Max Planck Institute
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The role of the kink instability in magnetically driven jets

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Structure of the talk

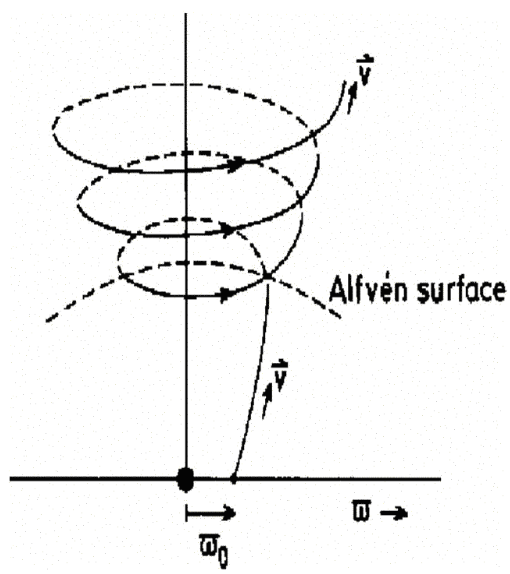
- Introduction
  - Magnetically launched jets
- MHD instabilities
  - Here we focus on the kink instability
  - The growth time scale of the instability
- The model
  - The RMHD equations
  - Modeling of the instability
  - Parameters
- Applications
  - AGN jets
  - Gamma-ray bursts
- Summary-conclusions

Magnetically launched jets I

- Relativistic and collimated outflows (jets) observed in Quasars and micro-Quasars
  - Also present in GRBs so that to overcome the compactness problem (e.g. Piran 1999) and explain the achromatic breaks in the afterglows (Rhoads 1997)
- The leading mechanism for jet formation and collimation in the (micro)-Quasar case is that of magnetic driving
- This mechanism has been applied to the case of stars (Weber & Davis 1967; Mestel 1968), pulsars (Michel 1969; Goldreich & Julian 1970), accretion disks (Blandford & Payne 1982), rotating black holes (Blandford & Znajek 1977)

Magnetically driven jets II

- Magnetic fields anchored to a rotating object can accelerate material centrifugally
- This takes place up to the Alfvén radius
  - There the toroidal and poloidal components of the field are comparable
  - Further out the toroidal component dominates
  - For Poynting (i.e., magnetically dominated) jets this is very close to the light cylinder



Magnetically driven jets III

- The flow is likely to cross the fast magnetosonic point at $r_f = \text{a few } r_L$ (Shakurai 1985; Li et al. 1992; Beskin 1998)
  - At this point the four velocity of the flow is $u \approx \mu^{1/3}$
  - The ratio of magnetic to kinetic energy flux is $\approx \mu^{2/3}$

  → *In the case of a Poynting jet, most of the energy remains in the magnetic field*

- Further acceleration of the flow is hard within ideal MHD except if the flow is decollimated (Li et al. 1992; Begelman et al. 1994)
  - See, however, Vlahakis & Königl 2003

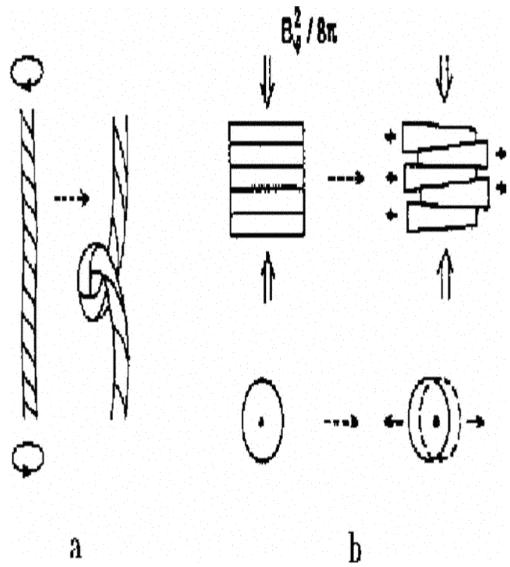
Instabilities in jets

- Magnetic jets have to survive a number of instabilities (e.g. Kadomtsev 1966) such as
  - Pressure driven instabilities
  - Kelvin-Helmholtz instabilities
    - Especially dangerous at the super-Alfvénic but sub-fastmagnetosonic region
  - Current driven instabilities
    - Very relevant for Poynting jets
    - The most dangerous is the m=1 kink instability
- *Here we focus on the effect of the kink instability on the dynamics of the jet*

