Jet Production In Accreting Black Hole Systems

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In Order to Understand Jets From Accreting Black Holes, We Must Consider

1. All celestial sources that produce cosmic jets (not just black holes)

2. How magnetic fields can turn a rotating accretion inflow into a collimated, high-speed jet outflow

3. Black hole sources that accrete matter at significantly different rates (low, high, very high, super-Eddington)

4. Sources that do NOT produce jets as well as those that do

5. Black holes that produce jets by rotation of the accretion flow and of the black hole itself

6. Cosmic black hole systems of all masses, from 10 $M_\odot$ – 10^{10} $M_\odot$

Conclusions

1. Jets are Nature's response to the "angular momentum problem"; they carry away a.m. from a rapidly-rotating star/BH

2. $- dB_\phi^2 / dZ$ pressure accelerates plasma upward, B_ϕ^2/R "hoop stress" pinches it into a jet

3. A reasonable hypothesis is that a black hole jet is ejected whenever the accretion disk is geometrically THICK

4. Radio jets appear to be suppressed when the disk is THIN or when the radiation energy density is very high

5. BP (disk driven) jets appear to dominate in X-ray binaries; BZ (black hole driven) process appears important for AGN

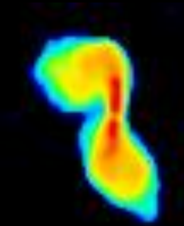
In Order to Understand Jets from Accreting Black Holes, We Must Consider

… All Celestial Sources that Produce Cosmic Jets

Astrophysical Jets are Ubiquitous Throughout the Universe

- Jets are produced by stars that are being born, dying, and dead; also by black holes of all known masses

SUPERMASSIVE BLACK HOLES



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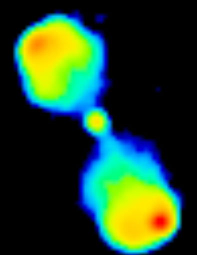

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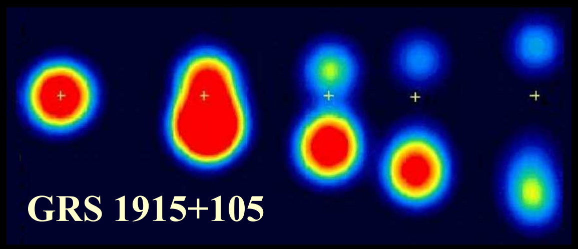
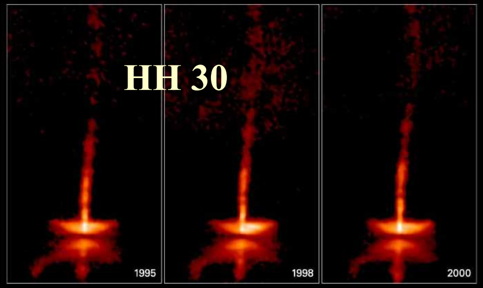
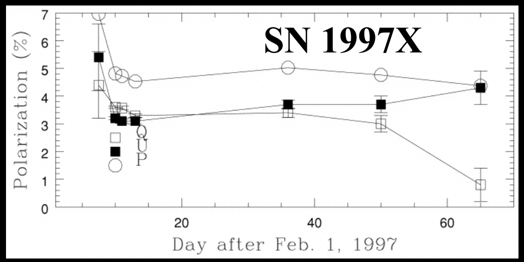
STELLAR-MASS BLACK HOLES

