A photon breeding mechanism of the high energy emission of relativistic jets

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Relativistic jets of AGNs can radiate away a substantial fraction of their kinetic energy due to exchange of interacting photons between relativistic fluid and external environment.

Main interactions: 1. pair production high energy photon + UV photon -> e^+e^-
2. inverse Compton scattering

High energy photons can breed exponentially as neutrons in nuclear chain reaction in supercritical regime producing a substantial viscosity between the jet and ambient medium. Under favorable condition the jet becomes self-luminous without any charged particle acceleration. Under less favorable conditions the mechanism amplifies the output of charged particle acceleration by orders of magnitude.

Preceding relevant papers.

Arav, Begelman (1992), ApJ, 401, 125

Jet energy dissipation through photon exchange between the jet and external environment due to Compton scattering . Requires a dense environment. Could be the case for SS433.

Derishev et al. (2003) Phys Rev D, 68, 43003

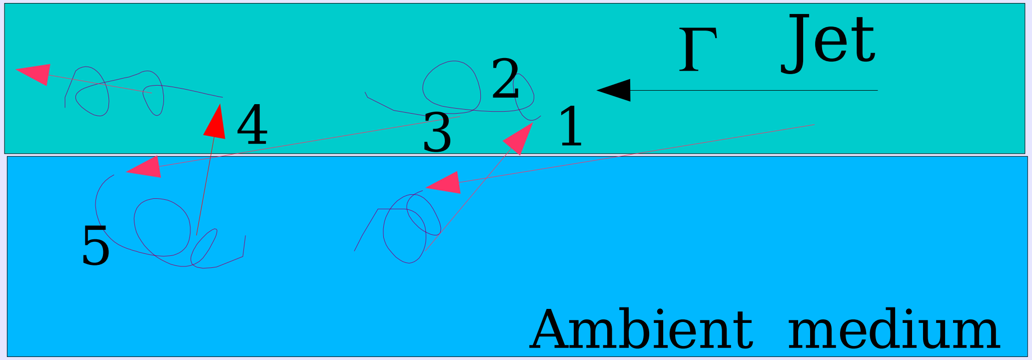
The general idea that shocks and shear layers can accelerate particles due to exchange of neutral particles converting into charged particles.

Stern (2003) MNRAS, 345, 590

First numerical simulations of the mechanism applied to relativistic shocks (GRBs). Observation of a dramatic effect of *Electromagnetic catastrophe* when the velocity jump disappears due to violent dissipation of the shock energy into radiation.

How the mechanism works

Very roughly it can be represented as a 5-step cycle with energy transmission C_i at each step



1. An external photon produces a pair in the jet. ($C_1 \sim 1$ for a 100 GeV photon).
2. The pair gains energy respectively the ambient medium frame when it turns around in the jet magnetic field. ($C_2 >> 1 \sim \Gamma^2$ on average)
3. Comptonization of soft external photons by the pair ($C_3 < 1$ but can reach 0.5 - 0.7).
4. A photon leaves the jet and interacts in the ambient medium ($0.1 < C_4 < 0.5$)
5. Reflection: pair production – Comptonization – back to the jet ($C_5 < 0.3$)

Runaway condition (criticality)

$C_1 \times C_2 \times C_3 \times C_4 \times C_5 > 1$

Then photons breed exponentially.

(the average energy does not rise – this is a breeding, not an acceleration)

What we need to launch the mechanism:

