and then crosses again the shock front has gained an energy such that

$$\frac{\delta p}{p} = \frac{4 u_1 - u_2}{3 v \cos \theta_1},$$

where $\theta_1$ is the angle of the magnetic field line with respect to the shock normal, and $u_1$ and $u_2$ are respectively the upstream and downstream velocities of the flow. $v$ denotes the velocity of the particle ($v \simeq c$ for a relativistic particle).

Its residence time in the vicinity of the shock is determined by the downstream spatial diffusion coefficient $D$ through: $t_r = 2D/u_2^2$. It thus depends on the main microscopic ingredient of the theory namely the pitch angle frequency $\nu_s \equiv < \Delta \alpha^2 > / \Delta t$, where $< \Delta \alpha^2 >$ is the mean quadratic variation of the pitch angle during an interval $\Delta t$, larger than the correlation time. In fact the diffusion coefficient depends on the shock obliquity and one defines an effective diffusion coefficient that combines the parallel and perpendicular coefficients, $D_\parallel = \frac{1}{3} \nu_s^2$ and $D_\perp = \frac{1}{4} r_L^2 \nu_s$, where $r_L = p/eB$ is the Larmor radius of the particle. However the perpendicular diffusion coefficient likely reaches the Bohm’s value $D_B = \eta_0 r_L v$ with $\eta_0 \simeq 5 \times 10^{-2}$; its derivation for relativistic particles can be found in [25]; so $D_{eff} = D_\parallel \cos^2 \theta_2 + D_\perp \sin^2 \theta_2$. Except for almost perpendicular shocks (which would be the most efficient for particle acceleration.
if Bohm’s diffusion is at work [20,12], the parallel diffusion prevails.

At each crossing, the particle has a probability \( \eta = 4u_2/v \) to escape. For relativistic particles \( v \approx c \) and the crossing frequency is almost \( \nu_c = 1/(\eta t_r) \). The acceleration rate is therefore such that

\[
< \Delta p > / \Delta t = \frac{4}{3} \frac{u_1 - u_2}{v \cos \theta_1} \nu_c p = \frac{r - 1}{3t_r} p .
\]  

For non-perpendicular shocks, the acceleration time scale \( t_1 \) of this first order Fermi process is thus \( t_1 = t_r \sim (c^2/u_2^2)\nu_s^{-1} \). If the suprathermal particles would couple with the thermal medium through ordinary collisions, the energy exchange would lead to a thermalization of the fast particles. The coupling with the thermal medium is not collisional, it is through the magnetic disturbances (likely Alfven waves) of the thermal medium. Often the Alfven velocity is smaller than the velocity of light and thus the magnetic component of the Lorentz force is larger than the electric one by a factor \( v/V_A \). Therefore in first approximation, the interaction with quasi static magnetic disturbances produces pitch angle scattering, which of course does not lead to thermalization.

**Stochastic acceleration**

Alfven waves in a turbulent plasma produce not only a pitch angle scattering but also an energy diffusion which is of second order in \( V_A/c \) and is also a second order process in term of Fokker-Planck description. One has

\[
< \Delta p^2 > / 2\Delta t = \frac{p^2}{2t_2} \sim \frac{V_A^2}{c^2} \nu_s p^2 .
\]  

This defines the characteristic time \( t_2 \) of a second order Fermi type acceleration process, which does not tend to thermalize either. Since the downstream flow after a shock has a subsonic velocity \( u_2 \), for a magnetic field at rough equipartition, \( u_2 \sim V_A \). It means clearly, as recognized by Jones [13] and somehow by Campenau and Schlickheiser [5], that the second order process is not less efficient than the first order Fermi process at shock, since both times are of order \( (c^2/V_A^2)\nu_s^{-1} \) and are controlled by the same pitch angle scattering frequency.