-> *This study suggests it is efficient in accelerating the flow through dissipating Poynting flux*

The kink instability I

- Well known in plasma physics from Tokomak experiments
- Drives its energy from the φ component of the magnetic field
- Linear stability analysis shows that the growth time scale is the Alfvén crossing time (Begelman 1998; Appl 2000)



The kink instability II

- The non-linear development of the instability is controversial
- *3D RMHD simulations will provide the answer*
- The instability may proceed on the Alfvén crossing time scale to rearrange to B-field (Lery et al. 2000; Baty & Keppens 2002)

  $t_k = r\theta\gamma / v_{A,\varphi}$ "fast kink"
- It is also possible that the jet develops a "back bone" of strong poloidal field that slows down instabilities (Ouyed et al. 2003)

  $t_k = (r\theta\gamma / v_{A,\varphi}) \cdot e^{B_p^{co}/B_\varphi^{co}}$ "slow kink"

The model I

- We follow the flow from the fast magnetosonic point assuming
  - *radial and steady flow: do not address the issue of collimation*
  - *Ignore the θ-structure of the jet*
- Ignoring (for the moment) radiative losses, mass and energy conservation yield

$$\dot{M} = r^2 u \rho c$$

$$L = w r^2 \gamma u c + v (r B_\varphi)^2 / 4\pi$$

- An important quantity for the flow is the ratio σ of the Poynting to the kinetic energy flux

The model II

- The system of equations is complete with the use of the momentum equations, equation of state (that of ideal ionized gas) + induction equation
- For *ideal* MHD the induction equation yields

$$\partial_r r v B_\varphi = 0$$

- The last expression is modified (see Drenkhahn & Spruit 2002; "non-axisymmetric rotator") to account of the instability-dissipated energy to

$$\partial_r r v B_\varphi = -\frac{r B_\varphi}{c t_k}$$

Equations…

$$\partial_r r^2 \rho u = 0$$

$$\partial_r r^2 \left(w\gamma u + \frac{\beta B_\varphi{}^2}{8\pi} \right) = 0 - r^2 \gamma \frac{\Lambda}{c}$$

$$\partial_r r^2 \left(w u^2 + P + \frac{(1+\beta^2 B_\varphi{}^2)}{8\pi} \right) = 2rP - r^2 u \frac{\Lambda}{c}$$

$$\partial_r \beta r B_\varphi = -\frac{r B_\varphi}{c t_k}$$

$$P = (\gamma_a - 1)e$$

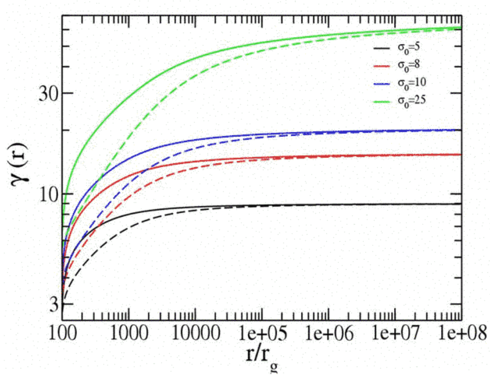
$$w = \rho c^2 + e + P$$

Model parameters

- The model parameters determine the initial conditions of the flow at the fast point
- They are $L, r_f, \sigma_o, B_{r,o}/B_{\varphi,o}, \theta$
- Solving the RMHD equations we follow the characteristics of the flow $\rho, e, p, \gamma, B_\varphi, B_r$ as a function of radius