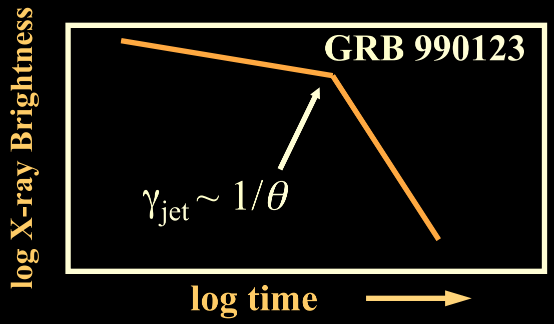


FORMING STARS



DYING STARS

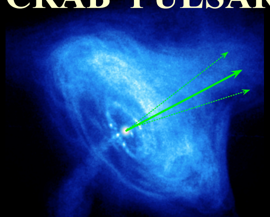


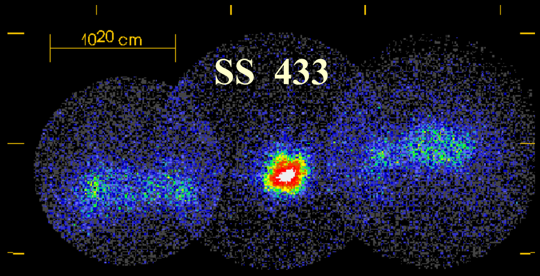


DEAD STARS

R AQUARII

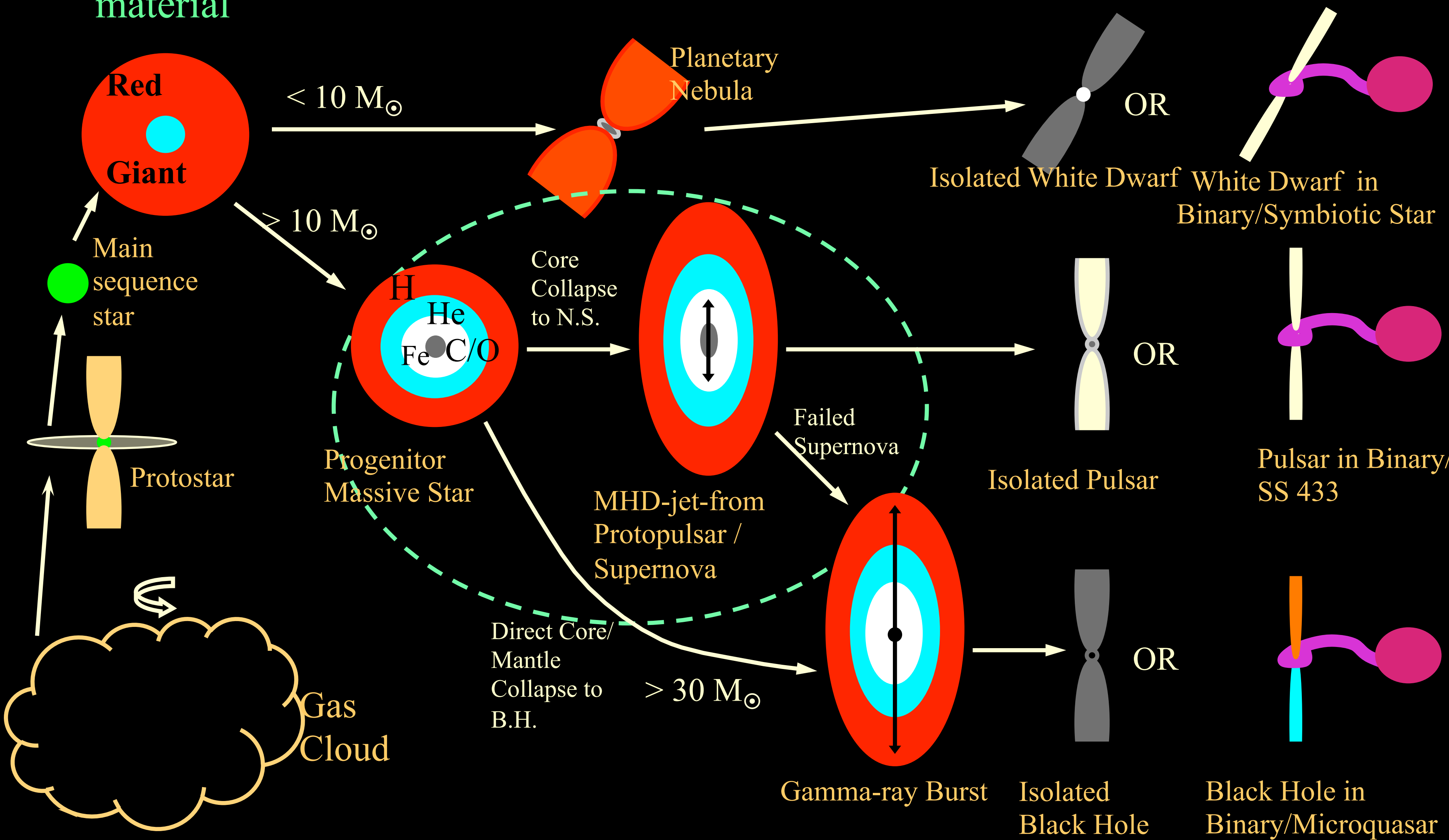
CRAB PULSAR





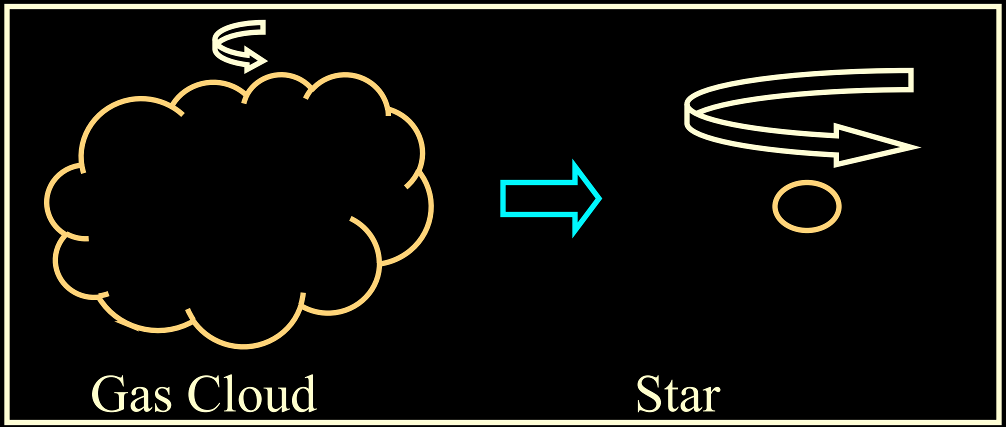
Jets are One of Nature's Answers to The Angular Momentum Problem

- Jets in stars are produced whenever there is an accretion or collapse of the stellar material



Cosmic Jets are Driven by Rotational Kinetic Energy, Created by Gravitational Contraction

- Conservation of angular momentum: $I\,\Omega = \text{const}$ ➔ $\Omega \propto 1 / I$



Dorothy Hamill

- Example: the primitive solar nebula
  - Angular momentum transport in the accretion disk <u>still would leave the sun spinning near breakup</u> (nearly Keplerian rotation)
  - <u>Production of a JET by the sun in its protostellar stage likely was responsible for its slow spin today</u>
- What physical process can produce jets and carry away ang. mom.?
  - MAGNETIC FIELDS

In Order to Understand
Jets from Accreting Black Holes,
We Must Consider

… How Magnetic Fields Can Turn a Rotating Accretion Inflow into a Collimated, High-Speed Jet Outflow

Basic Principles of Magnetohydrodynamic Jet Production

- Basic Ideal Magnetohydrodynamics:
  - Plasma can flow along magnetic field lines, not across them ("field frozen in")

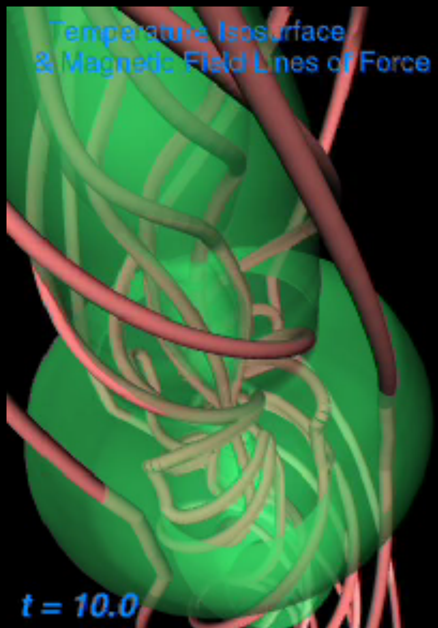
  - The conservation of momentum equation in MHD is given by

$$\rho V \, dV/dt = -\nabla (p + B^2 / 8\pi) + (\mathbf{B} \bullet \nabla \mathbf{B}) / 4\pi - \rho (GM/r^2) \, \mathbf{e}_r$$

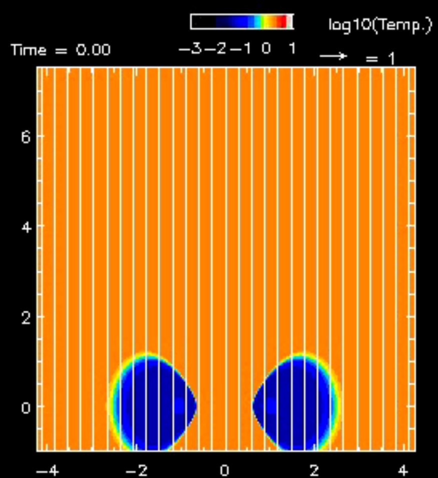
  - This generates 3 important waves in ideal MHD
    - Slow magneto-acoustic: $\nabla p / \rho \rightarrow V_S \approx c_s \equiv (\Gamma p / \rho)^{1/2}$
    - Alfven (transverse): $(\mathbf{B} \bullet \nabla \mathbf{B}) / 4\pi \rho \rightarrow V_A = B / (4\pi\rho)^{1/2}$
    - Fast magneto-acoustic: $\nabla (p + B^2 / 8\pi) / \rho \rightarrow V_F \approx c_{ms} \equiv (c_s^2 + V_A^2)^{1/2}$
  - In STRONGLY-MAGNETIZED plasmas
    - $V_S << V_A < V_F$
    - So, jets accelerated by magnetic fields must pass through Slow, Alfven, and Fast critical surfaces

Basic Principles of Magnetohydrodynamic Jet Production

- The basic ideas of jet launching and collimation were worked out long ago (Goldreich & Julian [1969]; Blandford [1976]; Lovelace [1976]; Blandford & Znajek [1977]; Blandford & Payne [1982])
  - Field is anchored in rotating plasma and in external “load”
  - Differential rotation twists up field into helical (barber pole) configuration
  - Magnetic pressure gradient (dB_ϕ^2 / dZ) accelerates plasma vertically out of system



Uchida et al. (1999); Nakamura (2001)



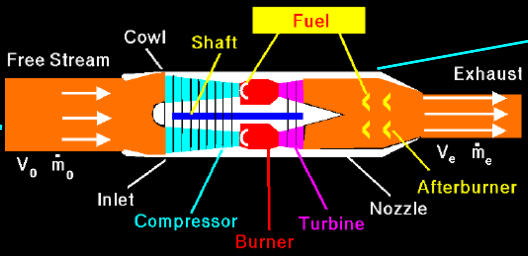
Kudoh, Matsumoto, & Shibata (1998)

- Magnetic tension [hoop stress] ($-B_\phi^2/R$) pinches and collimates the outflow into a jet
- Outflow jet speed *initially* is of order the escape speed from the inner edge of the torus ($V_{jet} \sim V_{Alfven} \sim V_{esc}$)
- Jet direction is along the rotation axis