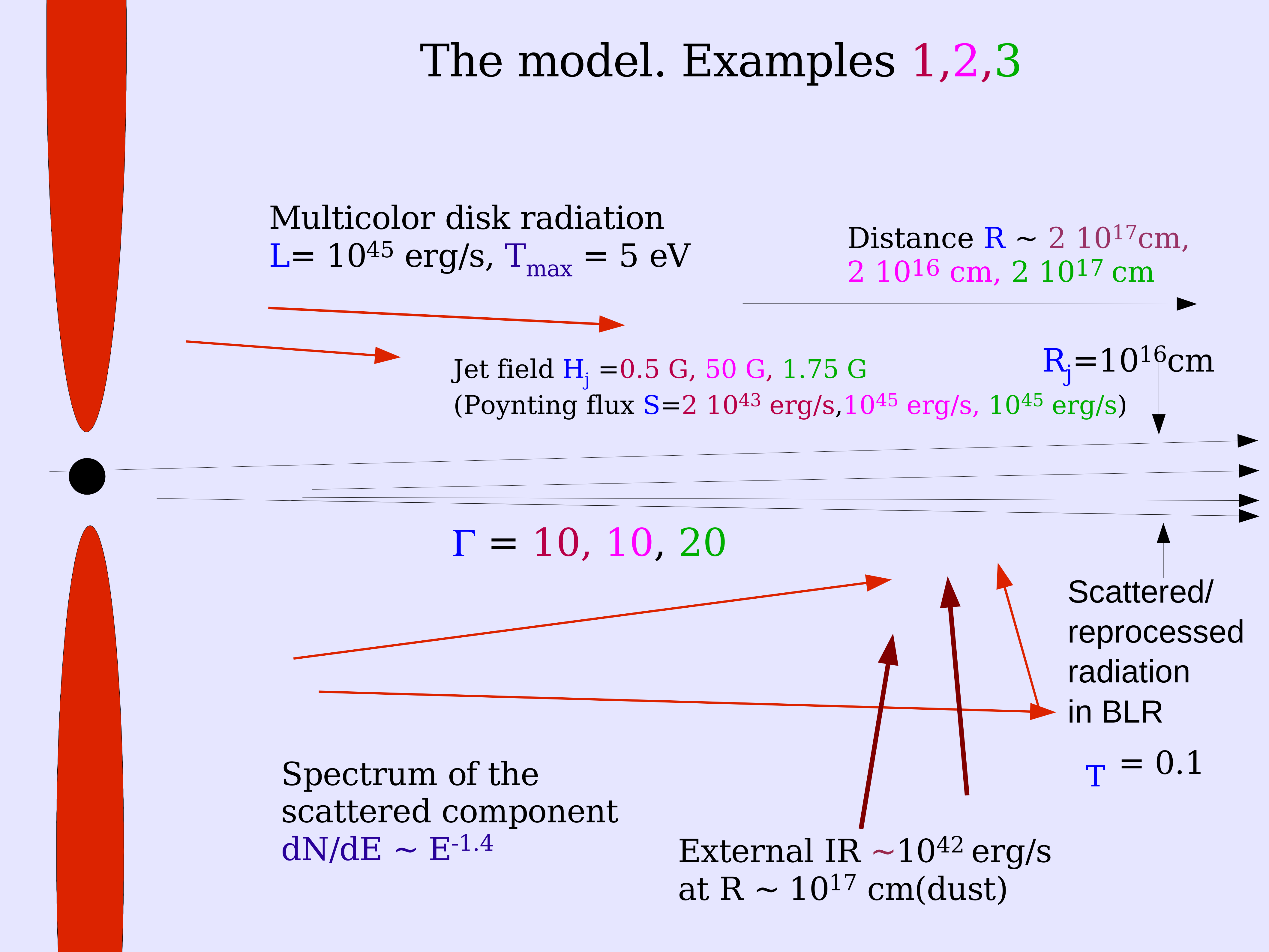
1. Transversal magnetic field in the jet H_j to provide step 2 (energy gain).

2. Transversal magnetic field H_e in the external environment to provide step 5 (reflection).

3. Soft background radiation to provide steps 1, 4 via pair production and steps 3,5 via Comptonization.
There are two components:
- direct radiation of the disk (multicolor blackbody)
- scattered, nearly isotropic component from the broad line region and surrounding dust.
First, “longitudinal”, component is sufficient at steps 1 and 5, the second is necessary at steps 3 and 4.

