International Journal of Modern Physics D
Vol. 17, No. 9 (2008) 1611–1617

GAMMA-RAY EMISSION OF RELATIVISTIC JETS AS A SUPERCRITICAL PROCESS

B. E. STERN[*,†,‡] and J. POUTANEN[‡,§]

[*] *Institute for Nuclear Research, Russian Academy of Sciences,*
Prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia

[†] *Astro Space Center, Lebedev Physical Institute,*
Profsoyuznaya 84/32, Moscow 117997, Russia
[†] *stern@bes.asc.rssi.ru*

[‡] *Astronomy Division, Department of Physical Sciences,*
P.O.Box 3000, 90014 University of Oulu, Finland
[§] *juri.poutanen@oulu.fi*

Received 30 January 2008
Accepted 29 February 2008

Supercriticality of the same kind as that in a nuclear pile can take place in high-energy astrophysical objects producing a number of impressive effects. For example, it could cause an explosive release of the energy of a cloud of ultrarelativistic protons into radiation. More certainly, supercriticality should be responsible for energy dissipation of very energetic relativistic fluids such as ultrarelativistic shocks in gamma-ray bursts and jets in active galactic nuclei (AGNs). In this case, the photon breeding process operates. It is a kind of converter mechanism with the high-energy photons and e^+e^- pairs converting into each other via pair production and inverse Compton scattering. Under certain conditions, which should be satisfied in powerful AGNs, the photon breeding mechanism becomes supercritical: the high-energy photons breed exponentially until their feedback on the fluid changes its velocity pattern. Then the system comes to a self-adjusting near-critical steady state. Monte-Carlo simulations with detailed treatment of particle propagation and interactions demonstrate that a jet with a Lorentz factor $\Gamma \approx 20$ can radiate away up to a half of its total energy, and for $\Gamma = 40$ the radiation efficiency can be up to 80 per cent. Outer layers of the jet decelerate down to a moderate Lorentz factor 2–4, while the spine of the jet has a final Lorentz factor in the range 10–20 independent of the initial Γ. Such sharp deceleration under the impact of radiation must cause a number of interesting phenomena such as formation of internal shocks and an early generation of turbulence.

Keywords: Acceleration of particles; active galaxies; jets; gamma-rays; nonthermal radiation mechanisms.

1. Supercritical Processes in High-Energy Astrophysics

The term “supercriticality” has different meanings. Here we use the same meaning as in nuclear physics: the condition of exponential runaway behaviour of the system (nuclear explosion or nuclear pile). So far two kinds of supercritical phenomena have been proposed in high-energy astrophysics: an explosive energy release of a cloud of ultrarelativistic protons into photons ("proton bomb") and dissipation of the bulk energy of relativistic fluids into radiation.

Let us consider a magnetized cloud of relativistic protons with typical Lorentz factor γ_p. These protons do not radiate much, because the synchrotron radiation and the inverse Compton scattering rates for protons are suppressed by factor $(m_e/m_p)^2$ with respect to electrons. Suppose N seed photons with energy $\varepsilon_t \sim 200\text{MeV}/\gamma_p$ interact with protons producing pions decaying into high-energy electrons or photons. They, in turn, produce a wide spectrum of softer photons, with the number ξN of them on average interacting with the high-energy protons again. If $\xi > 1$ then the process has a supercritical character: the number of photons rises exponentially until the protons cool down, so that the supercriticality condition breaks down and the energy release terminates. If the energy supply to protons continues then the system reaches supercriticality and explodes again. Such scenario was proposed and studied with numerical simulations[1] and analytically.[2]

The supercriticality condition depends on the radiation spectrum emitted by the particles produced in photo-meson interaction. The hardest possible spectrum is the fast-cooling power-law $dN/d\varepsilon \propto \varepsilon^{-3/2}$. The softest spectrum is that of the saturated pair cascade $dN/d\varepsilon \propto \varepsilon^{-2}$,[3] which takes place in a dense soft photon field.

The cross-section of photo-meson production multiplied by the fraction of energy transfered to pions, x, is (see Ref. 4) $\sigma(p\gamma)x \sim 0.7 \times 10^{-28}\text{cm}^2$ in the photon energy range ~ 250 MeV–2 GeV in the proton rest frame. The number of produced photons which can interact again is $N \sim 1/\gamma_p$ in the first case and $N \sim 1/\gamma_p^2$ in the second case. Then condition $\xi > 1$ translates to $\rho_E > 10^{25}$ erg cm^{-2} in the fast cooling case and $\rho_E > 10^{25}/\gamma_p$ erg cm^{-2} in the cascade case, where ρ_E is the column energy density of protons across the cloud.