Advanced Jet MHD: Jet Acceleration and Collimation

- Terrestrial jets are made with metallic nozzles

A Terrestrial Jet Engine



metallic housing

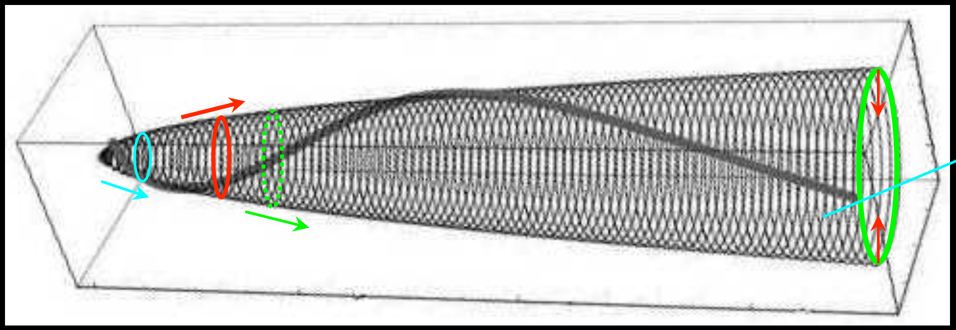
- Cosmic jets made with magnetic nozzles.
  - Plasma (ionized gas) can flow along a magnetic field, but <u>not across it</u>

Modified Slow Point ($V_\theta = V_{slow}$)

Alfven Point ($V_{jet} = V_{Alfven}$)

Modified Fast Point ($V_\theta = -V_{fast}$)

A Cosmic Jet Engine



magnetic field lines

SMSS

AS

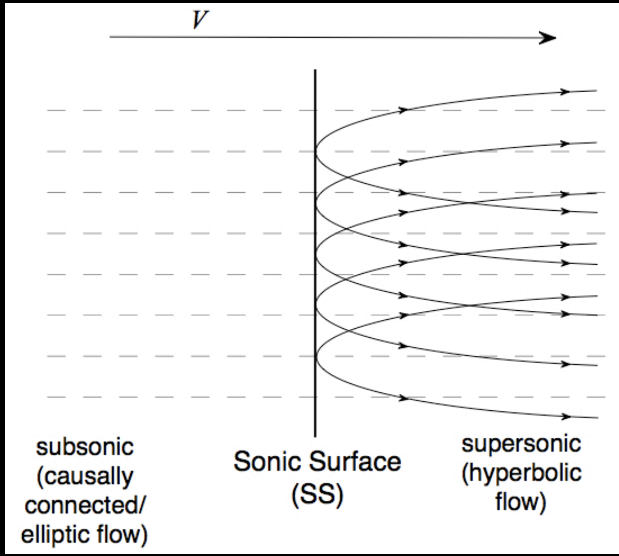
$V_{jet} = V_{fast} = (V_A{}^2 + c_S{}^2)^{1/2}$ (not a singular point)

FMSS

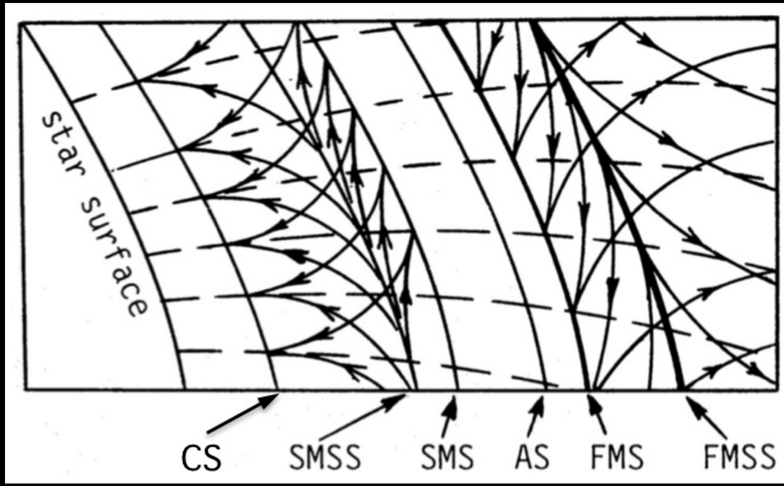
- Cosmic jets accelerate & collimate over long distances

HD Wind vs. MHD Wind/Jet

- The Parker (Solar) Wind
  - One "*critical*" surface
    - Sonic Surface (SS or "sonic point"; $V = c_s$)
  - Information flows:
    - In all directions below SS
    - Only in flow direction above SS



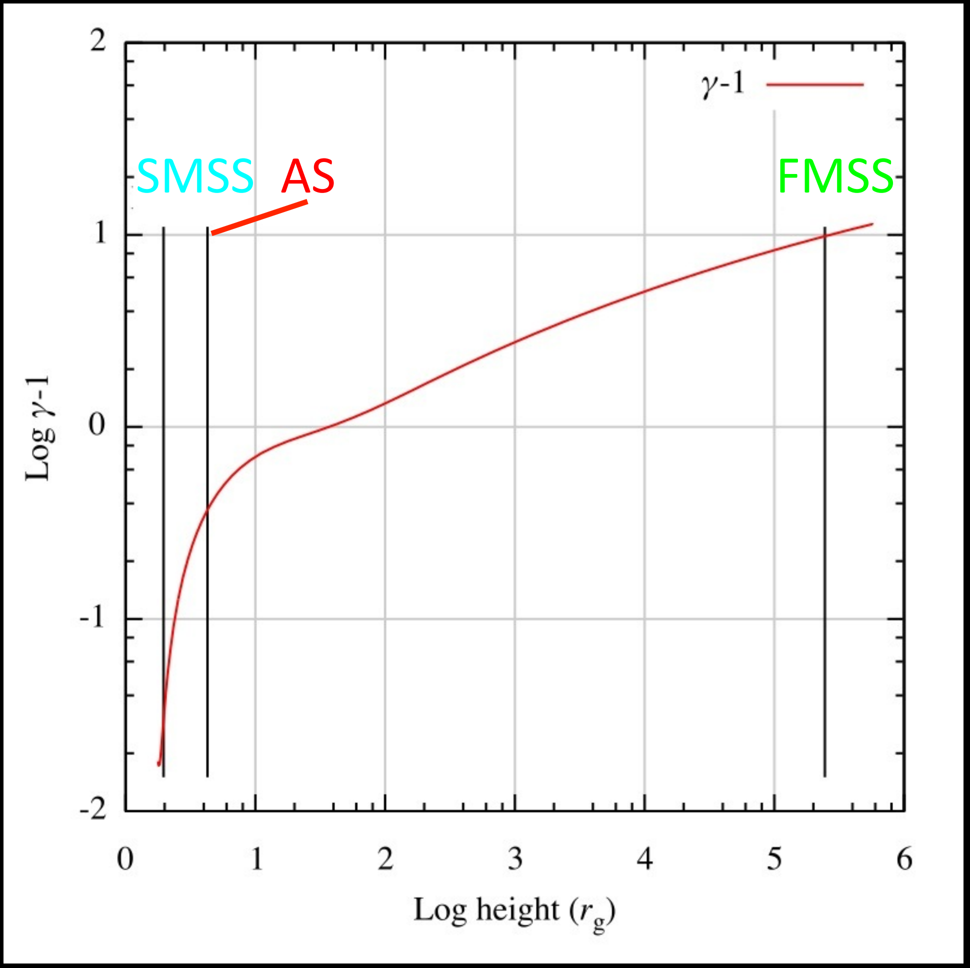
- Accelerating/Collimating MHD Wind
  - Three critical surfaces ($V_S < V_A < V_F$)
    - Cusp Surface (CS)
    - Slow Magnetosonic Surface (SMS)
    - Fast Magnetosonic Surface (FMS)
  - Three "*separatrix*" or singular surfaces
    - Slow Magnetosonic (SMSS)
    - Alfven Surface (AS)
    - Fast Magnetosonic (FMSS)
    - The FMSS is the magnetosonic "horizon", just like the Parker SS



Bogovalov (1994)

