The Phoenix Fire Hypothesis:

How Astrophysical Jets are Reborn In a Master Recollimation Shock Into their Final Observed Form

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

Fire = A Jet Recollimation Shock at a significant distance from the BH

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

- Tenet #1: All jets are electromagnetically accelerated in an Acceleration & Collimation Zone (ACZ) that ends with the jets being hyper-*magneto*sonic 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

- Tenet #3: The strength of the Recollimation shock determines the final jet properties:
  - Moderately strong shock: preserve strong helical field, but reduce jet to trans-magnetosonic
  - Very strong shock: turbulent MHD reconnection dissipates helical field into internal energy, which is radiated away. Jet becomes cool and super-sonic (technically still super-magnetosonic)
  - The FR I / II break, therefore is a matter of non-dissipative *vs.* dissipative recollimation shocks

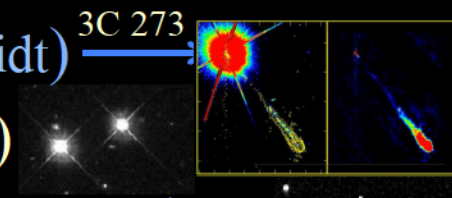
Outline

- Class Divisions in AGN Sources:
  - RL *vs*. RQ
  - HERGs *vs*. LERGs (high-excitation emission lines or not)
  - BL Lacs *vs*. FSRQs (")
  - FR Is *vs*. FR IIs (jet morphology / power dichotomy)
- Comprehensive Discussion of FR I Sources:
  - Theory: Launching, Acceleration, & Collimation of MHD Jets
  - Observations: M87 & BL Lac – ONLY POSSIBLE WITH VLBA
- Speculation on Other Objects:
  - FR II Sources
  - GRBs
  - X-ray Binaries
  - Protostellar Jets

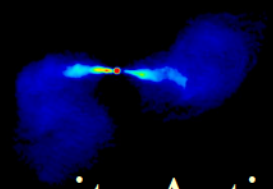
Major Types of Active Galactic Nuclei Systems

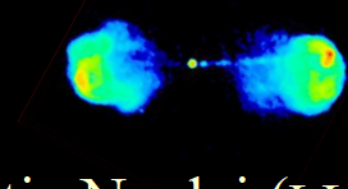
Types of AGN:

- Active galactic nuclei (1908-18; Fath, Slipher, Curtis)
- Seyfert galaxies (1943; Seyfert)
- Radio galaxies (1949; Bolton *et al.*)
- Radio *loud* quasars (1963; M. Schmidt)
- Radio *quiet* quasars (1965; Sandage)
- BL Lac Objects (radio loud; 1968; J. Schmitt)
- Inactive Galactic Nuclei (1974; Balick & Brown)
- Luminosity/Morphology correlation (1974; Fanaroff & Riley)



FR I: "low" radio luminosity $P_{178} < 10^{25}$ W/Hz

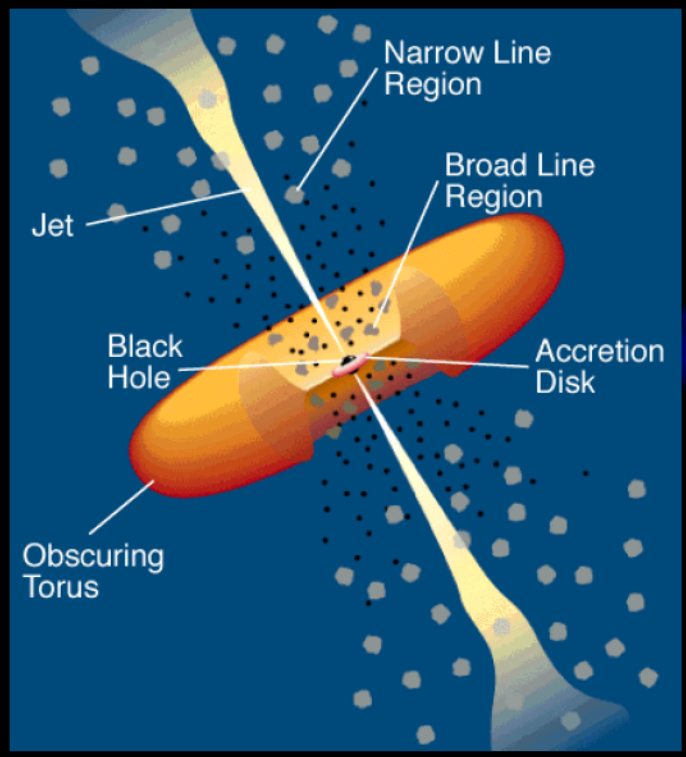




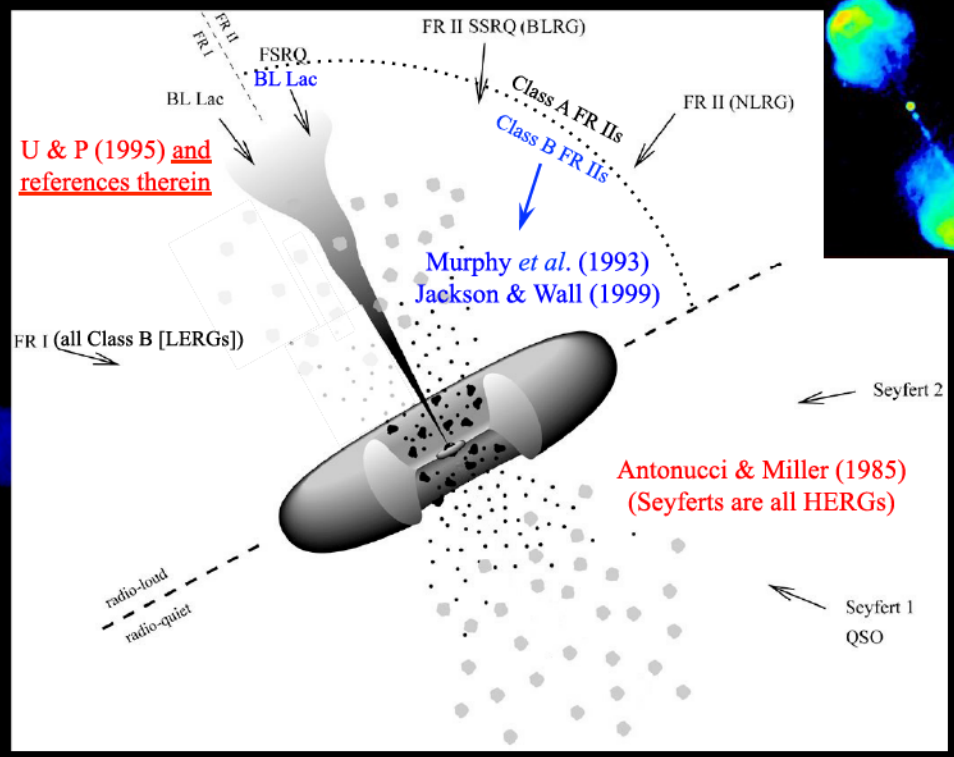
FR II: "high" radio luminosity $P_{178} > 10^{25}$ W/Hz

- Low-Luminosity Active Galactic Nuclei (LLAGN; 1980; Heckman)

Many AGN can be Unified by Viewing Angle



Urry & Padovani (1995)



(adapted from) Torres (2004)

- Orientation effects explain:
  - HBL BL Lacs as FR Is (all LERGs) seen end-on (HBL/LBL = hi/lo freq peaked BL Lac)
  - FSRQs as Class A (HERG) FR IIs seen end-on (Class A = HERG = hi excitation RG)
  - LBL BL Lacs as Class B (LERG) FR IIs seen end-on (Class B = LERG = lo excitation RG)
- Orientation effects DO NOT EXPLAIN:
  - Fundamental Radio-loud / Radio-quiet dichotomy (thought to be a BH spin effect)
  - Fundamental FR I / II dichotomy (thought to be a trans/super-sonic jet effect)
- There MUST be more to AGN than just orientation; There must be REAL astrophysics going on

Accretion Models Can Explain Class A / B Division

90° jet viewing angle 0°

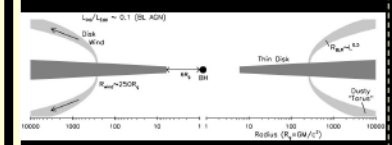
log radio jet power

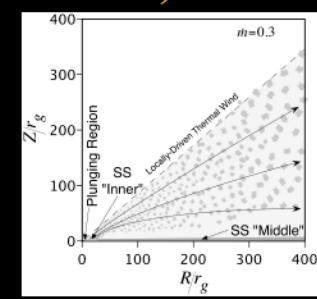
FR II Class A NLRG BLRG	FSRQ
"Class A / B Break"	
FR II Class B	LBL
"FR I / II Break"	
FR I Class B Radio LLAGN	HBL

accretion models

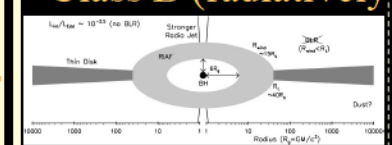
log accretion power

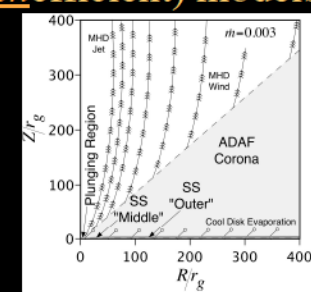
Class A (radiatively efficient) models





Class B (radiatively *in*efficient) models



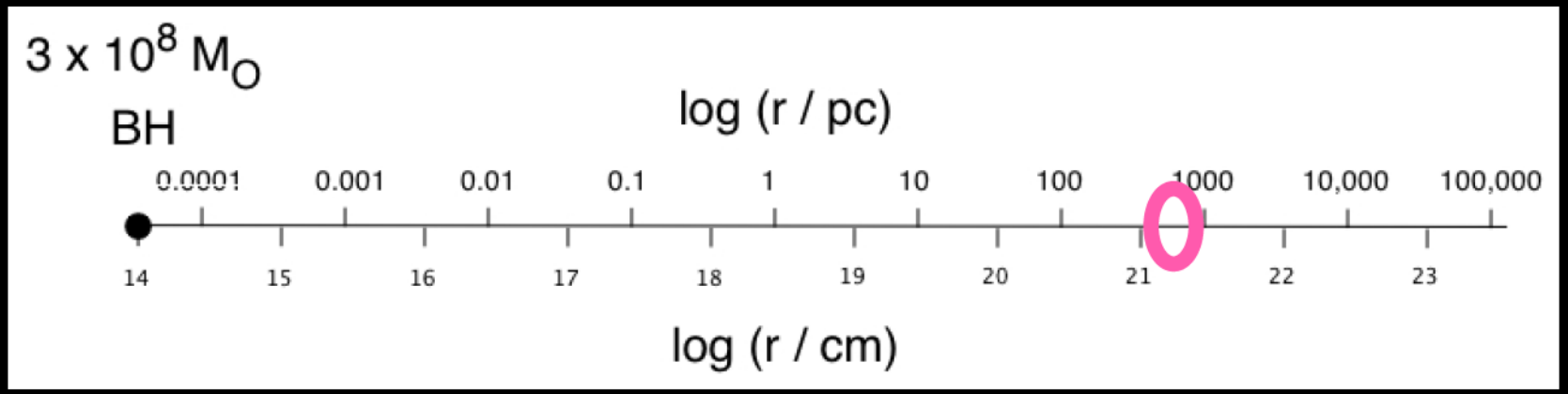


Trump *et al.* (2011) Meier (2012)

