# Gamma-Ray Burst Jets: Beyond the Progenitor Star

Alexander Tchekhovskoy[1], Ramesh Narayan[1], and Jonathan C. McKinney[2]

[1] *Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*
[2] *Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, P.O. Box 20450, MS 29, Stanford, CA 94309, USA; Chandra Fellow*

## Abstract

Gamma-ray bursts (GRBs) power relativistic jets with Lorentz factors $\gamma$ of a few hundred and opening angles $\theta \lesssim 0.1$ radians. Achromatic breaks in GRB afterglow light curves indicate that $\gamma\theta \gg 1$. However, magnetohydrodynamic (MHD) simulations of collimated jets generally give $\gamma\theta \lesssim 1$, indicating a conflict between these models and observations. In this talk we present a new class of MHD jet simulations in which the simulated jet is confined by a GRB progenitor star, modeled as a rigid confining wall that extends out to a certain radius. Beyond this radius, the jet becomes deconfined. We find that the onset of deconfinement outside the star causes a burst of acceleration with negligible change in the opening angle. In our fiducial model with a stellar radius equal to $10^{4.5}$ times that of the central compact object, the jet achieves an asymptotic $\gamma \sim 500$ far outside the star and an asymptotic $\theta \sim 0.04$ rad, giving $\gamma\theta \sim 20$. These values are consistent with observations of typical long-duration GRBs, and explain the occurrence of jet breaks within the context of MHD jets.

## Introduction

Relativistic jets are an ubiquitous feature of many accreting black holes and neutron stars. The physics behind jet production appears to be robust and not sensitive to the details of the central object. Jets in long-duration GRBs achieve $\gamma > 400$ Lithwick & Sari (2001). Observations of jet breaks in GRB afterglows indicate a broad distribution of jet opening angles, with typical opening angles $\Theta_j \sim 0.05$ rad. These estimates imply that GRB jets have $\gamma\Theta_j \sim 10{-}30$. It is generally assumed that $\gamma$ and $\Theta_j$ are related, though the exact relation is not well understood.

Komissarov (2009) argued, based on numerical simulations, that relativistic jets confined by an external medium should have $\gamma\Theta_j \lesssim 1$. On the other hand, a completely unconfined split-monopole flow achieves larger opening angles with $\gamma\Theta_j > 10$ (Tchekhovskoy et al., 2009a). According to the collapsar model of GRBs (MacFadyen & Woosley, 1999), the jet in a GRB is produced by an accreting stellar-mass black hole at the center of a collapsing massive star. As the jet propagates out, it is collimated by the pressure of the stellar envelope; however, once the jet emerges from the star it is effectively in vacuum and the jet propagates freely with no confinement. Thus a GRB jet corresponds to a hybrid scenario which involves both confinement and free propagation. We show that the asymptotic properties of such a hybrid jet far from the star are essentially the same as of unconfined split-monopole models of (Tchekhovskoy et al., 2009a).

## Results

We have carried out idealized numerical simulations to answer this question. The relativistic jets we model are confined out to a certain distance by a rigid wall which has the appropriate shape to mimic the effect of a stellar envelope. The jets are then effectively unconfined beyond this distance. We neglect gravity and

