Reconfinement shocks in relativistic AGN jets

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Stationary knots observed in many AGN jets can be explained in terms of a reconfinement shock that forms when relativistic flow of the jet matter collides with the external medium. The position of these knots can be used, together with information on external pressure profile, to constrain dynamical parameters of the jet. We present a semi-analytical hydrodynamical model for the dynamical structure of reconfinement shocks, taking into account exact conservation laws both across the shock surface and in the zone of the shocked jet matter. This approach allows us to include variations of the flow parameters along the radial coordinate. As the pressure just behind the shock is lower than the external pressure, the position of the reconfinement is larger than predicted by simple models. A portion of kinetic energy is converted at the shock surface to internal energy, with efficiency increasing strongly with both bulk Lorentz factor of the jet matter and the jet half-opening angle. Our model may be useful as a framework for modeling non-thermal radiation produced within the stationary features.

Introduction

Interaction between AGN jet and its environment leads to formation of a reconfinement shock. The connection between geometrical properties of the shock surface and physical matter parameters has been studied by Komissarov & Falle (1997). Under many simplifying assumptions they provided simple analytical formulae. In order to test their predictions, we have developed two models based on exact conservation laws for ideal relativistic gas. Assuming static external medium, we only have one shocked zone bounded with the shock surface $r_s(z)$ and contact discontinuity $r_c(z)$. This basic structure is shown in Fig. 1. The jet is launched from the vicinity of the central source with a half-opening angle Θ_j, it achieves its maximum width r_m at $z = z_m$, then it reconfines at $z = z_r$ with a half-closing angle Θ_r.

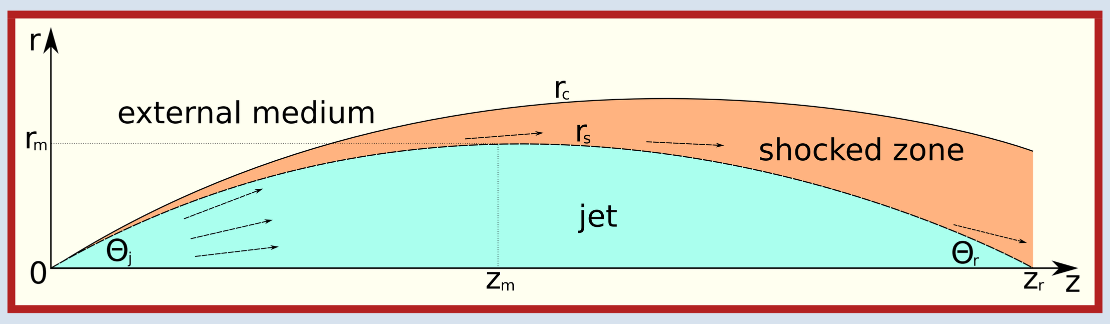

Figure 1: Structure of the reconfinement shock for static external medium.

The parameters needed to describe a model are: jet bulk Lorentz factor Γ_j, initial half-opening angle Θ_j, kinetic power L_j, external pressure $p_e(z)$, specific heats ratio of the shocked matter γ_s. Given the flow parameters of the jet and the external medium, we calculate the flow parameters of the shocked zone and the inclination angles of the boundary surfaces.

Model 1 (*blue lines*) is based on assumption that the pressure behind the shock is equal to the external pressure ($p_s = p_e$). The flow parameters behind the shock are found by solving the exact relativistic shock-jump equations. This model lacks a consistent description of the shocked zone (if contact discontinuity surface is defined as a surface parallel to the local velocity field, mass flux across the zone is not conserved).

Model 2 (*red lines*) includes transverse structure of the shocked zone. Parameters just behind the shock are treated as independent of the parameters at the contact discontinuity. As we add 4 degrees of freedom, 4 additional equations are needed. We take full set of conservation laws for the shocked zone, based on Bromberg & Levinson (2007). The profiles of pressure and density across the zone are assumed to be linear functions of r.