But Not FR I / II Division

- The FR I / II division is NOT the same as the BL Lac / FSRQ (LERG / HERG) division
  - The key is the existence of FR II Class B (LERG) sources that appear as (L)BL Lacs when viewed end-on
- The FR I / II division is more likely due to a change in the production or propagation properties of the radio jet itself
- NOTE: The FR II Class B / LBL objects are more rare and primarily at high redshift
- At low - moderate redshift, BL Lacs (HBLs) ≈ FR Is and FSRQs = FR IIs

Where in its Travels Does a Jet Decide to be an FR I or II?



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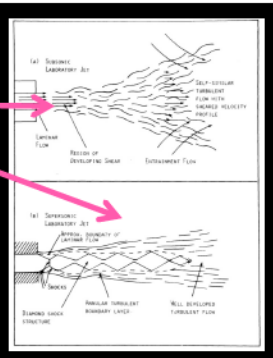
  - FR Is as tran*sonic* jets that decelerate
  - FR IIs as super*sonic* jets that continue so out to the hot spots and radio lobes
  - Geoff put the radius where this occurs at ~600 pc (galaxy "core" radius)



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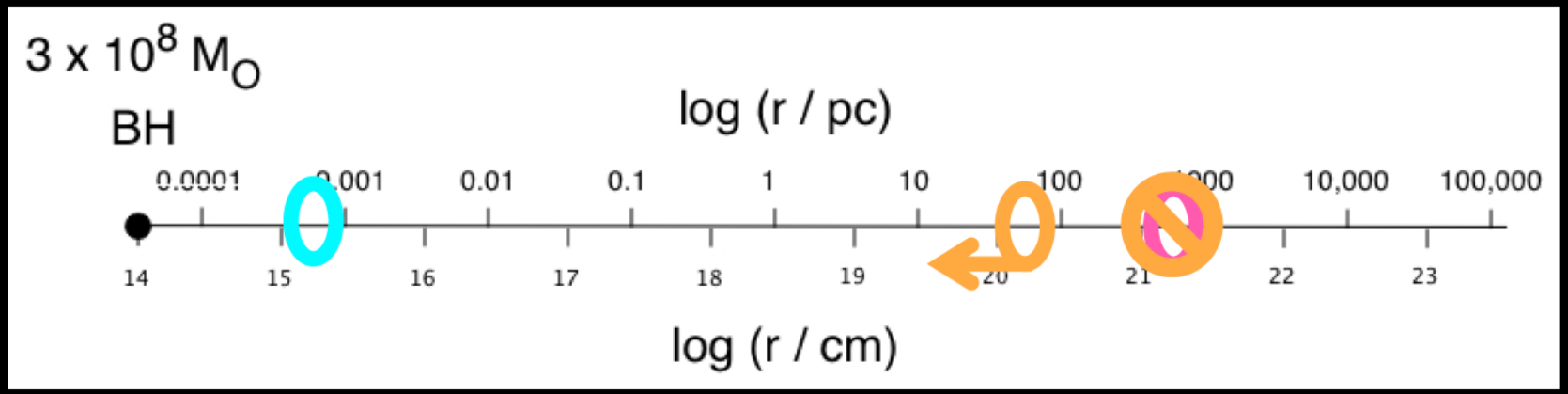

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  - So, jets know they will be an FR I or FR II < 10-100 pc from the BH
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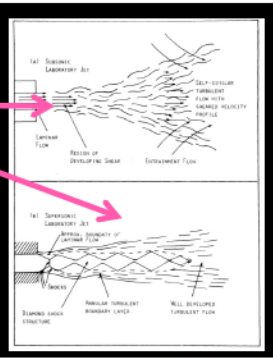
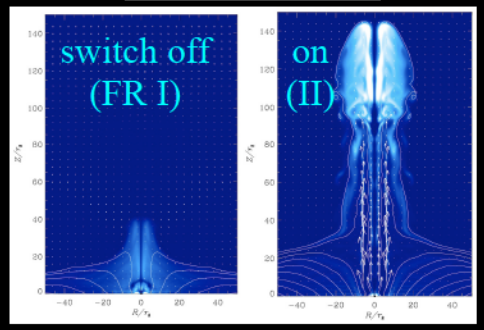
  - Like an "Eddington limit" for magnetic fields
  - Occurs in inner accretion disk at ~10-20 r_H (< 10^{-3} pc)





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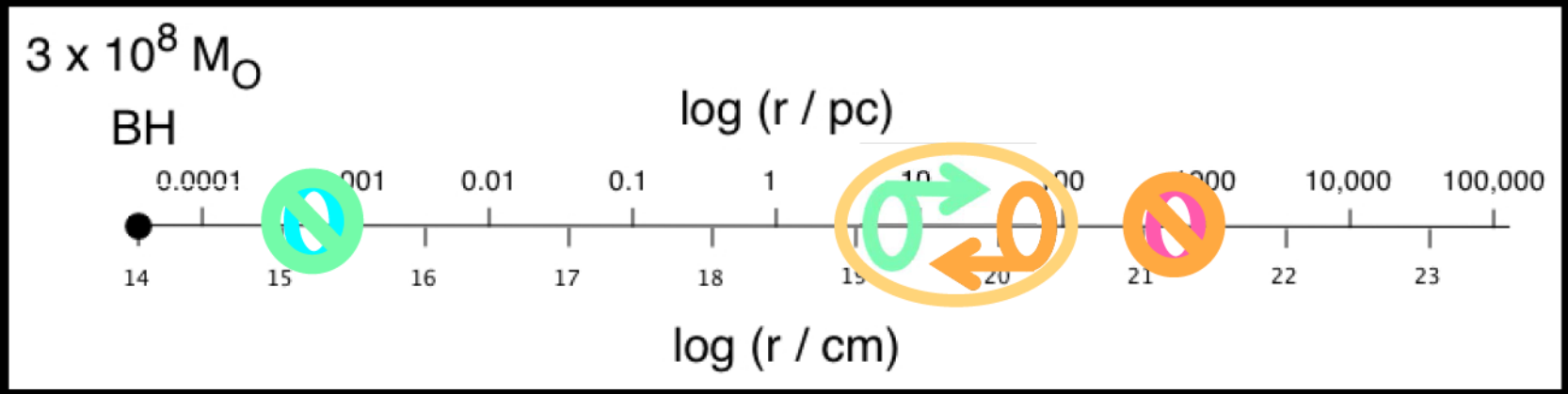

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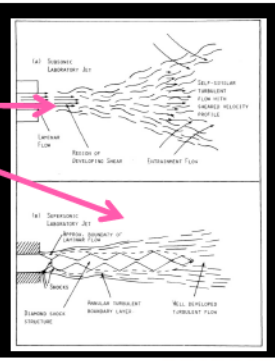
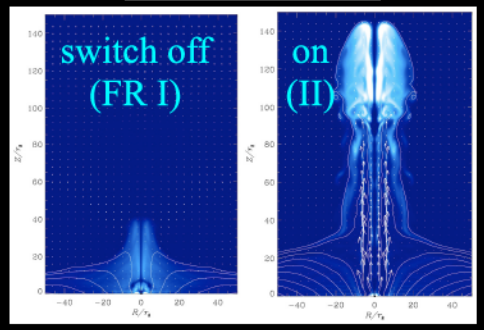
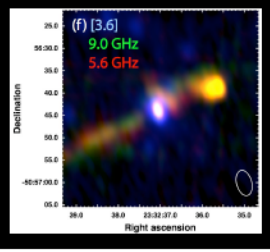
- Gopal-Krishna & Wiita (2000): the HYMOR test
  - HYbrid MORphology objects have one FR I jet & one FR II jet !
  - Such sources appear to exist for ≥ (jet travel time to the lobes) ≈ 3 x 10^5 yr.
  - Time for galactic ISM weather to alter the 2 jets should be $\tau_{weather} \geq 10\ \tau_{dyn} = r / \sigma_V$
  - At 10-20 r_H, 10 τ_{dyn} ~ 6 wks! So, magnetic switch cannot be FR I / II process
  - For $\tau_{weather} \geq 3 \times 10^5$ yr, we need r > 7 pc (or less).
  - **NOTE: Also ~ r_{Bondi} (BH Bondi radius or BH sphere of influence; Nakamura 2012)**







Tsai et al. (2013)

What does Theory Tell Us About Jet Launching, Acceleration and Collimation?