4. A relatively thin ($\Delta \ll R_{jet}$) transition layer between relativistic jet and ambient medium. Δ can be much larger than Larmor radius of high energy charged particles but should be less than photon free path length. In examples below the requirement is $\Delta < 0.01\ R_{jet}$

5. A seed high energy photon.



The model. Examples 1,2,3
Multicolor disk radiation
L= 10^45 erg/s, T_max = 5 eV
Distance R ~ 2 10^17 cm,
2 10^16 cm, 2 10^17 cm
Jet field H_j =0.5 G, 50 G, 1.75 G
(Poynting flux S=2 10^43 erg/s,10^45 erg/s, 10^45 erg/s)
R_j=10^16 cm
Γ = 10, 10, 20
Scattered/
reprocessed
radiation
in BLR
T = 0.1
Spectrum of the
scattered component
dN/dE ~ E^-1.4
External IR ~10^42 erg/s
at R ~ 10^17 cm(dust)

Examples 1 and 3: only external IR – UV radiation with energy density 0.05 of direct disk radiation and spectrum $dN/dE \sim E^{-1.4}$.
Example 2 - additional radiation associated with jet with the spectrum $dN/dE \sim E^{-1.5}$ and energy density comparable with that of the direct disk radiation.

The numerical model

Jet: the cylinder split into 500 shells which can independently decelerate, (one dimensional dust approximation)

Start: a small amount of seed high energy photons + soft photon background

Simulation: Large particle nonlinear Monte-Carlo code (Stern 1988, Stern et al. 1995). Compton scattering, pair production, synchrotron radiation, fine tracking in magnetic field.

We solve a time dependent problem (a transition process from a non-radiating initial state) instead of a search for a steady state solution because we have no realistic hydrodynamical treatment.

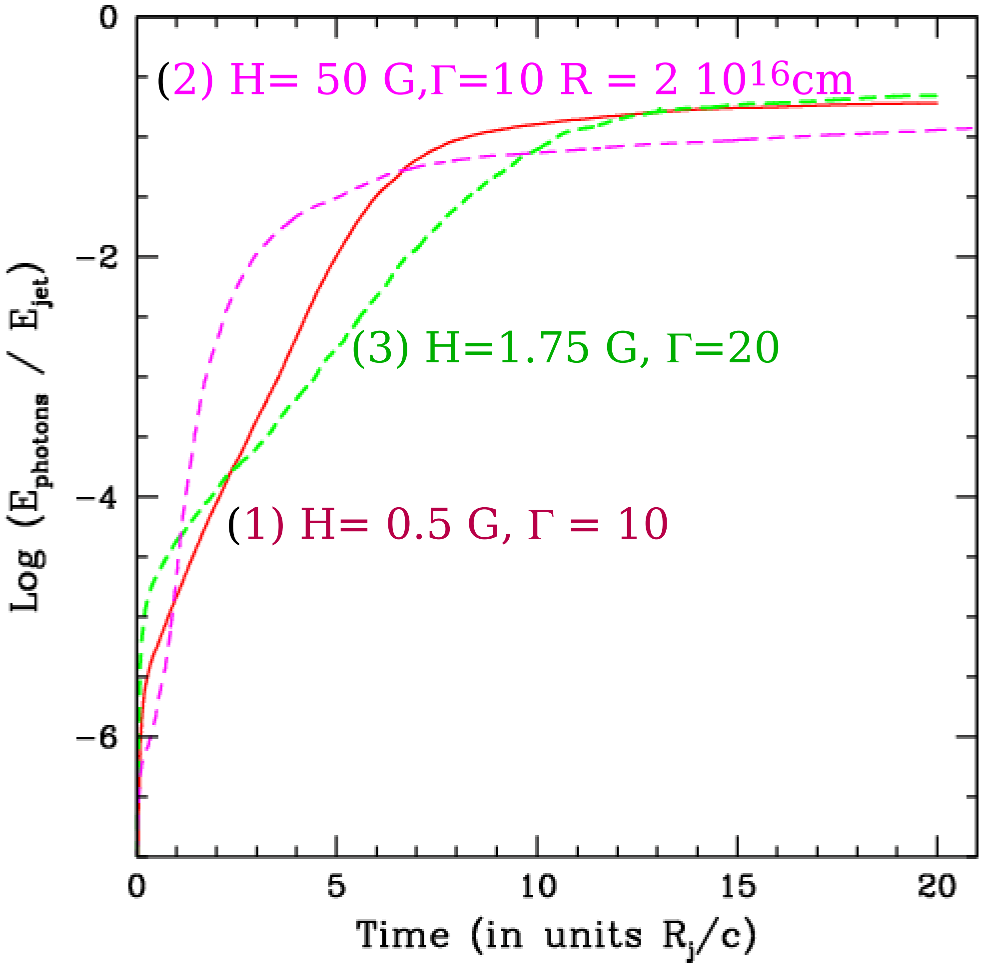
Output: emitted synchrotron and Comptonized photons of evolving spectrum and intensity, differential deceleration of the jet