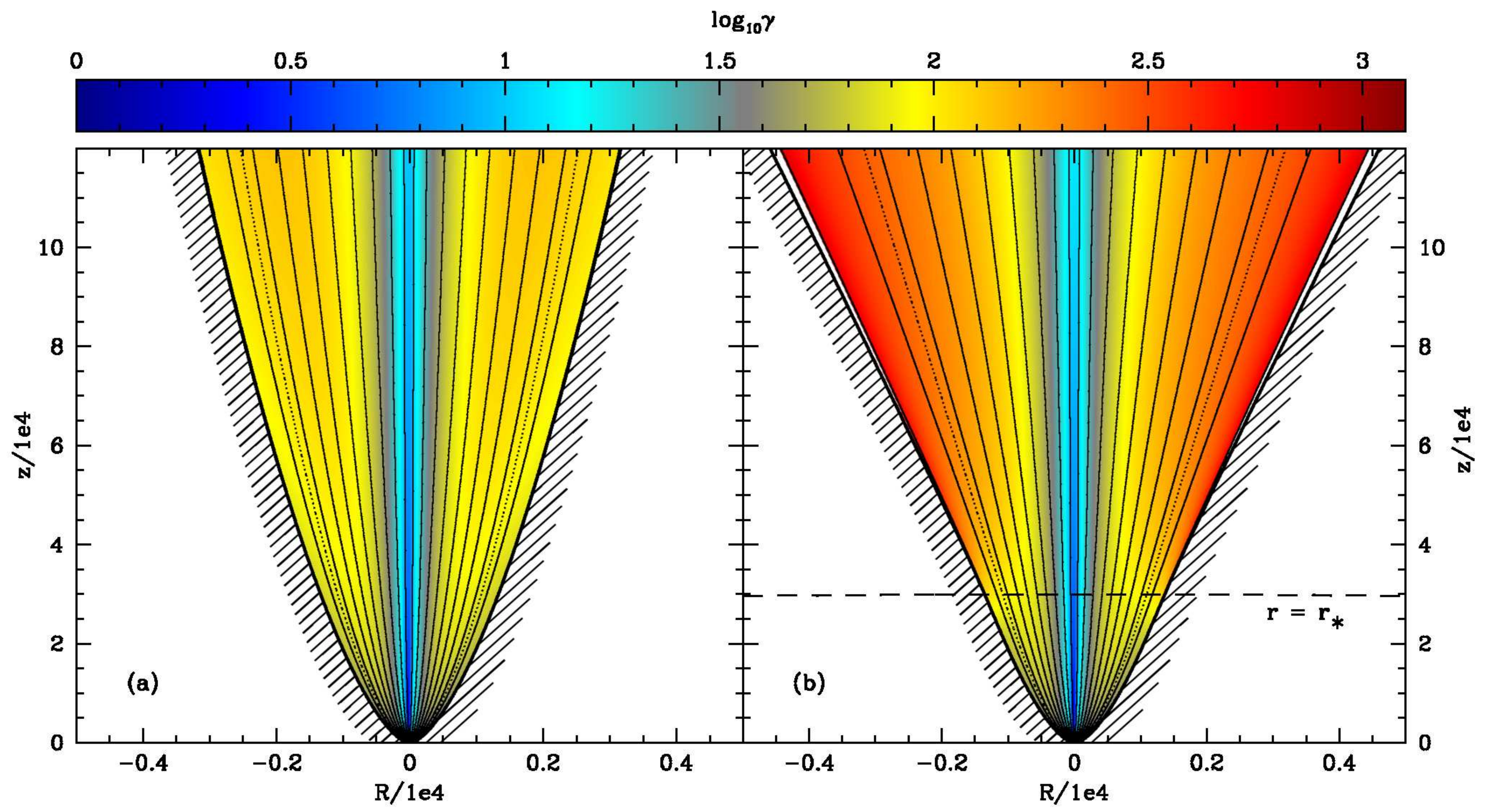


Figure 1: Meridional jet cross-section, showing color-coded logarithm of the Lorentz factor $\gamma$ overlaid with poloidal field lines (thin solid lines corresponding to $\Psi^{1/2} = 0.1, 0.2, \ldots, 1$). Thick solid lines show the position of the wall and dotted lines show the half-energy field line. [Panel a]: Jet confined continuously by a wall out to a large distance (model M$\infty$). [Panel b]: Jet confined by a collimating wall until $r = r_* = 3 \times 10^4$, shown by the horizontal dashed line, after which the wall opens up and the jet becomes deconfined: it separates from the wall and is surrounded effectively by vacuum (model M4). Once the jet becomes deconfined, $\gamma$ increases abruptly while the jet opening angle changes negligibly.

set the speed of light and the radius of the compact object to unity, $c = r_0 = 1$.