2.2 *Acceleration time scale and maximum energy*

The pitch angle scattering frequency depends only on the momentum of the particle and the detailed dependence is determined by the Alfven wave spectrum. Only particles having a Larmor radius comparable to a wavelength
of the spectrum undergo scattering. In particular, the minimum momentum \( p_0 = m_p V_A \) for interaction is determined by the smallest wavelength \( \lambda_0 = 2\pi V_A / \omega_{cp} \) (\( \omega_{cp} \) is the cyclotron pulsation of the non relativistic protons) and the maximum momentum achievable by Fermi acceleration is given by the maximum wavelength \( p_m = p_0 \lambda_m / \lambda_0 \). The momentum dependence of the pitch angle scattering frequency is sketched in fig.1, for an Alfven spectrum in \( \omega^{-\beta} \), \( \nu_s \propto p^{\beta-2} \) between \( p_0 \) and \( p_m \).

![Diagram showing the momentum dependence of the pitch angle scattering frequency.](image)

**Fig. 1.** The momentum dependence of the pitch angle scattering frequency. Magnetic perturbations scatter preferentially particles having a Larmor radius close to the wavelength of Fourier mode. The minimum wavelength determines the threshold for scattering and acceleration, and the maximum wavelength determines the maximum energy for the particles to be scattered and accelerated. The efficiency of the scattering and of the acceleration at a given energy depends on the amplitude of the (nearly) resonant mode, the Alfven spectrum being in \( \omega^{-\beta} \). Precise coefficients can be calculated in quasilinear theory valid for a turbulence level \( \eta \ll 1 \). However the estimate is still roughly correct for \( \eta \sim 1 \).

What are the best conditions to get a fast acceleration? Clearly the fastest acceleration process takes place in a relativistic plasma that has an Alfven velocity close to the velocity of light. The modified Alfven velocity in a relativistic plasma is given by:

\[
V_{A,rel} = \frac{c}{\sqrt{1 + 2 \frac{T_m}{P_m}}},
\]

(5)
where $P$ is the relativistic pressure and $P_m$ is the magnetic pressure. At equipartition the modified Alfvén velocity equals the relativistic sound velocity $c/\sqrt{3}$. Since these plasmas are supposed to be magnetically confined the propagation velocity of the electromagnetic waves is close to the velocity of light. Under those conditions, pitch angle scattering and acceleration works with the same time scale and the usual expansion in power of $V_A/v$ cannot be done. Moreover the second order Fermi process is efficient and one does not know whether the first order Fermi process works at relativistic shocks.

**Electron relativistic plasmas**

As we just saw, for high energy particles, the only efficient scattering process comes from the resonant interaction of these particles with Alfvén waves, which occurs with the waves having a wavelength almost equal to the Larmor radius of the scattered particle. In ordinary plasmas, the most massive component is due to non relativistic protons and the Alfvén waves develop at wavelengths larger than $V_A/\omega_{cp}$. This puts a severe threshold for resonant interaction, especially for the electrons that must be very energetic already: $p_0 > m_pV_A$; the corresponding threshold energy $\epsilon_0 \simeq p_0c$ is of order one MeV in supernovae remnants and often of order 100 MeV in extragalactic jets. However all the single charged relativistic particles having the same momentum are accelerated in the same way by the Fermi processes. Saying that protons are accelerated more efficiently than electrons is not true. The only trouble in ordinary plasmas is that protons are more numerous above the resonance threshold and the electrons must be efficiently injected above the threshold to participate to the Fermi processes. Several processes are known to inject electrons in the cosmic ray population, such as the development of a parallel electric field component in magnetic reconnections, or short waves (magnetosonic or whistler) [23].

In compact objects, "exotic" plasmas can be created with a copious relativistic electron (positron) component. The cauldron of the black hole environment [9,17] could likely be dominated by the pair plasma. When the most massive component is due to relativistic electrons (positrons), they are more numerous above the resonant threshold. Under these interesting conditions, the power of the acceleration process goes almost entirely in the radiative particles, which is the best regime to have the most efficient conversion of energy into radiation.