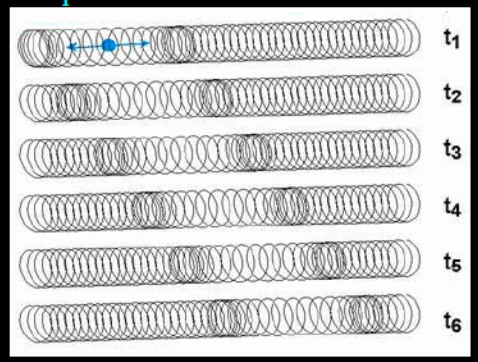
First we have to understand MHD waves (magnetosound and Alfvén waves)

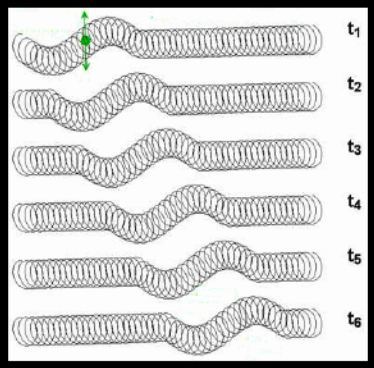
MHD Waves and Shocks in MHD Jets

- Basic propagation speeds in a magnetized plasma
  - Plasma sound speed: $c_s = (\Gamma\, p_{gas} / \rho)^{1/2}$
  - Alfven speed: $V_A = (B^2 / 4\pi\rho)^{1/2} = (2\, p_{mag} / \rho)^{1/2}$
  - Magnetosound speed: $c_{ms} = (c_s^2 + V_A^2)^{1/2}$
- MHD Waves in Magnetically-Dominated Helical Field Jets ($U_{mag} > U_p$; $V_A > c_s$)
  - FAST-mode waves/shocks propagate by compressing the HELICAL magnetic field

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

FAST- Mode Wave/Shock



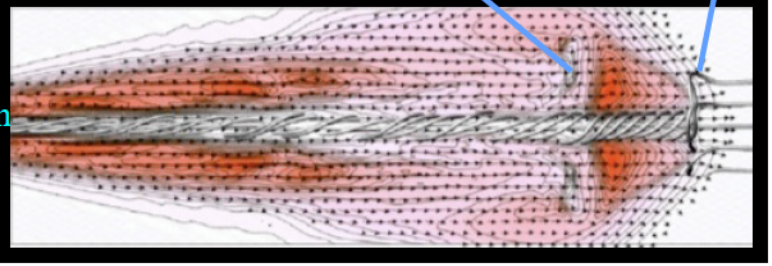


ALFVEN-Mode Wave

$V_{pattern} = V_A \cos\chi < V_A$

  - ALFVEN-mode waves displace the field in the transverse direction, propagating along $B_{longitudinal}$
  - SLOW-mode waves/shocks would, at first, look like FAST-mode ones, but moving much slower
    - Plasma is compressed, synchrotron emission enhanced
    - BUT, MAGNETIC FIELD STRUCTURE REMAINS UNCHANGED
    - However, the slow-mode wave/shock would ROTATE AROUND THE JET AXIS *w.r.t.* the ROTATING FIELD, possibly producing strong synchrotron polarization rotation

SLOW- Mode Wave/Shock $V_{pattern} \geq V_S \approx c_s \cos\chi$

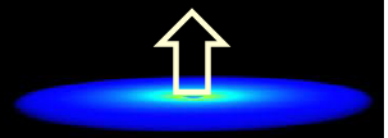


Nakamura (2001)

Launching of MHD Jets

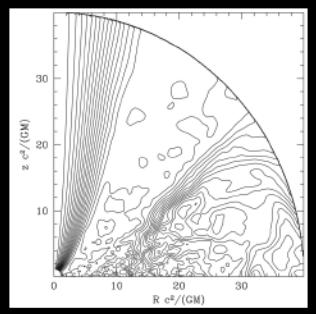
Definition of Jet Launching: Lifting jet plasma out of the deep, tidal compact object potential so it can be accelerated and collimated largely free of gravitational effects

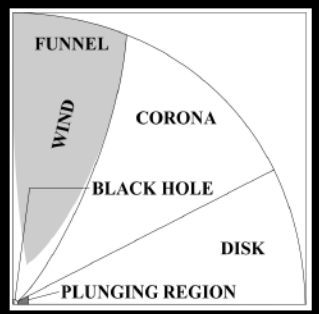
- Tidal force in Z direction for constant $Z << R$ is quark-like



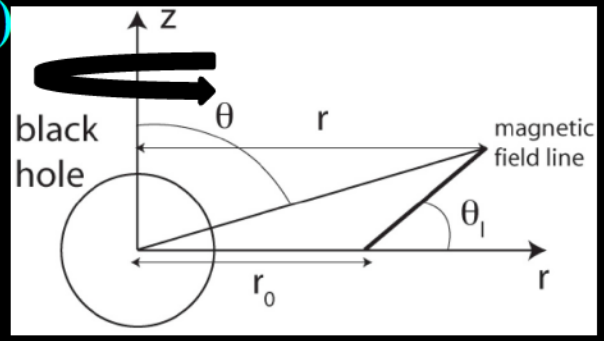
$$-GM\,Z\,/(R^2+Z^2)^{3/2} \approx -GM\,Z/R^3 \propto -Z$$

McKinney & Gammie (2004)





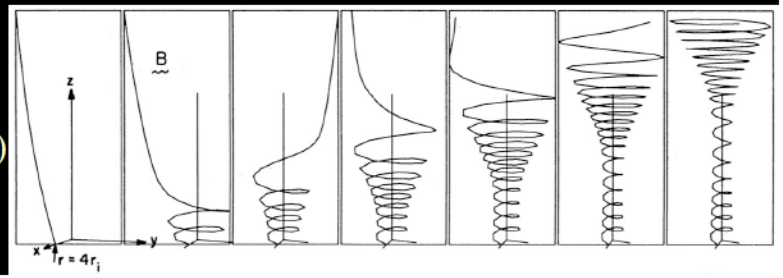
- Slow MHD Mode (gas pressure) Launching
  - Typical of most hot plasma RIAF / jet simulations
  - Magnetized plasma lifted up to $Z \sim R$
  - Acceleration & collimation takes place for $Z > R$
- Alfven Mode Launching ("fling"; magneto-centrifugal)
  - Rotating magnetic field, loaded with cold plasma
  - 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 $Z < R$

Uchida *et al.* (2001)

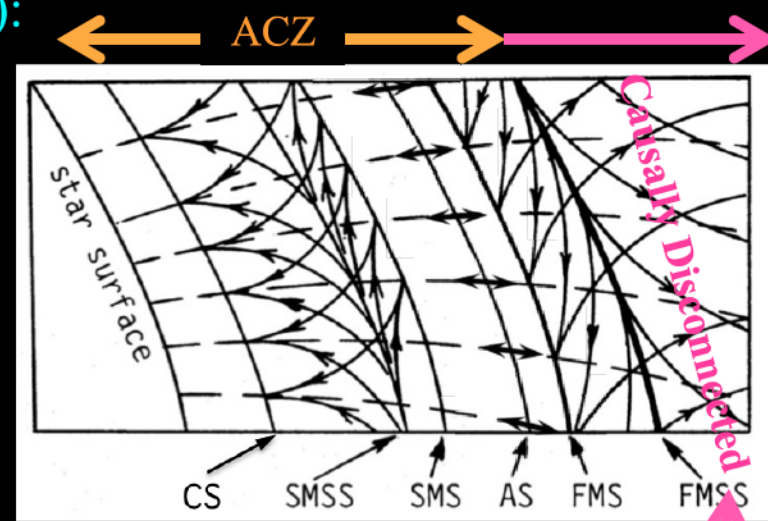


Ustyugova *et al.* (1995)

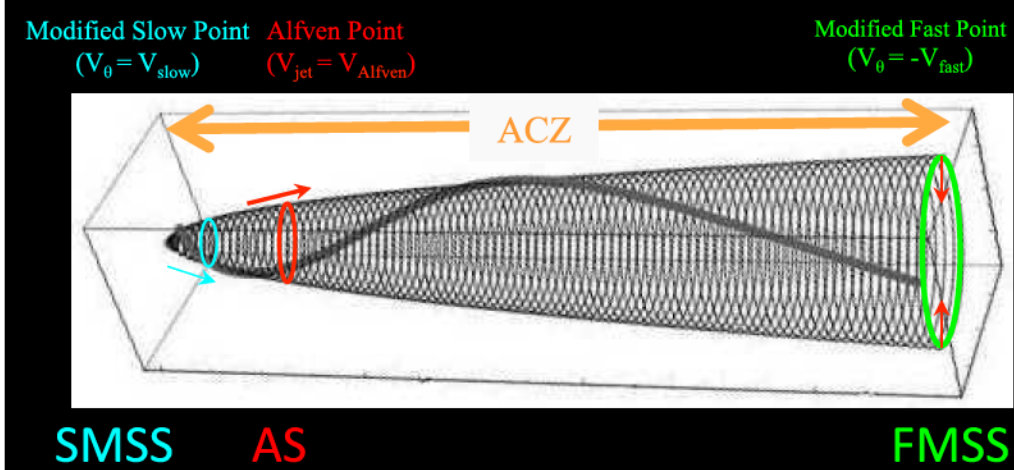
Acceleration and Collimation of MHD Jets

Once launched, all MHD jets should have similar ACZs: acceleration and collimation will occur as the jet passes through multiple critical and separatrix surfaces

- Critical Surfaces are where $V_j = (V_C, V_S,$ 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 in a steady wind equation



Bogovalov (1994); Contopoulos (1996)

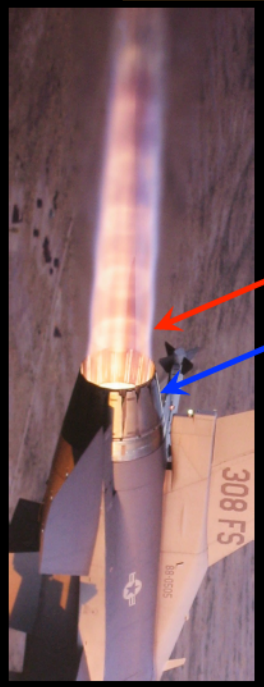


NOTE: Beyond the magnetosonic horizon (FMSS), information flow (characteristics) points only DOWNSTREAM.