Advanced Jet MHD: Jet Acceleration and Collimation

K.E. per Unit Mass
(γ-1) vs. Height in Jet



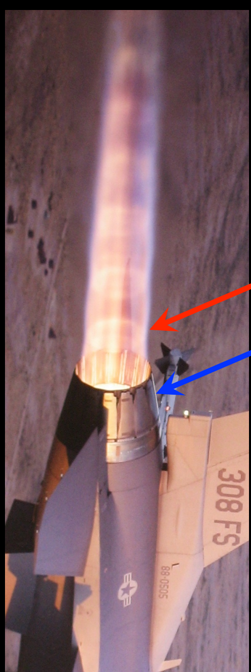
- Just like a terrestrial particle accelerator (e.g., LHC) <u>a rotating magnetic field can accelerate a plasma beam to highly relativistic speeds</u>

- Here $\gamma = (1-V^2/c^2)^{-1/2} \approx 11$ or $V_{jet} \approx 0.9959$ c

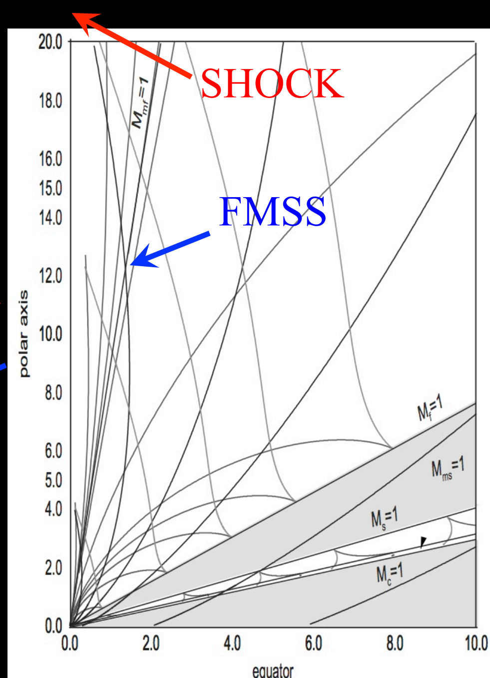
Polko, DLM, & Markoff (2011)

The Theoretical Case for A Collimation Shock in Most Jets

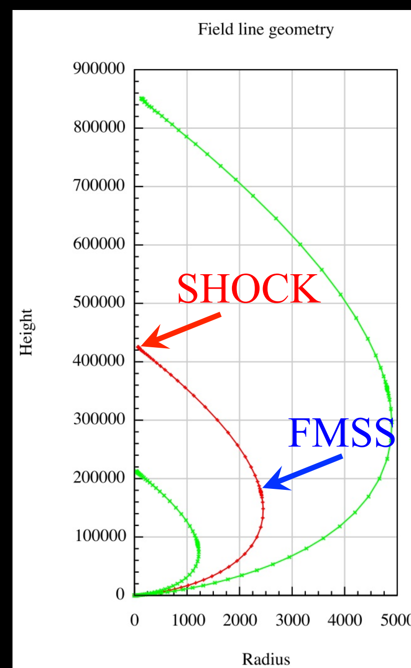
- MHD jet models with an FMSS, AND jet simulations, predict re-collimation at end of the Acceleration & Collimation Zone
  - *Beyond FMSS velocity toward polar axis > fast magnetosound speed*
  - *But, the flow also is causally disconnected from the central engine*



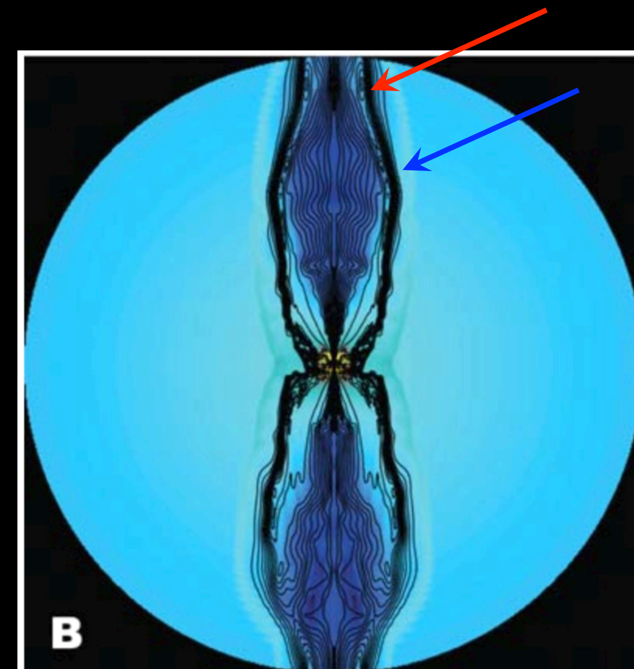
F-16 Convergent Nozzle



Vlahakis et al. (2000)



Polko, DLM, & Markoff (2011)

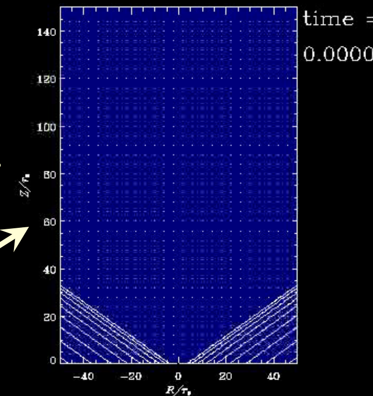


McKinney (2006)

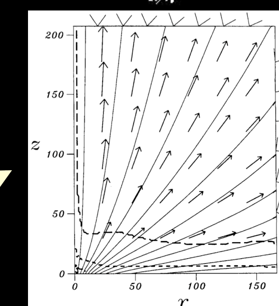
At Least Three Methods of Launching a Jet From an Accretion Flow

- PROBLEM: It is very difficult to launch plasma vertically from a thin accretion disk on the equator (Ogilvie & Livio 1998)

DLM et al. (1999)



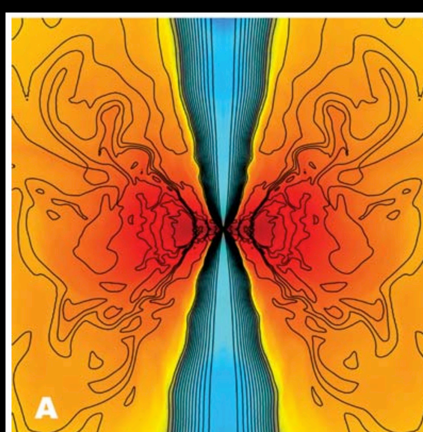
- SOLUTION #1: Magnetic Tower/Switch ($Z_{FMS} \sim R$; Lynden-Bell 1996; DLM et al. 1997)
  - a FAST MAGNETOSONIC solution



Ustyugova et al. (1999)

- SOLUTION #2: Cold, Magneto-Centrifugal ($Z_{AS} \sim R$; Blandford & Payne 1982)
  - an ALFVENIC solution

- SOLUTION #3: Hot, Magneto-Centrifugal ($Z_{SMS} \sim R$; Ustyugova et al. 1995 … McKinney 2006)
  - a SLOW MAGNETOSONIC solution



McKinney (2006)

