Relativistic, under-dense outflows

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Outline

- Introduction
- Two-fluid simulations
- Analytic model of an electromagnetic precursor

Under-dense vs. over-dense

- Can the plasma screen out the electric field?
- Answer depends on the electron density and time available

$\omega/\omega_{\mathrm{pe}} \ll 1$	YES – *over-dense*
$\omega/\omega_{\mathrm{pe}} > 1$	NO – *under-dense*

- . . . and on the amplitude $\omega_{\mathrm{pe}} = \left(4\pi n_{\mathrm{e}} e^2/\langle\gamma\rangle m\right)^{1/2}$
- Over-dense: only MHD modes (magnetosonic, Alfven), phase speeds subluminal
  ⇒ use ideal-MHD, force-free. . .
- Under-dense: high-frequency, transverse electromagnetic modes possible, with superluminal phase speed
  ⇒ use (at least) two-fluids.

Under-dense zones in a conical $e^{\pm}$ jet/beam

Three dimensionless jet parameters:

1. $(\text{Mass-loading})^{-1}$ $\mu = L/\dot{M}c^2$
2. Magnetization $\sigma_0 = \text{Poynting flux}/\text{K.E. flux}$
3. *A parameter describing the jet composition: e/m*
    - $\text{Cross-jet potential} \times e/mc^2$: $a_0 = eBr/mc^2$
    - $(\text{Dimensionless luminosity/unit solid angle})^{1/2}$:

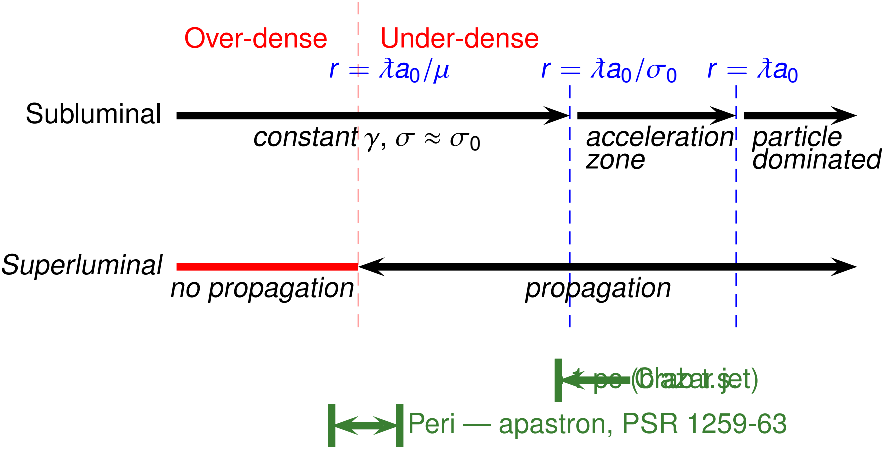
      $a_0 = (4\pi L/\Omega_\mathrm{s})^{1/2}\left(e^2/m^2c^5\right)^{1/2}$

Constraints/Estimates:

1. $a_0 = 3.4 \times 10^{14}\sqrt{4\pi L_{46}/\Omega_\mathrm{s}}$
2. $\sigma_0 \lesssim \mu^{2/3}$ (for a supermagnetosonic jet)
3. Pair multiplicity $\kappa_0 = a_0/(4\mu) > 1$

Under-dense zones in a conical jet

Fluctuation wavelength λ, $a_0 \gg \mu \gg \sigma \gg 1$

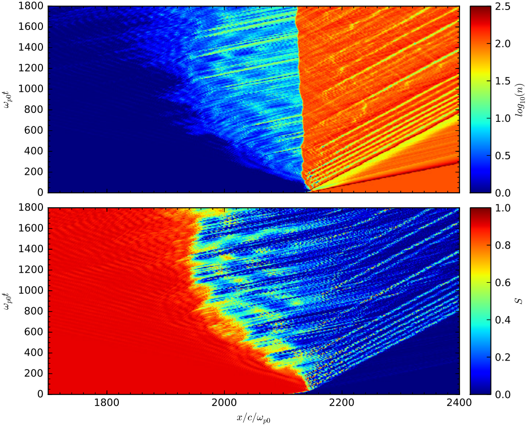


Two-fluid simulations

Simplest description that includes superluminal, electromagnetic modes is one with two charged fluids Amano & Kirk ApJ (2013)

- Relativistic, finite temperature electron & positron fluids
- 1D in space, 3D in momentum and EM fields
- Initial conditions:
    - Left half: circularly polarized, cold, static shear, $\gamma = 40$, $\sigma = 10$, $\lambda \approx \lambda_{\rm g}/4$
    - Right half: shocked (R-H conditions) unmagnetized plasma

