PHYSICS OF BLACK HOLE ENVIRONMENTS AND JET LAUNCHING

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Several classes of compact objects such as Active Galactic Nuclei, Micro-Quasars, Pulsars and probably Gamma Ray Bursts, display powerful winds and jets. Relativistic flows are observationally evident in AGNs and micro-Quasars, and very likely in pulsars and GRBs. Three models of jet formation are still under debate and will be briefly presented. For all these classes of objects, the magnetic field is supposed to play a major role in launching and collimating the flow, together with transfering the angular momentum. It probably plays an important role for the turbulent transport in accretion disks also. Regarding the high energy radiation of relativistic jets and the cosmic ray generation, the magnetic field, which is concentrated in the black hole environment, is of course the acceleration agent and could produce the Ultra High Energy Cosmic Rays in some extragalactic objects.

1 Introduction

The physics of Black Hole environments has been developed first of all to account for the powerful radiation of compact objects of the Galaxy and of Active Galactic Nuclei, that cannot be explained by nuclear physics. The accretion of matter onto a Black Hole can convert mechanical energy into black body radiation quite efficiently and thus accounts for the X-ray luminosity of galactic compact objects and for the UV-luminosity of Active Galactic Nuclei. The low energy aspect of these objects is nevertheless the most powerful one. Then jets have been discovered in some of these objects, and the fraction of their population displaying jets is still increasing. The high energy aspect of these black hole candidates seems linked with the relativistic ejection. This is clear for Blazars and BL-Lacs, which intensively radiate gamma-rays, upto the TeV range for few of them, with a rapid variability, which is understandable thanks to the beaming effect by the relativistic jets. Micro-quasars, recently discovered [13], look like a reduced scale model of radio-quasars, and the scale reduction, especially of time scales, is a good fortune for the investigation of the accretion-ejection physics.

There are mostly theoretical arguments but also some observational hint that Gamma Ray Bursts (GRB) are associated with highly relativistic expansion, possibly collimated as well. The flow is supposed to come from the environment of a black hole formed by the collapse of a super massive star (hypernovae scenario) or by merging of two compact objects.

Relativistic jets from AGNs and micro-quasars have bulk Lorentz factors Γ of the order 10, whereas GRBs are supposed to come from relativistic flows with $\Gamma = 10^2 - 10^3$. Note that the pulsar winds, made of electrons and positrons, plausibly have $\Gamma \sim 10^6$.

I will present the main points of the standard accretion theory, briefly indicate the new trends in this topics. Then I will present the three models of jet formation that are still under debate, namely, first, the launching from a fastly rotating black hole, second, the launching from an accretion disk and, third, the launching by the Compton rocket effect. I will indicate how the high energy spectrum reflects the nature of the jet formation and finally indicate the performance of Fermi acceleration in jets with respect of the high energy production.

2 The Accretion Power

The standard accretion disk theory (Shakura & Sunyaev 1973) can be summarized as follows.

- Matter is in Keplerian motion around the central black hole of mass M_*: $\Omega(r) = (\frac{GM_*}{r^3})^{1/2}$. Except at large distance, the disk mass is dominated by the central black hole mass. However self-gravity could be important in the developement of waves in the disk.
- Matter is concentrated in a geometrically thin disk of half width $h(r)$ as long as $\frac{P}{\rho\Omega^2 r^2} \simeq \frac{h^2}{r^2} \ll 1$. The hydrostatic equilibrium governs the vertical structure of the disk of mass density ρ and pressure P.
- No accretion flow towards the central black hole is possible without angular momentum and thus energy dissipation. It is supposed that a viscous torque allows accretion, each matter ring giving up some amount of angular momentum to its external neighbour and thus falling adiabatically to a lower orbit. In steady state, the accretion rate is thus determined by the viscosity: $\dot{M}_a \equiv -\int \rho u_r 2\pi r dz = constant \propto viscosity$. However only transient phenomena allow to know the viscosity from the observations.
- Viscous heating maintains the temperature against the black body radiation cooling. The assumption of optically thick disk is generally consistent, except possibly in the innermost region where the accretion regime could change into an "advection dominated accretion flow" (14) that could be optically thin.

