HIGH ENERGY PLASMA PHYSICS
IN BLACK HOLE ENVIRONMENT WITH JETS

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The Compton Gamma Ray Observatory revealed the high energy emission of some Active
Galactic Nuclei called "Blazars"; few of them have also been observed by ground Cerenkov
arrays. Those sources observed with Whipple Observatory emit gamma rays up to few TeV.
From the spectral data and variability measurements, a purely electrodynamical description of
this emission can be proposed, provided that it comes from relativistic flares at the beginning
of the jet. Because of the source compacity, the creation of electron-positron pairs and their
escape from the black hole environment could likely explain the shape of the spectra. A plasma
dominated by relativistic electrons (positrons) close to equipartition with the magnetic field
is a suitable acceleration medium that can account for both the required high Lorentz factors
and the short variability.

1 Pair creation

Active Galactic Nuclei are compact sources in a precise physical sense, for 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 size $R$ by:

$$l \equiv \frac{\sigma_T L_X}{4\pi R m_e c^3}.$$  \hspace{2cm} (1)

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 a consequence of the Penrose mechanism, the effect of a gap parallel
electric field in the vicinity of a rotating black hole, of the Fermi acceleration mechanisms that
maintain hadronic collisions (proton-proton collisions and proton-soft photon collisions) and the
inverse Compton process. The observed gamma radiation cannot escape from the central region.
However the gamma emission is observed only in some blazars (Von Montigny et al. 1995) that
have jets with superluminal motions and is understood if one takes into account the Doppler
beaming. Indeed the relativistic motion (of bulk Lorentz factor $\gamma_b$) 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 $D$:

$$D \equiv \frac{1}{\gamma_b(1 - \beta_b \cos \theta)}.$$  \hspace{2cm} (2)
Superluminal motions indicate that the Doppler factor is large and thus the radiation is beamed towards the observer according to:

\[ I(\omega, \theta) = D^3 I_0(\frac{\omega}{D}) , \]  

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

So 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 (Henri, Pelletier, Roland 1993). 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 (Marcowith, Henri, Pelletier 1995). It takes into account the Inverse Compton process on the UV bump and the pair creation process by two gamma photons, the X- and \(\gamma\)-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 \(\gamma\)-rays being still in the optically thick regime, whereas the X-rays are in optically thin regime to \(\gamma\gamma\)-pair production. So far 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 (Dermer and Schlickeiser 1992) predicts the canonical 1/2 steepening. A pair model has been proposed also by Blanford and Levinson (Blandford and Levinson 1995), but they considered the pair creation with the UV-photons only (whereas our model takes mostly into account the creation by two gamma photons) and they did not consider the reacceleration of the pairs, which is an important aspect of our model. Indeed reacceleration of pairs tends to produce a pair creation catastrophe that could likely explain the fast variability.

2 The acceleration processes

The acceleration of particles in astrophysical media depends on large magnetic disturbancies. As long as the electric field associated with these disturbancies is neglected, the suprathermal particles suffer pitch angle variations only since the magnetic field "does not work". Thus a plasma having random magnetic disturbancies plays the role of a scattering medium for the particles characterized by a pitch angle scattering frequency \(\nu_s\) (generally much smaller than the synchrotron frequency at the same energy \(\omega_s\)).

The most easily excited magnetic perturbations are in the form of Alfven waves, that are electromagnetic waves that propagate along the average magnetic field with a phase velocity \(V_A\). The electric component is smaller than the magnetic one by a factor \(V_A/c\) so that the electric force acting on a particle of velocity \(v\) is smaller than the magnetic force by a factor \(V_A/v\). The relative rate of change of the energy is then smaller than the relative rate of change of the pitch angle by a factor \(V_A^2/v^2\). So a source of so-called second order Fermi acceleration is a region of space where a plasma has electromagnetic random disturbancies that maintain a diffusion in energy space, and the change in momentum \(\Delta p\) during a time \(\Delta t\) larger than the correlation time is such that

\[ \frac{\langle \Delta p^2 \rangle}{2\Delta t} \sim \frac{V_A^2}{v^2} \nu_s p^2. \]  

The second order Fermi process has an acceleration rate \(\nu_2 \sim \frac{V_A^2}{v^2} \nu_s\).
It is often said that the first order Fermi process at shocks is more efficient; this is not plainly true. When a shock develops in a scattering medium, the particles undergo elastic "collisions" with upstream disturbancies that flow at a supersonic velocity $u_1$, whereas they collide with disturbancies that flow at a subsonic velocity $u_2$ downstream. They gain energy as they cross the shock front either from upstream or from downstream. The average (over pitch angles) momentum gain at each cycle is