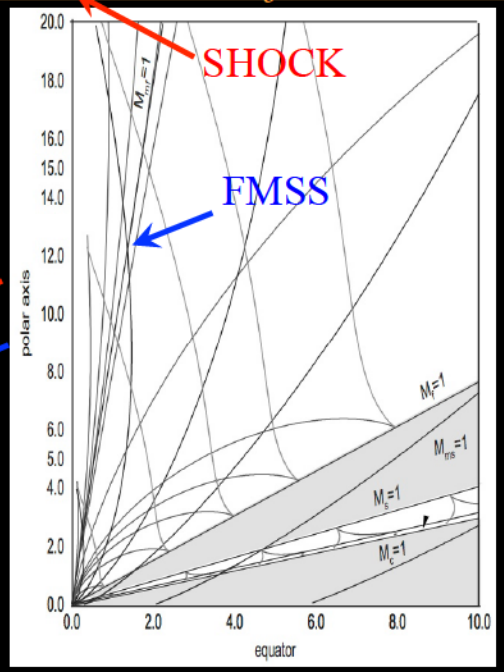
Therefore, NO EVENT OR FEATURE BEYOND THE FMSS CAN AFFECT THE STRUCTURE OF THE ACZ (via MHD waves)

The Theoretical Case for A Recollimation Shock in Most Astrophys. Jets

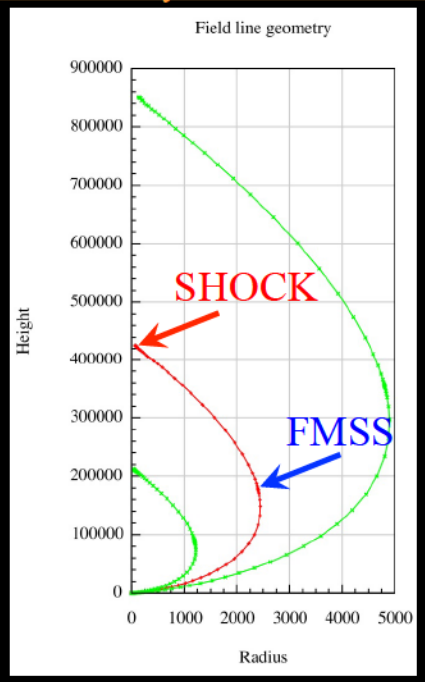
- MHD jet models with an FMSS, AND jet simulations, show recollimation at end of the Acceleration & Collimation Zone (ACZ)
  - *Beyond FMSS velocity toward polar axis –V_θ > fast magnetosound speed c_{ms}*
  - *This should form a recollimation shock*
  - *Remember that the flow also is causally disconnected from the central engine*



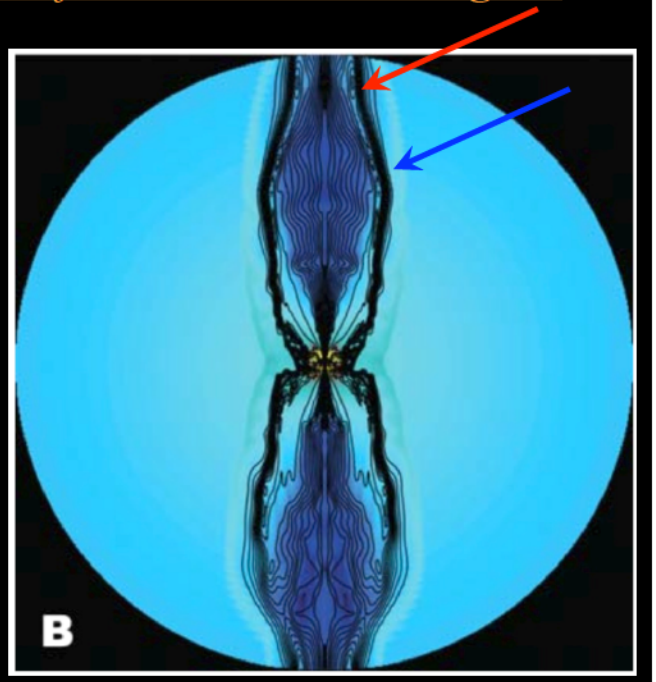
F-16 Convergent Nozzle



Vlahakis et al. (2000) (non-relativistic)



Polko, DLM, & Markoff (2011,13,14)



McKinney (2006) (relativistic)

What is the State of the Jet Right Before and After the RCS?

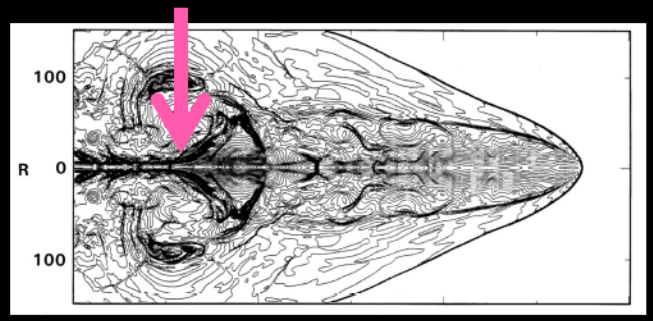
- Pre-shock flow
  - Kinetic energy Flux Dominated ($V_j >> [V_A^2 \ (R_j \Omega_f)]^{1/3}$)
  - Plasma internal energy still dominated by helical magnetic field ($U_{mag} >> U_p$; $V_A >> c_s$)
  - Hyper-magnetosonic ($V_j >> c_{ms} \sim V_A$)

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

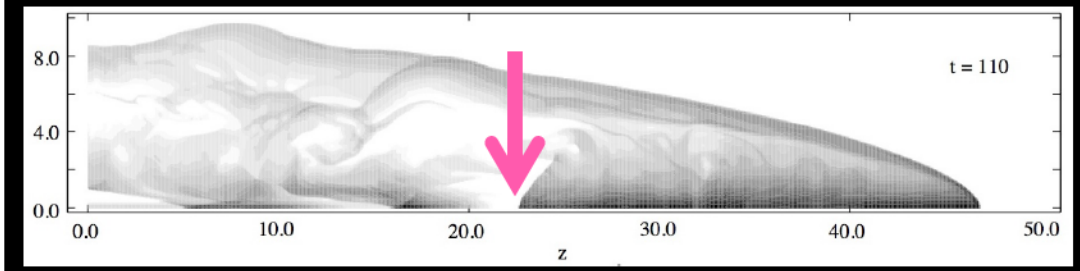
(Clarke *et al*. 1986; Lind *et al*. 1989; Komissarov 1999; Kraus & Camenzind 2001)

- 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

repeat



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



Komissarov (1999; relativistic)

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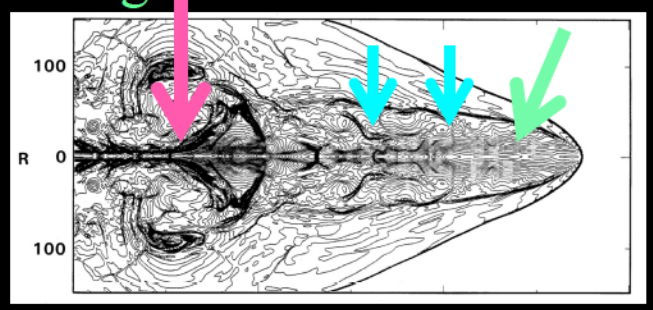
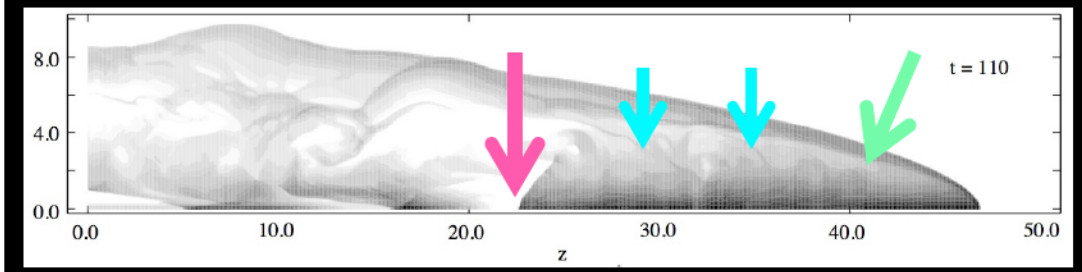
repeat

- Post-shock flow
  - Slows from hyper- to trans-magnetosonic ($V_j \sim c_{ms} \sim V_A$) ➔ **a new type of jet**
  - Still dominated by helical magnetic field
- A "magnetic chamber" forms that periodically ejects plasma pulses

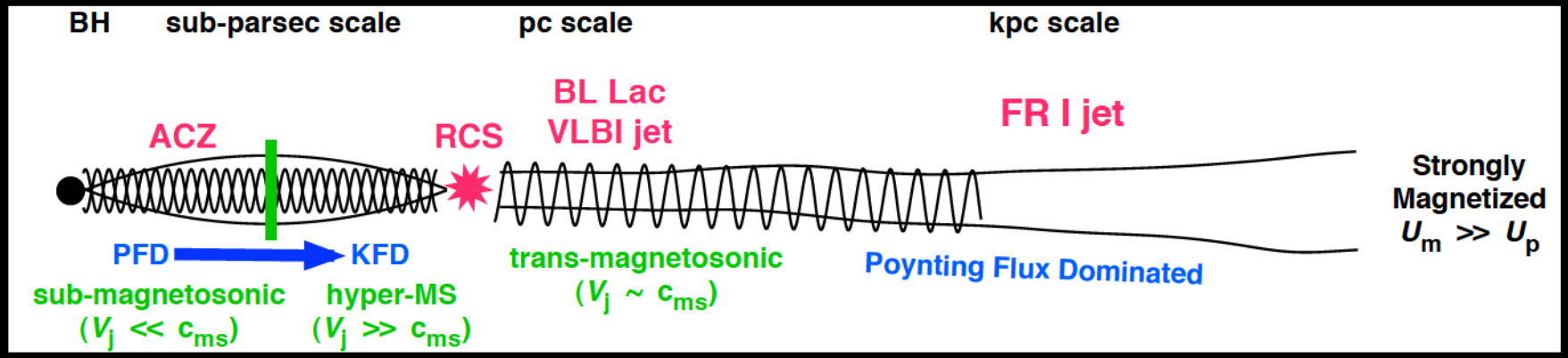


Lind, Payne, Meier, & Blandford (1989; NR)



Komissarov (1999; relativistic)

FR I Theory Recap:

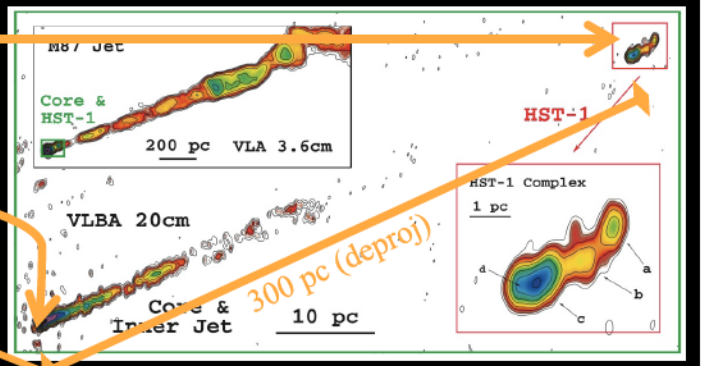


Can We See this Kind of Behavior In Nearby FR I AGN Jets?:

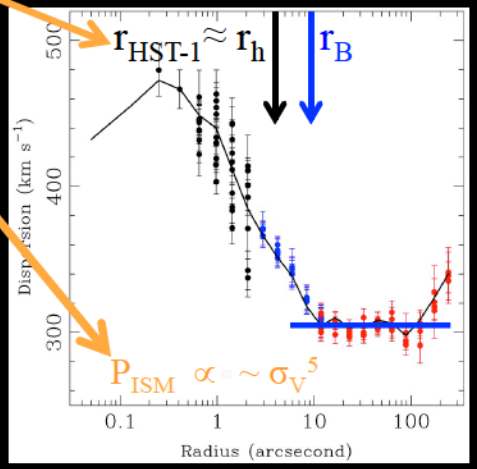
Yes. In M87 (amazing)
And in BL Lac (even more amazing!)