Where one can find such a cloud of ultrarelativistic protons? A possible site for this phenomenon, gamma-ray bursts (GRBs), was proposed by Ref. 5. Indeed, all scenarios of GRBs involve ultrarelativistic shocks, where the space between the shock front and the contact discontinuity is filled with ultrarelativistic protons.

Another possible class of supercritical phenomena can take place in relativistic flows. A first example is the supercritical pair loading in AGN jets near the accretion disc's hot corona which emits hard X-rays.[6] If the jet Lorentz factor at such distance is $\Gamma \sim 10$, then cool pairs moving with the jet can up-scatter X-rays to MeV energies and these photons in their turn, interacting with the same X-rays, can produce new pairs.

A more powerful and universal way of dissipation of relativistic fluids into radiation, is associated with the converter mechanism suggested in general form by Derishev *et al.*[7] and in a more specific form of a runaway (supercritical) electromagnetic cascade in ultrarelativistic shocks by Stern.[8] We later performed a numerical study of the converter mechanism, in its electromagnetic version, operating in relativistic jets of blazars[9,10] and found that it has a supercritical character: the high-energy photons and relativistic e^+e^- pairs breed exponentially.

2. Converter Mechanism and Photon Breeding

The converter mechanism is an alternative to the Fermi acceleration for relativistic flows in a dense radiation field. In the Fermi mechanism a charged particle gains energy being scattered many times between media moving with respect to each other. In the converter mechanism, a quantum of energy moves between media in a form of a neutral particle and scatters taking a form of a charged particle. The conversion of a particle is due to interaction with a soft background radiation. In the case of an ultrarelativistic flow, the converter mechanism can be more efficient than Fermi acceleration because a neutral particle can more easily cross the boundary between the flow and the external environment.

There can be two types of charge exchange cycles: (1) proton–neutron cycle with proton conversion into neutron via photo-meson production and subsequent neutron decay, (2) photon–electron/positron cycle with conversion due to photon-photon pair production and inverse Compton scattering.

The important feature of the second cycle is the absence of any limitation of the number of participating particle such as the baryon number conservation in the first case. High-energy photons and pairs can breed exponentially at certain conditions being fed by the bulk energy of the flow.[8–10]

A very simplified description of the photon breeding cycle for the case of a relativistic jet can be represented by five steps.

(i) An external high-energy photon of energy ε enters the jet and interacts with a soft background photon producing an electron-positron pair.
(ii) The time-averaged Lorentz factor of the produced pair (as measured in the external frame) gyrating in the magnetic field of the jet, becomes $\gamma \sim \Gamma^2\varepsilon$.
(iii) The electrons and positrons in the jet Comptonize soft photons (internal synchrotron or external) up to high energies.
(iv) Some of these photons leave the jet and produce pairs in the external environment.
(v) Pairs gyrate in the magnetic field and Comptonize soft photons more or less isotropically. Some of these Comptonized high-energy photons enter the jet again.

In this cycle, the energy gain, $\sim \Gamma^2$, is provided by the isotropization of the charged particles in the jet frame and is taken from the bulk energy of the flow. Other steps in the cycle are energy sinks. The whole process proceeds in a runaway regime, with the total energy in photons and relativistic particles increasing exponentially, if the amplification coefficient (energy gain in one cycle) is larger than unity.

This new mechanism is actually much simpler in the description than Fermi acceleration, which depends on detailed geometry of the magnetic field and the poorly understood supply of seed nonthermal particles. Once the velocity pattern for the fluid, the magnetic field and the external radiation field are specified, the fate of each high-energy photon and its descendants can be reproduced (in statistical sense) from first principles, because the interaction cross-section are known with high accuracy. The question whether a photon produces a runaway avalanche or not, can be answered exactly.

3. Dissipation of Jet Bulk Energy into Radiation

Stern and Poutanen[9,10] performed a detailed numerical simulation of the photon breeding in AGN jets. The simulation of the particle emission propagation and interactions was exact and based on first principles, while the fluid dynamics was treated with a simplified 2D ballistic approximation. Here we present some results obtained under assumption that the main emission site is the broad emission line region.[10] The soft photon background which is necessary for the converter mechanism was composed from direct radiation of accretion disc and an isotropic component, which includes reprocessed/scattered radiation of the disc and surrounding dust.

