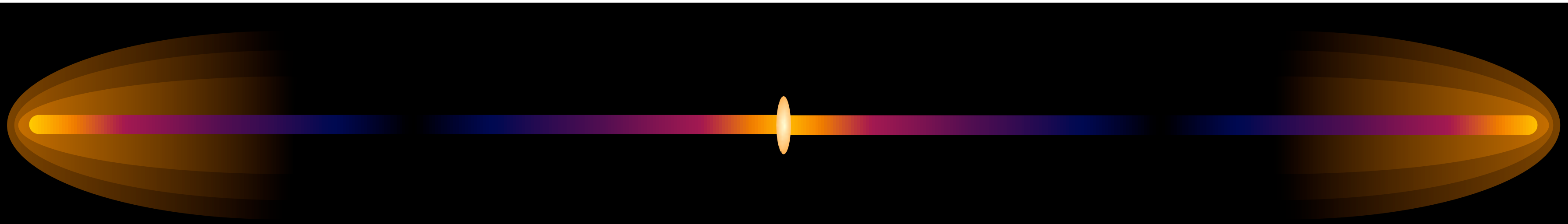

The Role of Magnetic Fields in the Production and Propagation of Relativistic Jets

(A Review with a Suggested Paradigm)

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The Innermost Regions of Relativistic Jets
And Their Magnetic Fields
Granada, Spain; 10 June 2013

Outline

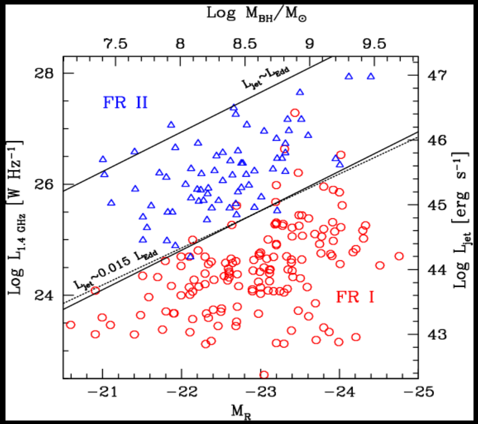
N.B.: I will discuss mainly AGN jets in this brief review.
However, what we learn from AGN jets likely will affect how we view
GRB, XRB, and even proto-stellar jets

- Talk Summary: Class Divisions in AGN Jets
- Preliminary Discussion: MHD Waves and MHD Jets
- Launching, Acceleration, Collimation of MHD Jets
- Beyond the Magnetosonic Horizon

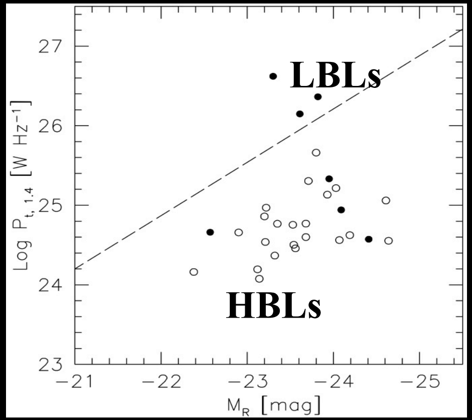
Summary: Class Divisions in AGN Jets

- Two widely-held cherished beliefs…
  - All sources appearing as BL Lacs when viewed nearly end-on and imaged with VLBI on the parsec scale are, in fact, drawn from the same population: the class of FR I radio sources
  - All sources appearing as Quasars when viewed nearly end-on and imaged with VLBI on the parsec scale are, in fact, drawn from the same population: the class of FR II radio sources

Ghisellini & Celotti (2001)



Giroletti *et al.* (2006)



- …Lead to a surprising conclusion
  - Jets not only <u>*know early*</u> whether or not they are going to be an FR I or FR II, i.e. within only 10^{5-6} stellar (BH) radii of the jet launch point, but they also <u>*have acquired morphological and magnetic properties*</u> that are related to what type of jet they eventually will be

➔ The origin of the FR sequence lies very deep in the nucleus of the host galaxy

Summary: The "Phoenix-Fire" Paradigm For the Birth of Astrophysical Jets

Fire = The Jet Recollimation Shock at significant distance from the BH

Phoenix (bird) = The Jet itself, which is reborn in the shock in its (nearly) final form

- Tenet #1: All jets have an Acceleration & Collimation Zone (ACZ) that ends with the jets being hyper-magnetosonic and passing through a magnetosonic (MS) horizon
- Tenet #2: Beyond the MS horizon, jets pass through at least one (re-)collimation shock (RCS), in which they are reborn as a new type of jet that can propagate long distances

- The goal in this talk is to discuss (on the basis of observations and simulations) the possible properties of the RCS and the post-shock jet:
  - Is the jet super-, trans-, or sub- (magneto-)sonic (V_j vs. $c_{ms} = [c_s^2 + V_A^2]^{1/2}$)?
  - Is it Kinetic (KFD) or Poynting (PFD) Flux Dominated ($\frac{1}{2} \rho_0 V_j^3$ vs. $\rho_0 R_j \Omega_f V_A^2$)?
  - What is the jet's internal magnetic properties (U_p vs. U_{mag} or c_s vs. V_A) ?
- Could processes in the RCS be the origin of the Fanaroff & Riley sequence?

Preliminary Discussion: MHD Waves and MHD Jets

Preliminaries: MHD Waves

It is **more** important for jet astronomers to understand MHD waves than for (optical) stellar astronomers to understand nuclear reactions.
Why? Because MHD waves are potentially observable in jets.

- HydrodynamicWaves (NR):

$$\frac{\partial\rho}{\partial t} + \boldsymbol{V}\cdot\nabla\rho + \rho\nabla\cdot\boldsymbol{V} = 0$$
$$\rho\frac{\partial\boldsymbol{V}}{\partial t} + \rho\,\boldsymbol{V}\cdot\nabla\boldsymbol{V} = -\nabla p$$
$$p = K_\Gamma\,\rho^\Gamma$$

HD Equations

→

$$\rho = \rho_0 + \delta\rho\,\exp\left[\mathrm{i}(\boldsymbol{k}\cdot\boldsymbol{X} - \omega t)\right]$$
$$\boldsymbol{V} = \delta\boldsymbol{V}\,\exp\left[\mathrm{i}(\boldsymbol{k}\cdot\boldsymbol{X} - \omega t)\right]$$
$$p = p_0 + \delta p\,\exp\left[\mathrm{i}(\boldsymbol{k}\cdot\boldsymbol{X} - \omega t)\right]$$

HD Linear Perturbations
$(V_0 = 0)$

→

$$-\omega\,\delta\rho + \rho_0\,\boldsymbol{k}\cdot\delta\boldsymbol{V} = 0$$
$$-\omega\,\rho_0\,\delta\boldsymbol{V} = -\boldsymbol{k}\,\delta p$$
$$\delta p = \left(\frac{\Gamma p_0}{\rho_0}\right)\delta\rho$$

HD Linearized Equations

→

HD Dispersion Relations

no transverse sound waves $\quad 0 = 0$

longitudinal $\quad \omega^2 - c_s^2\,k^2 = 0$

↓

$$V_{ph} = \frac{\omega}{k} = \pm c_s = \left(\frac{\Gamma p_0}{\rho_0}\right)^{1/2}$$

Sound (Acoustic) Waves

- Magnetohydrodynamic Waves (NR):