The success of the model depends on its energy budget, that must be examined both locally and globally. The quasi-Keplerian assumption leads to a simple energy balance at steady state: each ring carries a mechanical energy (rotation energy + gravitation energy) per unit mass of $(-1/2)GM_*/r$ and this radial energy flux is balanced by the energy flux radiated at the surface. The local energy budget is therefore:

$$\frac{1}{2}\dot{M}_a\frac{GM_*}{r^2}2\pi r dr = 2\sigma_{st}T_s^4 2\pi r dr \ , \qquad (1)$$

where T_s is the temperature of the observed radiation at the surface of the disk. For AGNs, the black hole has a mass $M_* \sim 10^8 M_\odot$ which leads to a maximum temperature $T_{max} \sim 10eV$ and the black body emission is in the UV-range. In microquasars, where $M_* \sim 10 M_\odot$, the black body is emitted in the soft X-ray range.

The global energy budget is straightforward by integrating the local balance from infinity to the radius r_i of the last stable orbit. The accretion power is thus:

$$P_a = \frac{1}{2}\dot{M}_a\frac{GM_*}{r_i} = \varepsilon \dot{M}_a c^2 \ , \qquad (2)$$

with $\varepsilon \sim 10$ percent. The observed luminosity L is supposed to be explained by the power liberated through the accretion: $L = P_a$, which puts a requirement on the accretion rate. To explain the luminosity of $10^{45} - 10^{46} ergs/s$ of quasars, the accretion rate must reach $\dot{M}_a \sim 1 M_\odot$ per year. In micro-quasars the requirement is $10^{-7} M_\odot$ per year. This is actually a severe constraint on the viscosity, which turns out to be the major problem of the accretion disk theory.

Collisional viscosity cannot account for this requirement; the hope lies on the developement of a strong turbulence having a correlation length on the order of h, that would provide an effective viscosity such that $\nu_{eff} = \alpha C_s h$ with $\alpha \sim 0.10$.

When changing the mass of the central black hole, it is convenient to compare the physical quantities to the fiducial Eddington values. The Eddington limit is achieved when the accretion saturates because the radiation pressure of the black body balances gravitation. The Eddington luminosity depends on the black hole mass only, and therefore the accretion rate is proportional to M_* and equals one solar mass per year for $M_* = 10^8 M_\odot$. One can write:

$$P_a = \frac{\dot{M}_a}{\dot{M}_{Edd}} \frac{M_*}{10^8 M_\odot} \times 10^{46}\ erg/s\ . \tag{3}$$

A crucial ingredient of the theory for the jet formation and the high energy phenomenon is the magnetic field. It is frozen in astrophysical media and is advected by the accretion flow and dissipated in the accretion disk by the turbulent effective resistivity or by reconnections. It turns out that its average intensity cannot be larger than its equipartition value (i.e. the value corresponding to a magnetic pressure equal to the kinetic pressure on the equatorial plane fo the disk), for MHD stability reason, and thus, in the central region:

$$B \sim B_{eq} = (\frac{M_*}{10^8 M_\odot})^{-1/2} \times 10^3 G\ , \tag{4}$$

or less...The magnetic energy density is therefore more or less inversely proportional to the black hole mass.

3 The three scenarii of jet formation

3.1 Spinning Black Hole

In 1977, Blandford and Znajek [3] proposed to tapp the rotation energy of a spinning black hole ($0.29 M_* c^2$ can be extracted). The membrane paradigm helps to figure out how it can work, because the black hole horizon can be assimilated to a conductor with vacuum impedance [7]. Therefore, provided that an external magnetic field is supported by the accretion disk, the black hole rotating in a bipolar magnetic field can be considered as an unipolar inductor. The magnetic torque extracts the rotation energy and converts it into poloidal Poynting flux. Then relativistic jets are produced by coupling the Poynting flux with matter. Detailed analytical and numerical calculations has been made by Max Camenzind in the nineties (see for instance [5]). For given mass parameter m and spin parameter a (in the same reduced unit), the maximum Poynting flux (obtained by optimizing the field line rotation) due to black hole slowing down is given by:

$$P_{sd} = (\frac{a}{m})^2 (\frac{B_n}{10^3 G})^2 (\frac{M_*}{10^8 M_\odot})^2 \times 10^{41} erg/s\ , \tag{5}$$

The spin parameter a is constrained by the Kerr metric such that $|a| \leq m$. The slowing down time scale is can easily be longer than the Universe age. A spinning black hole, through the Kerr metric (Lens-Thiring effect) and dissipation, tends to henforce matter of the innermost region of the accretion disk to rotate in the equatorial plane orthogonal to the rotation axis of the black hole. The gyroscopic effect of the spinning black hole allows to maintain a stable axis for a long time.