Results

We present here the results obtained assuming cold jet (of negligable pressure) and uniform external pressure. In the model of Komissarov & Falle (1997), under such conditions the jet boundary is expected to be parabolic. Position of the reconfinement can be estimated as:

$$z_r \simeq \Lambda \equiv \sqrt{\frac{\mu \beta_j L_j}{\pi p_e c}}, \qquad (1)$$

where $\mu = 17/24$. Consequently, we expect $z_m \simeq z_r/2$ and $\Theta_r \simeq \Theta_j$.

We have tested these predictions in both our models with the same parameters. The results are presented as a function of the product of Γ_j and Θ_j. As the two extreme states of shocked matter, we consider $\gamma_s = 4/3$ (*solid lines*) and $\gamma_s = 5/3$ (*dashed lines*).

The z_r/Λ, z_r/z_m and Θ_r/Θ_j ratios are shown in Figs. 2, 3 and 4, respectively. We find, that Model 1 agrees very well with the results of Komissarov & Falle (1997) for $\Gamma_j\Theta_j < 1$ and is still in agreement for larger opening angles. Model 2 produces a jet more than twice longer, the maximum width position is slightly closer than $z_r/2$ and the half-closing angle a bit smaller than Θ_j.

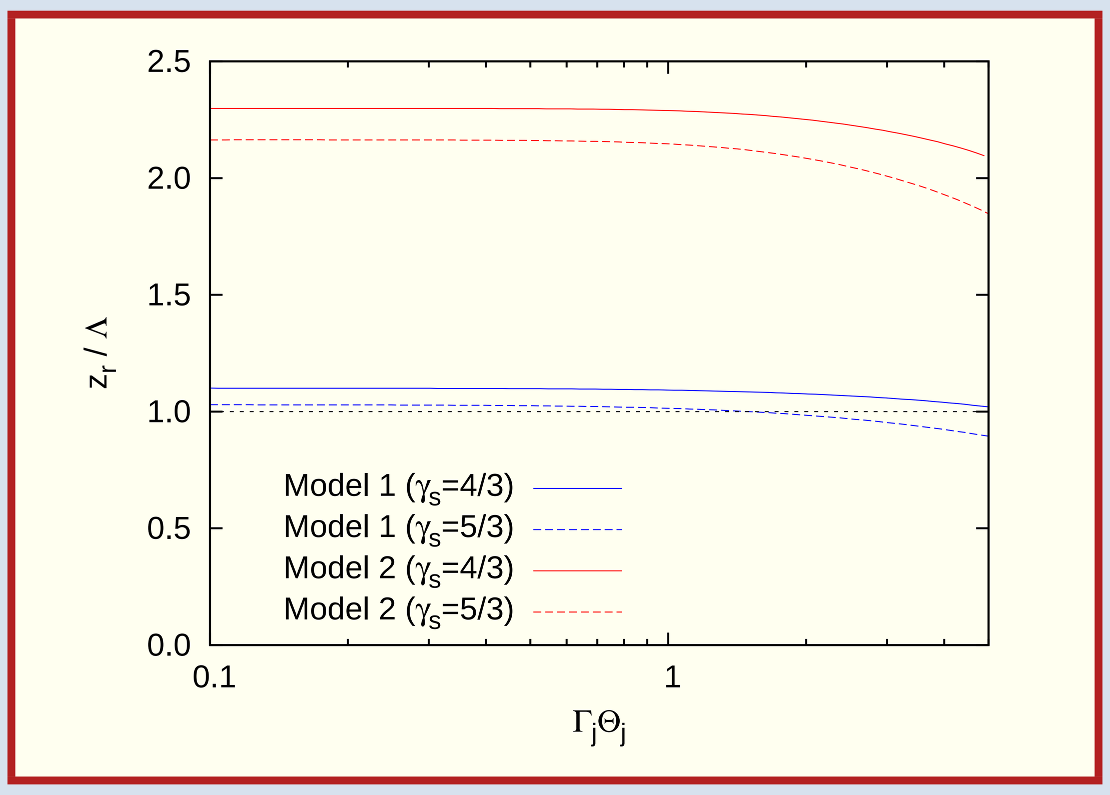

Figure 2: The ratio of the reconfinement position z_r to the characteristic length Λ as a function of $\Gamma_j\Theta_j$.

