The Dynamics of Magnetized GRB Outflows

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Outline:

- Magnetic driving of GRB outflows
- Exact relativistic-MHD solutions
- The baryon loading problem

- GRBs and their afterglows are inferred to arise from rapid ($\Delta t \sim$ seconds), variable ($\Delta t/\delta t \sim 10^2$) ejection episodes of energetic ($\mathcal{E} \sim 10^{51}$ergs), highly relativistic ($\gamma \sim 10^2 - 10^3$), and highly collimated ($\vartheta \sim 2^{\rm o} - 20^{\rm o}$) outflows. Most of the progenitor models involve a BH–debris disk system.

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– unlikely that the disk is optically thin to neutrinos (Di Matteo, Perna, & Narayan 2002)
– strong photospheric emission would have been detectable (Daigne & Mochkovitch 2002)
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☞ dissipation of magnetic fields
generated by the differential rotation in the torus $\Rightarrow e^\pm$/photon/baryon “magnetic” **fireball**
– collimation
– strong photospheric emission

☞ MHD extraction (**Poynting** jet)

A recent measurement of a high $(80 \pm 20\%)$ linear polarization in the prompt γ-ray emission in GRB 021206 has been interpreted as evidence that the underlying outflow was driven by a large-scale, ordered magnetic field (Coburn & Boggs 2003).

- $\mathcal{E} = \frac{c}{4\pi} \underbrace{\frac{\varpi\Omega}{c} B_p}_{E} B_\phi \times \text{ area } \times \text{ duration } \Rightarrow$

$$\frac{B_p B_\phi}{(2 \times 10^{14}\text{G})^2} = \left[\frac{\mathcal{E}}{5 \times 10^{51}\text{ergs}}\right] \left[\frac{\text{area}}{4\pi \times 10^{12}\text{cm}^2}\right]^{-1} \left[\frac{\varpi\Omega}{10^{10}\text{cm s}^{-1}}\right]^{-1} \left[\frac{\text{duration}}{10\text{s}}\right]^{-1}$$

  - from the BH: $B_p \gtrsim 10^{15}$G (small B_ϕ, small area)
  - from the disk: smaller magnetic field required $\sim 10^{14}$G
    * If initially $B_p/B_\phi > 1$, a **trans-Alfvénic** outflow is produced.
    * If initially $B_\phi/B_p > 1$, the outflow is **super-Alfvénic** from the start.

- Is it possible to "use" this energy and accelerate the matter ejecta?

Ideal Magneto-Hydro-Dynamics

in collaboration with Arieh Königl

- Outflowing matter:
  - baryons (rest density ρ_0, bulk velocity $\mathbf{V}$)
  - ambient electrons (neutralize the protons)
  - $e^{\pm}$ pairs (Maxwellian distribution)
- photons (blackbody distribution)
- large scale electromagnetic field $\mathbf{E}\,,\mathbf{B}$

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Assumptions:

❶ axisymmetry

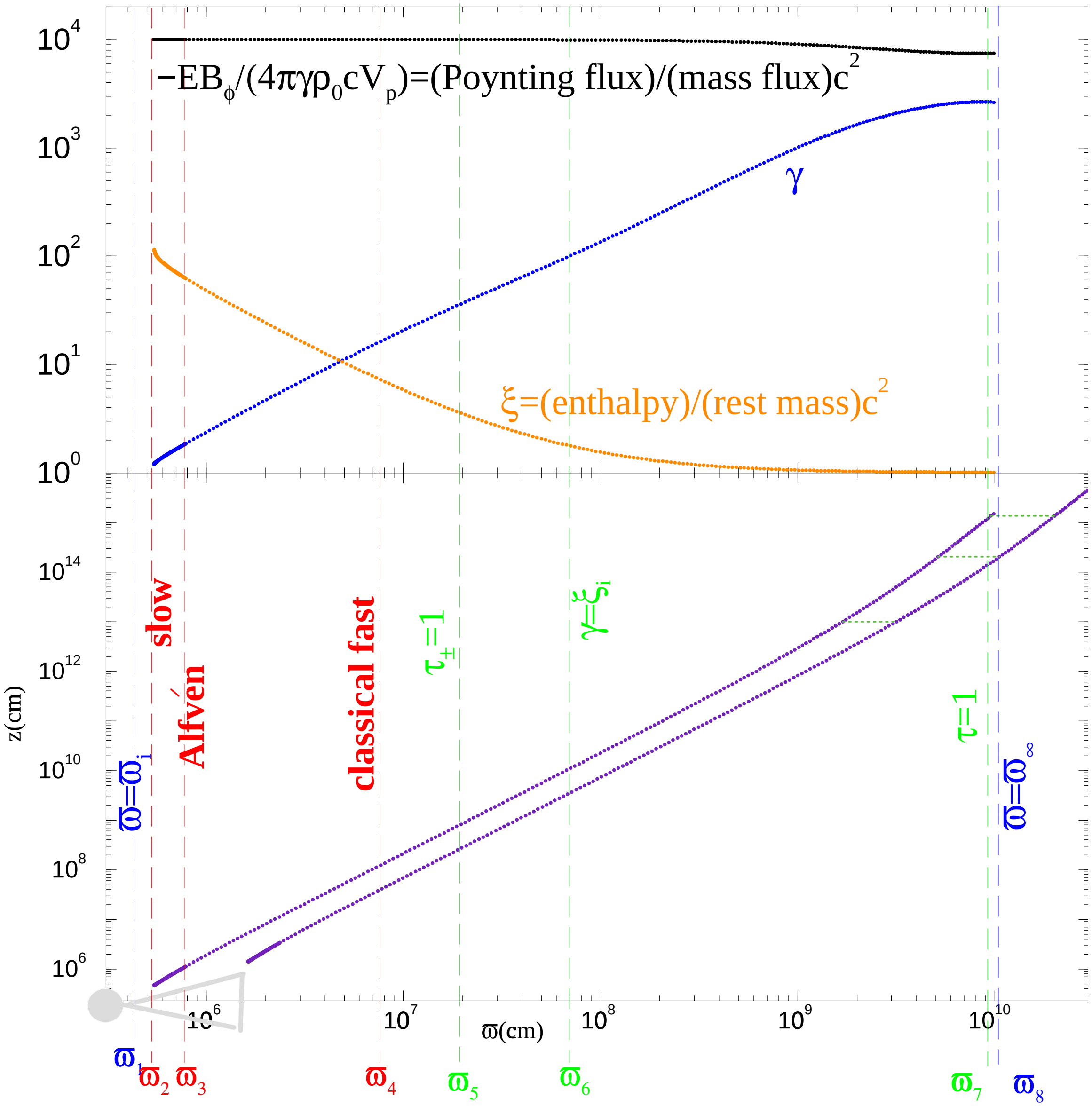
❷ highly relativistic poloidal motion ($\gamma \gg 1$)

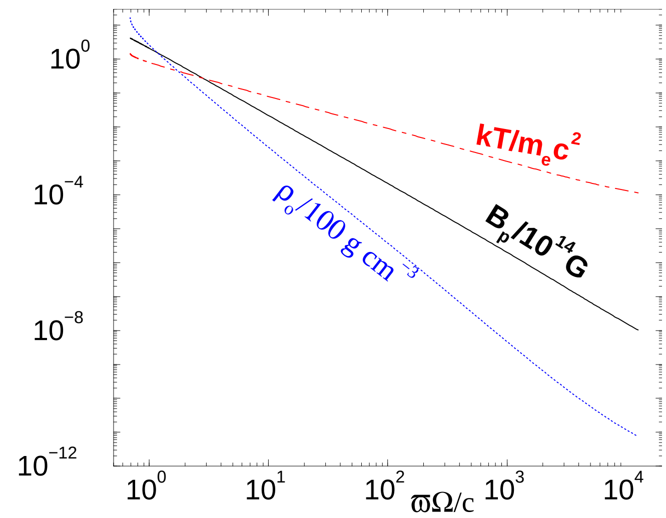
❸ quasi-steady poloidal magnetic field $\Leftrightarrow \mathbf{B}_p \parallel \mathbf{V}_p$

