Magnetic Field Reconnection as a Possible Source of Nonthermal Processes in Accreting Relativistic Systems

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I. Recent observations of the *EGRET*-telescope aboard the Compton Gamma Ray Observatory *(CGRO)*, results from Čerenkov shower telescopes, and fast variability studies have demonstrated the dominant role of nonthermal processes for some accreting relativistic objects. This is perhaps an unexpected result, because the basic assumption of the standard accretion models (Shakura & Sunyaev 1973, Sunyaev & Titarchuk 1980, Galeev et al. 1979) is the thermal nature of all processes that determine the energy output. At the same time, the recent observations argue that the source of the emission is not the thermal plasma as a whole, but a very small fraction of charged particles accelerated to very high energy ($\varepsilon / \mathrm{mc}^2 > (30–1000)$ with a "universal" energy spectrum $n_\varepsilon \sim \varepsilon^{-\alpha}$. These observational results suggest a revison of the global approach to the accretion process to find any new (or forgotten "old") energy conversion mechanisms with predominately nonthermal output (Lynden-Bell 1969, Ikhsanov & Pustil'nik 1994).

II. The nature of the energy source and mechanisms of energy conversion to either plasma heating ("thermal" mode) or to acceleration of charged particles ("nonthermal" mode) is the main question for accretion theories.

The primary source of the energy in both approaches is the same – gravitational energy of the accreted plasma or kinetic energy of the rotation of the central body is converted into kinetic energy of the plasma. The distinction between "thermal" and "nonthermal" models arises at the next stage – conversion of the plasma kinetic energy as a whole to energy in emitted charged particles.[1]

The "thermal" concepts assume that the main mechanism of kinetic energy dissipation is plasma heating by friction or by compression. The "nonthermal" approach is based on the existence of magnetic fields (either "frozen" in the accreted plasma, or external fields in the magnetosphere). It is assumed that any dynamo-processes would convert kinetic energy to magnetic field energy. Exactly these fields and their currents are the physical base of acceleration processes in the nonthermal models of accretion. Evolution of these current structures is

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[1] I would like to note here that the standard list of emission mechanisms (bremsstrahlung, cyclotron or synchrotron radiation, Compton scattering, and plasma waves...) operates for both thermal plasmas and beams of ultrarelativistic particles.

very similar to the situation for solar and stellar flares and to the numerous laboratory experiments: global fast MHD-instability of the current structures lead to the formation of singular lines and current pinches, local dissipative instabilities lead to current disruption with fast magnetic field reconnection and development of high plasma turbulence. As a consequence numerous electrostatic "double layers" develop and effective acceleration of charged particles takes place in these regions. Emitted structures in the "nonthermal" models are the magnetic corona above the accretion disc and/or polar Z-pinch structures formed above the central object (Ikhsanov & Pustil'nik 1994).

III. Expected observational manifestations for thermal and nonthermal accretion models, possible "experimentum crucis", results of recent observations:

A choice among these two theoretical possibilities could be made only on the basis of the results of an "experimentum crucis". In other words, we would have to know the critical values of any observational parameters (energy, spectral slope, variability, etc.) which is impossible for most models [2]. We analyze from this point of view the expected manifestations of "thermal" and "nonthermal" classes of models and the comparisons to observations.

1. Energy spectra.

(a) "Thermal accretion" – the spectrum consists of the sum of Planck spectra from different parts of the accretion disc or accretion column. An additional spectral distortion may be caused by inverse Compton scattering of thermal emission of high energy electrons in the corona (resulting in the generation of a power spectrum), cyclotron scattering in a magnetized plasma (spectral breaks and lines could be generated).

The "first principles" limitation of particle energies (and, correspondingly, photon energies) for thermal models is the rest energy of particles. This limit is caused by the fact that the source of thermal energy is the kinetic energy of falling matter. The maximum kinetic energy is

$$E_{\max} = 0.5\ m_p\ c^2 = (0.3\ \text{MeV} - \text{for electrons};\quad 0.5\ \text{GeV}\ - \text{for protons})$$

In reality, the upper limit for the emitted spectrum, predicted by numerous models and numerical simulations, is not more than $\sim$ 100 keV. However, we will use as the absolute limit of energy for "thermal emission" $\varepsilon_{cr}^{th} = 0.5 - 1$ GeV as model-independent.

(b) "Nonthermal accretion models" assume high-energy particle acceleration by electric fields with a single power law spectrum with a wide range of energies (or the sum of power law components). Maximum energies for these particles (and, correspondingly, photons) are determined by potential drops in the acceleration region $\varepsilon = eE_* l_*$. For estimating the upper limit, using the size of the acceleration region $l_* = \zeta_l r_g$ and the induced electric field determined by the regular magnetic field value $E = \zeta_E H_0$, we obtain the critical value

$$\varepsilon_{cr}^{nth} = 10^{13}\text{eV (for AGN)} - 10^{17} eV \text{ (for neutron stars)}\ .$$

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[2] If models are tuned too much in order to fit all observational data through "games with free parameters", it would not be science altogether.

The emission spectrum is determined by energy loss processes (synchrotron radiation, Compton scattering and plasma waves, creation of an e^+e^- pair plasma, inelastic scattering of high energy particles with π –mesons and γ - quanta.