Results

In all cases we observe an exponential rise of the energy release.

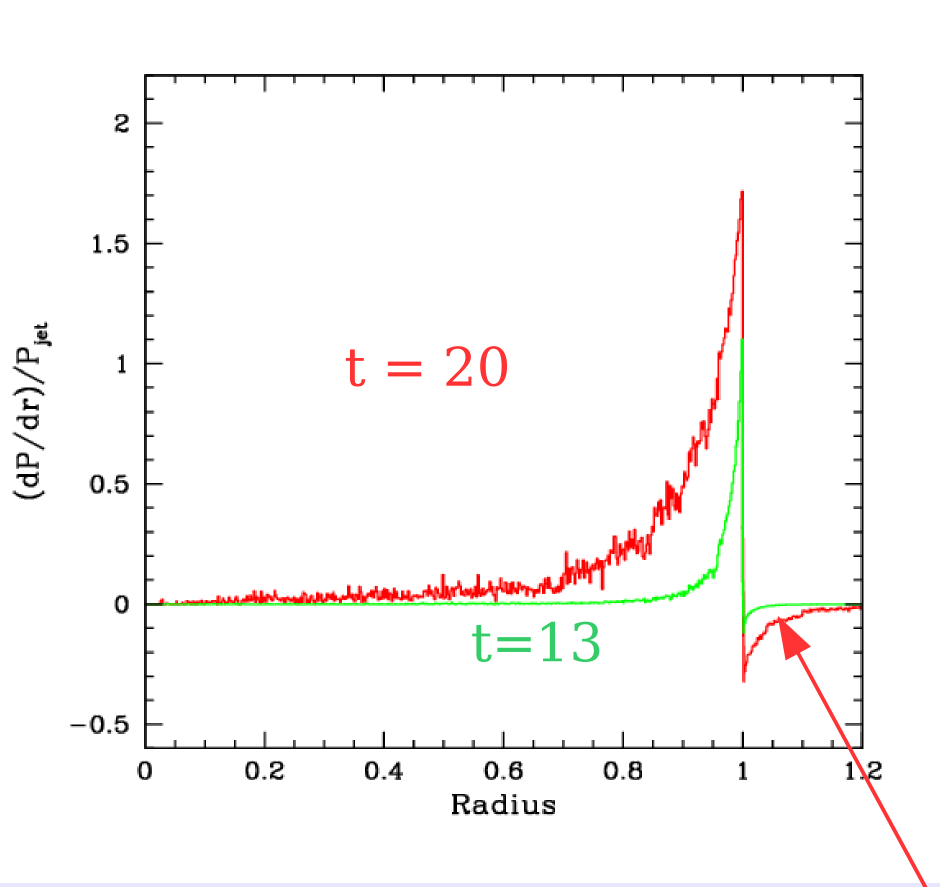
We track the evolution up to the conversion of 20% of the jet kinetic energy into radiation.