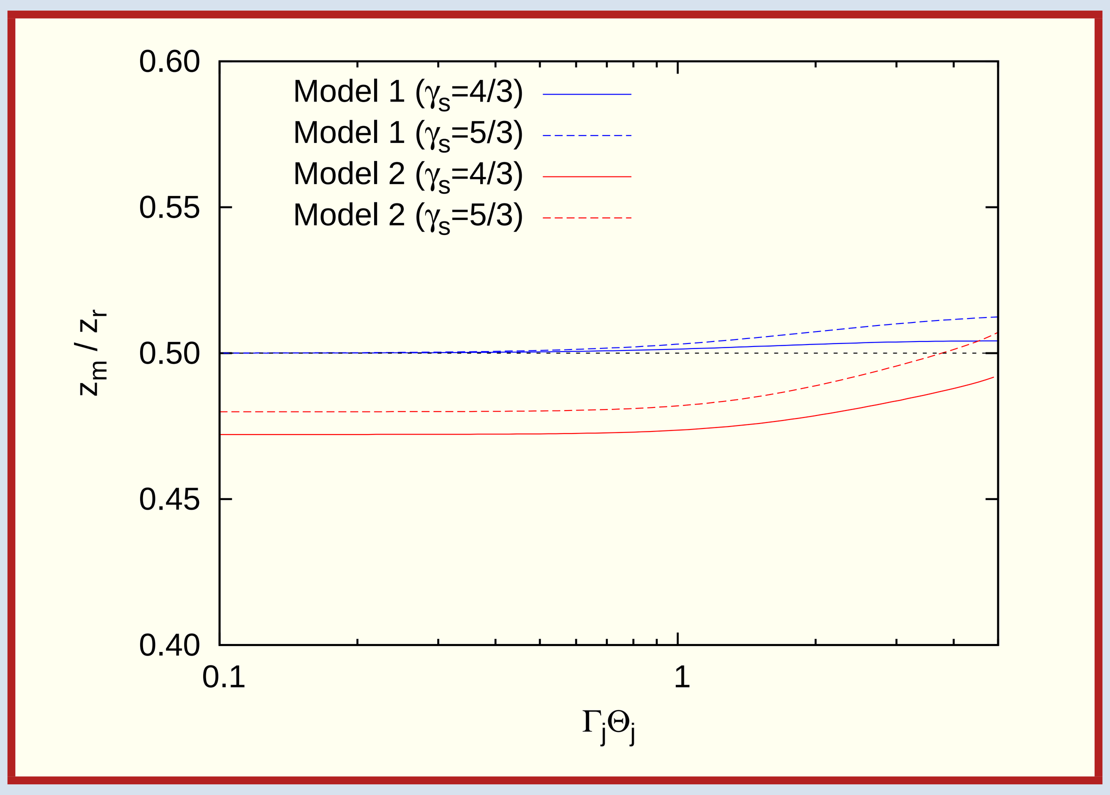

Figure 3: The ratio of the maximum jet width position z_m to the reconfinement position z_r as a function of $\Gamma_j\Theta_j$.