These exotic plasmas (either simply relativistic electrons dominated with non relativistic protons or pair dominated) have interesting dynamics. First, they can be propelled at relativistic velocities by the Compton rocket effect provided that they are maintained hot in the cauldron [9,24]. Second, the investigation of the nonlinear regime of Alfvén disturbances [19] shows that acceleration works efficiently only when the magnetic pressure is larger than the plasma pressure. Overpressured plasmas (not confined) suffer radiative cooling and thus come back to rough equipartition. The nonlinear development of
such waves gives rise to intense relativistic fronts that accelerate particle more efficiently than through familiar Fermi processes. The average acceleration time scale can easily be as short as hundred gyro-periods.

For a first investigation, we will express the efficiency of the acceleration process by a factor $A$ that measures the acceleration time in term of the gyro-period:

$$t_a = AT_g(\gamma)$$  \hspace{1cm} (6)

(some authors take $A = 10$, or even one! this is not reasonable and inconsistent with the observed synchrotron emission). The acceleration factor $A$ depends on the shock obliquity (if any), of the turbulence spectrum, of the energy of the particle. In the case of shock acceleration, it reaches a minimum value for nearly perpendicular but still subluminal shocks, if the Bohm’s diffusion prevails downstream. Then $A \simeq 0.5c^2/u_2^2$, but the crossing number $(c/4u_2)$ must remain large for the theory to apply; typically $u_2$ must remain smaller than $0.1c$, which puts $A$ significantly larger than 10 in the best conditions.

At a given momentum, electrons, positrons and protons are accelerated at the same rate, only loss processes make difference in the shape of their spectra by introducing a cut-off. Their number densities differ because of the threshold defined by the smallest momentum $p_0$. In ordinary plasma, like in the interstellar medium, protons can reach more easily the threshold momentum than electrons, that is probably why they are more numerous in the galaxy cosmic ray population. The synchrotron loss time for electrons and positrons is

$$t_{rad}(\gamma) \simeq 0.75 \cdot 10^9 \gamma \left( \frac{1 \text{G}}{B} \right)^2 \text{sec.}$$  \hspace{1cm} (7)

Electrons suffer Inverse Compton losses in the nuclei also; however assuming that the soft photon energy density is not much larger than the magnetic energy density, the synchrotron time given by eq.(7) is a correct estimate of the radiation time scale. The maximum energy achievable by the acceleration process is obtained by setting $t_a(\gamma_{me}) = t_{rad}(\gamma_m)$; thus

$$\gamma_m \simeq 4.6 \times \frac{10^7}{\sqrt{A}} \left( \frac{1 \text{G}}{B} \right)^{1/2}.$$  \hspace{1cm} (8)

The energy of protons is limited by two conditions: the size of the accelerator and the residence time of the proton in the accelerator. These two conditions are roughly numerically equivalent to the more accurate conditions: the larger size of the magnetic perturbations and the characteristic time of variability.
of the source. Independently of the efficiency of the acceleration process, the maximum energy achievable by protons in an accelerator of size $R$ is:

$$\gamma_{mp} \simeq 10^{12} \frac{R}{1\text{pc}} \frac{B}{1\text{G}}.$$  \hspace{1cm} (9)

However the most severe constraint generally comes from the residence time $t_{res}$:

$$\gamma_{mp} \simeq 1.5 \times 10^{3} \frac{t_{res}}{A} \frac{B}{1\text{sec}1\text{G}}.$$  \hspace{1cm} (10)

We remark that the maximum energy depends on the product of the magnetic field intensity by a size (the residence time is proportional to the size of the accelerator). This tends to favor the vicinity of the black hole to achieve the highest energy, because this product is likely decreasing with the distance to the black hole.