Further simulation should account for hydrodynamical effects.

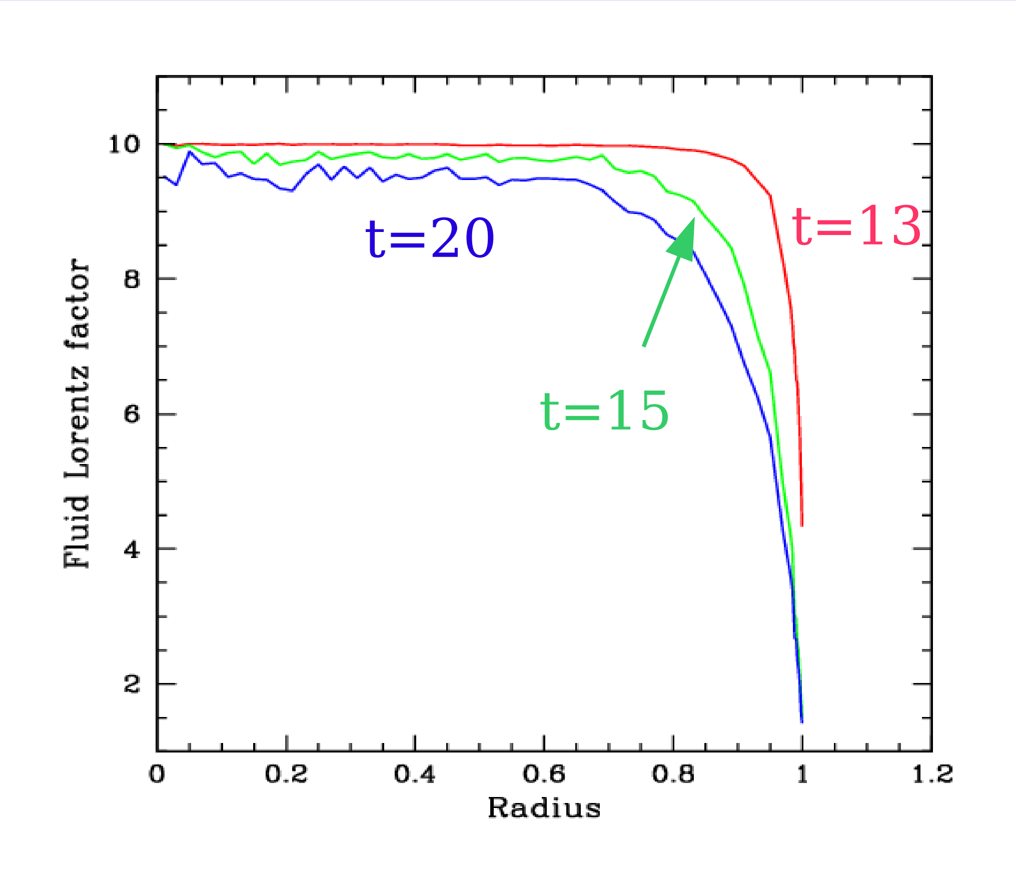


Total energy release in photons vs. time

Example1. The supercritical regime starts in a thin “active zone” $\Delta R \sim 0.02 R_j$ at the jet boundary. Then, the active layer extends up to $0.2\ R_j$