There are three obvious problems (and some others more technical):

- first, the power is always much smaller than the accretion power, whatever the mass, because, as previously seen (4), the magnetic pressure varies inversely proportional to M_*;

- second, the intense radiation field generated by the accretion disk, exerts an efficient radiation drag on the relativistic jets;

- third, this type of jet launching is very continuous and does not seem to be compatible with the high variability observed in blazars, that are characterized by tremendous flares.

This mechanism is also considered to account for the generation of the ultrarelativistic wind of GRBs. A magnetic field of $10^{15}G$ is even envisaged. This could work during several milliseconds, afterwards the accretion disk will not be able to support such a field and an electromagnetic pulse should be produced. Rees and Meszaros [19] have considered the possibility of electromagnetic triggering of GRBs; but some fine tuned baryon loading is required to account for the afterglow.

3.2 Launching by the accretion disk

The theory of jet launching by accretion disks was opened in 1982 by Blandford and Payne[2] and then many works have been done by several authors following this trail. The tenets of the theory are the following. A bipolar magnetic field is supposed to thread the disk, in order to extract its angular momentum. A simple and important result of this work is that some amount of matter can escape from an accretion disk provided that it flows on field lines that bend on the disk surface with an angle larger than 30^0 with respect to the axis. A tiny amount of this rerouted matter is enough to transfer the angular momentum. The outflow does not rotates (Ω) exactly at the same speed than the magnetic lines anchored on the disk (Ω_*) and differential rotation generates a toroidal component of the magnetic field: $B_\phi \propto (\Omega - \Omega_*)$. The toroidal component is responsible for three major effects: i) the magnetic braking insuring the angular momentum transfer along the jet, ii) the propulsion of matter by the Poynting flux rapidly converted into bulk motion at MHD approximation, iii) the self-collimation due to its tension effect (cylindrical collimation is achieved as long as a net poloidal current is carried by the jet [12]; which requires a closure by a return current in the jet cocoon).

The energy budget of the accretion disk is accordingly modified: a ratio χ of the accretion power is converted into radiation, $L = \chi P_a$ and the other part into twin jet power, so that each jet has a power

$$P_j = \frac{1-\chi}{2} P_a \ . \tag{6}$$

When most of the power in the jet has become kinetic, $P_j \simeq \dot{M}_j(\Gamma - 1)c^2$ and the asymptotic bulk motion is such that

$$\Gamma \simeq 1 + \frac{1-\chi}{24}\frac{\dot{M}_a}{\dot{M}_j} \ . \tag{7}$$

Since only a tiny fraction of matter is rerouted from the accretion disk to the outflow, with a mass flux $\dot{M}_j \ll \dot{M}_a$, the jet velocity is larger than the Keplerian velocity of the foot point. If the magnetic field extracts most of the angular momentum of the accretion disk (which requires the restrictive conditions for launching found by Ferreira and Pelletier [8]), then $L \ll P_a$ and the power in each jet is close to the half of the accretion power $P_j \simeq P_a/2$. In particular, a magnetic field close to equipartition is required. Recently, more flexible solutions have been derived with both magnetic and viscous torque breaking in the disk, together with additional heating, like for instance a coronal heating. These results obtained by Casse and Ferreira [6] require always a magnetic field close to equipartition, but they allow that jet power and disk luminosity are a sizable fraction of the accretion power. Thus, since the power in the jets can be comparable to the luminosity of the disk, $\Gamma \sim 10$ is obtained when $\dot{M}_j \sim 10^{-3}\dot{M}_a$, whereas a more loaded jet with $\dot{M}_j \sim 10^{-1} - 10^{-2}\dot{M}_a$ is subrelativistic. The two extreme cases of a light and a loaded jet, calculated by Casse and Ferreira, are displaid on fig.(1). In the case of GRBs,