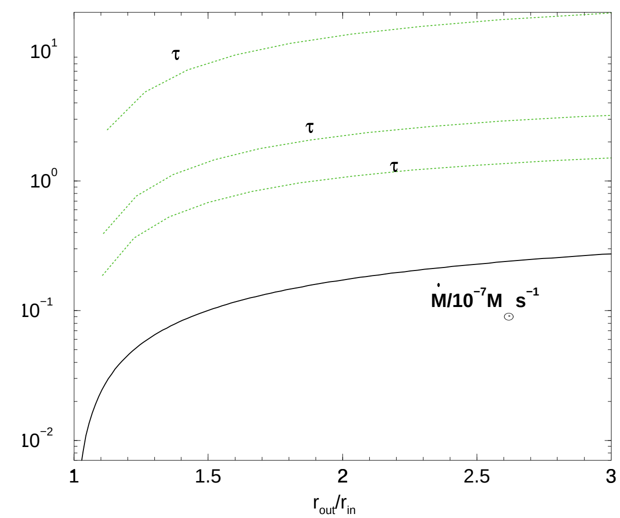
❹ adiabatic evolution: $P \propto \rho_0^{4/3}$, $\xi c^2 = c^2 + 4P/\rho_0$
($P =$ total pressure, $\xi c^2 =$ specific enthalpy)

❺ radial self-similarity (separation of variables)

Trans-Alfvénic Jets (Vlahakis & Königl 2001 ApJL, 2003a ApJ)