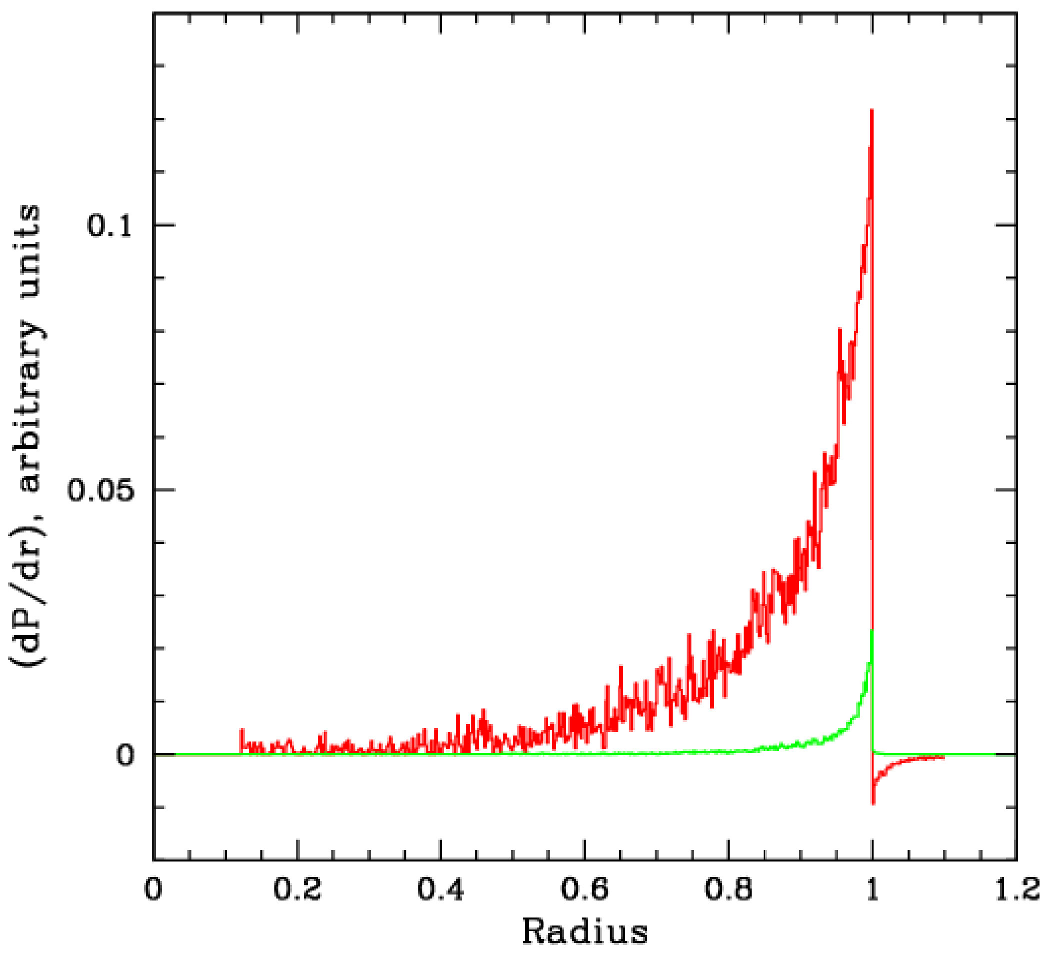
Momentum transferred to/from photons

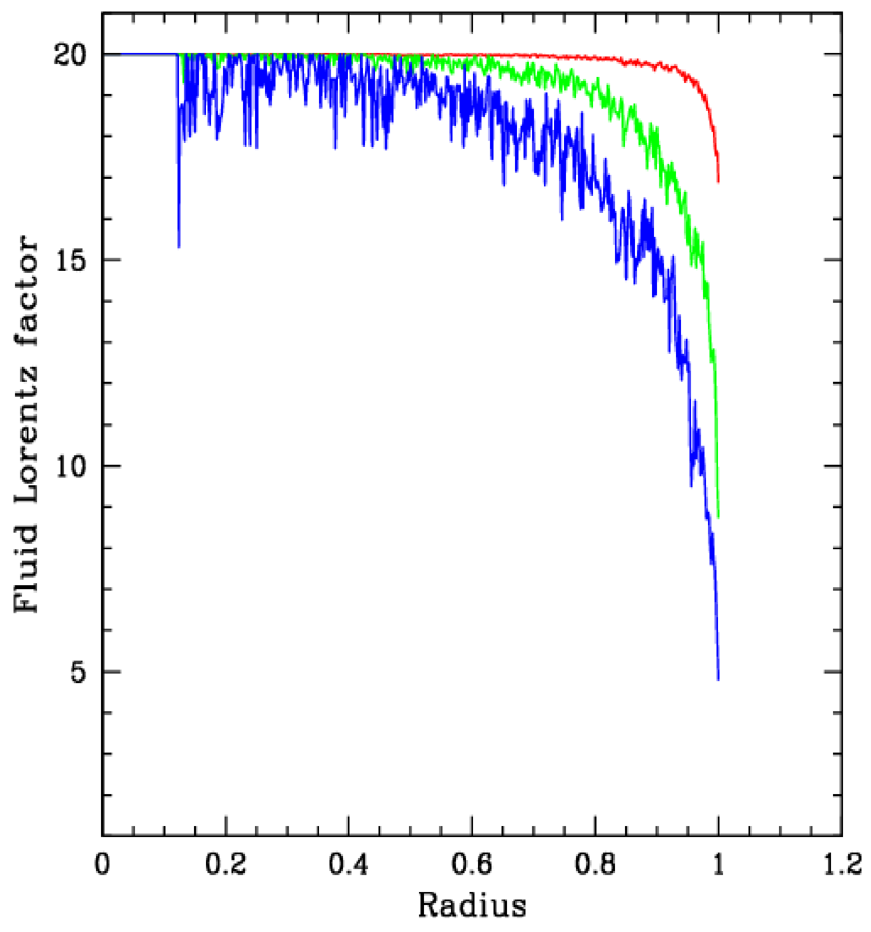


Jet deceleration: Lorentz factor of the fluid versus radius

To avoid acceleration of ambient medium to relativistic speed its density should be $\rho > 10^4/\mathrm{cm}^3$

Example 3. Here the “active zone” is wider than in the case of example1: $\Delta R \sim 0.05\ R_j$ at the start.