In Order to Understand Jets from Accreting Black Holes, We Must Consider

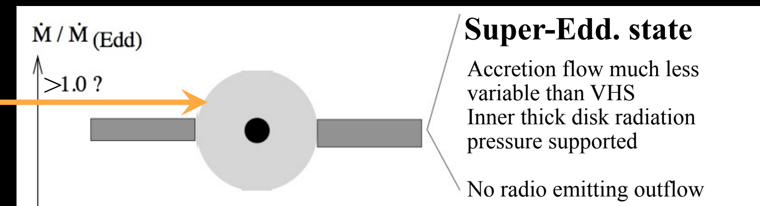
… Black Hole Sources that are Accreting Matter at <u>Different</u> ($\dot{m} \equiv \dot{M} / \dot{M}_{Edd}$) <u>Rates</u> (low, high, very high, super-Eddington)

and

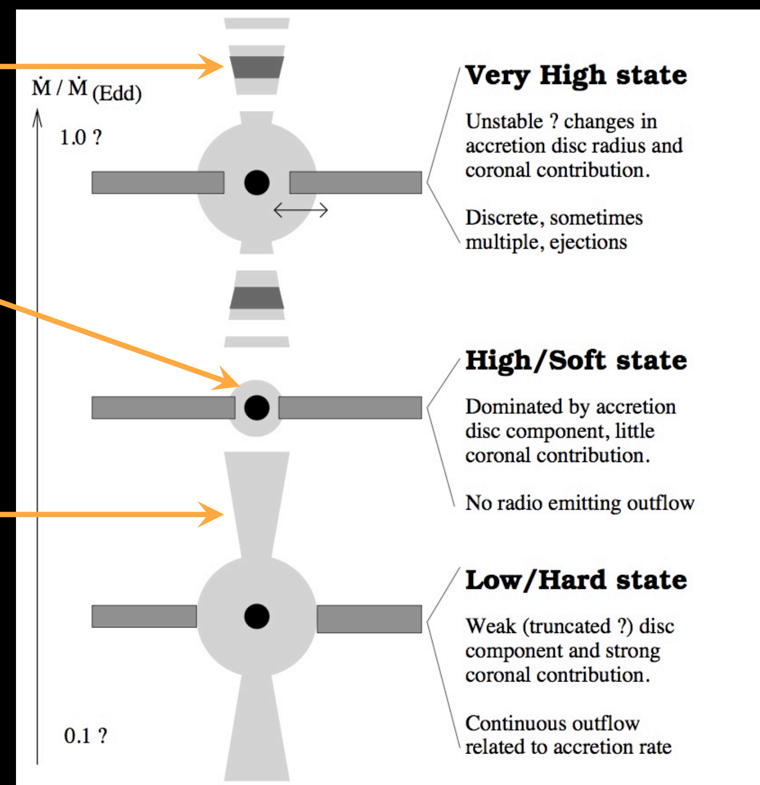
… Sources that Do NOT Produce Jets as Well as Those that Do

In a Single Binary Black Hole System the Jet Production can Vary Drastically

- SUPER-EDDINGTON State: $(1 < \dot{m})$
  Radio jet not detected



- VERY HIGH/UNSTABLE State: $(\sim 0.3 < \dot{m})$
  Jet is very strong but unsteady, often ejected every ¼ - ½ hour or so
- HIGH/SOFT State $(0.05 < \dot{m} < \sim 0.3)$:
  Jet is not detected (suppressed by x 50 – 300)
- LOW/HARD State $(\dot{m} < 0.05)$:
  Jet is weak but steady



Relation between models for BHC X-ray states and observed radio emission

Fender (1999)

- Two ways to suppress a radio jet:
  - Suppress the production of the jet itself
  - Suppress the radio emission

Jet Suppression By a Reduced Vertical Magnetic field B_Z

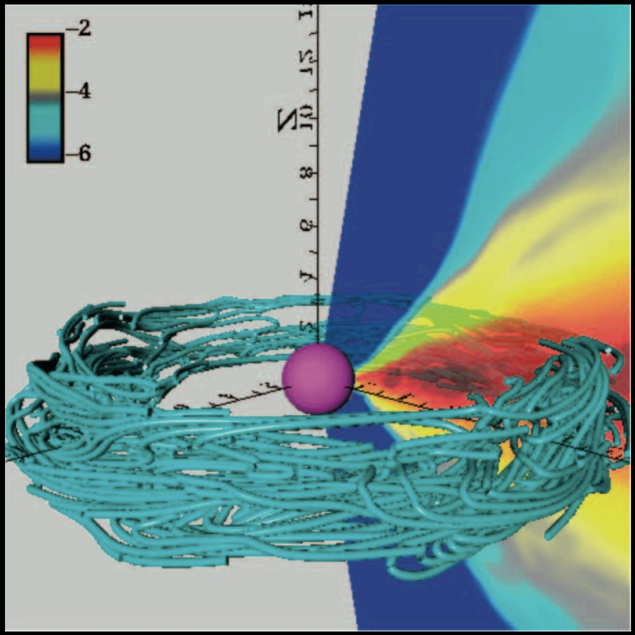
- The total power of a magnetically-driven jet produced by a rotating accretion flow is given by (Blandford & Payne 1982)

$$L_{jet} = B_{Z0}^2 \; R_0^2 \; V_{\phi 0}$$

- Most of the accretion disk magnetic field is in the azimuthal component B_ϕ, and we might expect the vertical component to be related to B_ϕ as

$$B_Z \approx B_\phi \, (H_0/R_0)^{\,p} \qquad \text{where } p \geq 1$$

or $$L_{jet} = B_{\phi 0}^2 \; R_0^2 \; V_{\phi 0} \; (H_0/R_0)^{2p}$$



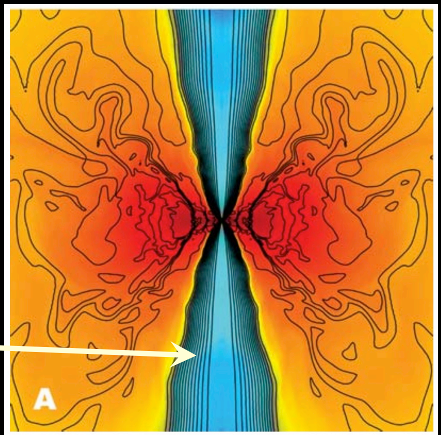
Hirose et al. (2004)

- HIGH/SOFT state disks are very thin ($H_0/R_0 \sim 0.01$), with $B_{\phi 0} \sim 10^8$ G
- LOW/HARD "disks" are very thick ($H_0/R_0 \sim 1$), with $B_{\phi 0} \sim 10^7$ G ($\dot{m} \sim 0.05$)
- <u>So, suppression factors of a hundred or more are quite possible with this method</u>

Jet Suppression By a Reduced Vertical Magnetic field B_Z

- However, there is a related process that may be even more important, and more effective, in quenching jets

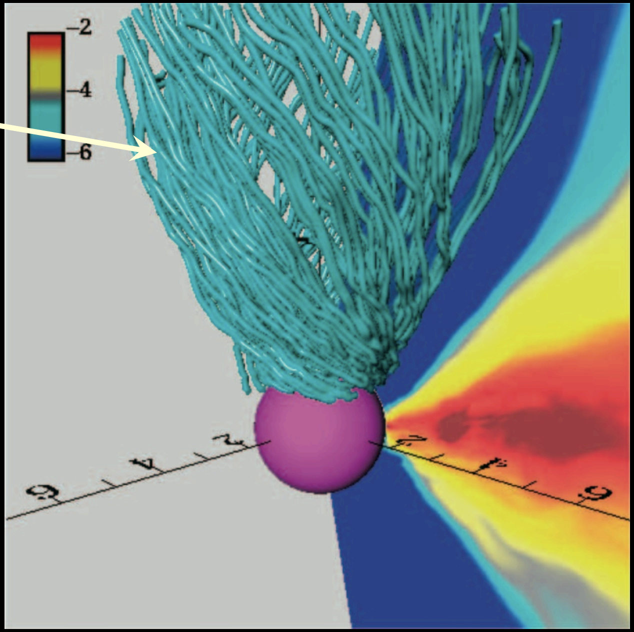
- In full accretion disk simulations jets are produced mainly in the funnel of a very thick disk ($H_0/R_0 >> 1$)



McKinney (2006)

- Very thick disks produce well-ordered, strong magnetic fields near the funnel edge
- This may be the MAIN METHOD by which Nature allows black hole accretion inflows to produce strong jets