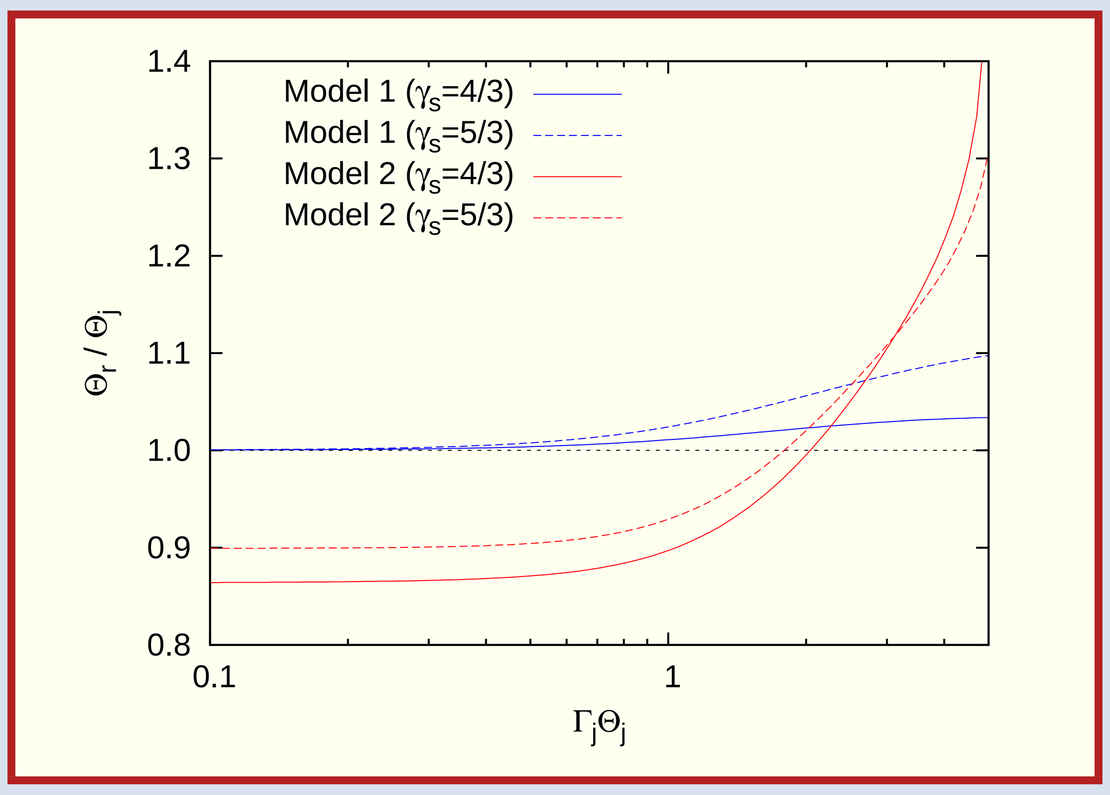

Figure 4: The ratio of the half-closing angle Θ_r to the half-opening angle Θ_j as a function of $\Gamma_j\Theta_j$.

Kinetic energy of the cold jet matter crossing the shock surface is converted into internal (thermal) energy with efficiency ϵ_{th} (*thermalization efficiency*). Fig. 5 shows this efficiency calculated in our models with the same parameters as before. The results from the two models are very similar, we find that ϵ_{th} depends strongly on $\Gamma_j\Theta_j$, achieving values higher than 6% for $\Gamma_j\Theta_j > 1$.