To initiate the photon breeding one needs a number of seed high-energy photons. Their origin is not important as their number can be arbitrarily small. Figure 1 represents a simulation starting from the seed gamma-rays corresponding to the extragalactic gamma-ray background. The energy release increased by 20 orders of magnitude during $250 R_j/c$ ($\sim$ 3 years for the jet radius $R_j = 10^{16}$ cm) and came

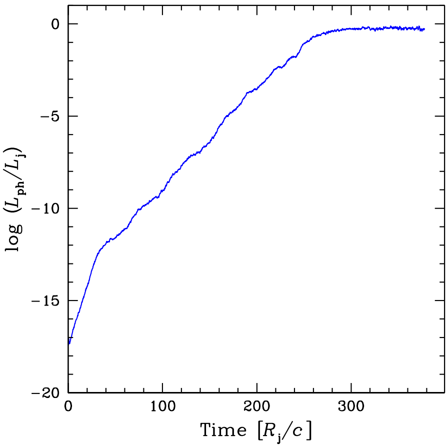

Fig. 1. Fraction of the jet power converted into photons versus time. The initial density of the high-energy, seed photons corresponds to the extragalactic gamma-ray background. Parameters: distance from the central engine $R = 2\times10^{17}$ cm, jet radius $R_j = 10^{16}$ cm, jet and disc luminosities $L_j = L_d = 10^{44}$ erg s^{-1}, and Poynting flux of $L_B \approx 10^{43}$ erg s^{-1}. From Ref. 10.

to the steady state at the level ~ 0.5 of the total jet bulk energy. The rapid rise at small times corresponds to the exponential growth of the photon avalanche as it moves downstream with the flow. Then as the avalanche reaches the end of the "simulation volume" (of length $20R_j$) it cannot grow further, and the growth is further supported by the up-streaming photons, which provide a spatial feedback loop.

We have performed several tens of simulation runs[10] and explored the parameter space, where the photon breeding can work. A schematic representation of the results is given in Fig. 2. The minimal jet Lorentz factor for the supercritical breeding was $\Gamma = 8$. At a moderate Lorentz factor the mechanism works only at favourable conditions. One of this conditions is weak magnetic field. The magnetic energy flux of the jet should be much smaller than the accretion disc luminosity. Otherwise the synchrotron losses by pairs at step (iii) of the breeding cycle dominate over Compton losses. The synchrotron photons are too soft to produce pairs and do not participate in the breeding, reducing its efficiency. If the jet has low magnetization ($\sigma \ll 1$) or the jet power is smaller than the disc luminosity, the breeding is favoured.

The second favourable condition is the presence of a soft isotropic radiation field. The broad line photons and scattered photons from the disc are not sufficiently soft, because pairs in the jet at step (iii) interact with them in a deep Klein-Nishina regime. Therefore again synchrotron radiation reduces the breeding efficiency. A softer radiation can be supplied by the surrounding dust or by the jet itself.

The third condition is a high accretion disc luminosity, $L_d > 10^{43}/R_{17}$ erg s^{-1} (where $R_{17} = R/10^{17}$cm is the distance from the disc to the site of the photon

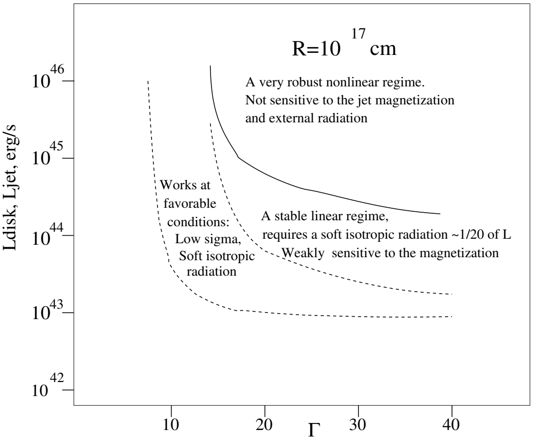

Fig. 2. Working areas of the photon breeding mechanism in luminosity–Lorentz factor plane. Solid curve refers to the jet power, dashed curves to the disc luminosity.

breeding), which is necessary to provide sufficient photon-photon opacity across the jet.