The Pre-RCS and Post-RCS Jets in M87

- M87 has a Recollimation Shock (RCS): HST-1
  - Virtually STATIONARY jet component HST-1, 300 pc from the M87 core (deprojected)
  - 30-35 yr time lag between core flaring and RCS flaring
  - HST-1 occurs at the BH radius of influence $r_h = r_B/2$
  - At $r \approx r_h$ the ISM becomes uniform pressure & confining



HST-1 in M 87 (Cheung *et al*. 2007; **VLBA**)



Gebhardt *et al*. (2011)

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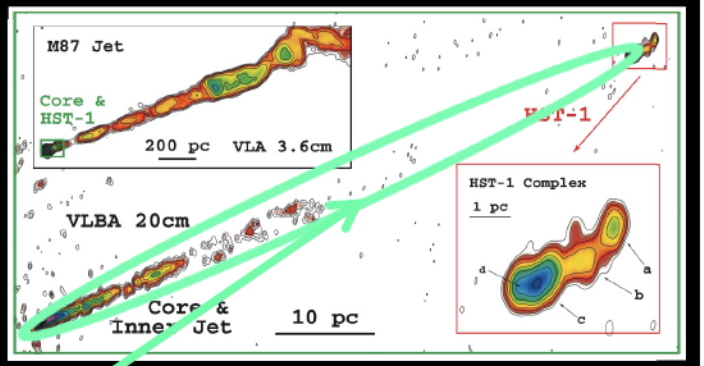

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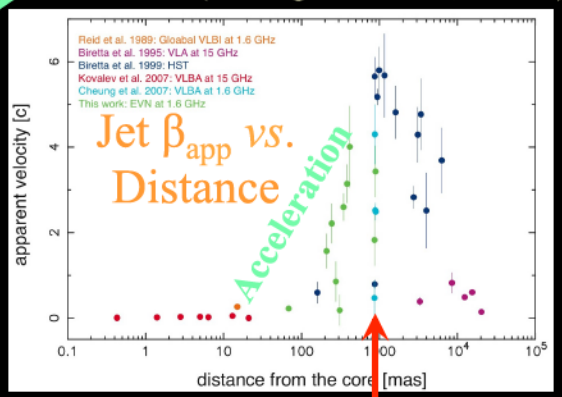
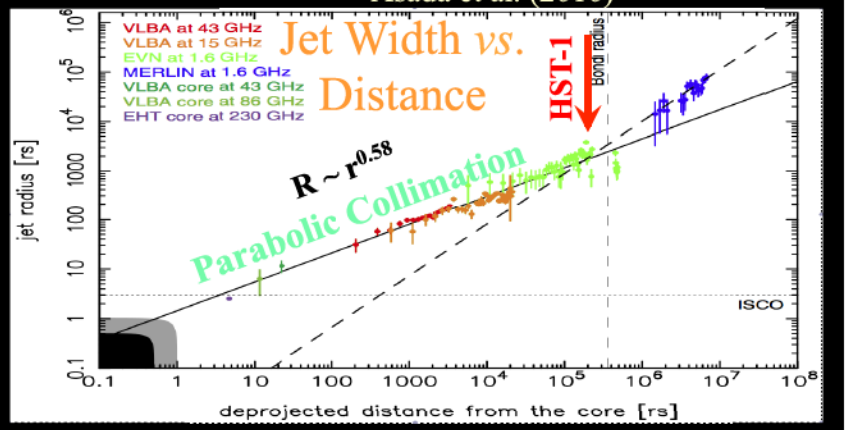


Asada et al. (2010)



Nakamura & Asada (2013)

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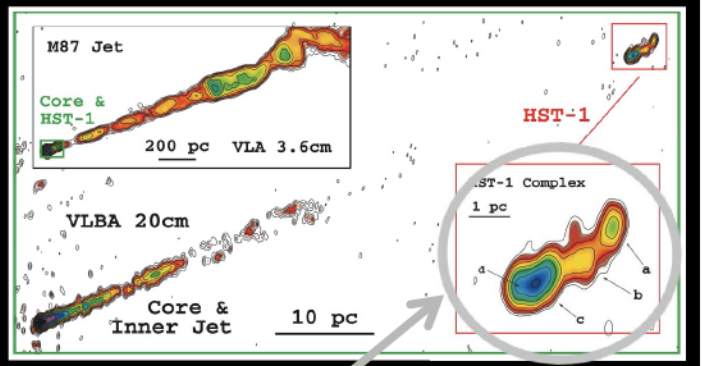
  - Can reproduce all components seen with one jet pulse
  - Some move very slowly (against flowing jet)



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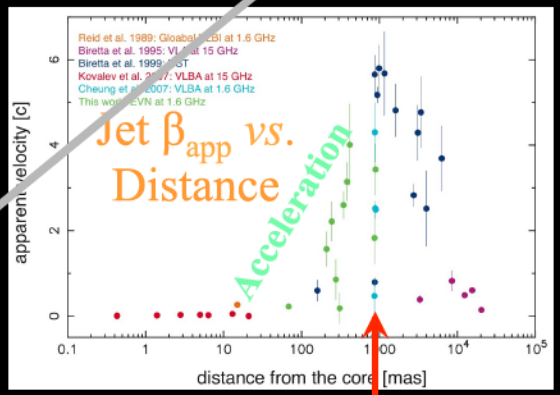

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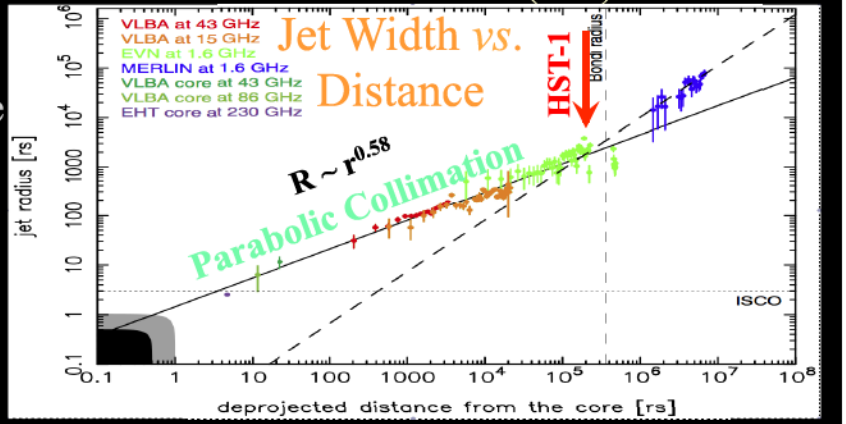

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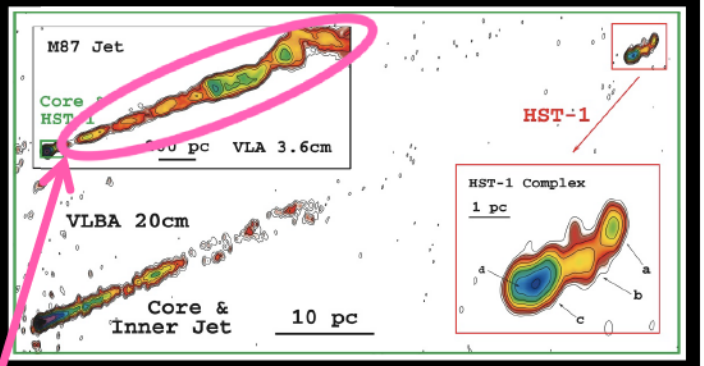
  - Can reproduce all components seen with one jet pulse
  - Some move very slowly (against flowing jet)
- Post-RCS Jet – Bicknell FR I Deceleration
  - Jet decelerates to SUB-LUMINAL speeds
  - Jet flow expansion is CONICAL (not collimating)
- All Results Very Consistent with Phoenix Fire Hypothesis



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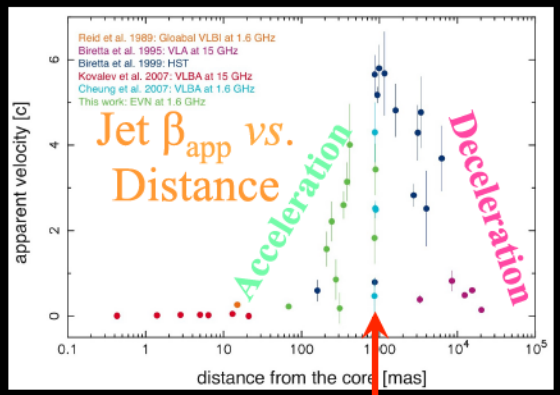