3 The gamma-ray emission of Blazars

3.1 Observational constraints

Non-thermal electromagnetic emission, i.e. synchrotron and high energy radiation, is so far the only direct evidence for the existence of highly relativistic particles in AGN. The high energy cut-off and variability timescale of its spectrum provide thus important constraints on the size and the physical characteristics of the accelerating region. All radio-loud objects are characterized by an intense non-thermal synchrotron emission ranging from radio to optical, and sometimes hard X-ray range. The corresponding high energy component extends from soft X-ray to hard gamma-ray range. In leptonic models, it is interpreted as the Inverse Compton scattering of soft photons, either the synchrotron or the thermal emission from an external accretion disk. In hadronic models, it is the result of pair cascades resulting from initial photopion processes. In any case, observation of photons with an energy $\gamma m_e c^2$ requires particles with a Lorentz factor at least $\gamma$.

The high energy cut-off is not well measured by the current observations. Most gamma-ray emitting AGNs seen by EGRET up to 30 GeV have not been detected by higher energy ground-based Cerenkov telescopes, while the extrapolation of the EGRET spectra should have often fallen above their sensitivity limit. The lack of available instruments in the 30 GeV-300 GeV range has up to now prevented us to better determine the position of the high energy cut-off. The actual starting of improved sensitivity Cerenkov telescopes like
the CELESTE project should help to fix this issue. However, interpretation of the cut-off can be complicated by the extragalactic absorption on the IR-optical-UV background [26]. Assuming a cut-off around 50 GeV, a conservative estimate of the maximal Lorentz factor is thus about $10^5$. Flares on timescales of some days have often been observed in radio-loud quasars such as 3C279 and 3C273, which gives a size of $\sim 10^{16}$ cm for a static isotropic emission zone. With the huge luminosity observed during the flares, this should produce the complete absorption of gamma-rays by pair production. As we discuss in the next sections, this paradox can only be solved by invoking an emission zone with a relativistic bulk motion in a direction close to the observer’s line of sight.

Three objects however have already been detected by Cerenkov telescopes above 200 GeV: Mrk 421, Mrk 501 and 1ES 2344+51.4. They all belong to the class of BL Lacs, and are relatively close objects with an intrinsic relatively low luminosity. As a class, BL Lacs are characterized by the weakness of the thermal component and of their emission lines (if any). The synchrotron component power is often comparable to the high energy one. There seems to be also a strong correlation between the frequency of the maximum of the synchrotron component and that of the high energy component. Indeed, all TeV blazars are X-ray BL Lacs, for which the synchrotron component extends also to the hard X-ray range. In the case of Mrk 501, a spectacular synchrotron flare has been observed by Beppo SAX up to 100 keV, with a corresponding simultaneous TeV flare [21]. In the leptonic model, it is thus plausible that the entire spectrum is mainly produced by SSC process, with a variable maximum particle Lorentz factor and/or magnetic field. Observation of photons up to 10 TeV imply the existence of particles with $\gamma_{\text{max}} \geq 2 \times 10^7$. These particles can produce synchrotron radiation up to 100 keV provided that magnetic field $B \simeq 0.02$G. Moreover, flares are observed with timescales less than one hour, which implies a accelerating region as small as $10^{14}$ cm for a static source. However, as we discuss below, all these estimates must again take into account the bulk motion of the relativistic jet which emits this high energy radiation.

3.2 Hadronic versus electrodynamic processes

It turns out that fast variability is more likely related to the variation in the acceleration process rather than in photons burst [11]. So to know whether the underlying physics of gamma-emission is of hadronic or electrodynamic nature, we look at the characteristic time for particle acceleration in the region where the gamma source is located. This source is likely located around $100r_G$ at the beginning of the jet [10,16].