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\boldsymbol{V}) = 0$$
$$\rho\frac{\partial\boldsymbol{V}}{\partial t} + \rho\,\boldsymbol{V}\cdot\nabla\boldsymbol{V} = -\nabla\left(p + \frac{B^2}{8\pi}\right) + \frac{1}{4\pi}\boldsymbol{B}\cdot\nabla\boldsymbol{B}$$
$$p = K_\Gamma\,\rho^\Gamma$$
$$\frac{\partial\boldsymbol{B}}{\partial t} + \boldsymbol{V}\cdot\nabla\boldsymbol{B} = \boldsymbol{B}\cdot\nabla\boldsymbol{V} - (\nabla\cdot\boldsymbol{V})\,\boldsymbol{B}$$

MHD Equations

→

MHD Dispersion Relations

transverse $\quad \left[\omega^2 - (\boldsymbol{k}\cdot\boldsymbol{V}_{\mathrm{A}})^2\right] = 0$

longitudinal $\quad \left[\omega^4 - k^2\,\omega^2\,c_{ms}^2 + (\boldsymbol{k}\cdot\boldsymbol{V}_{\mathrm{A}})^2\,k^2\,c_s^2\right] = 0$

→

$$V_{phA} = \pm V_{\mathrm{A}}\cos\theta = \pm\,\boldsymbol{k}\cdot\boldsymbol{V}_{\mathrm{A}}/\,k$$
$$\boldsymbol{V}_{\mathrm{A}} \equiv \frac{\boldsymbol{B}}{(4\pi\,\rho_0)^{1/2}}$$

Alfven Waves

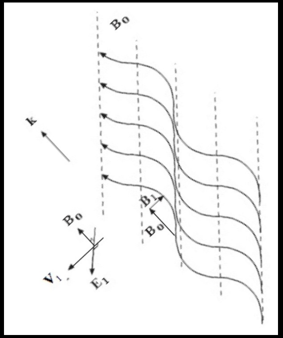
↓

$$V_F^2 = \frac{1}{2}\left[c_{ms}^2 + \left(c_{ms}^4 - 4\,c_s^2\,V_{\mathrm{A}}^2\cos^2\theta\right)^{1/2}\right]$$
$$V_S^2 = \frac{1}{2}\left[c_{ms}^2 - \left(c_{ms}^4 - 4\,c_s^2\,V_{\mathrm{A}}^2\cos^2\theta\right)^{1/2}\right]$$
$$c_{ms} \equiv \left(V_{\mathrm{A}}^2 + c_s^2\right)^{1/2}$$

Magneto-Acoustic Waves

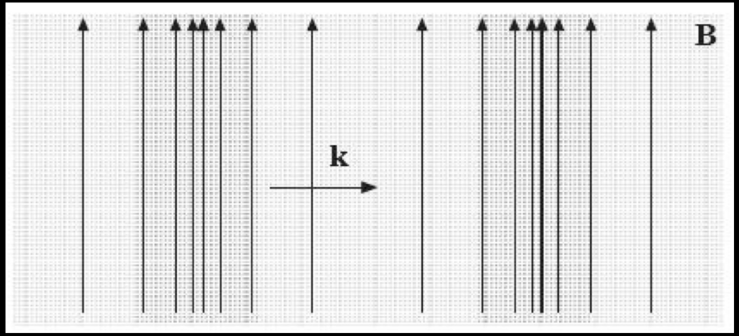
Preliminaries: Properties of MHD Waves

- MHD Waves in Magnetically-Dominated Plasmas ($U_{\mathrm{mag}} >> U_{\mathrm{p}}$; $V_{\mathrm{A}} >> \mathrm{c}_{\mathrm{s}}$)



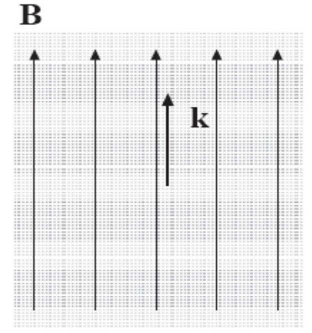
Alfven Wave ($V_{\mathrm{ph}} = V_{\mathrm{A}} \cos\theta$)

$V_{\mathrm{ph,\,A,\,||}} = V_{\mathrm{A}}$; $V_{\mathrm{ph,\,A,\,perp}} = 0$



Fast Wave ($V_{\mathrm{ph}} = V_{\mathrm{F}}$)

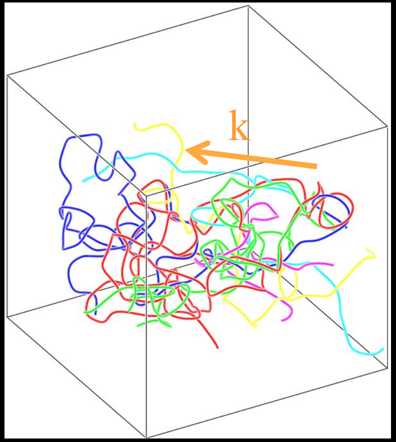
$V_{\mathrm{ph,\,F,\,||}} = V_{\mathrm{A}}$; $V_{\mathrm{ph,\,F,\,perp}} = (V_{\mathrm{A}}{}^2 + \mathrm{c}_{\mathrm{s}}{}^2)^{1/2}$



Slow Wave ($V_{\mathrm{ph}} = V_{\mathrm{F}}$)

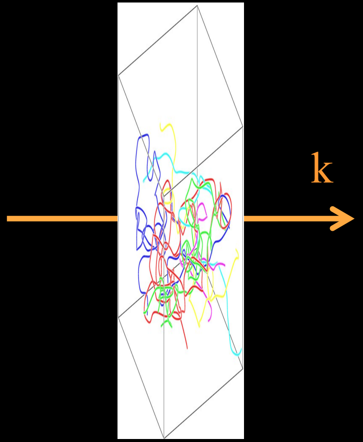
$V_{\mathrm{ph,\,S,\,||}} = \mathrm{c}_{\mathrm{s}} << V_{\mathrm{A}}$; $V_{\mathrm{ph,\,S,\,perp}} = 0$

- MHD Waves in Particle-Dominated Plasmas ($U_{\mathrm{p}} >> U_{\mathrm{mag}}$; $\mathrm{c}_{\mathrm{s}} >> V_{\mathrm{A}}$)



Alfven Wave (unimportant)

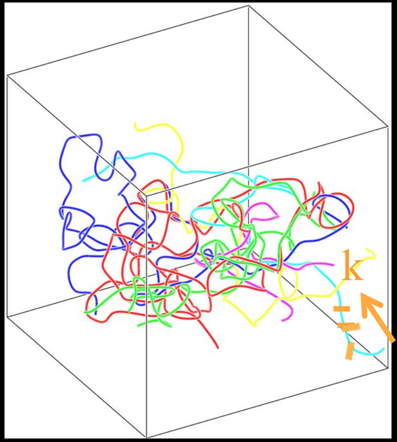
$V_{\mathrm{ph,\,A,\,||}} = V_{\mathrm{A}} << \mathrm{c}_{\mathrm{s}}$; $V_{\mathrm{ph,\,A,\,perp}} = 0$



Fast (~Sound) Wave

$V_{\mathrm{ph,\,F}} = \mathrm{c}_{\mathrm{ms}}$

(*cf*. Hughes *et al*. 1985)



Slow Wave (unimportant)