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

(5)

The acceleration rate depends on the frequency of shock crossing. A particle having a velocity $v$ upstream that crosses the shock front has a probability $\eta = 4u_2/v \ll 1$ to escape downstream (Bell 1978). Thus the crossing frequency is $1/\eta t_e$ where $t_e$ is the average time that a particle stays in the diffusion region in the vicinity of the shock before escaping. That time is $t_e \sim (v^2/u_2^2)^{1/2}$, which implies a crossing rate smaller than the diffusion rate $\nu_c \sim (u_2/v)^{1/2}$. The acceleration rate at shock is thus given by

$$\frac{<\Delta p>}{\Delta t} \sim \frac{(u_1 - u_2)u_2}{v^2} \nu_s p$$

(6)

This acceleration rate is not significantly larger than the second order Fermi one (Jones 1994). Its major interest is that the ratio of the acceleration rate $\nu_1$ over the escape rate is a number that depends on the shock compression ratio only: $\nu_1 t_e = (r-1)/3$ with $r = u_1/u_2$ close to 4 in a strong non relativistic adiabatic shock. Which leads to the formation of a power law energy spectrum behind the shock that is proportional to $\varepsilon^{-2}$.

Regarding the generation of high energy gamma rays at the beginning of the jets, or the neutrino emission in the nucleus, it is not at all useful to invoke large shocks!.. Large shocks are not expected in these regions. So we can invoke simply the second order Fermi acceleration in the central region and keep the large shocks for the jet hot spots.

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

$$V_s = \frac{C}{\sqrt{1 + 2 \frac{P}{P_m}}}$$

(7)

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 work 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 shocks (Baring, these proceedings).

2.1 Electron relativistic plasmas

In the Fermi processes there is an essential microphysics ingredient, namely the pitch angle scattering frequency. 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 $V_A/\omega_{cp}$ ($\omega_{cp}$ is the cyclotron pulsation of the non relativistic protons). This puts a severe threshold for resonant interaction, especially for the electrons that must be very energetic already: $p > m_p V_A$. 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.

In compact objects, "exotic" plasmas can be created with a copious relativistic electron (positron) component. The "cauldron" of the black hole environment (Henri and Pelletier 1991, Marcowith, Pelletier, Henri, 1997) 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 relativistic electron 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 (Henri and Pelletier 1991). Second, the investigation of the nonlinear regime of Alfven disturbances (Pelletier, Henri, Marcowith 1997) 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. This regulation process stops the pair creation catastrophe due to second order Fermi acceleration. The high energy cut-off is determined by the balance between the fastest radiation loss rate and the Fermi acceleration rate. Estimates are given further on.

Note that a plasma dominated by highly relativistic protons is much more difficult to confine. Proton acceleration is limited by the largest wavelength of the magnetic disturbances beyond which scattering no more works. This is of course in the hot spots of FR2 jets that can be found the best acceleration sites for protons, and this could be the origin of the high energy cosmic rays.

2.2 Time scales

For a black hole of $10^8$ solar masses, the gravitational radius $r_G$ is of order of one astronomical unit and a source of radius $100r_G$ has a light travel time of 30 hours. This leads to intraday variability because the observed time is reduced by the jet Doppler factor:

$$\tau_{\text{obs}} = \frac{\tau_{\text{int}}}{D}. \quad (8)$$

At a distance of $100r_G$ from the black hole, a magnetic field of order 100$Gauss$ can be expected and the photon energy density is comparable to the magnetic energy density. So the radiation loss time of the relativistic electrons having a Lorentz factor of $10^3$ is about 100s. A second order Fermi process can easily prevent their energy loss, for the required pitch angle frequency is only $10^{-8}\omega_s!$. The TeV photons would require relativistic electrons with Lorentz factors of order $10^6$; this is achieved by Fermi process if the pitch angle frequency is $10^{-3}\omega_s$.

3 Discussion

An interesting debate raised to know whether the underlying physics that explain the gamma emission of blazars is of hadronic or electrodynamic origin. This 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, Mrk 501 etc.). The Klein-Nishina limit seems to be the major limitation of the inverse Compton emission on accretion disk UV-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 (Henri, Marcowith, Pelletier 1995) was able so far to explain a gamma-spectrum index which is twice the X-spectrum index as observed.

The future multiwavelength campaigns will be crucial to discriminate between the various models by observing the flares and their growth sequence in each spectral bands. The delays between each band are predicted differently by the models.

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