- While this new concept needs to be studied quantitatively in detail, it could imply $p >> 1$, which would allow jet quenching factors of many thousands or more



Hirose et al. (2004)

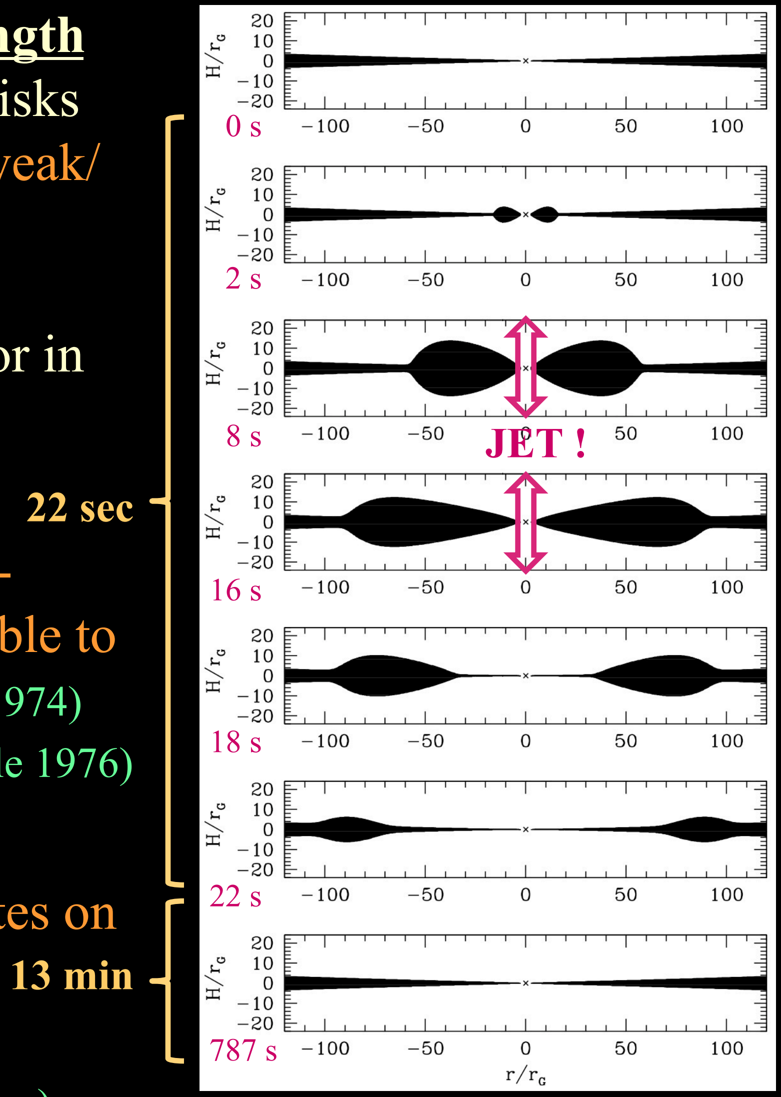
Jet Suppression
By a Reduced Vertical Magnetic field B_Z

- So, the difference between **magnetic field strength and structure** in geometrically thick and thin disks can explain the difference between strong and weak/ non-existent jets in the hard and soft states

- Can this same effect explain the strange behavior in the very high state?   … YES

- Accretion disks with ~ 0.3 < $\dot{m}$ have a radiation-pressure-dominate ("inner") region that is unstable to
  - Secular (accretion) instabilities (Lightman & Eardley 1974)
  - Thermal instabilities (Shakura & Sunyaev 1976; Pringle 1976)

- They cycle through temporary hard and soft states on time scales of
  - ¼ hour or so (secular time)
  - with fine-scale structure on seconds or less (thermal time)

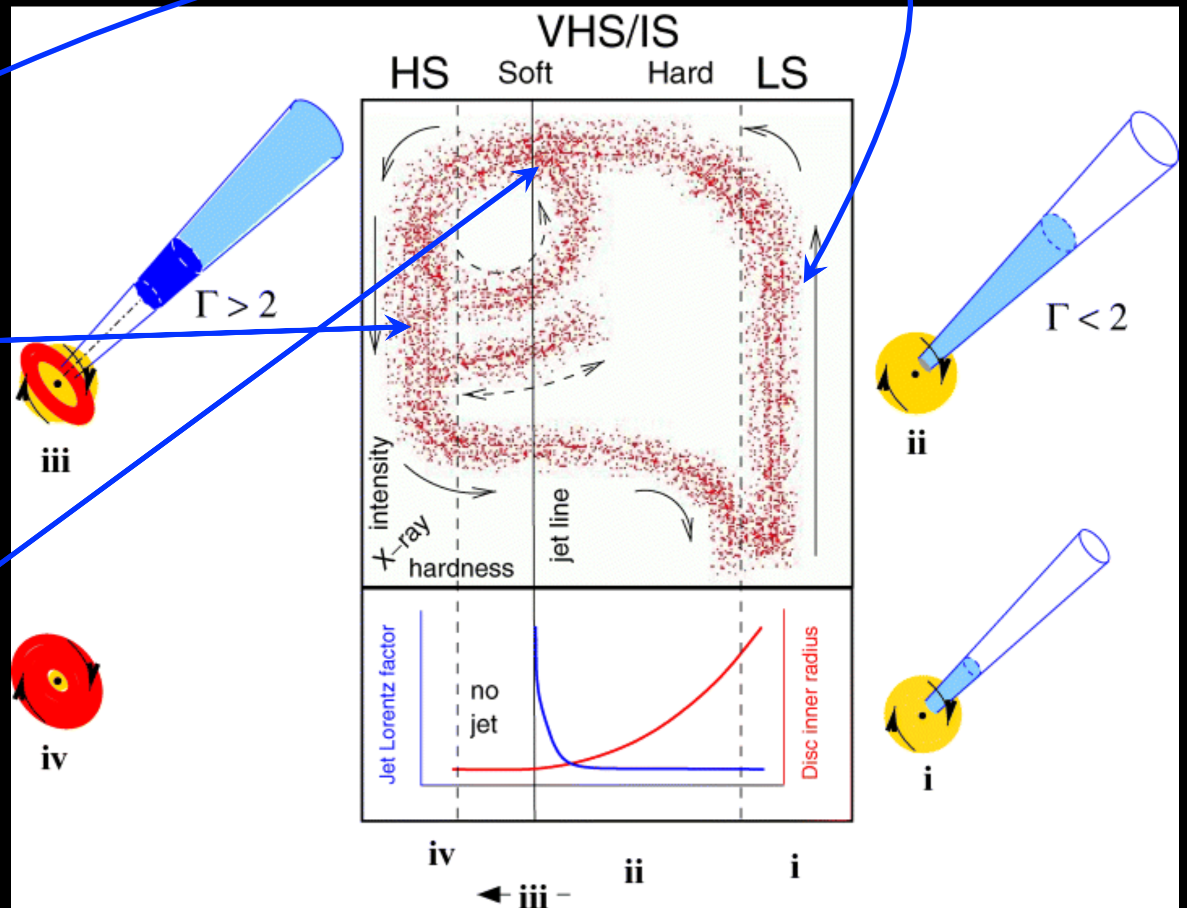


Szuszkiewicz & Miller (2001)

Same Effect in the Hardness-Intensity Plot

- The hypothesis is that ALL disk-driven jets are produced when (<u>and only when</u>) the disk is in a geometrically thick state

- Weak, steady jet in low/ hard state
- No jet is seen from the thin disk in the high/soft state
- Accretion disk cycles through geometrically thick and thin states on short time scales



Fender et al. 2004

Variability on Secular & Thermal Time Scales Can Explain a Lot of Black Hole Properties