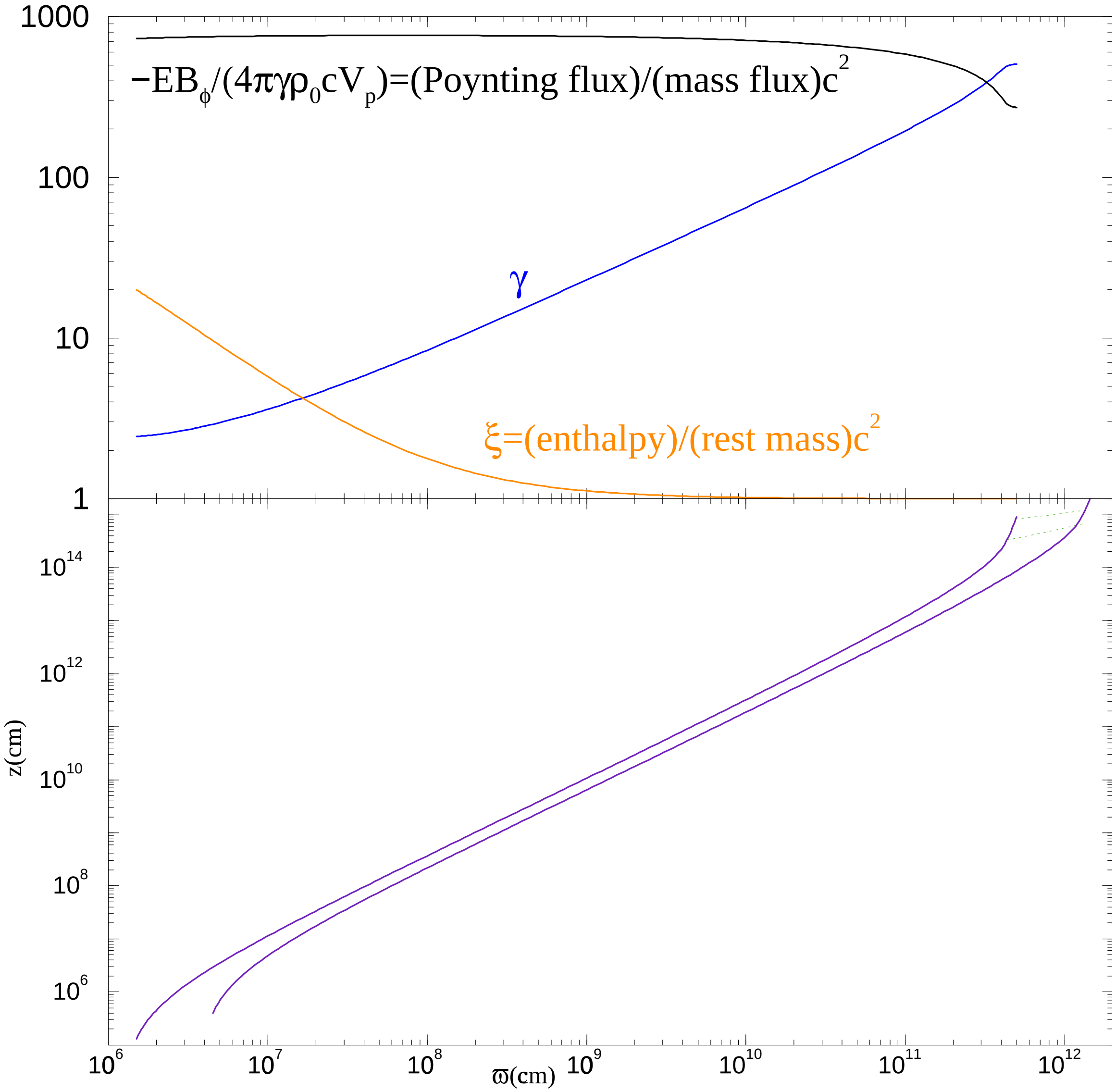


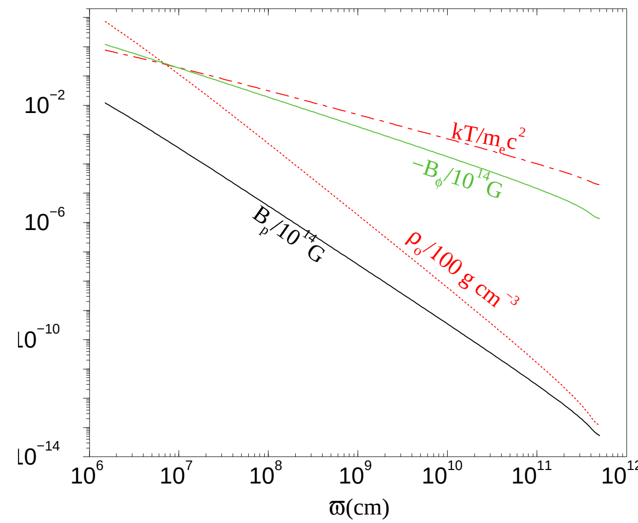


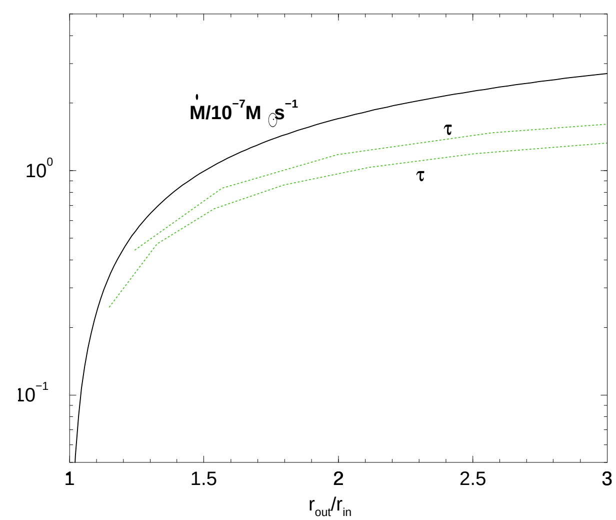


- $\varpi_1 < \varpi < \varpi_6$: Thermal acceleration - force free magnetic field ($\gamma \propto \varpi$, $\rho_0 \propto \varpi^{-3}$, $T \propto \varpi^{-1}$, $\varpi B_\phi = const$, parabolic shape of fieldlines: $z \propto \varpi^2$)
- $\varpi_6 < \varpi < \varpi_8$: Magnetic acceleration ($\gamma \propto \varpi$, $\rho_0 \propto \varpi^{-3}$)
- $\varpi = \varpi_8$: cylindrical regime - equipartition $\gamma_\infty \approx (-EB_\phi/4\pi\gamma\rho_0 V_p)_\infty$