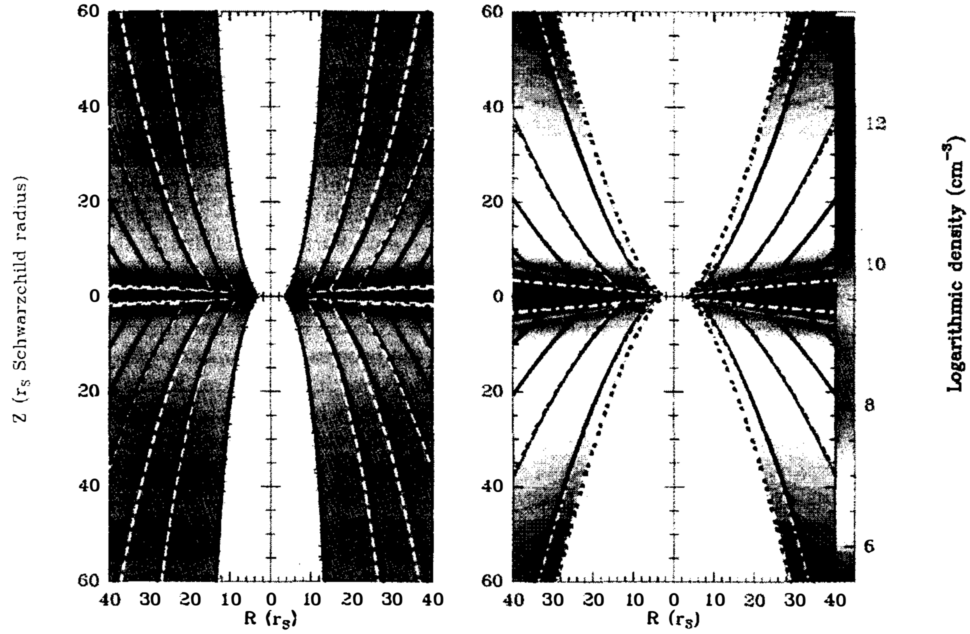

Figure 1: Two extreme cases of jet formation: the left picture corresponds to a heavy and slow jet, the right one to a light and fast jet

the very super-Eddington situation makes the accretion-ejection structure very peculiar and not yet understood.

3.3 Compton Rocket effect

With the two previous scenarii, we can be faced to the following difficulties: first, tapping the spinning black hole provides a Poynting flux too low compared to the accretion power and relativistic motions would be dissipated by Compton drag; second, the jets launched by the accretion disk have the required power and the large scale flows are easily explained, but they likely have a mass flux $\dot{M}_j > 10^{-3}\dot{M}_a$ and thus the bulk Lorentz factor is midly or subrelativistic, $\Gamma \sim 2$. If this is so, what produces the observed relativistic ejections? The third possibility was proposed by O'Dell[16] who calculated the Compton rocket effect in e^+e^--clouds moving in the anisotropic radiation field of the accretion disk. In this mechanism, the Compton effect produces either a drag or a propulsion depending of the bulk motion and internal energy of the cloud. This was also investigated by Phinney[17] who has shown that the Compton drag eventually dominates and makes $\Gamma \rightarrow 2$, because of the radiation cooling. However the conditions are changed in a "two-flow" model (see Henri and Pelletier[11]). Indeed the subrelativistic MHD jet produced by the disk can help the Compton rocket effect. This flow is not subjected to Compton drag; moreover, because of the centrifugal effect, the space near the axis inside the jet is almost empty. In this region above the black hole, $\gamma\gamma$-pair production can occur easily, $\tau_{\gamma\gamma} > 1$ within $100 r_G$. In spite of the Compton drag, Compton rocket propulsion of pair clouds can achieve $\Gamma \sim 10$ upto $10^3 r_G$, as long as their relativistic internal energy is maintained by in situ stochastic acceleration caused by the magnetic disturbances coming from the subrelativistic jet. This is one of the major interest of the "two-flow" model, which has also other advantages:

it reconciles the observations of subrelativistic large scale jets with the observation of relativistic flaring core jets; moreover the MHD jet channels the relativistic flow which seems to have no self-confinement property (Bogovalov[4]).