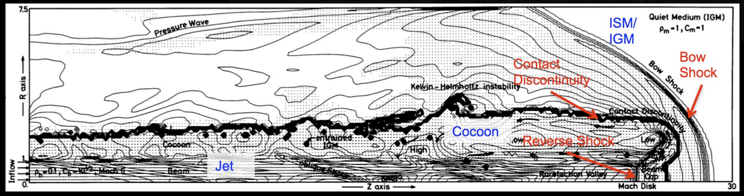
$V_{\mathrm{ph,\,S,\,||}} = V_{\mathrm{A}} << \mathrm{c}_{\mathrm{s}}$; $V_{\mathrm{ph,\,S,\,perp}} = 0$

- NOTE: When $V_{\mathrm{A}} \sim \mathrm{c}_{\mathrm{s}}$ (equipartion), all 3 types (Alfven, fast, slow) are important

Types of MHD Jets

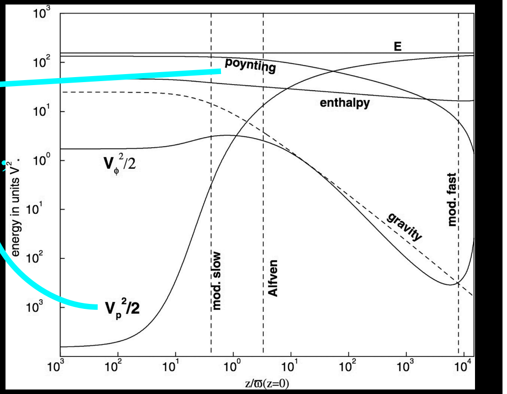
Dreher *et al.* (1987)

- Kinetic Flux Dominated (KFD; $V_j \gg [V_A^2 \ max(R_j\Omega_f, V_j)]^{1/3}$)
  - EXAMPLE: Cyg A, probably all other FR IIs
    - Morphology similar to UNMAGNETIZED HD simulations (Norman *et al.* 1982)
    - Hot spots of FR IIs are below equipartition ($U_p \gg U_{mag}$; Werner *et al.* 2012)
  - Jet propelled forward by ram pressure of plasma flow
  - $F_{Kinetic} = \gamma\,(\gamma - 1)\,\rho_0\, c^2\, V_j \approx ½\, \rho_0\, V_j^3$



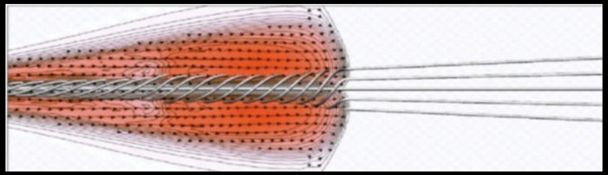
Norman *et al.* (1982)

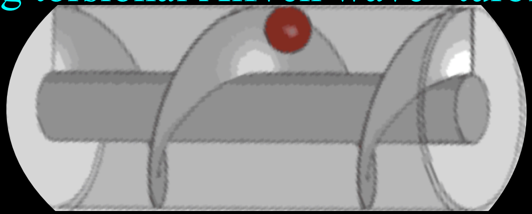
- Poynting Flux Dominated (PFD; $V_j \ll [V_A^2 \ max(R_j\Omega_f, V_j)]^{1/3}$)
  - EXAMPLE: Acceleration and Collimation Zone (ACZ)
  - Jet plasma propelled forward by rotating torsional Alfven wave "turbine"



Vlahakis *et al.* (2000)

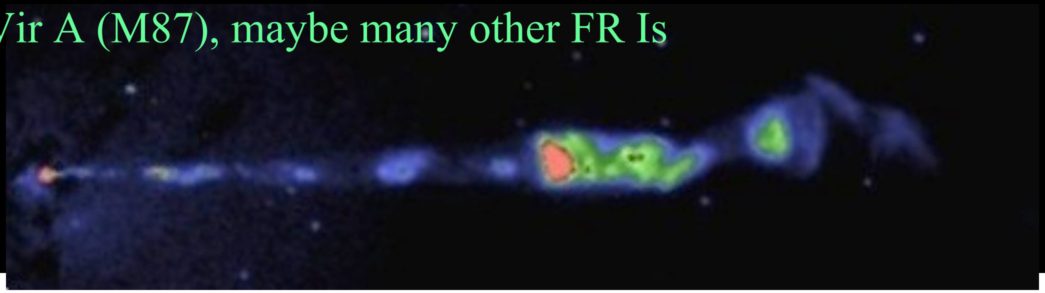
Nakamura (2001)





- $F_{Poynting} = \rho_0\, R_j\Omega_f\, V_A^2\, (\cos\alpha \ \sin\alpha)$ (α = pitch angle)

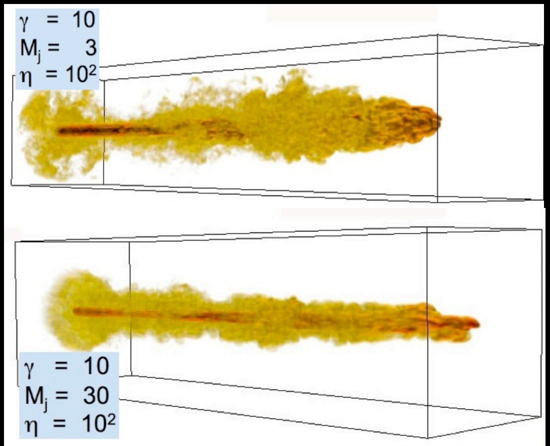
- Hybrid ($V_j \sim [V_A^2 \ max(R_j\Omega_f, V_j)]^{1/3}$)
  - Possible EXAMPLE: Vir A (M87), maybe many other FR Is



Perlman *et al.* (1999)

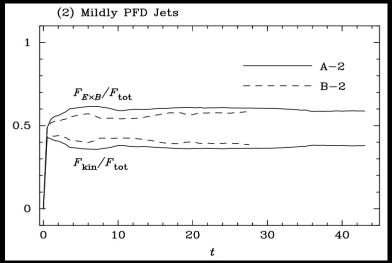
Helical Kink Instabilities in MHD Jets

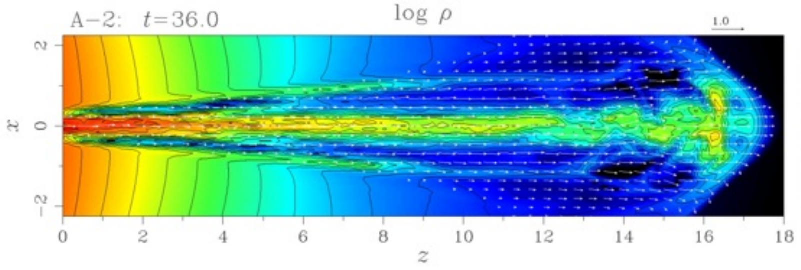
- Highly KFD jets ($V_{\rm j} >> [V_{\rm A}^2\ max(R_{\rm j}\Omega_f, V_{\rm j})]^{1/3}$)
  - Are subject to Kelvin-Helmholtz instabilities
  - But not the magnetic helical kink
  - KH stability increases with Mach number (and γ)



Rossi *et al.* (2008)