For electrons at the gamma-ray photosphere, located around $100r_G$ (a day-
light, more or less), where presumably most of the gamma-emission takes place, a magnetic field of 10 G leads to $\gamma_{me} \sim 10^6$ within 10 sec. with $A = 10^3$. For protons at the gamma-ray photosphere, they could reach $10^{10}$ GeV, but in 10 years with $A = 10^3$, whereas the variability time scale and the transit time for a jet portion of $100r_G$ is not more than a day. This reduces the energy to $10^6$ GeV.

### 3.3 The blazar spectra and variability

If emitted by a spherical static source, the gamma radiation observed in blazars could not escape from the central region because of its compactness. However the gamma emission is observed only in some blazars [18] that have jets with superluminal motions and is understood if one takes into account the Doppler beaming. Indeed the relativistic motion (of bulk velocity $\beta c$ of corresponding bulk Lorentz factor $\gamma_b \equiv 1/\sqrt{1-\beta_b^2}$ of the emitting cloud along a direction having a rather small angle $\theta$ with respect to the line of sight produces relativistic aberrations that depends on the Doppler factor $\delta$:

$$\delta \equiv \frac{1}{\gamma_b(1-\beta_b\cos\theta)}$$  \hspace{1cm} (11)

Superluminal motions indicate that the Doppler factor can be as large as 10-20 and thus the radiation is beamed towards the observer according to:

$$I(\omega, \theta) = \delta^3 I_0 \left( \frac{\omega}{\delta} \right) ,$$  \hspace{1cm} (12)

thus the luminosity appears much larger than its intrinsic value which, in fact, remains smaller than the UV bump. Moreover the variability time scale appears shorter by a Doppler factor:

$$\tau_{obs} = \frac{\tau}{\delta} .$$  \hspace{1cm} (13)

Since the variability time gives the maximum size of the source, the gamma emission region is not larger than $100r_G$.

Thus the natural understanding of the high energy emission of blazars is to consider that it comes from the region where relativistic clouds become optically thin to gamma rays at about $100r_G$ [10]. A detailed calculation of the radiative transfer of the high energy photons (X and gamma) emitted by the electrons of a relativistic jet in the anisotropic radiation field of an accretion
disk has been performed [16]. It takes into account the Inverse Compton process on the UV bump and the pair creation process by two gamma photons, the X- and γ-rays being generated by the Inverse Compton process and there is also a small contribution of the annihilation. Because of the stratification and the growth of the pair density up to a value that makes the source optically thick to Thomson scattering of the soft photons, the spectrum breaks around few MeV, the higher γ-rays being still in the optically thick regime, whereas the X-rays are optically thin to γγ-pair production. This model is the only one that accounts for the observed spectrum break, since it predicts that the gamma index is twice the X index, whereas the incomplete Compton cooling model [6] predicts the canonical 1/2 inflection.

3.4 Comparison of the electrodynamics models

In these models, the high energy photons come from the comptonisation of various sources of soft photons by relativistic electrons or electron-positron pairs. The leptonic plasma is assumed to be isotropic in a blob moving relativistically away from the central source.

Models with no pair creation

In the model of Dermer & Schlickeiser [6], the soft photons source is the accretion disk radiation. The high energy emission takes place in a small angle \( \sim 1/\gamma_b \) from the direction of the jet axis with a bulk Lorentz factor set to a constant (typically \( \gamma_b \approx 10 \)). The spectral break (0.5) is due to incomplete cooling of the electrons distribution. Electrons are just injected, and there is no pair creation. All the energy are emitted in the same region which implies that simultaneous variation should be observed in all wavelength. It was argued [28] that this model could not avoid pair creation unless the source of gamma-ray photons is located at distances \( \geq 10^{17} \) cm from the central black hole. At this distance the direct disk radiation is strongly redshifted, and Sikora et al. proposed that the dominant contribution to the soft photons density energy is the rescattered radiation from BLR clouds. In their model, they took the same assumptions as Dermer & Schlickeiser for the description of the electronic plasma and they also considered that all energy photons are emitted in the same region.