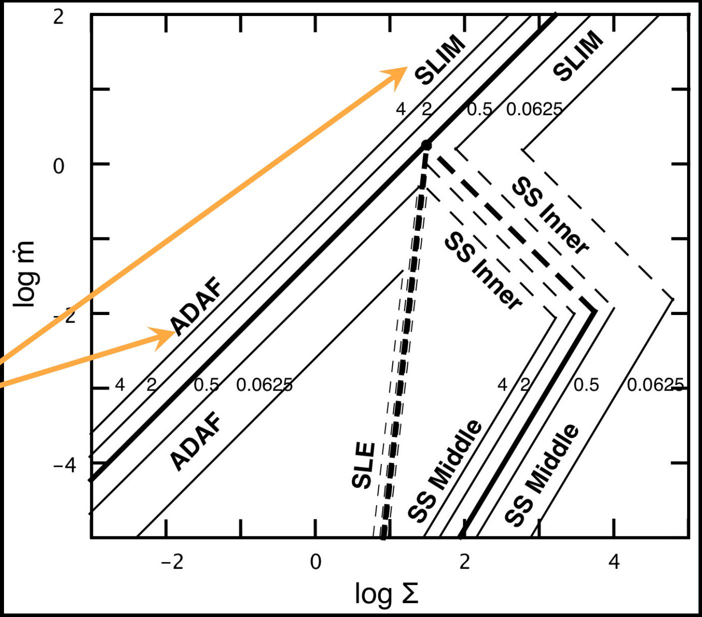
Source	$M/M_\odot$	Accretion State	Phenome-non	M/M_{Edd}	Time Scale	Theory	Observed
1915+105	14	SPL	Explos. Jet	> 0.3	Secular	19 m	13 – 22 m
``	14	SPL	Broad QPO	> 0.3	Thermal	0.05 – 1 s	0.13 – 0.25 s
ULX P098	25	Super-Edd	Wind Variations	100	Secular	~ 30 hr	3 – 22 hr
``	25	Super-Edd	``	100	Thermal	0.1 s – 7 m	< 1 hr
NGC 5548	1 – 4 x 10^7	Seyfert 1	Optical Variability	~ 0.1	Secular	7000 yr	---
``	1 – 4 x 10^7	Seyfert 1	``	~ 0.1	Thermal	0.1 – 4 mo	3 mo
Quasars	10^9	Type 1	Optical Variability	0.01 – 1	Secular	0.5 – 2 Myr	---
``	10^9	Type 1	``	0.01 – 1	Thermal	11 – 150 yr	2 – 20 yr

- NOTE: secular (accretion) times for SMBHs are much longer than human lifetimes
- Any variability we see in Active Galactic Nuclei must be on a thermal time

Suppression of Jet Radio Emission By Radiation Drag?

- Can jet suppression by a thin accretion disk explain jet suppression in the super-Eddington state?

  … VERY UNLIKELY
- "Disks" in the super-Eddington state are actually very geometrically thick, just like ADAFs
- They and ADAFs are actually on the same branch of accretion models in the $\dot{m} - \Sigma$ plane
- Super-Eddington accretion inflows
  - Like all other inflows, must be driven by MHD turbulence
  - Must be geometrically thick (radiation pressure supported)
  - So, they SHOULD produce strong MHD winds and jets

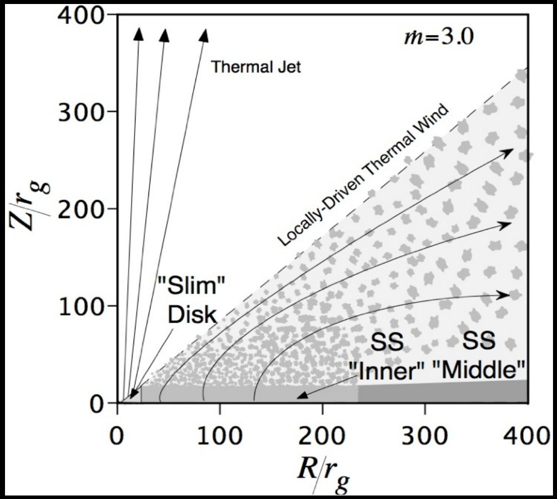


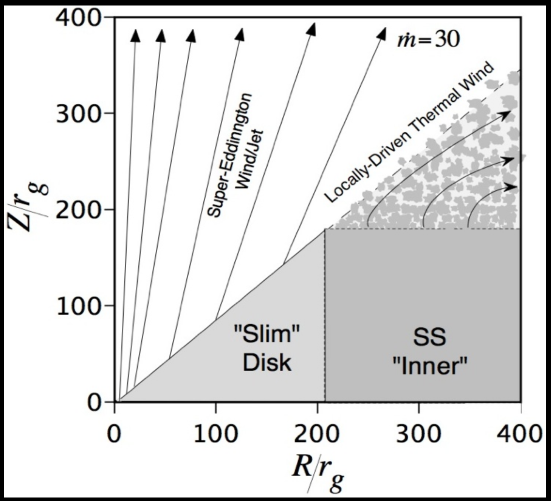
The Accretion Rate vs. Surface Density Plot for Most Disk Models (after Chen et al. 1995)

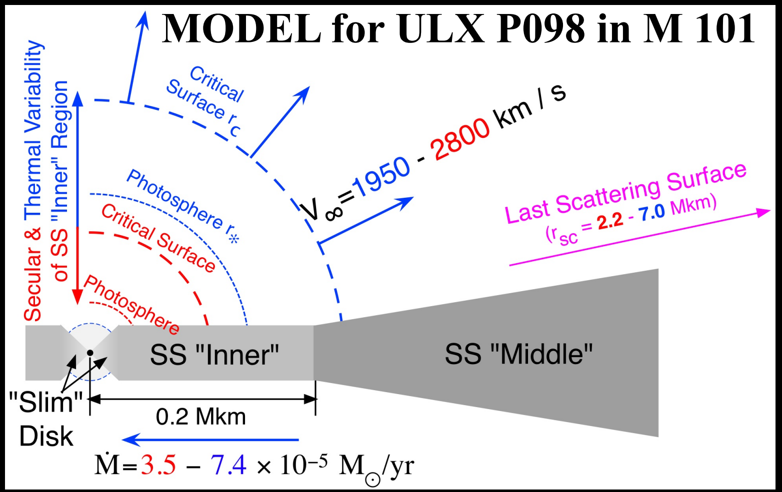
- Yet, we do NOT observe strong radio emission from super-Eddington BHs. WHY?
- This is a MAJOR UNSOLVED PROBLEM in the theory of jet / accretion flow interaction
- SPECULATION:
  - The only real difference between ADAFs and super-Eddington inflows is the high-intensity radiation field in the latter
  - Does the strong radiation field inhibit generation of relativistic electrons (Antonucci 1993)?

Suppression of Jet Radio Emission By Radiation Drag?