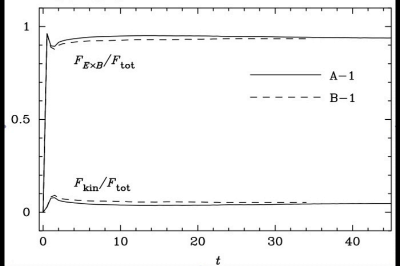
- Hybrid jets ($V_{\rm j} \sim [V_{\rm A}^2\ max(R_{\rm j}\Omega_f, V_{\rm j})]^{1/3}$)
  - Are subject to helical kink instabilities, but only moderately so

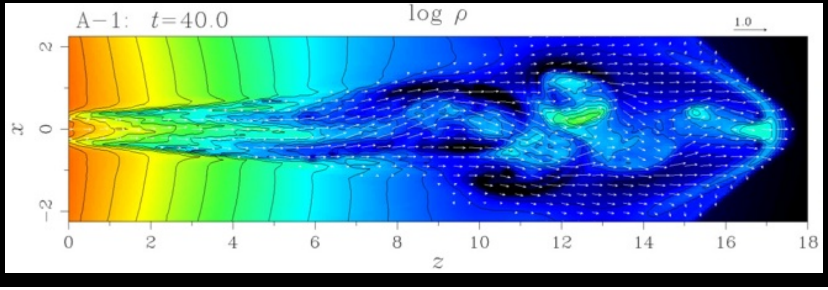




Nakamura & Meier (2004)

- Highly Poynting Flux Dominated jets ($V_{\rm j} << [V_{\rm A}^2\ max(R_{\rm j}\Omega_f, V_{\rm j})]^{1/3}$)
  - Are subject to significant helical kink instabilities
  - There are some indications that increasing Lorentz factor might mitigate these, but no definitive studies yet



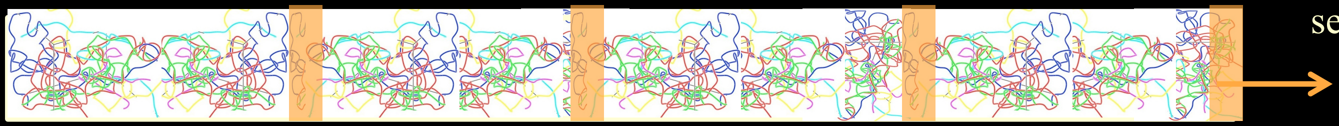


Nakamura & Meier (2004)

MHD Waves and Shocks in MHD Jets

- MHD Waves in Particle-Dominated Jets ($U_p >> U_{mag}$; $c_s >> V_A$)
  - Alfven and Slow-mode waves are probably unimportant; only FAST (~sound) waves and shocks

see Hughes *et al*. (1985)

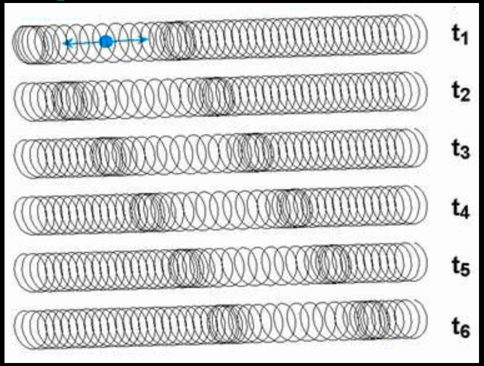


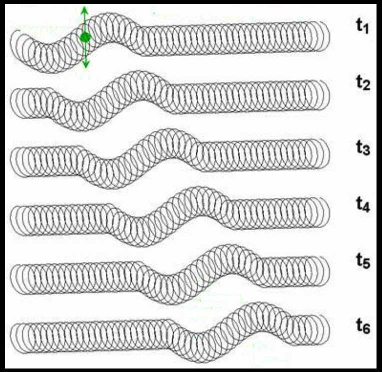
$V_{pattern} \geq V_F = c_{ms} \approx c_s$

- MHD Waves in Magnetically-Dominated Jets ($U_{mag} > U_p$; $V_A > c_s$)
  - FAST-mode waves/shocks would appear very similar to the above, but increasing the order of a **HELICAL** field

$V_{pattern} \geq V_F = c_{ms} > V_A$

FAST- Mode Wave/Shock

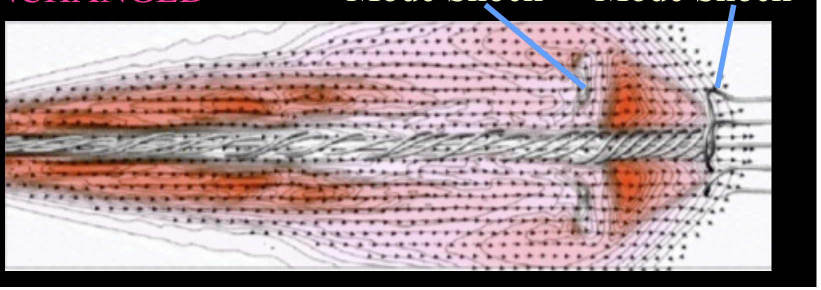




ALFVEN-Mode Wave

$V_{pattern} = V_A$

  - ALFVEN-mode waves would be very distinctive; NOTE: there are no Alfven shocks
  - SLOW-mode waves/shocks would, at first, look like FAST-mode ones
    - Plasma is compressed, synchrotron emission enhanced
    - BUT, MAGNETIC FIELD STRUCTURE REMAINS UNCHANGED
    - However, the slow-mode wave/shock would ROTATE AROUND THE JET AXIS, possibly producing strong synchrotron polarization rotation



SLOW-Mode Shock

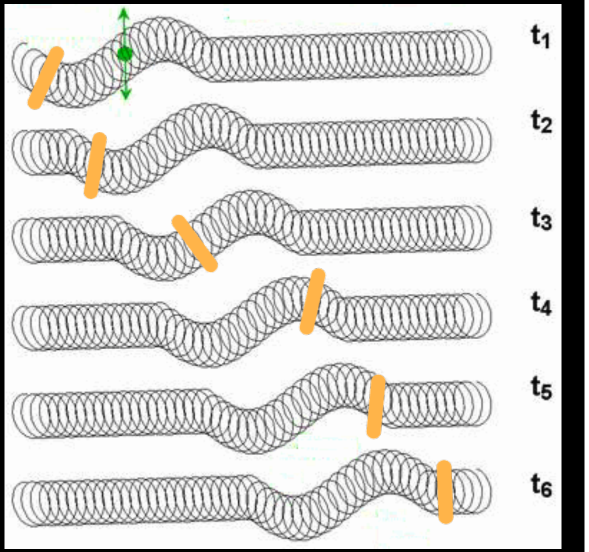
FAST-Mode Shock

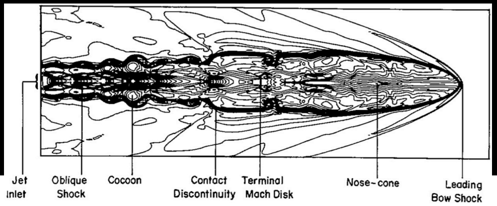
Nakamura (2001)

Application: Important Question for Observers

Which of these two forces dominates in the PORTION of the jet that I am observing?