We have run a number of simulations with different shapes of the collimating wall, and with different values of the confinement radius $r_*$ that bracket the possible range of progenitor star radii in GRBs. The results for other collimating wall shapes are not qualitatively different. As a baseline model, we first consider the case $r_* \to \infty$, i.e., a model in which the jet is continuously collimated by a wall out to an arbitrarily large distance. We refer to this as model M$\infty$. Figure 1a shows a meridional cut through the steady-state solution we obtain at the end of the simulation. Consider next a model with $r_* = 3 \times 10^4$, i.e., a model in which the wall collimates exactly as in model M$\infty$ until $r \sim r_*$, but the wall then smoothly opens up, allowing the jet to decollimate. We refer to this as model M4. The steady state solution is shown in Figure 1b reveals that the jet undergoes an abrupt burst of acceleration immediately after it leaves the star while the change in the opening angle is negligible.

Figure 2 shows the radial dependence of various quantities. In addition to the models M$\infty$ and M4 already discussed, we consider two additional models: model M3 with $r_* = 3\times10^3$ and model M5 with $r_* = 3\times10^5$. For each model, we show results corresponding to the "half-power" field line, i.e., the field line for which half the jet power is carried by field lines inside of this line and half by field lines outside. For the continuously confined model M$\infty$, the value $\gamma\Theta_j \simeq 2$, in agreement with Komissarov (2009). However, for all deconfined models M$3{-}5$, the results are qualitatively similar: the jet undergoes a burst of acceleration just outside of the star in which its Lorentz factor increases by a factor of $\sim 10$ but opening angle stays the same. This effect leads to values $\gamma\Theta_j \gtrsim 10$ for all of our deconfined models.