Inhomogeneous Synchrotron Self-Compton emission were proposed [8] to explain BL-Lac spectrum where there is no evidence of accretion disk nor lines in the observations. The soft photons are synchrotron photons emitted in the jet and the resultant spectrum is a sum of local synchrotron and comptonization emission in the inhomogeneous jet. This model predicts that flux variation is greater at high energy than at low ones. A spectral break can be explain by
the inhomogeneous geometry of the jet, and can be different from 0.5. Nevertheless the model has the so-called ”Inverse Compton Catastrophe” problem close to the nucleus [7]. However it seems to work nicely for BL-Lacs.

Models with pair creation

Blandford and Levinson [4] combined Inverse Compton on UV-photons from the disk, rescattering radiation or jet itself. They took into account opacity to pair creation on the soft photons and solved numerically the kinetic equations for the different populations in the comoving frame with constant bulk Lorentz factor ($\gamma_b = 10$). The electron-positron pairs are injected to some threshold corresponding to acceleration efficiency. The emergent X-ray to gamma-ray spectrum exhibits a spectral break due to pair opacity effect. The breaking energy and the index variation depend on the spectrum and radial variation of the soft radiation. In this model X-ray and submm to optical emission originates from region 100 times closer to the central engine than gamma-ray emission and $10^4$ times closer than radio emission. One can then predicts the evolution time of an observed flare.

In the Henri et al. approach [9,10,16], the reacceleration process in an important aspect of the model. It maintains the source in a regime close to the pair-creation catastrophe, which is interesting to explain the fast variability. Moreover for a reheated pair plasma, the radiation pressure from the accretion disk due to Compton interaction (‘Compton rocket effect’) can gradually accelerate the plasma along the jet to high enough bulk Lorentz factor, which is not a free parameter in this model. They considered Compton interactions of a relativistic pair plasma on soft photons from an accretion disk. The pair plasma is created in the vicinity of the central black hole where the opacity to pair creation is greater than one. When the soft photon population is depleted by Compton interactions, the jet becomes optically thin to gamma photons which can escape. The dependence on energy of the photosphere explains the spectral break of the gamma spectrum around a few MeV. Indeed one has $\alpha_\gamma = 2\alpha_X$. The model predicts spectrum in good agreement with observation for 3C273, 3C279, and CenA. As in Blandford & Levinson model, due to pair opacity effects, X rays should arise before gamma-rays during a flare sequence, but with a much shorter delay. Nevertheless for a complete electromagnetic model, one needs to take into account Compton interactions on both UV-photons and synchrotron photons together with pair creation.

A very recent publication [29] gives a strong argument in favour of a pair model; this is based on the polarization measurement in the jet of 3C279.
4 Protons and hadronic processes

The extragalactic origin of high energy cosmic rays, beyond $10^{14}$ eV, is very likely. Active Galactic Nuclei and their extended regions are the most obvious candidates as being the acceleration sites. The other candidates are the Gamma Ray Bursts and the Topological Defects. The present knowledge of AGNs allows to give better estimates of the parameters to test this idea. High energy protons, especially beyond the threshold for the so-called GZK effect, produce gamma rays and high energy neutrinos through collisions with soft photons. The idea that the ultimate energy cosmic rays are produced in AGNs with a signature with the gamma rays and the neutrino emission is really appealing. However we show in the previous section that the gamma-ray emission of blazars is more likely explained by purely electrodynamical processes with Fermi acceleration of electrons. The nucleus that could be a source of gamma-rays is optically thick to them because of the pair production process. So we think that the gamma spectrum and the possible neutrino spectrum are not correlated. Although the gamma emission is more likely explained by electrodynamics, the protons acceleration and neutrino emission are likely to occurs in AGNs as well. We will present now our estimates of protons energy and neutrino flux.

4.1 The cosmic ray production in the AGN components

The two main regions of particle acceleration are the environment of the black hole and the hot spots (in case of FR2 jets).