- Particle (Plasma Pressure) Forces ($U_\mathrm{p} >> U_\mathrm{mag}$; $c_\mathrm{s} >> V_\mathrm{A}$)?
  - VLBI: Ballistic component motions (whether they are shocks or "blobs")
  - Spectrum: SSC analysis implies $U_\mathrm{mag} << U_\mathrm{p}$ (Werner *et al*. 2012)
  - Hot Spot/Lobe Morphology: Splash-back with cocoon (Norman *et al*.1982)
- Magnetic Forces ($U_\mathrm{mag} >> U_\mathrm{p}$; $V_\mathrm{A} >> c_\mathrm{s}$)?
  - VLBI:
    - Faraday rotation; Circular polarization; Helical magnetic field (Gabuzda *et al*. 2008)
    - NON-ballistic component motions ("pulled aside" by simultaneous Alfven wave; Cohen, this conference) $V_\mathrm{F,comp} / V_\mathrm{wave} \geq \sim \csc \alpha$
  - VLBI & VLA jets:
    - Strong polarization (>> 10%)
    - Helical kinks in the FLOW (not just pattern waves)
  - Hot Spot/Lobe Morphology:
    - Forward focusing (Clarke *et al*. 1986; Lind *et al*. 1989)





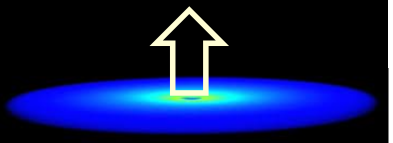
Launching, Acceleration, and Collimation of MHD Jets

Launching of MHD Jets

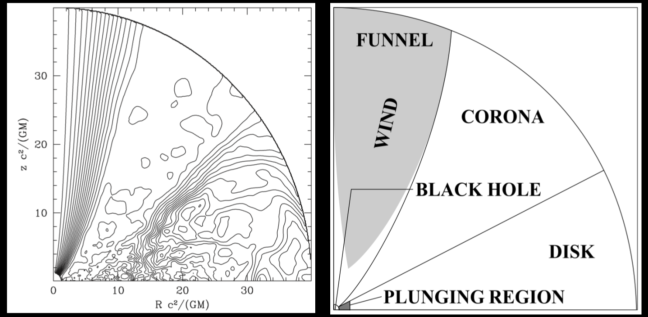
Definition of Jet Launching: Lifting jet plasma out of the deep, tidal compact object potential so it can be accelerated and collimated largely free of gravitational effects

- Tidal force in Z direction for constant $Z << R$ is quark-like

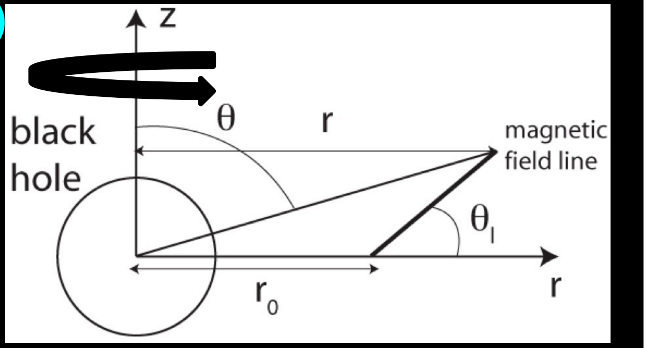
$$- GM\, Z \,/\, (R^2+Z^2)^{3/2} \approx - GM\, Z / R^3 \propto - Z$$



McKinney & Gammie (2004)



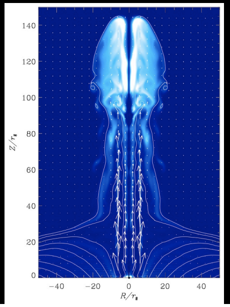
- Gas Pressure (~ slow MHD mode) Launching
  - Typical of most hot plasma RIAF / jet simulations
  - Magnetized plasma lifted up to $Z \sim R$
  - Acceleration & collimation takes place for $Z > R$
- Alfven Mode Launching (“fling”; magneto-centrifugal)
  - Rotating magnetic field, loaded with cold plasma
  - Requires $\theta_l < 60°$ (Blandford & Payne 1982)
  - Plasma is flung outward until it bends field into helix



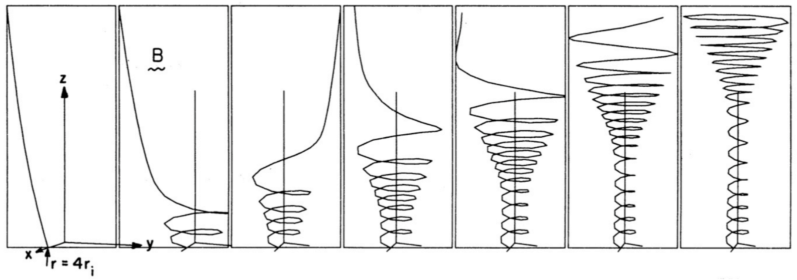
Lyutikov (2009)

- Fast MHD Mode Launching (“spring”; mag pressure)
  - “Magnetic tower”
  - Field is coiled in $Z < R$

Meier *et al.* (1997)



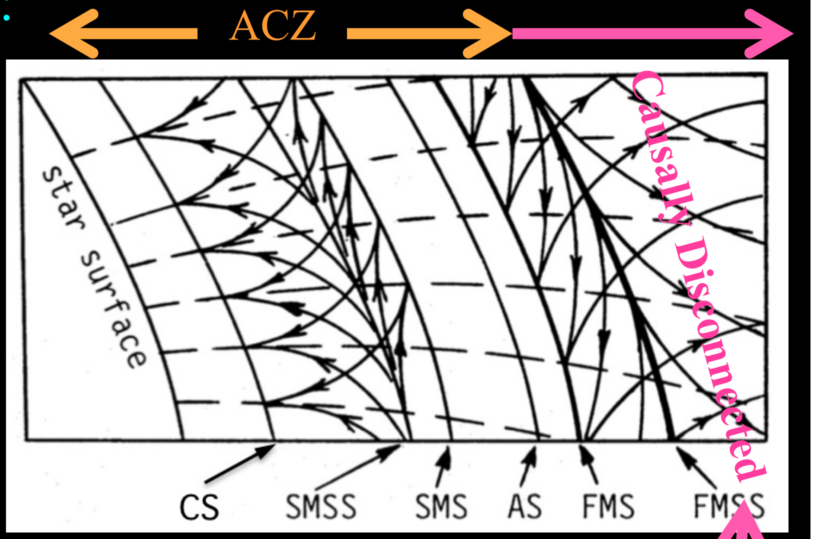
Ustyugova *et al.* (1995)



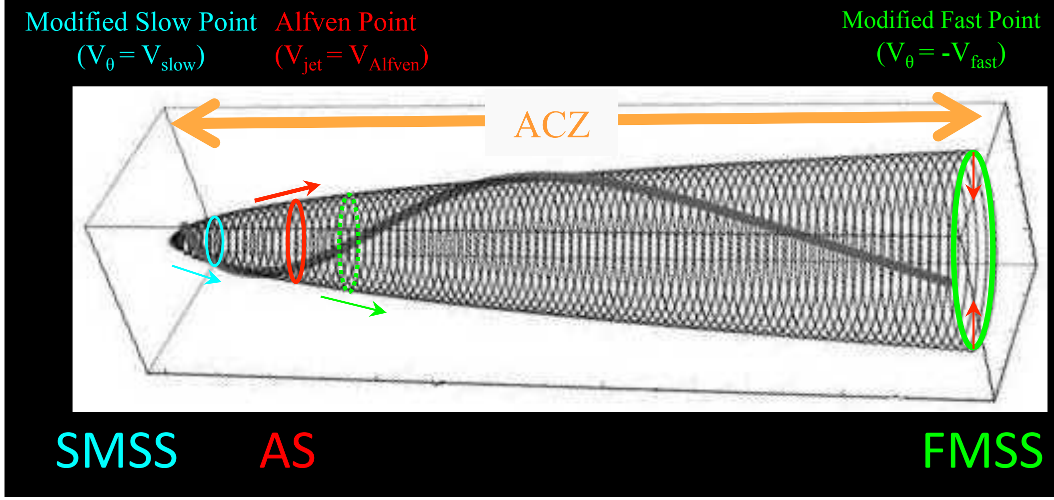
Acceleration and Collimation of MHD Jets