The pair cloud launching has two important signatures: i) A broken γ-spectrum is unavoidable (high energy gamma rays are emitted in opaque regime, whereas the lower energy part is emitted with $\tau_{\gamma\gamma} < 1$; the spectral break is such that $\Delta\alpha = \alpha_X$). The spectrum results from the stratification of the e^+e^--photosphere. ii) Fast flaring is inherent to pair production catastrophe. This stems from the cycle of the processes: acceleration of pairs — >Compton emission of γ-rays — >pair creation — >reacceleration of pairs, etc. Variability is due to the fact that the in situ reacceleration is quenched when too much pair pressure has been generated; however the pairs escape and reacceleration starts again. Such flare modeling based on pair catastrophe is currently developed by Gilles Henri and his students, Nicolas Renaud and Ludovic Saugé[10]. The figure 2 shows the rapidity and repeatability of the process. Pair opacity effect in GRBs is still an opened issue and would deserve more investigations in the future. Flares can also be triggered by MHD irruptive instabilities of the accretion disk, which, in fact, accelerate particles impulsively; both processes could be combined actually. The flaring behaviour observed in the whole electromagnetic spectrum including gamma-rays up to $10TeV$ in some class of AGNs, namely the "blazars", is probably not compatible with the spinning black hole scenario which is very continuous.

The magnetic field is probably responsable for instabilities generating the turbulence necessary to solve the transport problem in accretion disks[1]. However non steady accretion-ejection flows have also been observed in microquasars (their proximity and smallness compared to AGNs allow to follow their variations) and non steady theories are being developed[20].

4 The high energy phenomenon in Black Hole environments

By generating an accretion flow, Black Holes concentrate the magnetic field which plays a major role together with gravitation. It allows jet formation, it allows transport of angular momentum either regularly or through turbulence excitation in the accretion disk, it accelerates particles by the Fermi processes. But in Black Hole environments, the magnetic concentration that makes Fermi acceleration efficient makes also synchrotron loss very effective for both relativistic electrons and UHE-protons. The high energy phenomenon does not occur too close to the Black Hole; moreover the relativistic Doppler boosting and beaming occuring in the core jets are important in the understanding of the phenomenon. The Fermi acceleration of the relativistic electrons can easily explain with reasonable efficiency the whole non-thermal electromagnetic spectrum of micro-quasars, AGNs including BL-Lac radiating 10TeV gamma-rays, and GRBs. The balance between Fermi acceleration of time $\tau_a = \eta_a \tau_L$ and synchroron cooling leads to the following high energy cut off for the electrons:

$$\gamma^e_{syn} = \frac{10^8}{\sqrt{\eta_a}}\left(\frac{B}{1G}\right)^{-1/2} . \tag{8}$$

In BL-Lac for instance, the magnetic field must be fairly low to achieve TeV energy for electrons and not too low to achieve it in less than $10^5 sec.$ For the reasonable value $\eta_a = 10^4$ for electrons of that energy, the magnetic field must be such that $10^{-2}G < B < 1G$. This constraint is compatible with the estimate (9) derived from the observation of Mrk 501 . For UHE-protons, the synchrotron cooling is relevant since the cut off Lorentz factor is such that:

$$\gamma^p_{syn} = \frac{2 \times 10^{11}}{\sqrt{\eta_a}}\left(\frac{B}{1G}\right)^{-1/2} . \tag{9}$$