Time evolution

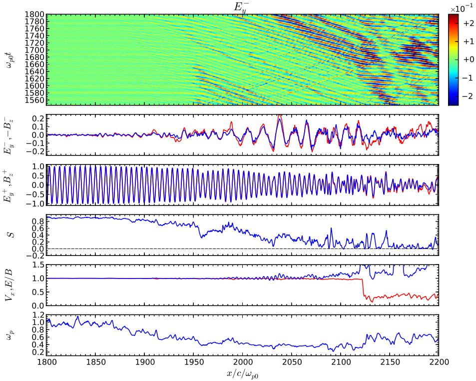


$\Gamma = 40$

$\sigma = 10$

$\omega = 1.2\omega_{\mathrm{p}}$

Wave helicity



Positive helicity injected wave (E^+, B^+).

Backwards propagating, negative helicity waves generated.

$E > B$ in precursor and downstream ($v_{\mathrm{wave}} = B/E$).

Simulation Results and Implications

- Poynting flux dissipated completely
- A precursor containing strong electromagnetic waves is formed
- A hydrodynamic shock remains
- Particles are not tied to magnetic field lines in the downstream medium

Radiation-damped precursor

Analytical model of wave deceleration by radiation damping Mochol & Kirk ApJ (2013).

Radiation mechanisms:

- synchro-Compton radiation (but with $\gamma \sim a$)
  - $\Omega_{\rm pulsar} \rightarrow eB_{\rm eff}/\gamma mc$
  - Frequency $\propto \gamma^2 B_{\rm eff} \propto \gamma^3 \propto 1/r^3$
  - Power $\propto \gamma^2 B_{\rm eff}^2 \propto \gamma^4 \propto 1/r^4$
- enhanced inverse-Compton radiation, in the presence of target photons
  - Frequency $\propto \gamma^2 \nu_{\rm target} \propto 1/r^2$
  - Power $\propto \gamma^2 U_{\rm target} \propto 1/r^2$

$\Rightarrow$ Gamma-ray binaries

Be star-pulsar binary

X-rays from interacting winds Tavani & Arons (1997)

Be star wind:

$\dot{M} \sim 10^{-8}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$

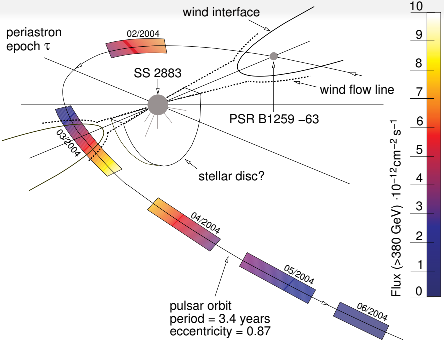
$v_\mathrm{wind} \sim 10^{3}\,\mathrm{km\,s}^{-1}$

Pulsar wind:

$L_\mathrm{s.d.} \approx 8 \times 10^{35}\,\mathrm{erg\,s}^{-1}$

Momentum balance:

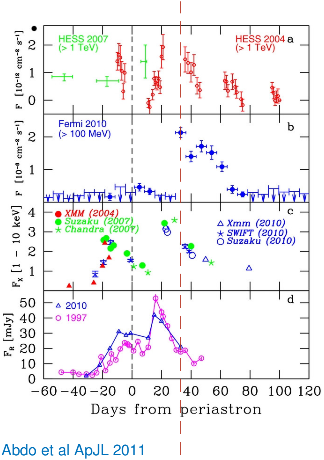
$$\frac{r_\mathrm{Be}}{r_\mathrm{p}} = \sqrt{\frac{L_\mathrm{s.d.}}{\dot{M} v_\mathrm{wind} c}} \sim 0.7$$



Based on cartoon by O. de Jager

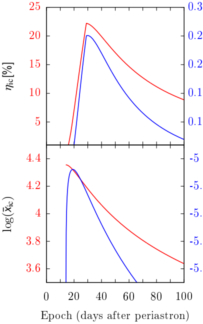
But $L_\mathrm{s.d.} \gg L_\mathrm{Be\ wind}$

GeV flare from PSR B1259−63



Abdo et al ApJL 2011

Stationary EM precursor



Efficiency

Characteristic frequency

Inverse Compton

Synchro-Compton

Conclusions

- Under-dense flows present in pulsar winds and possibly also in AGN jets
- Their interactions with obstacles differ substantially from those of MHD flows.
- An observable signature is predicted from “thermal” particles in an electromagnetic precursor (gamma-ray binaries)

Future work: particle acceleration properties. . .