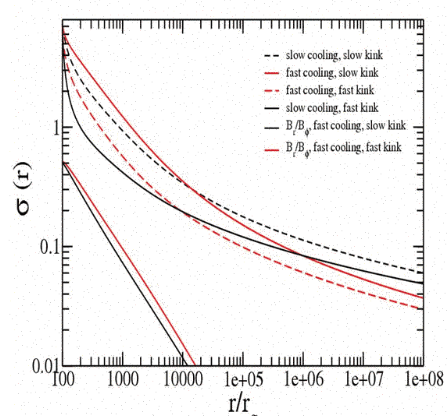
Results I: AGN jets

- The Lorentz factors ~10-20 of AGN jets imply $\sigma_o \sim 10$
- The flow accelerates fast and γ saturates within ~10^4 gravitational radii
- The instability has enough time to grow and convert most of the magnetic energy into kinetic
- A large fraction of the dissipated energy can in principle be radiated away within the "Blazar zone"



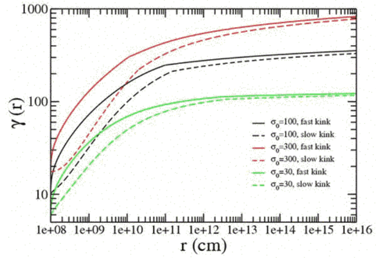
Results I: AGN jets (continued)

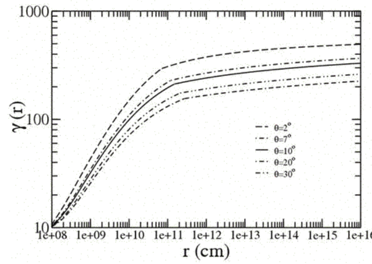
- The flow becomes matter dominated at ~1000r_g
- The toroidal component of the B-field dominates



Results II, GRB outflows

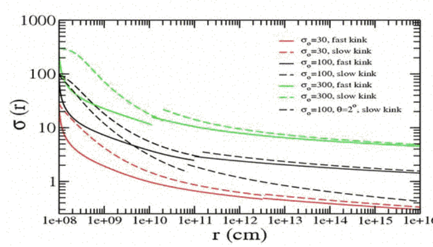
- Now there is another characteristic radius: that of the photosphere r_{ph}
  - An iterative procedure is followed to calculate its location
  - Radiation is coupled to matter bellow r_{ph} and does not interact above
- To overcome the compactness problem $\sigma_o \geq 30$
- Larger magnetization and smaller opening angles lead to faster flows
- The Lorentz factor does not saturate

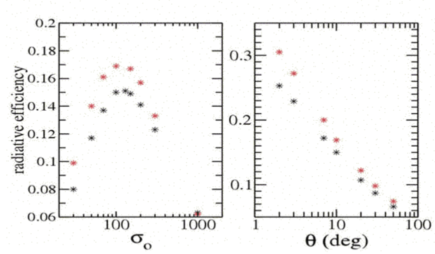




Results II, GRB outflows (continued)

- The conversion of magnetic to kinetic energy is partial
  - In the afterglow regime the ejecta are still moderately magnetized
  - Even more in the "internal shock regime"
    - This reduces further the efficiency of the shocks
- The instability-released radiation can be high ~20% of the flow luminosity





Summary-Conclusions

- We explored the role of the kink instability with the scenario of magnetically driven jets
- The instability is fed by B_φ and converts Poynting to kinetic flux
- It is very efficient in AGN jets which on pc scales become matter dominated
  - The instability-released energy could power the Blazar emission
- GRB jets remain moderately magnetized out to the afterglow region
  - Early afterglow observations can probe the ejecta content
  - The instability released energy can power the prompt emission efficiently

Current work: Photospheric emission

- Compton scattering can be important at the Thompson photosphere r_{ph} (see also Pe’er et al. 05)
- Applies to models with dissipation at r_{ph}
  - Internal shocks
  - Instability released energy
  - Magnetic reconnection models (Drenkhahn & Spruit 2002, Giannios & Spruit 2005)
- (unsaturated) Comptonization may lead to strong deviations from “quasi thermal” PE