To first order, all jet sources should have similar ACZs: acceleration and collimation will occur as the jet passes through multiple critical and separatrix surfaces

- Critical Surfaces are where $V_j = (V_C, V_S, \text{ or } V_F)$:
  - CS: Cusp Surface
  - SMS: Slow Magnetosonic Surface
  - FMS: Fast Magnetosonic Surface
- Separatrix Surfaces (internal boundaries, from which information flows up & down stream)
  - SMSS: Slow Magnetosonic Separatrix Surface
  - AS: Alfven Surface
  - FMSS: Fast Magnetosonic Separatrix Surface – the “magnetosonic horizon”
  - A streamline crossing a separatrix surface creates a singular point



Bogovalov (1994); Contopoulos (1996)



NOTE: Beyond the magnetosonic horizon (FMSS), information flow (characteristics) points only DOWNSTREAM.

Therefore, NO EVENT OR FEATURE BEYOND THE FMSS CAN AFFECT THE STRUCTURE OF THE ACZ (via MHD waves)

Beyond the Magnetosonic Horizon:
How the Jet is Dispatched in its Final Form

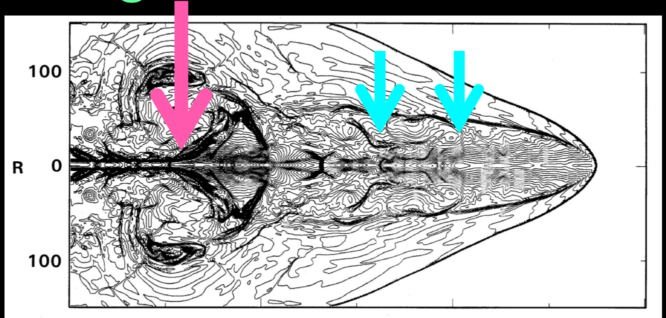
What is the State of the Jet Beyond the Magnetosonic Horizon?

- Kinetic energy Flux Dominated ($V_j >> [V_A^2\ max(R_j\Omega_f, V_j)]^{1/3}$)
- Plasma internal energy still dominated by helical magnetic field ($U_{mag} >> U_p$; $V_A >> c_s$)
- Hyper-magnetosonic ($V_j >> c_{ms} \sim V_A$)

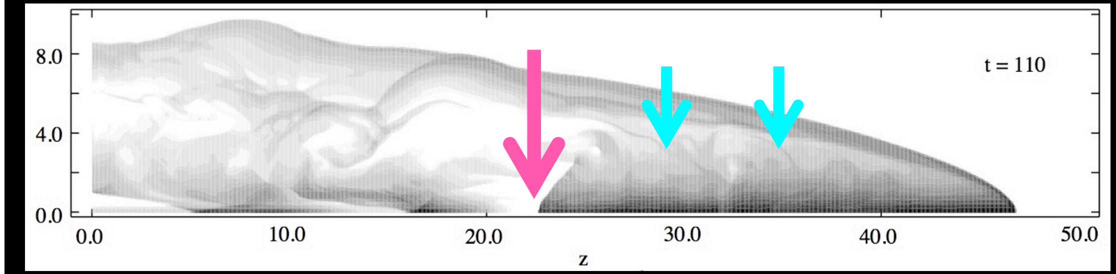
2-D Simulations of this Kind of Flow All Show the Same Results

(Clarke *et al*. 1986; Lind *et al*. 1989; Komissarov 1999; Kraus & Camenzind 2001)

- Flow is unstable to forming a strong, quasi-stationary magnetic pinch shock
  - Longitudinal compression increases toroidal field strength
  - Which pinches (increases hoop stress on) the plasma
  - Which further enhances the shock strength
- The post-shock flow is slowed to trans-magnetosonic ($V_j \sim c_{ms} \sim V_A$)
- A "magnetic chamber" forms that periodically ejects plasma pulses



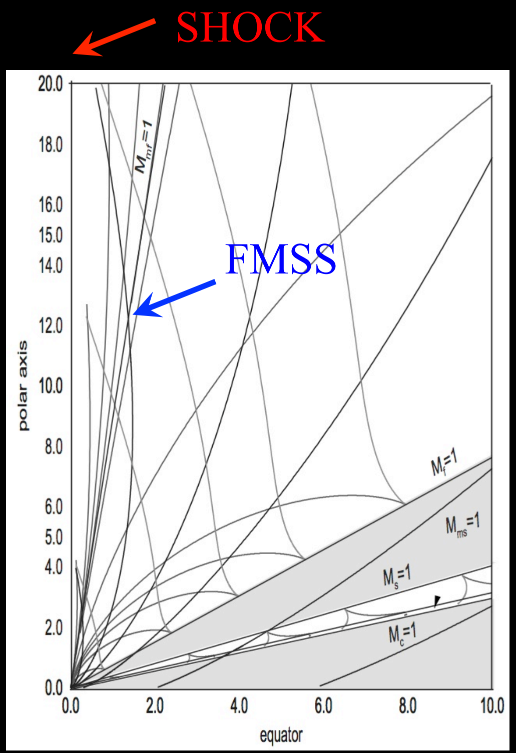
Lind, Payne, Meier, & Blandford (1989; NR)



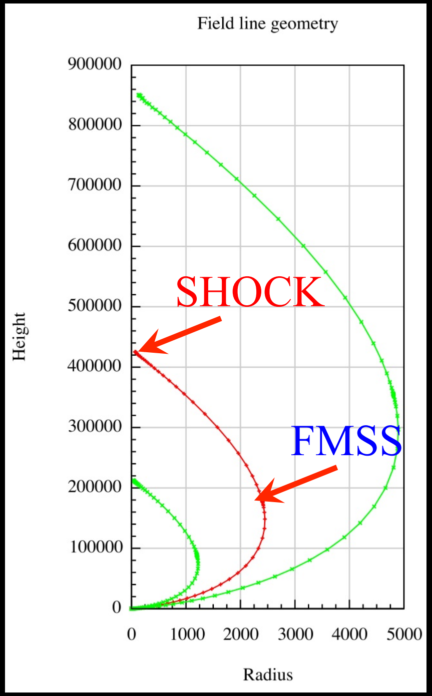
Komissarov (1999; relativistic)