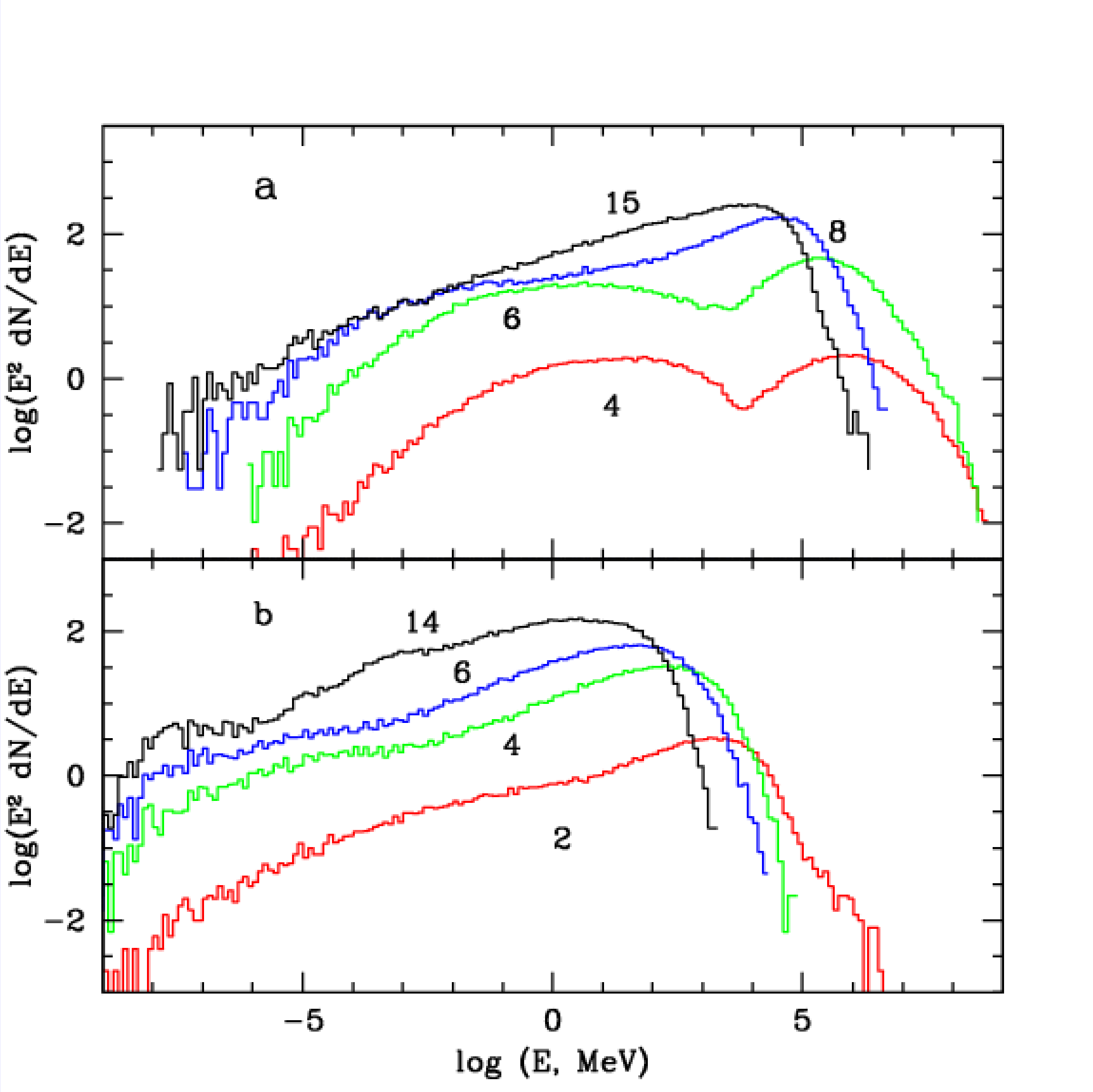


Weak field, R= 2 10^{17}cm
(Example 1)

Latest spectra are close to escape those. Cutoff at 50 GeV is due to photon-photon absorption on scattered UV radiation of the disk.

Strong field, R=2 10^{16}cm
(Example 2)

In this case the cutoff is at 30 MeV due to a nonlinear effect: scattered synchrotron radiation produces opacity for Comptonized photons. The reason is the higher compactness at a smaller R.



Instantaneous photon spectra (numbers indicate time in R_j/c units)

Some facts and conclusions

- Strong magnetic field inhibits the breeding because of synchrotron losses at step 3. Synchrotron photons do not participate in the breeding cycle. In magnetically dominated powerful (10^{45} erg/s) jet the supercritical breeding does not occur at $\Gamma \sim 10$ with external radiation only. Then additional radiation of the jet (example 2) or a higher Lorentz factor $\Gamma=20$ (example 3) is required.

- Intense soft photon background in IR range boosts the breeding as high energy electrons interact in Klein-Nishina regime with optical – UV photons. Softer IR photons give a more efficient Comptonization in Thomson regime.

- If the site of the main energy release is the broad line region then one should observe a spectral cutoff at ~50 GeV due to absorption by scattered UV radiation of accretion disk. TeV emission implies that photons are produced beyond BLR (e.g. at parsec scale).

-We cannot reproduce a clear two component spectrum as observed. The impression is that the softer (IR - X-ray) maximum requires an additional energy supply for gradual heating of pairs.

A possible scenario

1. The runaway cascade develops locally and fast where the boundary between jet and environment is sharpest and the magnetic field is weakest.

2. Due to the feedback from the cascade, the sharp boundary becomes smother and the cascade breeding goes slower but in the whole jet volume.

3. Some steady-state regime is reached due to
self-regulation via cascade feedback on the fluid dynamics.
Downstream photons provide a downstream feedback.

4. There is possible unstable behavior instead of a steady state regime: fast breeding in the most favorable place -> deceleration -> internal shock -> bright moving blob.