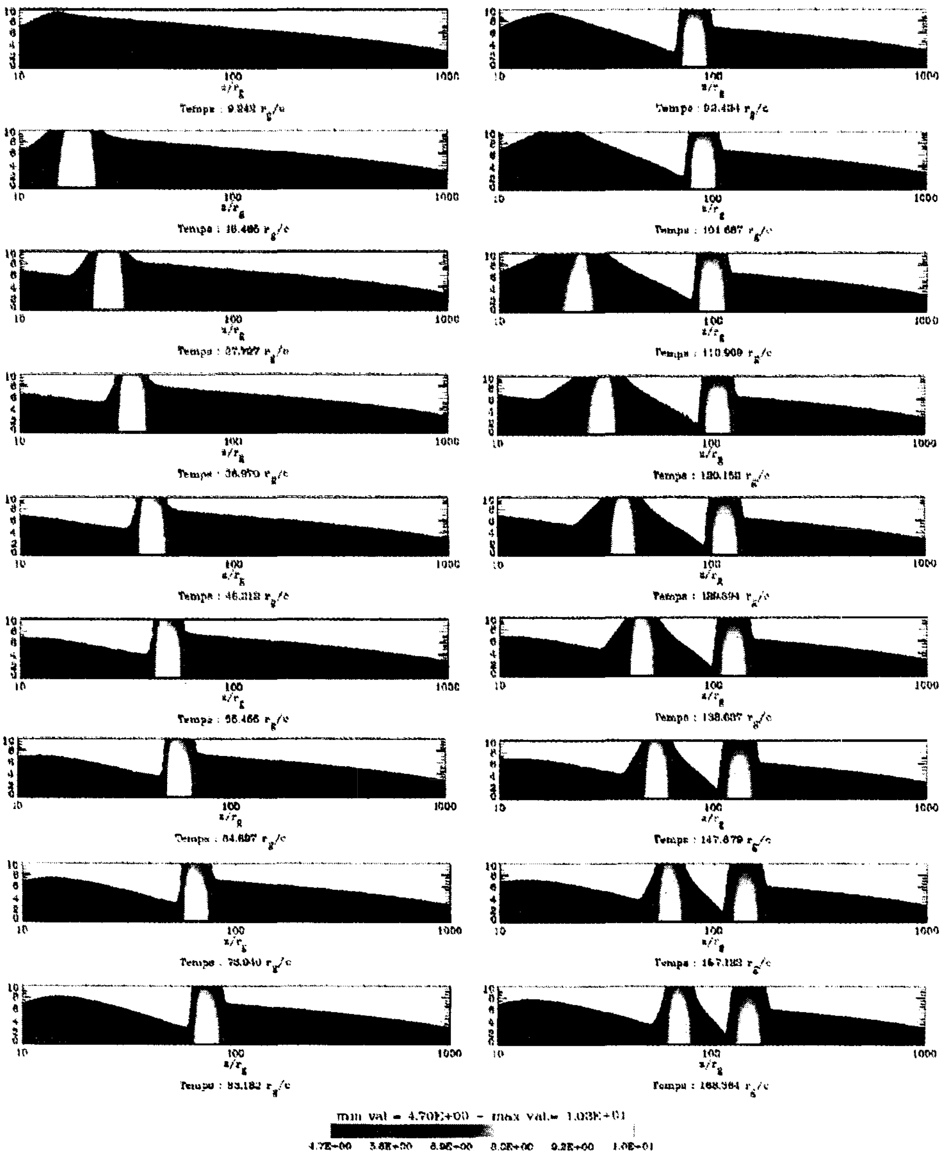

Figure 2: Simulation of flares produced by pair creation catastrophe

It is possible to get UHE-protons of $10^{19}eV$ comoving in an AGN jet with an extreme Fermi acceleration having η_a not larger than 10. Thus they can be produced in a jet region where $B < 100G$, provided they are confined within a jet radius R_j, which requires $B > (\frac{R_j}{10^{-2}pc})^{-1}100G$. The generation of UHE-protons generally requires an extreme regime of Fermi acceleration in these objects, if they are the sources of the cosmic rays beyond the GZK threshold. Strong MHD disturbances are necessary to scatter cosmic ray in a few Larmor time, and the relativistic regime of Fermi acceleration is required to get an acceleration time on the order of the scattering time. This seems to be possible in GRBs whose event rate within the sphere of $100Mpc$ is enough to account for the flux of UHE-cosmic rays.

The environment of Black Holes is therefore very rich in physical processes involved in the accretion-ejection flow where the high energy phenomena take place. OK, Black Holes have no hair; but they definitely have a big wig...

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