Possible Triggering of Recollimation Shocks

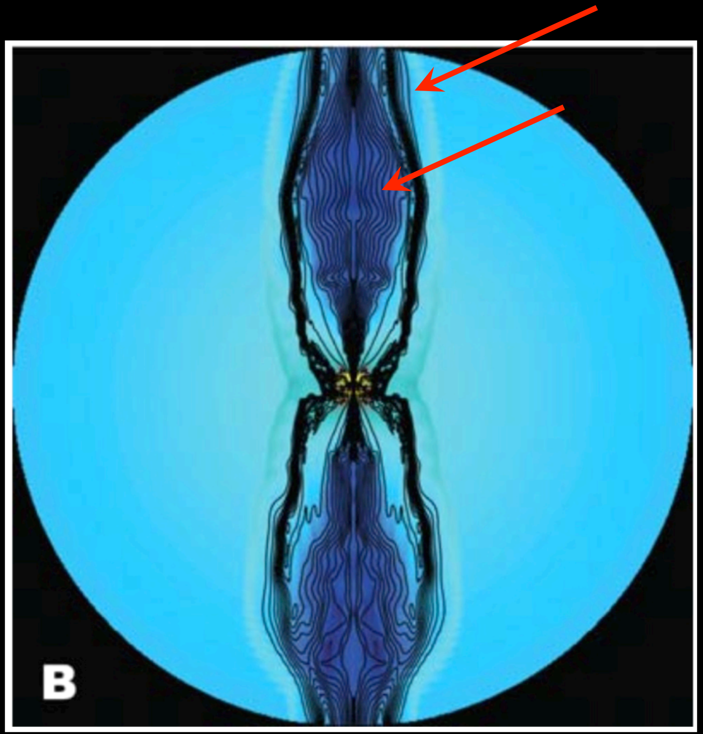
Self-similar models of the ACZ indicate that jets whose flow passes through the MS horizon likely will recollimate toward the jet axis, triggering the pinch shock



Vlahakis *et al*. (2000; NR)



Polko *et al*. (2013; Rel)

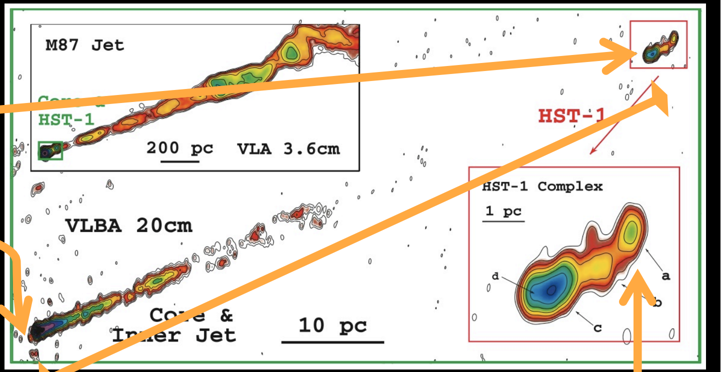


McKinney (2006; Rel)

- NOTE: Some people consider self-similar models to be controversial
  - We therefore need many more, and much longer, simulations like McKinney (2006)
  - Also, 2-D GSS models, *with separatrix surface enforcement*, would be very useful
- In these models recollimation shocks occur in the causally-*dis*connected region
  - RCS would *NOT* destroy the jet engine ➔ Steady state ACZ model is self-consistent

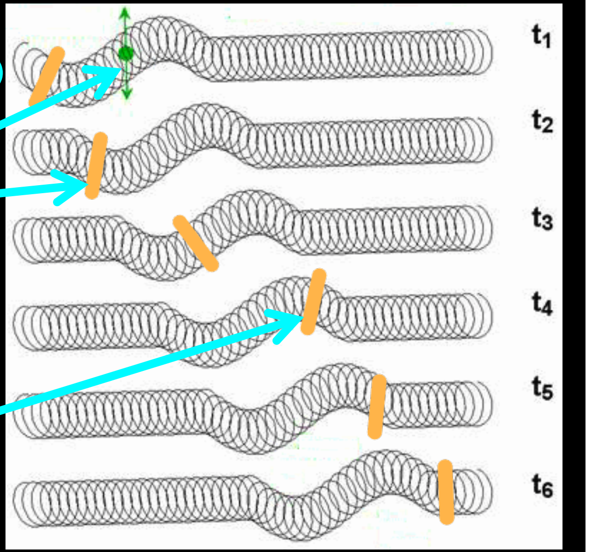
How Would an RCS and Its Post-Shock Jet Appear?

- Expected observational properties of RCS
  - Virtually STATIONARY VLBI jet component, many parsecs from the core
  - A time lag between core flaring and RCS flaring
    - Inferred power transmission speeds >> RCS speed (*e.g.*, Cen A, Tingay *et al*. 1998; BL Lac, Cohen, this conference)
    - Power is transmitted through ACZ primarily by Poynting flux



HST-1 in M 87 (Cheung *et al*. 2007)
(See also Agudo et al. 2012;
and BL Lac, Cohen, this conference)

- Expected observational properties of post-shock jet
  - Superluminal VLBI component ejections come from RCS, not core (Nakamura *et al*. 2010)
  - Post-shock jet should be trans-magnetosonic ($V_j \sim c_{ms} \sim V_A$), <u>completely new jet type</u> as shown in MHD simulations (Clark *et al*.; Lind *et al*.; *etc*.)
    - Helical magnetic field still very strong ($V_A > c_s$; $U_{mag} > U_p$; possibly >>)
    - EVPA will be parallel to jet axis
    - Large scale Alfven waves may be observable ($V_{wave} = V_A \sin \alpha$)
    - If $V_A \sim c_s$, moving components *<u>may</u>* be both
      - Fast MHD shocks ($V_{comp} \geq V_F$; compress helical magnetic field)
      - Slow MHD shocks ($V_{comp} \geq V_S$; compress only plasma; follow rotation of jet helix)
    - May observe moving components following a NON-BALLISTIC path (pulled aside by Alfven wave)



What We Know

- Theoretical
  - For a number of theoretical reasons at least one recollimation shock (RCS) is expected in a jet
    - Pinch-shocks form spontaneously in super-MS flows with strong helical fields
    - Self-similar models and some simulations of jets re-collimate far from the launch point
  - Simulations of such flows and shocks do re-structure the jet beyond the shock (super-MS ➔ trans-MS)
- Observational
  - A single stationary "component", with RCS-like properties, is seen in a number of BL Lac and FR I objects
  - These stationary features appear to eject classical moving components on their own – a property originally thought to be exclusive to VLBI "cores"
  - Shock models of these "components" work well in explaining radio flares

- So, a reasonable model for BL Lac sources may be the RCS one, where super-MS flow from the ACZ is converted into a trans-magnetosonic flow

What about Quasars and FR IIs?

Quasars and FR IIs have traditionally been modeled as hydrodynamic (KFD) flows

- FR IIs
  - Simple 2- and 3-D hydrodynamic simulations nicely explain the flow patterns of FR II hot spots and lobes, with no magnetic forces needed
  - SSC spectral synthesis of FR II hot spots shows $U_{mag} << U_p$; so there is little need for magnetic fields to explain the dynamical forces (only the spectrum itself)
- VLBI Quasars
  - Are modeled as having either longitudinal (EVPA normal to the jet) or tangled magnetic field, implying that hydrodynamic forces dominate