At a higher Lorentz factor the requirement of a weak magnetic field is relaxed. If $\Gamma > 20$, then a magnetically dominated jet with $L_j \sim L_d$ can radiate efficiently. The above conditions are relevant for the linear case, when the jet power is moderate and the soft synchrotron radiation of the jet is optically thin for gamma-rays. The non-linear effects appear at the jet power $L_j \sim 3\times10^{44}$ erg s^{-1} (for $R \sim 10^{17}$cm). At $L_j > 10^{45}$ erg s^{-1} the radiative steady-state becomes self-supporting even without external radiation.

The radiative efficiency of the jet increases with Γ and reaches 0.14, 0.56, 0.77, 0.82 for $\Gamma = 14, 20, 30, 40$, respectively.[10] A high efficiency implies that the jet undergoes strong deceleration. The distribution of terminal Γ across the jet is shown in Fig. 3. One can see that the deceleration is very inhomogeneous: the final Lorentz factor at the jet boundary is 2–4, while at the center its value is 10–14.

The resulting spectral energy distributions for a sequence of runs with varying luminosity are shown in Fig. 4. We see a tendency similar to the observed "blazar sequence": spectra for higher luminosity are shifted to lower energy. The observed blazar spectra demonstrate two distinct components traditionally interpreted as synchrotron and inverse Compton emission peaks of the same electrons. In our simulations the synchrotron and Compton components are broad and overlap. The possible reason for this difference is that the photon breeding mechanism works together with other mechanisms like diffusive or internal shock acceleration. Moreover, the photon breeding produces a strong impact on the jet, after the rapid inhomogeneous deceleration the jet should be highly perturbed. In our interpretation the soft blazar component is emitted further downstream due to a secondary

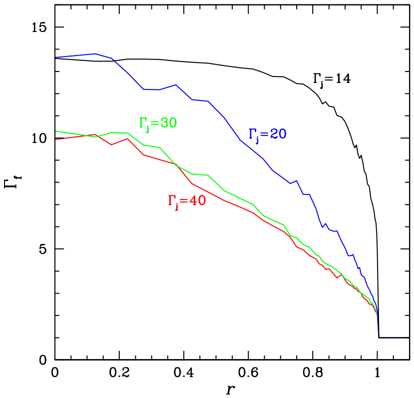

Fig. 3. Terminal Lorentz factor Γ_j at the outlet of the cylindric "simulation volume" with length $20R_j$ versus distance from the jet axis for different initial Lorentz factor of the jet.

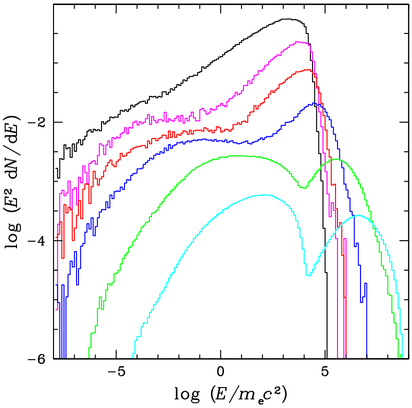

Fig. 4. Simulated spectra for the case $L_j = L_d$, $L_B = 0.2L_j$ and L_d varying from 5×10^{43} to 10^{46} erg s^{-1}.

process, e.g., diffusive reheating of cooled pairs produced by the photon breeding mechanism.

Acknowledgments

This work is supported by RFBR grant 07-02-00629-a, Ehrnrooth and Väisälä Foundations, and the Academy of Finland grants 110792 and 112982.

References

1. B. E. Stern and R. Svensson, in *Relativistic Hadrons in Cosmic Compact Objects*. eds. A. A. Zdziarski and M. Sikora, Lecture Notes in Physics, Vol. 391 (Springer-Verlag, Heidelberg, 1991), p. 41
2. J. G. Kirk and A. Mastichiadis, *Nature* **360**, 135 (1992).
3. R. Svensson, *Mon. Not. R. Astron. Soc.* **227**, 403 (1987)
4. V. Berezinsky, A. Z. Gazizov and S. I. Grigorieva, hep-ph/0107306
5. D. Kazanas, M. Georganopoulos and A. Mastichiadis, *Astrophys. J.* **578**, L15 (2002).
6. A. Levinson, *Astrophys. J.* **467**, 546 (1996).
7. E. V. Derishev *et al.*, *Phys. Rev.* D. **68**, 043003 (2003).
8. B. E. Stern, *Mon. Not. R. Astron. Soc.* **345**, 590 (2003).
9. B. E. Stern and J. Poutanen, *Mon. Not. R. Astron. Soc.* **372**, 1217 (2006).
10. B. E. Stern and J. Poutanen, *Mon. Not. R. Astron. Soc.* **383**, 1695 (2008).