(c) Observational results. Observations of *EGRET* aboard *CGRO* (Hartman et al. 1992, Hurley 1994) show that many accreting objects exhibit "universal" power law spectra $n_\varepsilon \sim \varepsilon^\alpha$ from 0.1 GeV to $\varepsilon \geq$ 10-30 GeV. The spectrum of many γ-ray bursts is also a similar power law up to this energy. The slope of the spectra for all these objects is nearly the same: $\alpha \simeq 1$. The bulk of total emitted energy emerges in the form of ultrarelativistics photons. Observations with VHE (Very High Energy) telescopes have detected numerous sources with emission in the energy range up to $\varepsilon \geq 10^{13}$ eV (Meintjes et al. 1992).

2. Variability.

(a) "Thermal accretion" models assume as a source of variability some kind of hot plasma motion (rotation, free fall) and excitation processes (shock waves, thermal instabilities). The minimum time scales of these processes are determined by hydrodynamic or thermal velocities, or radiation loss time scales: $\Delta t_{mine} = (r/v_{ff}; r/c_s; nkT/L_*)$ As the size of the emitting region for these objects is limited by $r_{min} = (2-3)\ r_g$, we may estimate the minimal time of "elementary flares" for "thermal" modes of accretion:

$$\Delta t_{\min} = (10 - 100\text{ms } for\ M_{bh} = 10 M_\odot; 1\text{ day} - 1\text{week } for\ M_{b.h.} = 10^8 M_\odot)$$

(b) The "nonthermal accretion" approach assumes that the flare process is caused by ultrarelativistic particle propagation and emission. The velocity of flare front motion for these models is c – the velocity of light. The minimum time of a flare in this picture is $\Delta t_{min} = d/c$. This time interval is 1-2 orders of magnitude shorter than that in the "thermal accretion" picture. Brightness temperature is also an essential parameter:

$$T_B = \frac{\Delta F_\nu}{c^2\ \nu^2\ d^2} \geq T_{B_{\min}} \frac{\Delta F_\nu}{c^4\ \nu^2\ \Delta t^2} \quad .$$

The value of kT_B sets the lower limit for the energy of emitted particles, $\Delta t_{\min}$ determined from observations of variability give a unique method for estimating particle energies.

(c) Observational results. The search for fast variability in the optical and X-ray emission from accreting compact objects demonstrates for several sources that this phenomenon is real and may be explained only by "nonthermal" accretion. As an example we may refer to the observations of ultra-short X-ray flares of Cyg X-1 up to 0.5 msec (Rothschild 1974), shot-noise component in its emission with $\tau \simeq 3msec$ (Meekins 1984). But the best evidence for the nonthermal nature of flares is provided by the optical emission from X-ray novae A0620-00, Nova Per 1992, and also from X-ray bursters of Type II (Beskin et al. 1983, Bartolini et al. 1994). The duration of flares (from 1 msec up to 100 msec) corresponds to brightness temperatures ranging from 10^9 K to 10^{10} K. These time scales and brightness temperatures are only expected in the nonthermal mode of accretion.

IV. Possible acceleration processes in the accretion plasma may be divided into two groups:

(a) Regular acceleration in large scale electric fields in the inner reconnection region or a place of current disruption (Dreicer 1959). The energy spectrum for this acceleration process has an exponential form. This process assumes free particle motion in the regular electric and magnetic field – an assumption that is not likely to be correct in reality, if we take into account processes of particle-plasma wave scattering.

(b) Stochastic acceleration resulting from diffusion processes in regions with large scale electric fields as well as diffusion in momentum-energy space.

The second process is based on inelastic "particle-plasmon" scattering, and is more less as effective as the first process (based on elastic collisions). In some intermediate region particle acceleration becomes "transparent" to inelastic scattering (for lower energies) and also for elastic scattering. The energy spectrum derived from stochastic acceleration is a power law. This fact is a consequence of Fermi's arguments (1949) – if the acceleration processes and particle dissipation have the same origin, the spectrum will be a power law with slope determined by the ratio of particle life time to the time scale of acceleration. This ratio is constant and does not depend on particle energy [3]. While the universal power law of the emission spectrum is understood as a natural consequence of diffusive acceleration, for now the origin of the "universal" slope ($\alpha \simeq 1$) is not so obvious. It may be result of the nonlinear self-agreement of the efficiency of acceleration and space diffusion from the acceleration region for situation with extremely high electric fields (compared with Dreicer's limit) in the very strong plasma turbulence (compared with thermal energy). Exactly this state has to arise in the region of current structure disruption. As we have shown in previous work (Ikhsanov & Pustil'nik 1994) the distribution of particle energies for this mechanism are in good agreement with observations.

References

Bartolini C., Piccioni A., Beskin G., Neizvestny S., 1994, ApJS 92, 455

Beskin G.M., et al.: 1983, Sov. Astron. Lett. 14, 156

Dreicer H., 1959, Phys. Rev. 115, 238

Fermi E., 1949, Phys. Rev. 75, 1169

Galeev A.A., Rosner R., Vaiana G.S., 1979, ApJ 229, 318

Hartman R.C., et al., 1992, ApJ 385, L1

Hurley K., et al., 1994, Nature 372, 652

Ikhsanov N.R., Pustil'nik L.A., 1994, ApJS 90, 959

Lynden-Bell D., 1969, Nature 233, 690

Meintjes P.J., 1992, ApJ 401, 325

Meekins J.F., 1984, ApJ 278, 288

Rothschild R.E., Bodt E.A., Holt S.S., Serlemitsos P.J., 1974, ApJ 189, L13

Shakura N.I., Sunyaev R.A., 1973, A&A 24, 337

Sunyaev R.A., Titarchuk L.G., 1980, A&A 86, 121

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[3] Exactly this physics lead to paradoxical power spectrum formation by Compton scattering of thermal Planck radiation of Maxwellian electrons (Sunyaev & Titarchuk 1980).