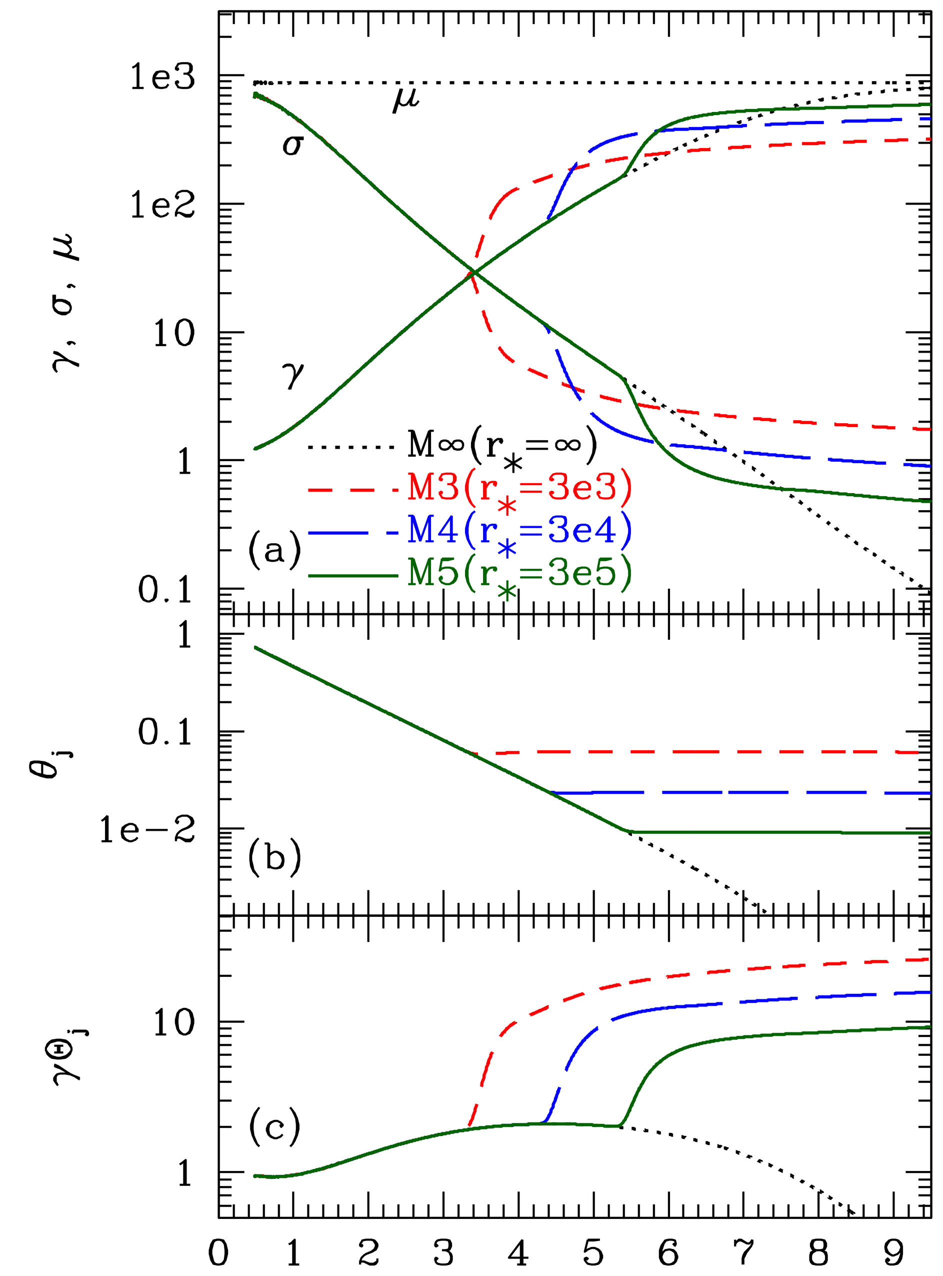


Figure 2: Dependence of various quantities along the half-energy field line for models M$\infty$, M3, M4, and M5. These models differ only in the jet confinement radius, i.e., the radius of the star $r_*$. [Panel a]: Lorentz factor $\gamma$, magnetization $\sigma$, and the total energy flux $\mu$. Model M$\infty$ shows continuous smooth acceleration, whereas the deconfined models M3–M5 show a "burst" of acceleration soon after the jet loses confinement. [Panel b]: Field line opening angle $\theta_j$ decreases continuously so long as the jet is confined by the wall, but it hardly changes outside the star. [Panel c]: The product of field line $\gamma$ and the *full* jet opening angle $\Theta_j$. In model M$\infty$, we have $\gamma\Theta_j \lesssim 1$ at all $r$. However, in models M3–M5 $\gamma\Theta_j$ increases abruptly soon after the jet becomes unconfined and reaches values $\sim 10{-}30$, as appropriate for GRB jets.

Observations of GRB afterglows place a firm constraint on the product of $\gamma\Theta_j$, requiring it to be much larger than unity (Tchekhovskoy et al., 2009b). Both confinement by the stellar envelope of the collapsar and free propagation outside the star are needed for the jet not only to have reasonable $\gamma \sim 100$ and $\Theta_j \sim 0.1$, but also the correct (large) value of their product $\gamma\Theta_j \sim 10$. Only a jet that is first confined and then deconfined can explain the most energetic long-duration GRBs with achromatic jet breaks. This work was supported by NASA grant NNX08AH32G (AT & RN), NSF grant AST-0805832 (AT & RN), NASA Chandra Fellowship PF7-80048 (JCM), and by NSF through TeraGrid resources, http://www.loni.org.

## References

Komissarov, S. S. e. a. 2009, MNRAS, 394, 1182

Lithwick, Y. & Sari, R. 2001, ApJ, 555, 540

MacFadyen, A. I. & Woosley, S. E. 1999, ApJ, 524, 262

Tchekhovskoy, A., McKinney, J. C., & Narayan, R. 2009a, ApJ, 699, 1789

Tchekhovskoy, A., Narayan, R., & McKinney, J. C. 2009b, ArXiv:0909.0011