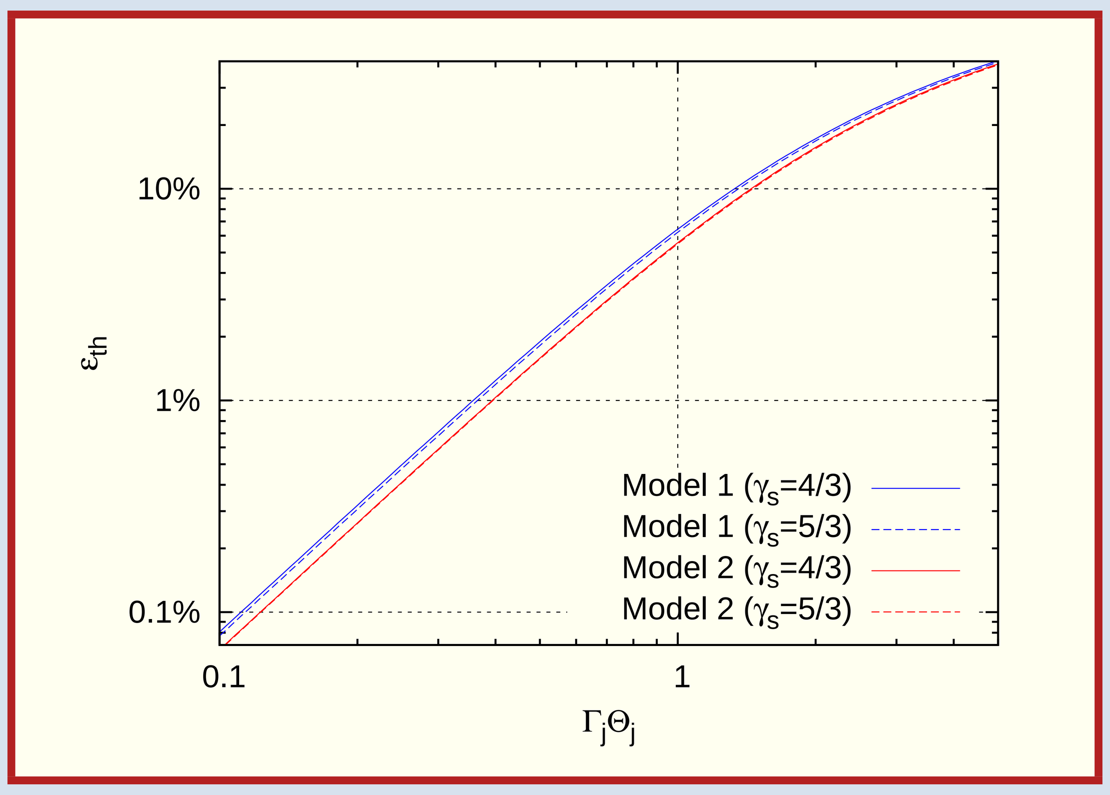

Figure 5: Thermalization efficiency ϵ_{th} as a function of $\Gamma_j\Theta_j$.

Although the total thermal energy flux produced in the two models is similar, its geometrical distribution is different. Fig. 6 shows the thermal energy flux per unit jet length dL_{th}/dz for the two models for $\Gamma_j = 10$ and $\Theta_j = 5°$. The dependence of the location of thermal energy flux maximum on $\Gamma_j\Theta_j$ is shown in Fig. 7. The $z_{th,max}/z_r$ ratio is smaller in Model 2 and it strongly decreases in both models for $\Gamma_j\Theta_j > 1$.