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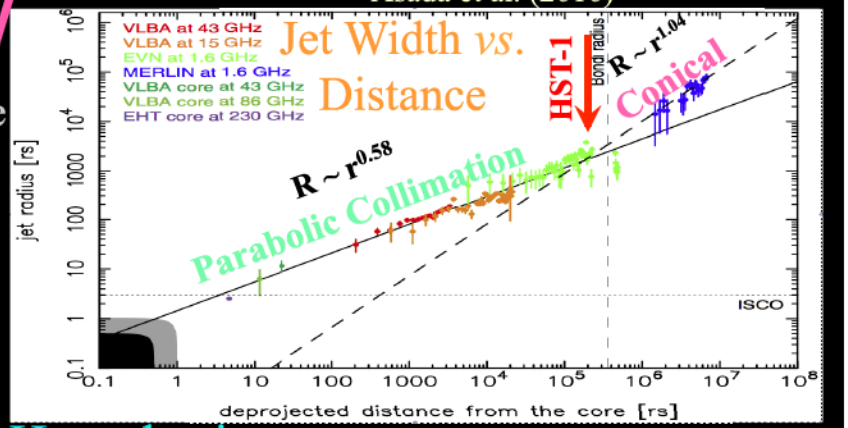

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The Recollimation Shock & Moving Components in BL Lac (Cohen et al. 2013)

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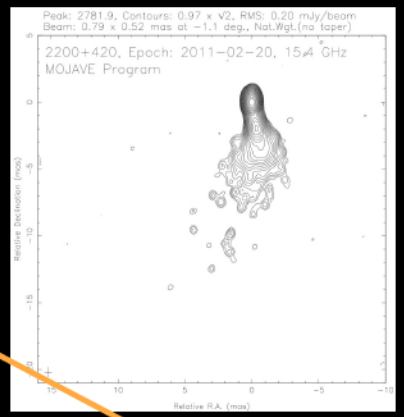
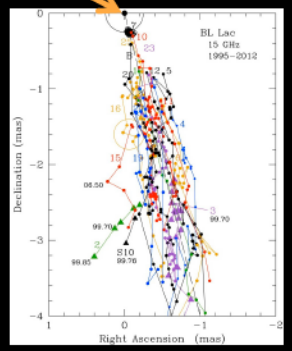
  - Further away (~270 *vs*. 15 Mpc [ang. size distance])

    ➔ RCS should be ~40 pc from BH or ~ 0.2 mas from core (projected)





VLBA resolution = 100 μas !!

ALL VLBA DATA

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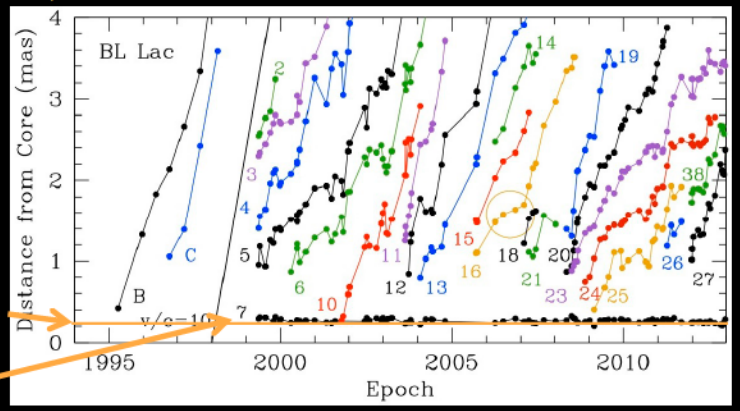
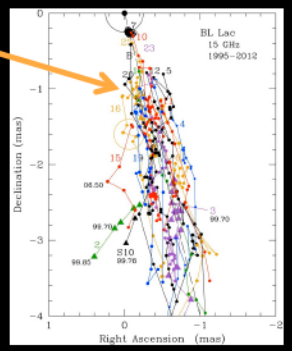


Cohen & the MOJAVE VLBA team (2013)



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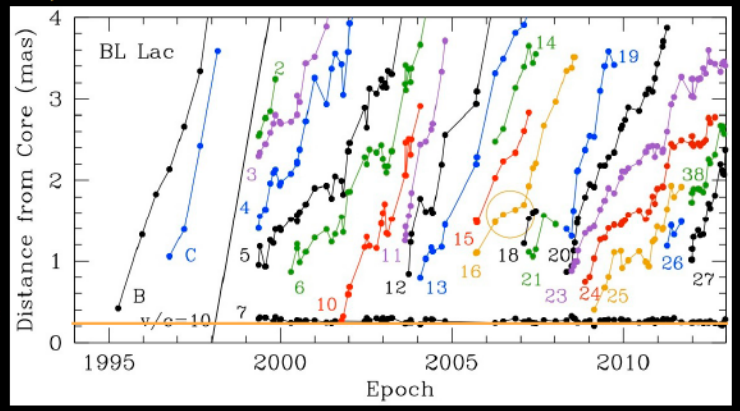
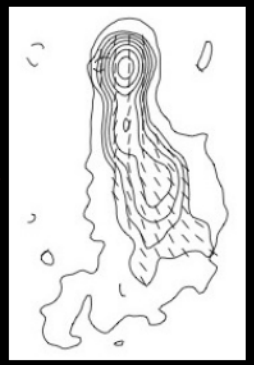


Cohen & the MOJAVE VLBA team (2013)

- The Post-RCS Jet ("current-carrying")
  - EVPA is primarily longitudinal in BL Lac (objects) ➔ helical magnetic field
  - Fractional polarization increases with distance from core ➔ conical flow



Electric Vector Polarization Angle plot

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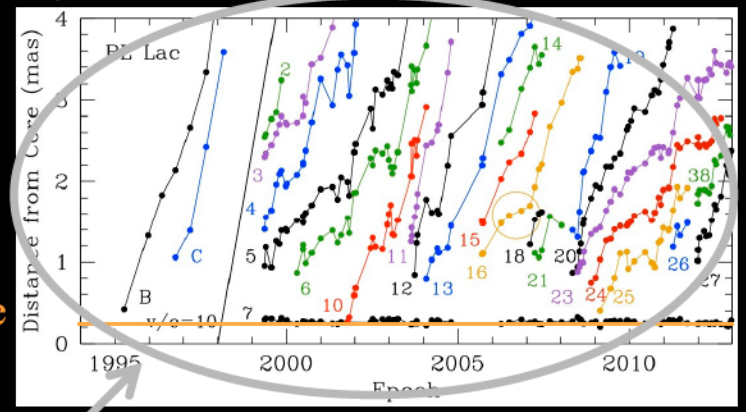

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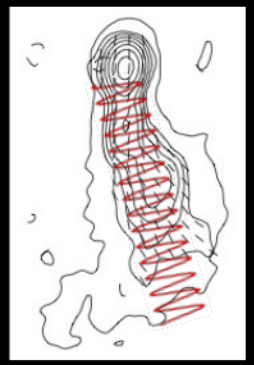


Electric Vector Polarization Angle plot

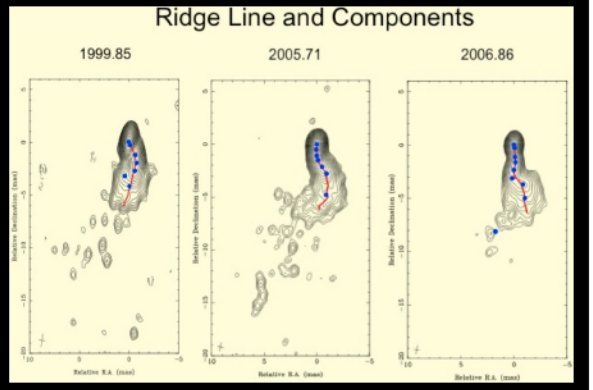
- The Moving Components in BL Lac
  - All are relativistic ($2c < V_{app} < 10c$)
  - We model the slowest component as a slow MHD wave and fastest as a fast MHD wave
  - Assuming $V_S \sim 0$ in jet frame, we find $\Gamma_F \approx 1.7$ in jet frame and $\Gamma_{jet} \approx 3.4$, *in galaxy frame*
  - This model does not allow us to determine relative magnetic field strength, V_A or c_{ms} in jet frame, but Γ_{jet} results similar to Nakamura's HST-1 simulations

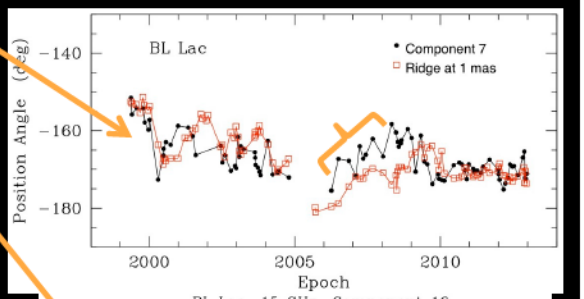
- But wait, there's more …

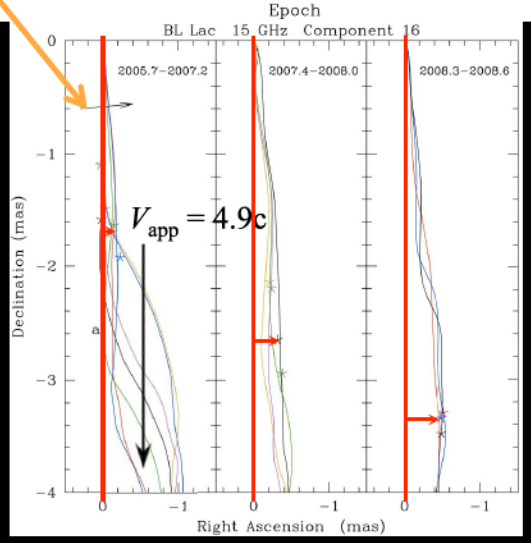
ALL VLBA DATA

Transverse Alfvén Waves in the BL Lac Jet (Cohen et al. 2014)

- BL Lac displays Transverse Waves !!
  - Wiggles that propagate down the jet with time
  - These waves seem to be generated by transverse shifts in C7 *w.r.t.* the core and, hence, in the inner jet position angle







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  - Speed of the wave is between slowest & fastest components:

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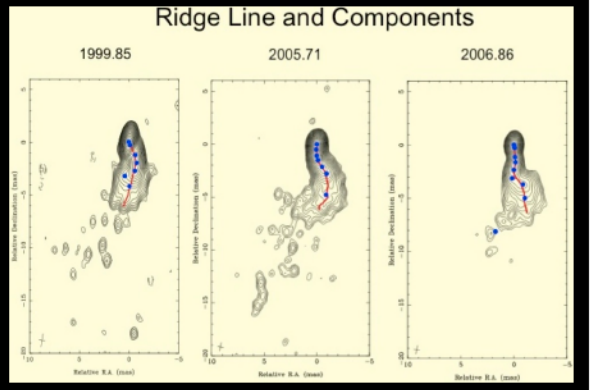
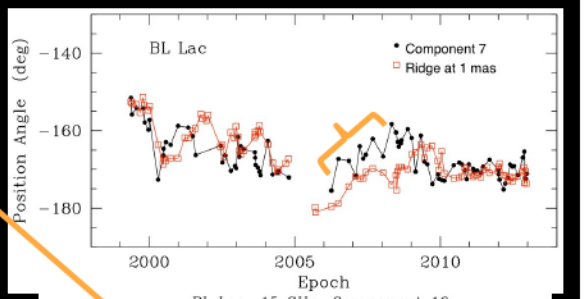
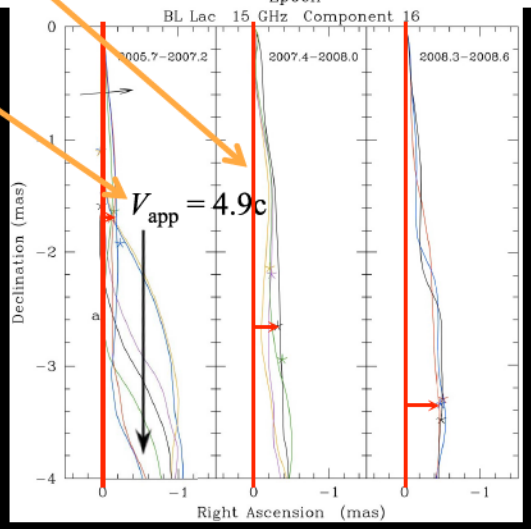
  - Moving components (e.g., C16) is drawn aside by wave
    - Components are not ballistic "blobs"







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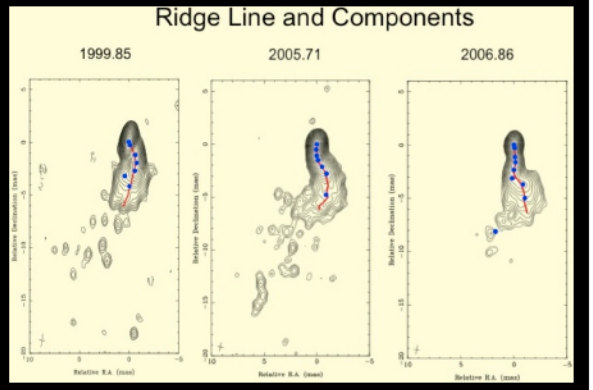
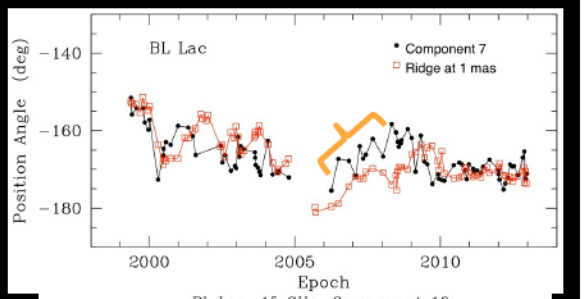
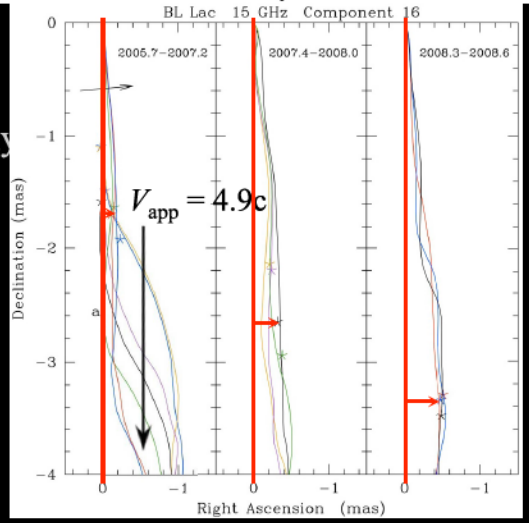
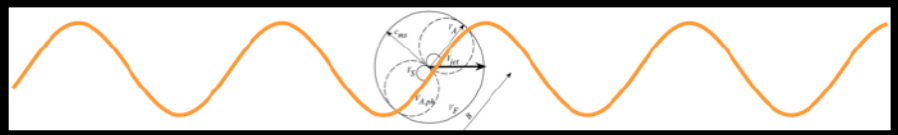


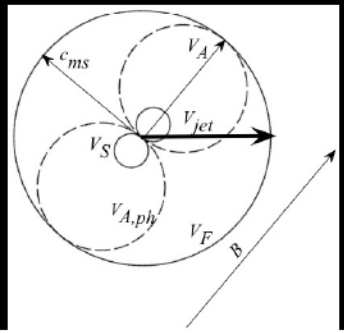


- We modeled the transverse waves as Alfven waves on B_Z
  - Specific model:
    - $V_{jet} \approx c_{ms}$ (trans*magneto*sonic flow; *cf.* LPMB, Bicknell) *in galaxy frame*
    - $V_{wave} \sim V_A \cos\chi$ in jet frame (*i.e.*, assume helical field)
    - Slowest & fastest components are $c_s \cos\chi$ & V_F in jet frame, respectively
  - Model results: $\Gamma_{jet}^{gal} \approx 2.5$ *in galaxy frame:*
    - In jet frame $c_s = 0.43c$, $V_A = 0.89c$, $c_{ms} = 0.92c$, $\chi = 41°$
    - $V_S = 0.32$ ($\Gamma_S^{jet} \approx 1.06$)
    - $V_{wave} = 0.67$ ($\Gamma_{wave}^{jet} \approx 1.35$)
    - $V_F = 0.89$ ($\Gamma_F^{jet} \approx 2.2$)





jet moving at $V \sim 0.92c$

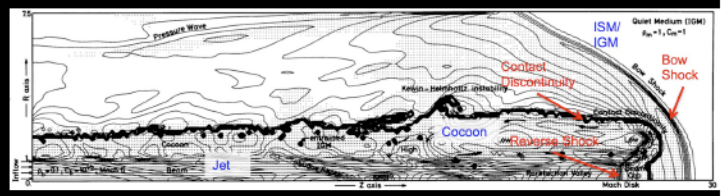


ALL VLBA DATA

What about FR IIs and Quasars?

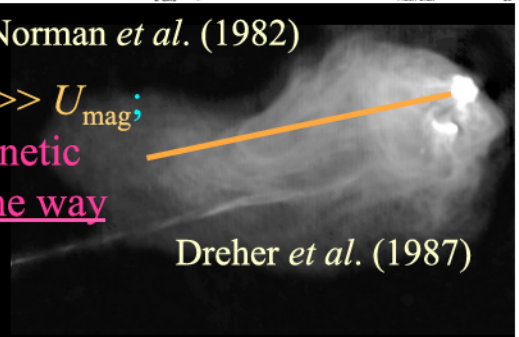
They have traditionally been modeled as hydrodynamic (KFD) flows

- FR IIs
  - Simple 2- and 3-D hydrodynamic simulations explain the flow patterns of FR II hot spots and lobes, with no magnetic forces needed



Norman *et al.* (1982)

  - SSC spectral synthesis of FR II hot spots (Werner et al. 2012) shows $U_p >> U_{mag}$; It is clear that, while FR II jets may have been accelerated by strong magnetic fields in the nucleus, somehow FR IIs have lost their strong field along the way

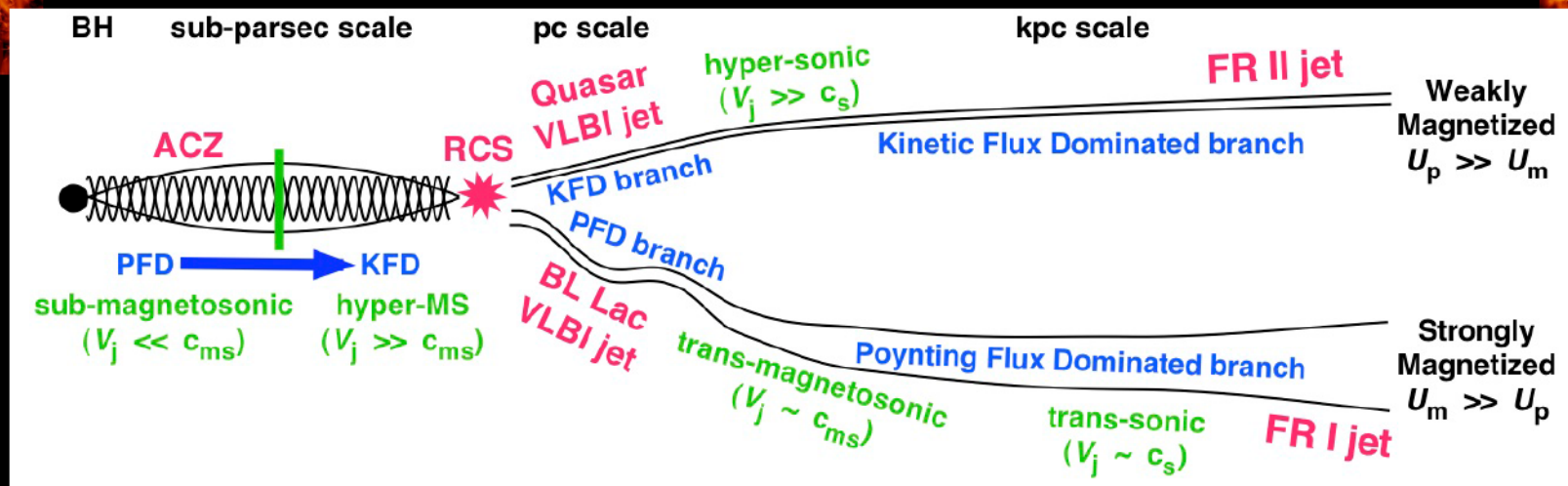


Dreher *et al.* (1987)

$V_{pattern} \geq V_F = c_{ms} \approx c_s$
see Hughes *et al.* (1985)