Super-Alfvénic Jets (Vlahakis & Königl 2003b ApJ)







- Thermal acceleration ($\gamma \propto \varpi^{0.44}$, $\rho_0 \propto \varpi^{-2.4}$, $T \propto \varpi^{-0.8}$, $B_\phi \propto \varpi^{-1}$, $z \propto \varpi^{1.5}$)
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The baryon loading problem

- Proton mass in jet: $M_{\rm proton} = 3 \times 10^6\ (\mathcal{E}/10^{51}\text{ergs})\ (\gamma_\infty/200)^{-1} M_\odot$.

- The disk would be $\sim 10^4$ times more massive even if 10% of its gravitational potentional energy could be converted into outflow kinetic energy (baryon loading problem).

A possible resolution (Fuller et al. 2000):

- If the source is neutron-rich, then the neutrons could decouple from the flow before the protons attain their terminal Lorentz factor.

- Disk-fed GRB outflows are expected to be neutron-rich, with n/p as high as $\sim 20 - 30$ (Pruet et al. 2003; Beloborodov 2003; Vlahakis et al. 2003).

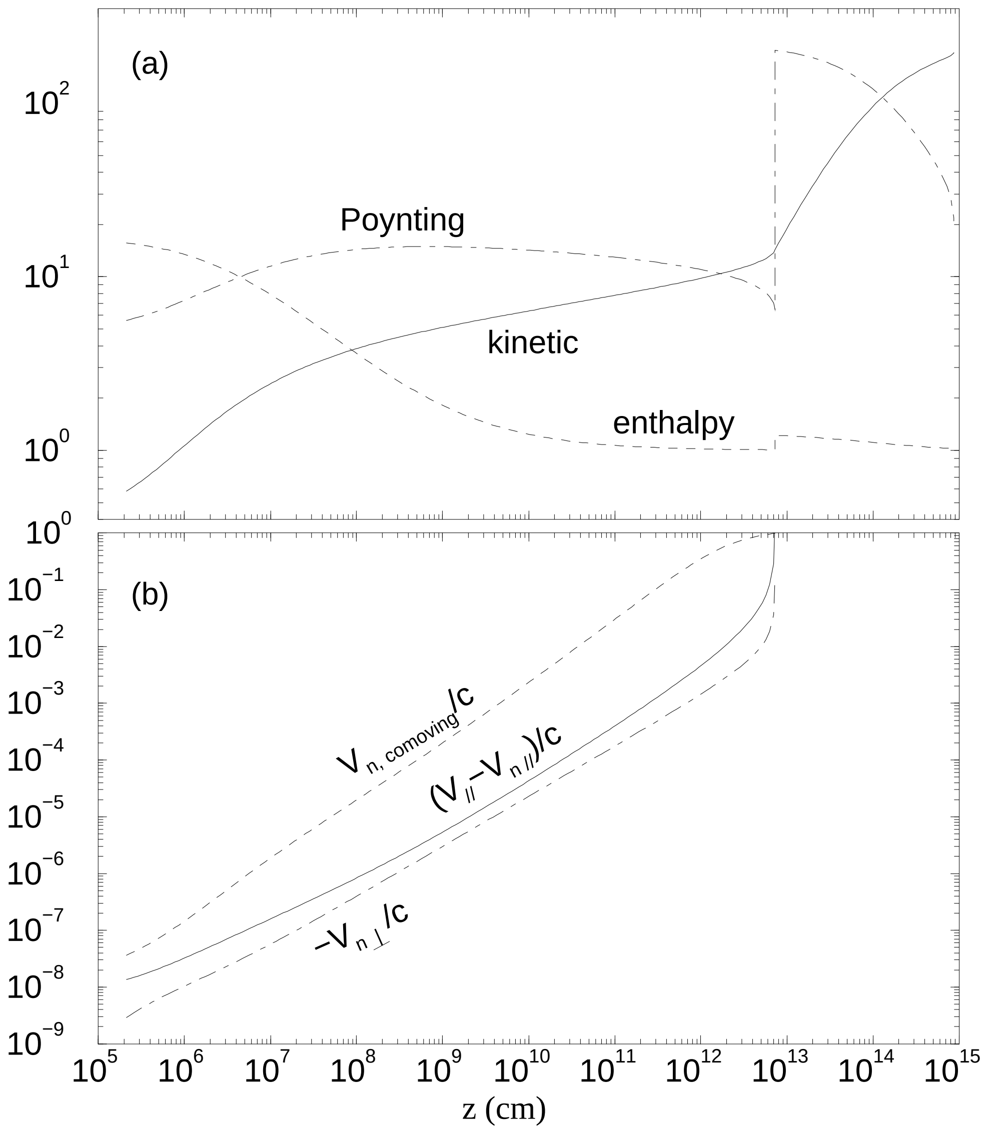
However, it turns out that the decoupling Lorentz factor $\gamma_{\rm d}$ in a thermally driven, purely hydrodynamic outflow is of the order of the inferred value of γ_∞ (e.g., Derishev et al. 1999; Beloborodov 2003), which has so far limited the practical implications of the Fuller at al. (2000) proposal.