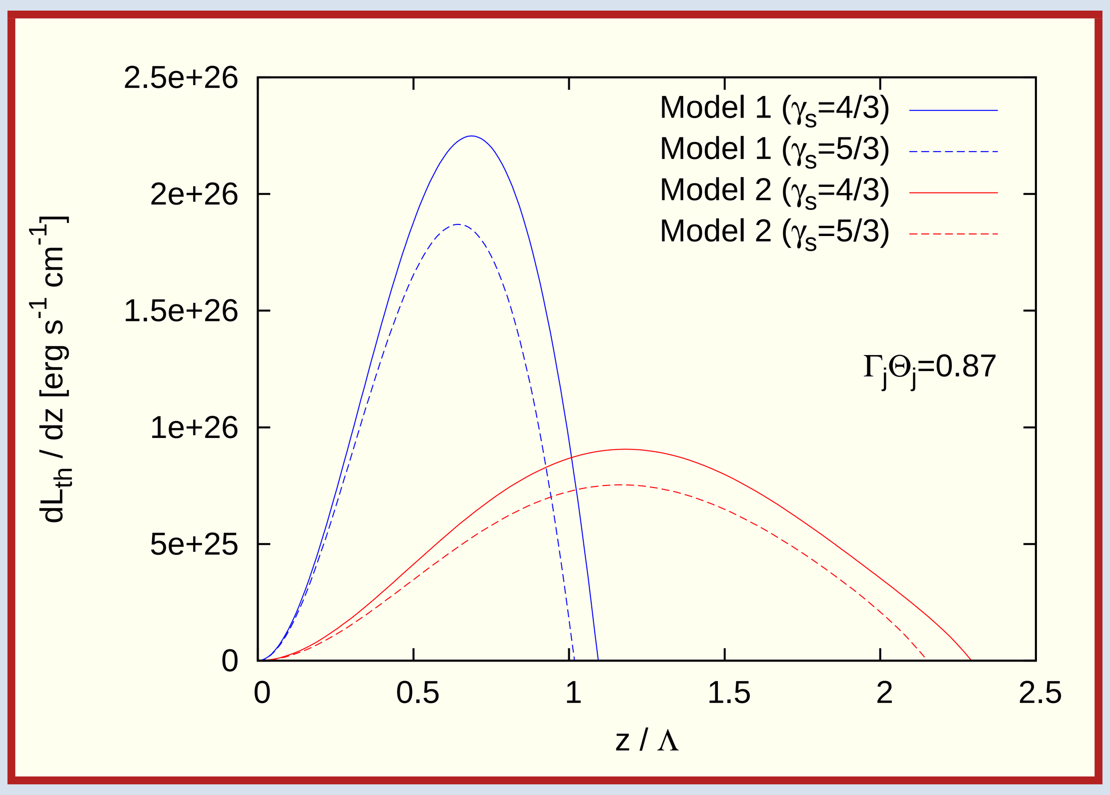

Figure 6: Longitudinal profiles of the thermal energy flux produced at the shock surface, calculated for $\Gamma_j = 10$ and $\Theta_j = 5°$.

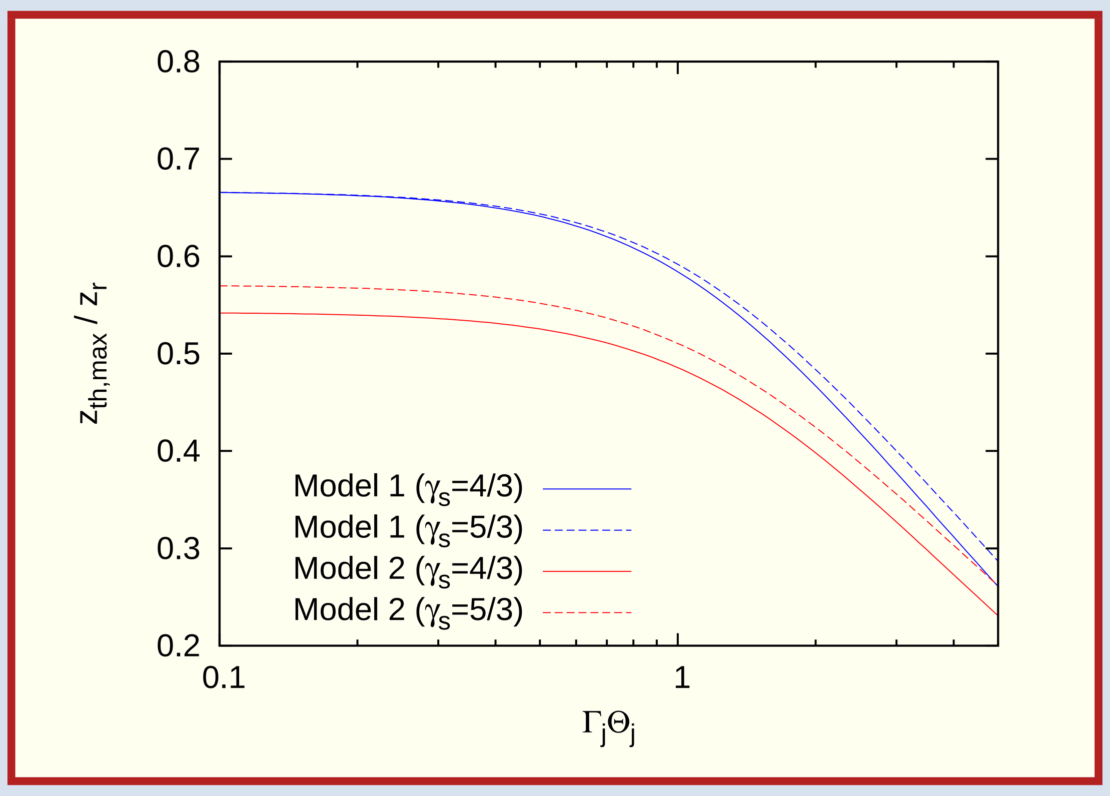

Figure 7: The ratio of the location of thermal energy flux maximum $z_{th,max}$ to the reconfinement position z_r as a function of $\Gamma_j\Theta_j$.

References

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