- VLBI Quasars
  - Are modeled as having either longitudinal (EVPA normal to the jet) or tangled magnetic fields, implying that hydrodynamic forces dominate even at the pc scale
  - So, FR II / FSRQ sources appear to lose their magnetic field inside just a few parsecs
- It is natural, therefore, to propose that a recollimation shock also is at work in FR IIs
  - Possible model: turbulent reconnection in the RCS; field dissipated to internal energy, then radiated
  - Reconnection rate would have to be very fast [$\tau_{recon} << (1/M_{ms}) (L_{RCS}/c_{ms})$]
  - Possible solution: Lazarian & Vishniac (1999): $\tau_{recon} = (1/M_{ms}^2) (L_{RCS}/c_{ms})$

The Current Proposed Paradigm



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

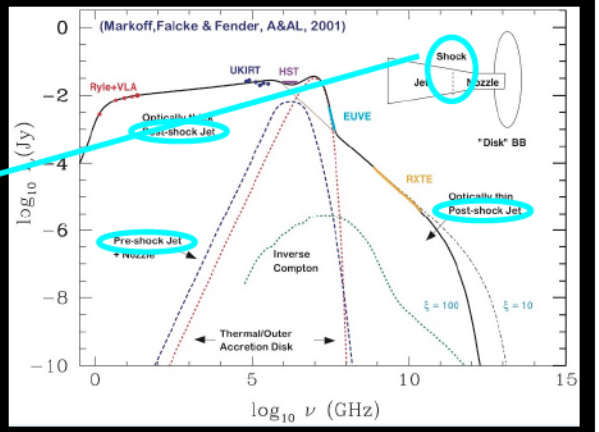
- Modest RCSs in moderate-power jets restructure the flow into a trans-magnetosonic, Poynting-dominated jet – an HBL / FR I source

- Strong RCSs in high-power jets actually dissipate the magnetic field, leaving a weakly-magnetized, still super-(magneto)sonic, kinetic-flux-dominated jet – a Quasar / FR II source

Other Types of Sources

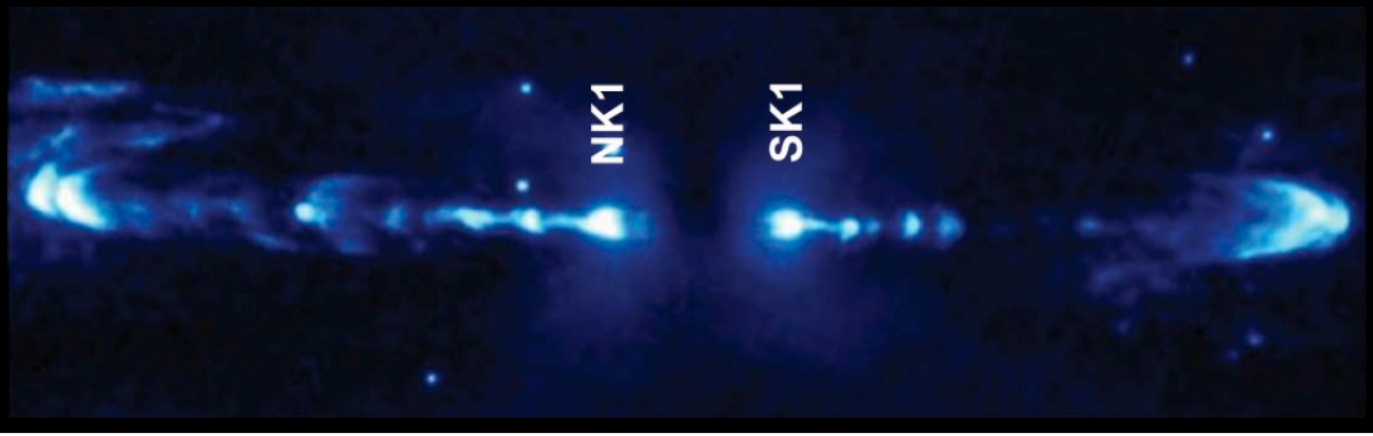
- GRBs: Dissipation in shocks below GRB photosphere (Bromberg 2011; Levinson 2012)

- X-ray Binary Jets: Models of broad-band emission require a strong shock after jet collimation (Markoff *et al.* 2001 *etc.*)



- Protostellar Jets: HH 212 shows (Correia et al. 2009):
  - (Non-relativistic) pair of strong shocks flanking central source
  - Multiple component (bow shock) ejections from each feature

Correia *et al.* (2009)

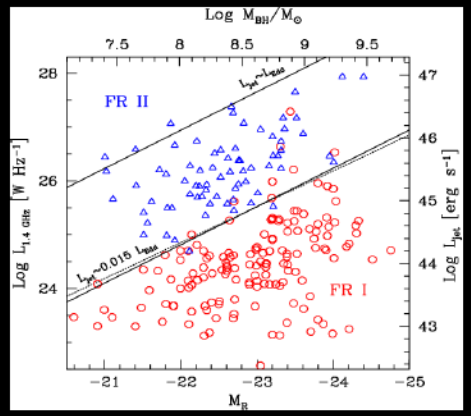


Backup

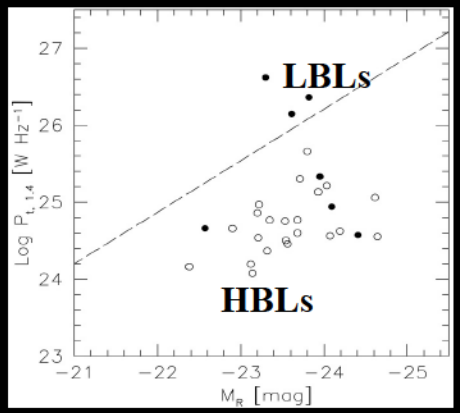
Summary: Class Divisions in AGN Jets

- Two widely-held cherished beliefs…
  - Most 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 *know early* 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 *have acquired morphological and magnetic properties* 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

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

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

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

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

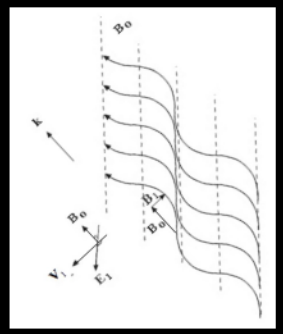
Alfven Waves

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

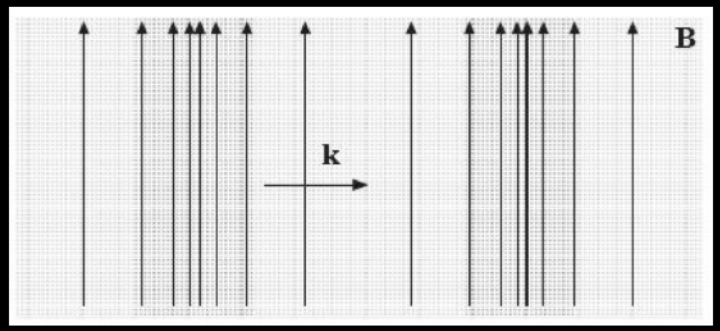
Magneto-Acoustic Waves

Preliminaries: Properties of MHD Waves

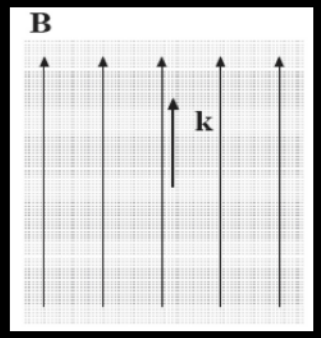
- MHD Waves in Magnetically-Dominated Plasmas ($U_{mag} >> U_p$; $V_A >> c_s$)



Alfven Wave ($V_{ph} = V_A \cos\theta$)
$V_{ph,\,A,\,\|} = V_A$; $V_{ph,\,A,\,perp} = 0$

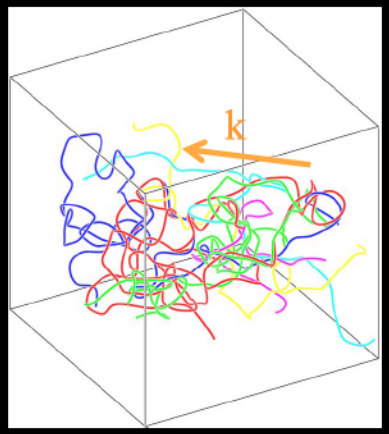


Fast Wave ($V_{ph} = V_F$)
$V_{ph,\,F,\,\|} = V_A$; $V_{ph,\,F,\,perp} = (V_A^2+c_s^2)^{1/2}$

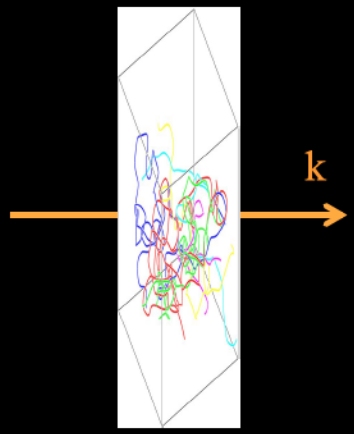


Slow Wave ($V_{ph} = V_F$)
$V_{ph,\,S,\,\|} = c_s << V_A$; $V_{ph,\,S,\,perp} = 0$

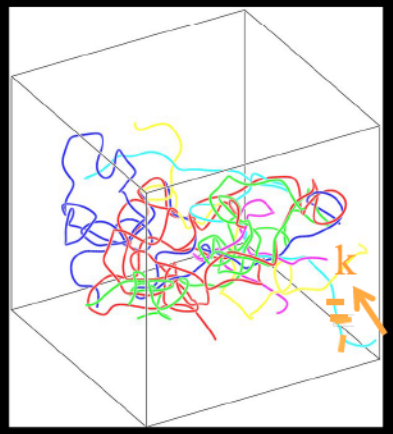
- MHD Waves in Particle-Dominated Plasmas ($U_p >> U_{mag}$; $c_s >> V_A$)



Alfven Wave (unimportant)
$V_{ph,\,A,\,\|} = V_A << c_s$; $V_{ph,\,A,\,perp} = 0$



Fast (~Sound) Wave
$V_{ph,\,F} = c_{ms}$
(*cf.* Hughes *et al.* 1985)



Slow Wave (unimportant)
$V_{ph,\,S,\,\|} = V_A << c_s$; $V_{ph,\,S,\,perp} = 0$

- NOTE: When $V_A \sim c_s$ (equipartion), <u>all 3 types (Alfven, fast, slow) are important</u>