Let us consider first the electrons.

i) Within $10 r_G$ in the vicinity of the AGN black hole, a magnetic field of order 1 kG (equipartition) can be concentrated. The electrons can therefore reach $\gamma_{me} \sim 10^5$ in $10^{-2}$ sec. with $A = 10^3$.

ii) In jet hot spots like those of Cygnus A, a typical value of the magnetic field is $B = 10^{-4}$ G; which gives $\gamma_{me} \simeq 4 \times 10^8$ within a time of $10^8$ sec. This value is a little too high, as compared to the synchrotron data; which means that the efficiency of the acceleration process, implied by chosing $A = 10^3$, is a little overestimated.

Let us consider the maximum energy that the protons can reach with the same assumption expressed by eq.(6) with $A = 10^3$ for the acceleration process. There are two limits: one is implied by the maximum MHD scale, the other by residence time of the proton in the accelerator.

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i) In the vicinity of the black hole, within $10r_G$, the protons could reach $10^{10}$ GeV within a year if they would be confined. However for a flow of velocity $c/10$, their residence time would fall to $10^5$ sec., which would reduce their maximum energy to $10^8$ GeV.

ii) In jet hot spots of size of order 1 kpc, the protons could reach $10^{11}$ GeV within $10^7$ years, which is comparable with the age of the source. But they could spend much less time in the hot spots; if the downstream flow has a velocity of $c/10$, they stay only $10^4$ years, which lower the maximum energy to $10^8$ GeV.

Only a significant increase of the efficiency of the acceleration process in favour of the protons, since this is not needed for the electrons, could compensate the shortness of the residence time in the nucleus and in the hot spot. But it is not reasonable to expect much better than a factor 10, since even for big magnetic disturbances, the time for pitch angle scattering is always longer than the gyroperiod and the Fermi acceleration time is always longer than the scattering time. Alternately, leaving the nucleus with $10^8$ GeV they could be reaccelerated all along the jet and reach $10^{11}$ GeV in the hot spot and then escape in the extended lobes. If so, the extragalactic jets could be the accelerators of the high energy cosmic rays [22,15].

The maximum energy achievable by the protons in an AGN is therefore:

$$\epsilon_{\text{max}} \simeq \frac{M_*}{10^8M_\odot} \frac{B}{1\text{kG}} \frac{10^{20}}{A} \text{eV}.$$ (14)

Nevertheless these estimates do not convince that AGNs definitely are the sources of the highest energy cosmic rays, since $A > 10$ (cf comments after equation (6)). Should we consider large structures like collisions of galaxies with shock fronts of Mpc size, but with magnetic fields as weak as $\mu$ Gauss?

4.2 gamma ray and neutrino emission

**Neutrino emission from the nucleus**

High energy neutrinos (energy larger than 100 MeV) can be emitted by pp-collisions, with a cross section $\sigma \simeq 2.7 \times 10^{-26}\text{cm}^2$ for proton energy larger than 2 GeV. The neutrino luminosity depends on the density of protons of momentum larger than $p$:

$$n(> p) = \chi n_* \left(\frac{p}{p_0}\right)^{1-\eta},$$ (15)
where \( n_\ast \) is the particle density in the disk and \( \chi \) is the fraction of proton number above the threshold \( p_0 \). Assuming \( n_\ast = 10^{14} \text{ cm}^{-3} \), it turns out that the direct pp-process is always very tiny.

The photo-production of pions is expected to be more efficient to produce neutrinos through the \( \Delta^- \)-resonance (the so-called GZK effect)[22]:

\[
\begin{align*}
(p, \gamma &\rightarrow p + \pi^0) \\
(p, \gamma &\rightarrow \Delta^+) \\
(n, \pi^+ &\rightarrow \ldots \rightarrow p + e^+ + e^- + \nu_e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu)
\end{align*}
\]

For a head-on collision, the threshold energy of the proton is

\[
\epsilon_{th} = \frac{m^2_\Delta - m^2_p}{4 \epsilon_\gamma} ;
\]

and the cross section \( \sigma_{p\gamma} \simeq 5.4 \times 10^{-28} \text{ cm}^2 \). The process can occur in the AGNs with the UV-photons where the threshold energy is of order \( 10^{16} \text{ eV} \), since we saw in the previous subsection that the protons can reach much higher energies.