Neutron-rich hydromagnetic flows

(Vlahakis, Peng, & Königl 2003 ApJL)

- Part of the thermal energy could be converted to electromagnetic (with the remainder transfered to baryon kinetic).
- The Lorentz factor increases with lower rate compared to the hydrodynamic case. This makes it possible to attain $\gamma_{\rm d} \ll \gamma_\infty$, as it is shown in the following solution.
- The energy deposited into the Poynting flux is returned to the matter beyond the decoupling point.

- Pre-decoupling phase:
  - The momentum equation for the whole system (protons/neutrons/$e^{\pm}$/photons/electromagnetic field) yields the flow velocity.
  - The momentum equation for the neutrons alone yields the neutron-proton collisional drag-force, and the drift velocity.
  - When $V_{\rm proton} - V_{\rm neutron} \sim c$ the neutrons decouple.
- Post-decoupling phase:
  - We solve for the protons alone ($+$ electromagnetic field).



(a) The three components of the total energy flux, normalized by the mass flux $\times\ c^2$.
(b) Proton–neutron drift velocity.

$n/p = 30$
decoupling at $\gamma_d = 15$

$\gamma_\infty = 200$
$\mathcal{E}_{\rm proton} \approx 10^{51}$ergs $\approx 0.5\ \mathcal{E}_{\rm neutron}$

Because of the magnetic collimation, the neutrons also acquire a transverse drift relative to the protons: $V_{\rm neutron,\perp} \sim 0.1c$ at decoupling.

Conclusion

- Trans-Alfvénic flow:
  - ⋆ The flow is initially thermally accelerated ($\xi\gamma = const.$; the magnetic field only guides the flow), and subsequently magnetically accelerated up to Lorentz factors corresponding to equipartition between kinetic and Poynting fluxes, i.e., $\sim 50\%$ of the initial total energy is extracted to baryonic kinetic. $\gamma \propto \varpi$ in both regimes.
  - ⋆ The fieldline shape is parabolic, $z \propto \varpi^2$ and becomes asymptotically cylindrical.

- Super-Alfvénic flow:
  - ⋆ Similar results, except that the Lorentz factor increases with lower rate: $\gamma \propto \varpi^{\beta}, \beta < 1$. Also $z \propto \varpi^{\beta+1}$.

- Neutron decoupling:
  - ⋆ In pure-hydro case $\gamma_{\rm d} \sim \gamma_\infty$.
  - ⋆ Magnetic fields make possible $\gamma_{\rm d} \ll \gamma_\infty$.
  - ⋆ The decoupled neutrons decay into protons at a distance $\sim 4 \times 10^{14}(\gamma_{\rm d}/15)$cm. In contrast with the situation in the pure-hydro case, these two components are unlikely to interact with each other in the hydromagnetic case since their motions are not collinear.
  - ⋆ Observational signatures of the neutron component remains an interesting problem for future research.