Large-scale magnetic fields in GRB outflows: acceleration, collimation, and neutron decoupling

Abstract. Using ideal magnetohydrodynamics we examine an outflow from a disk surrounding a stellar-mass compact object. We demonstrate that the magnetic acceleration is efficient (\( \gtrsim 50\% \) of the magnetic energy can be transformed into kinetic energy of \( \gamma > 10^2 \) baryons) and also that the jet becomes collimated to very small opening angles. Observational implications, focusing on the case of an initially neutron-rich outflow, are discussed in Königl’s contribution.

I IDEAL MAGNETOHYDRODYNAMICS

There is growing evidence in favor of magnetic driving in outflows associated with gamma-ray burst (GRB) sources [e.g.,] hereafter VK03a; see also Königl’s contribution in these Proceedings]VK03a. The dynamics of these outflows may be described to zeroth order by the ideal, axisymmetric, hydromagnetic equations, consisting of the Maxwell and momentum equations together with the conservations of baryonic mass and specific entropy. VK03a demonstrated that, under the assumptions of a quasi-steady poloidal magnetic field and of a highly relativistic poloidal velocity, these equations become effectively time-independent and the motion can be described as a frozen pulse, generalizing the so-called “frozen pulse” approximation already known in purely hydrodynamic models of GRB outflows PSN93. Introducing the magnetic flux function \( A \), the arclength along a poloidal streamline \( \ell \), and the operator \( \nabla_s \) that acts while keeping \( s \equiv ct - \ell \) constant, the momentum equation can be written as (see VK03a for details)

\[
\gamma \rho_0 \left( V \cdot \nabla_s \right) \left( \xi \gamma V \right) = \frac{\left( \nabla_s \cdot E \right) E + \left( \nabla_s \times B \right) \times B}{4\pi} - \nabla P. \tag{1}
\]

The large-scale electromagnetic field \( (E, B) \), the bulk flow speed \( (V) \), and the total \((\pm + \) radiation) pressure can be written as functions of \( A \) and the rest baryon density \( \rho_0 \)

\[
B = \frac{\nabla_s A \times \hat{\phi}}{\omega} + B_\phi, \quad E = \frac{-\Omega}{c} \nabla_s A, \quad V = \frac{A \Omega^2}{4\pi \gamma \rho_0 c^3 \sigma_M} B + \omega \Omega \hat{\phi}, \quad P = Q \rho_0^{4/3}. \tag{2}
\]

Faraday’s law and the conservations of specific entropy and mass imply that the functions \( \Omega, Q, \) and \( \sigma_M \) are constants of motion, i.e., functions of \( A \). By integrating equation (1) along \( V_p \) and \( \hat{\phi} \) one gets two additional constants of motion,

\[
\mu c^2 \xi_0 \sigma_M^2 = B, \quad \mu c^2 \xi_0 V = \frac{1}{c^3 \sigma_M} \frac{\xi_0}{\mu c^2 x_A}, \tag{3}
\]