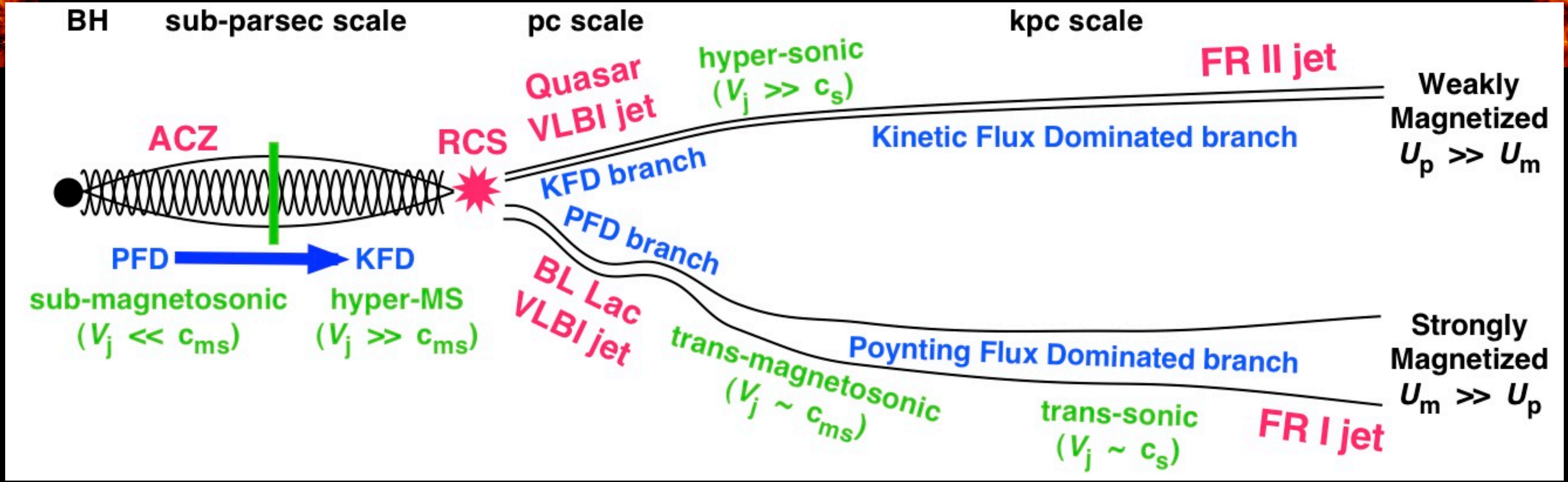
I see two possible scenarios for Quasar / FR II sources:

- 1. Very powerful QSR jets produce an even stronger RCS that becomes turbulent; it breaks, reconnects, and dissipates the magnetic field, but preserves jet momentum
- 2. No RCS forms at all. Instead, the jet emerging from the ACZ remains KFD, but its initially dominant magnetic field eventually decays as the jet propagates

Currently I favor option #1, based on a phenomenological argument:
GRB jets also seem to need rapid dissipation of the magnetic field far from the BH,
and FR IIs seem to be close cousins to GRBs

Problem: More powerful RCS in more distant Quasars may be *much* closer to the BH

The Current Proposed Paradigm



- The origin of the FR I / II (and corresponding BL Lac / Quasar) sequence may lie in the strength and nature of the recollimation shock (RCS) that is predicted to form in the causally-disconnected, hyper-magnetosonic flow that emerges from the acceleration and collimation zone (ACZ)

- Modest RCSs in moderate-power jets restructure the flow into a trans-magnetosonic, Poynting-dominated one, producing BL Lacs and FR Is

- Strong RCSs in high-power jets actually dissipate the magnetic field, leaving a super-sonic, kinetic-flux-dominated one, producing Quasars and FR IIs

Can We Use This?

Parametric Instability Heating of Solar Corona & Wind

Anna Tenerani (Caltech/JPL; U. di Pisa; LPP-Paris)

- Requirements
  - Low beta plasma ($U_{\mathrm{mag}} >> U_{\mathrm{p}}$; $V_{\mathrm{A}} >> \mathrm{c_s}$)
  - Torsional Alfven wave(s)
  - Outflow
- Mechanism
  - TAW scatters sound (slow-mode) waves downstream, which steepen into shocks
  - Shocks dissipate, heating plasma
  - TAW diminishes, eventually becoming turbulent, tangled
  - Instability shuts off when ($U_{\mathrm{mag}} \sim U_{\mathrm{p}}$)
- Relativistic jets:
  - Have all requirements
  - “Heating” = particle acceleration
  - Converts magnetically-dominated plasma to equipartition

[redacted]

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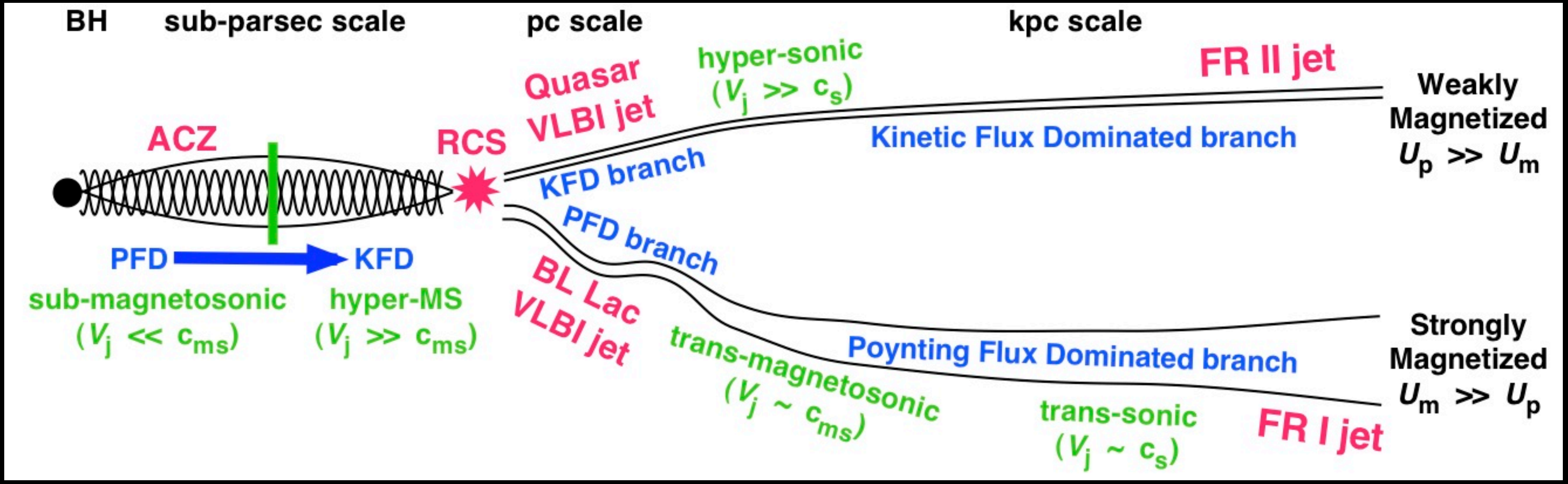
The implication is that powerful enough jets produce recollimation shocks that are strong enough to actually dissipate (tear apart and reconnect) the magnetic field while still conserving jet momentum. The jet, then, is reborn as a hypersonic KFD one.

- Theoretically, this is still untested (but is fairly straightforward to do)
- Observationally, however, it is clear that, at the parsec scale or below, jets know whether they are going to be a BL Lac or Quasar and, by inference, whether they are going to be an FR I or FR II

That is, the origin of the FR I/II morphology difference occurs at the sub-parsec scale, and likely has to do with the nature of the recollimation shock

Fundamental Observational Questions



- Is the VLBI jet of BL Lac truly PFD? If so, are all BL Lacs also PFD?
- Are FR Is and BL Lacs EXACTLY the same class? That is, is the FR I/II break IDENTICAL to the BL Lac/quasar break?
- Or, are there some quasar FR Is?
- Are there BL Lac FR IIs (LBLs)?