A neutrino emission is thus possible and

\[
L_\nu = \int \int \epsilon_\nu n_{ph} \sigma_{p\gamma} c_f d^3 p d^3 V \simeq \frac{\bar{\epsilon}_\nu}{\epsilon_{ph}} L_{UV} \sigma_{p\gamma} R \frac{n_p(> \gamma_{th})}{3} .
\]

We have got the following estimate:

\[
\frac{L_\nu}{L_{UV}} \sim 10^{14-8\eta} .
\]

For \( \eta = 2 \) there are enough protons above the high threshold \( (\gamma_{th} \sim 10^7) \) to have \( L_\nu \sim 10^{-2} L_{UV} \), whereas for \( \eta = 3 \) the ratio is only \( 10^{-10} \) ! \( \eta = 2 \) is expected in the vicinity of shocks. However after having traveled over a distance that makes them sensitive to diffusion or losses the integrated cosmic rays distribution decays from \( \eta = 2 \) to \( \eta = 2.7 - 3.1 \).

The GZK-effect occurs also during the propagation of the cosmic rays in the intergalactic medium where they collide with the cosmological black body. The threshold is of order \( 10^{20} \text{ eV} \) and cosmic rays of larger energy cannot come from sources beyond 100 Mpc [1].
Does the gamma-emission of blazars allow to discriminate whether the underlying physics is of electrodynamic or hadronic nature? This discussion focuses on the two issues of acceleration and variability. Of course the main argument in favor of the electrodynamic model is that the electrons allow a much faster variability than protons. The small size of the high energy sources revealed by their variability would imply a strong magnetic field to have proton Larmor radii smaller than the size. It is often unduly said that the electrons are not efficiently accelerated by Fermi processes, that shocks accelerate more efficiently than the second order Fermi process, and also that they accelerate mostly protons. It has been shown that these prejudices are not plainly true.

The analysis of the second order Fermi acceleration of the relativistic electrons does not reveal any serious difficulty to explain the gamma emission of blazars, even to explain the few TeV radiation of the BL-Lacs (Mrk 421, Mkr 501 and maybe 1ES 2344+514). The Klein-Nishina limit seems to be the major limitation of the inverse Compton emission on accretion disk photons, the cut-off should be at higher energy for the Synchrotron Self-Compton emission. Thus the emission of BL-Lacs beyond TeV energy is likely the SSC-radiation.

In the case of quasars, the inverse Compton process can also be accompanied by the pair creation process. This seems in fact unavoidable within $100r_G$, and it could explain nicely the spectrum break around few MeV. Indeed only the pair model [16] was able to explain so far a gamma-spectrum index which is twice the X-spectrum index as observed.

- Are AGNs the sources of the high energy cosmic rays? They are certainly sources of high energy cosmic rays but the possibility to reach $10^{20}$eV is difficult with the usual Fermi processes. Acceleration in relativistic plasmas seems promising [19].

- Are they localized sources of neutrinos? Yes certainly, but the flux would be measurable only if the cosmic ray index would be close to 2 in the source.

- Are the neutrino emissions correlated with the gamma-ray emission? The GZK-effect suggests that as many neutrinos as gamma photons are emitted; however we saw that gamma-photons cannot escape from the black hole environment; they come from the gamma-ray photosphere. Moreover we argued that the gamma spectrum is very likely explained by purely electrodynamical processes maintained by Fermi acceleration of electrons. Thus we think that the neutrino emission is not correlated with the gamma emission.
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