- POSTULATE: Thick, radiation-pressure-dominated accretion inflows DO PRODUCE JETS, but the effects of the strong radiation field inhibit the acceleration of non-thermal particles: i.e., the jets remain in a thermal state
- In the past many people have considered thick, radiation-pressure-supported disks and the dynamics of the funnel (Abramowicz et al. 1978; Paczynski & Wiita 1980; Begelman & DLM 1982; Proga & Begelman 2003; etc.)
- But I have seen none that combine MHD jet acceleration and radiation drag
- Sources where super-Eddington thermal jets may be playing a role:
  - Stellar black holes (SPL sources, ULXs, super-soft sources, SS 433)
  - SMBHs (Narrow-line Seyfert 1s; BAL QSOs)







In Order to Understand
Jets from Accreting Black Holes,
We Must Consider

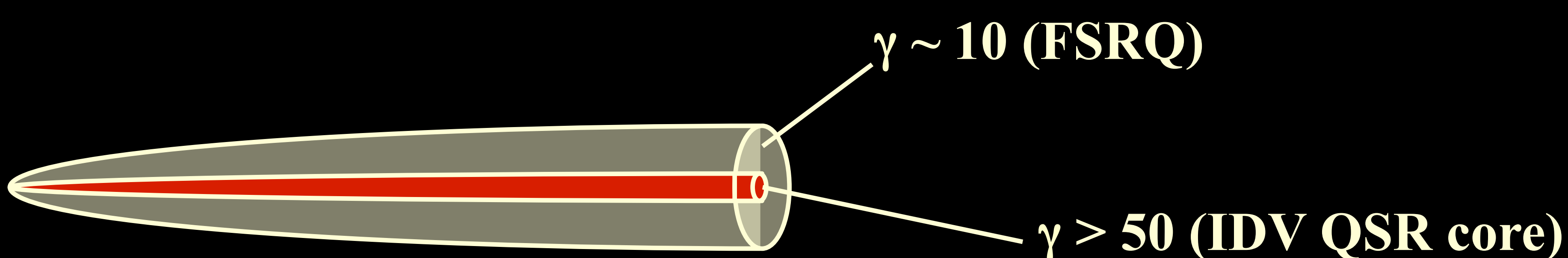
… Rotation of the Black Hole as well as
Orbital Rotation of the Accretion flow

and

… Cosmic Black Hole Systems of All Masses,
from $1\ M_\odot - 10^{10}\ M_\odot$

Black Hole Spin vs. Rotation of the Accretion Flow in Driving the Jet

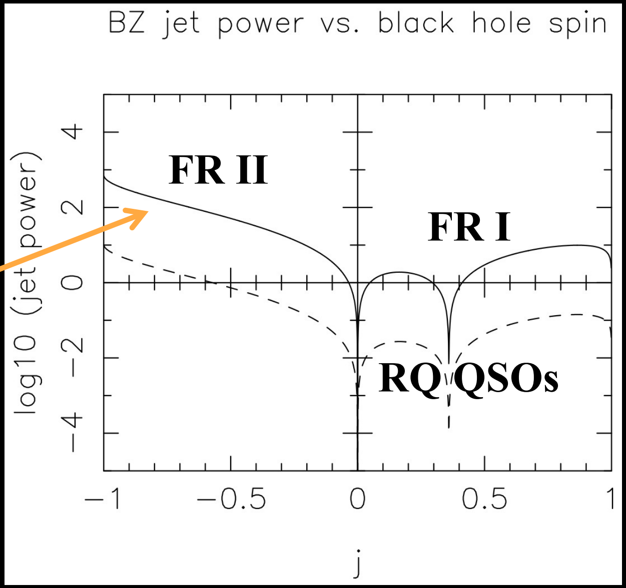
- UNSOLVED PROBLEM: What drives black hole jets?
  - Rotation of the accretion inflow (Blandford-Payne process) OR
  - Rotation of the black hole itself (Blandford-Znajek process)?
- Answer may be both:
  - Accretion inflow jet may produce an outer sheath ($\gamma < \sim 10$; generally visible)
  - Black hole jet may produce an inner core ($\gamma > 50$; very compact, strongly affected by relativistic beaming)

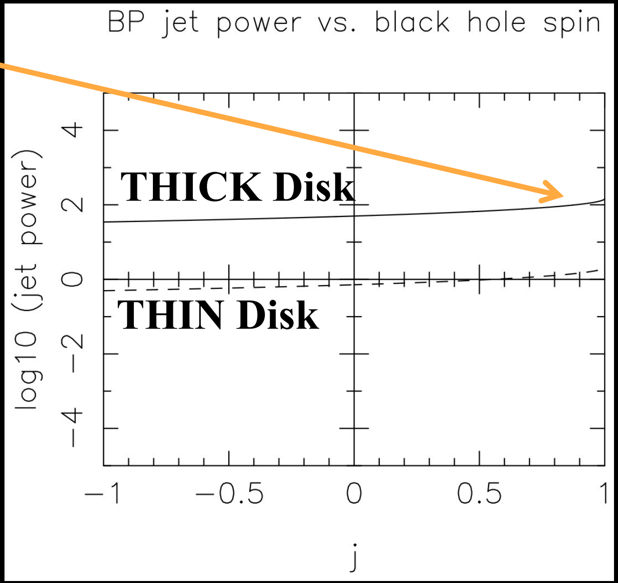


Black Hole Spin vs. Rotation of the Accretion Flow in Driving the Jet

- What are the two jets' relative strengths and applicability?
  - Black hole rotation tends to dominate when accretion inflow is opposite to black hole spin
  - Blandford-Znajek jets seem to fit AGN behavior quite well
  - Accretion disk jets tend to dominate when accretion inflow is in same sense as BH spin
  - BIG PROBLEM, HOWEVER: Numbers do not quite work out:

Predicted BP jet power is at least a factor of 10 too high, overwhelms BP power

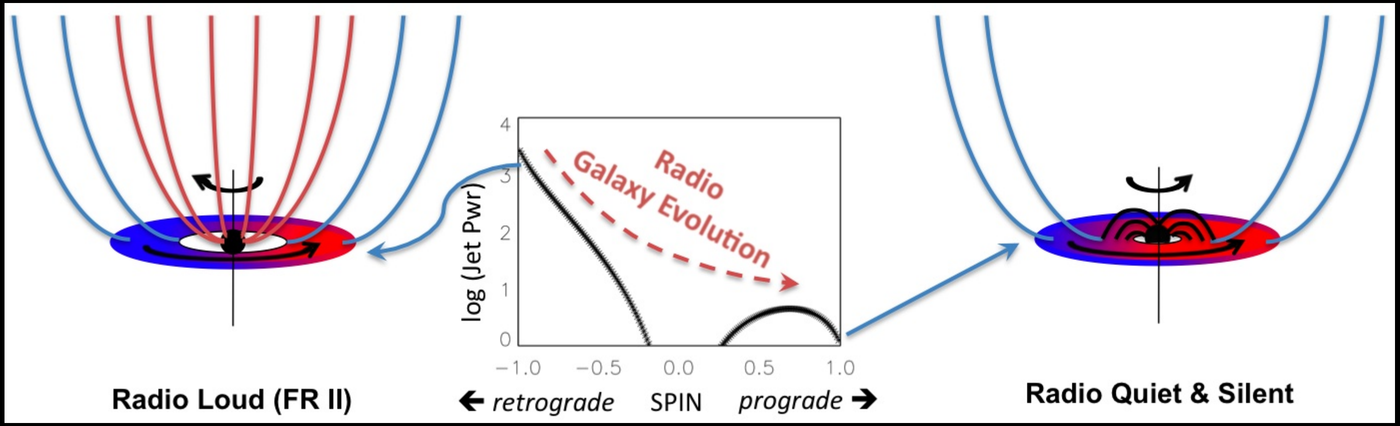




Role of Blandford-Znajek Jets

Having powerful FR II and even weaker FR I radio sources produced by retrograde accretion and radio quiet sources produced by prograde accretion SOLVES a BIG problem for **SUPERMASSIVE** black holes: the 'spin paradox'

- Radio galaxy observations had implied that SMBHs now spin **slowly**
  - Powerful FR II radio galaxies (rapid spin) were much more common at $z > 1$
  - SMBHs must now be spinning slowly (Wilson & Colbert 1995; DLM 1999)
- But optical observations of AGN imply black holes now spin **rapidly**
  - AGN appear to produce optical luminosity with efficiencies of 10 – 15 %
  - This implies that SMBHs are spinning rapidly: $0.7 < j < 0.9$ (Elvis et al. 2002)
- **All is now consistent**: SMBHs are now indeed spinning **rapidly**, but as prograde, radio weak systems (DLM & Garofalo 2010)



The Black Hole Mass-Accretion Rate Diagram