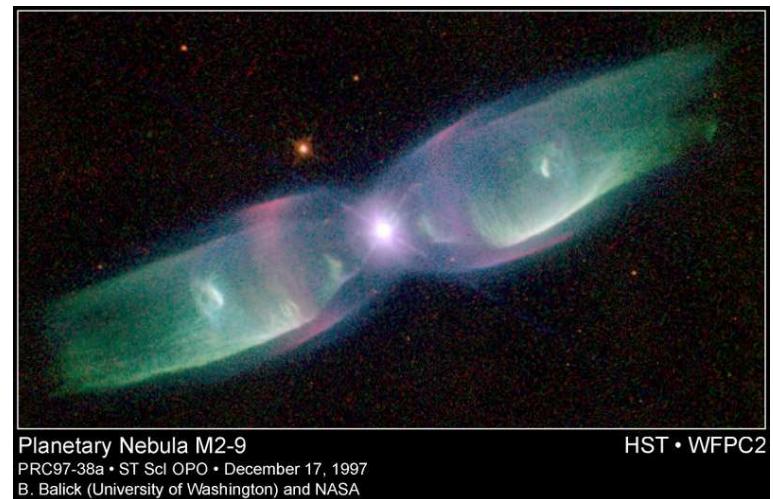
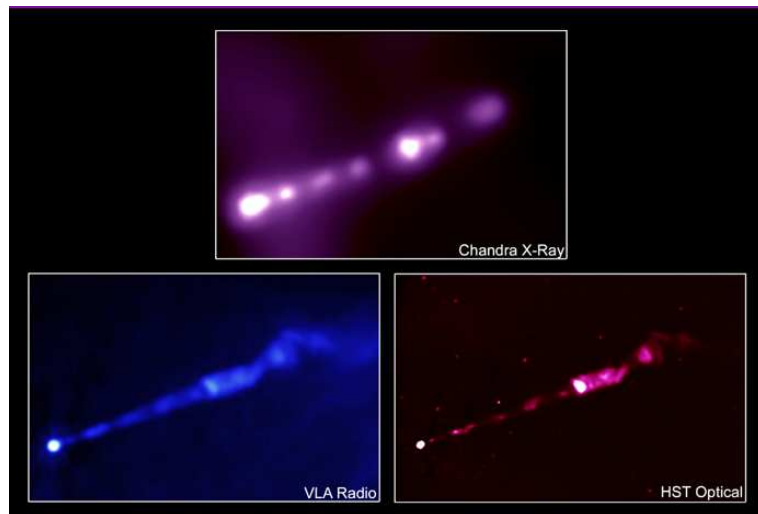
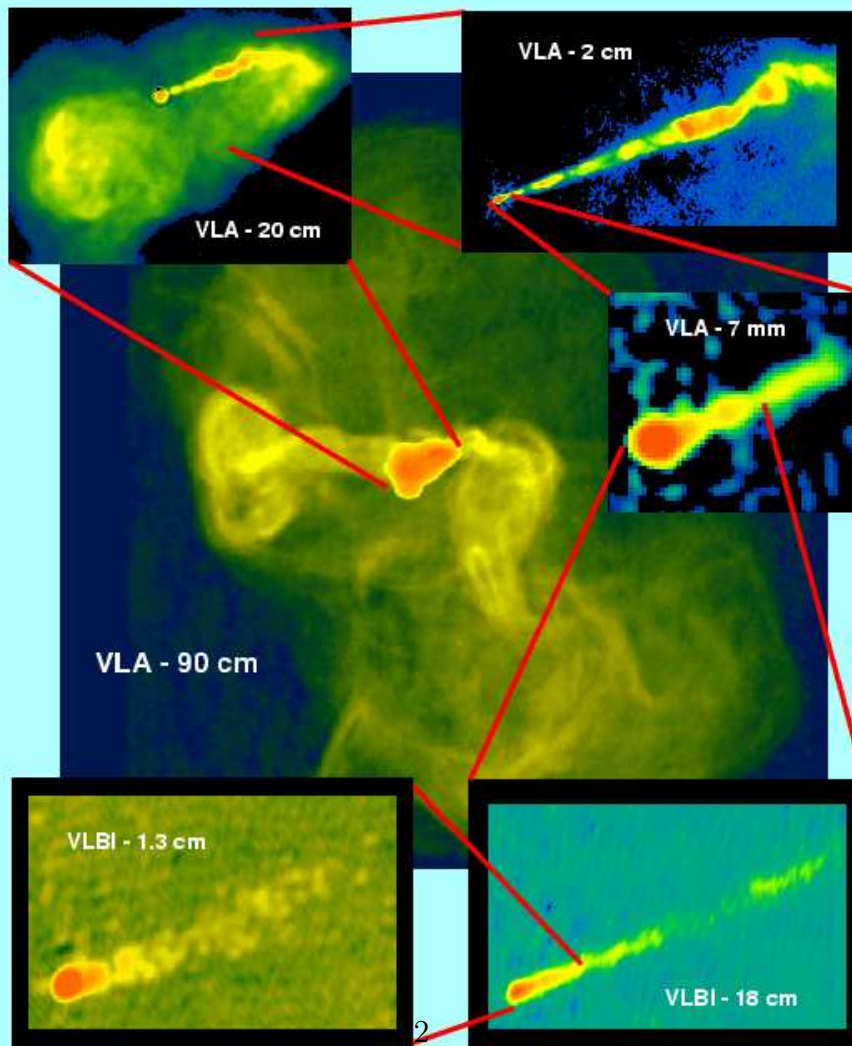


“OBSERVATIONS”

Eric Blackman (UR)



M87 -- From 200,000 Light-Years to 0.2 Light-Year



Credit: Frazer Owen (NRAO), John Biretta (STScI) and colleagues.
The National Radio Astronomy Observatory is a facility of the
National Science Foundation, operated under cooperative
agreement by Associated Universities, Inc.

LAUNCH vs. COLLIMATION vs. PROPAGATION

- Asymptotic propagation: ($r \gtrsim 100R_{obj}$) vs. launch region ($r \lesssim 50R_{obj}$)
- Observations resolve scales $r > 50R_{obj}$. Need microarcsec resolution to study launch region. Current resolution in radio: at 0.1-1 milliarcsec.
- *Theoretical* “consensus” that B -fields are dominant in launch region ($r \lesssim 50R_{obj}$) for all *formidable* astrophysical jets.
- Observations *indirectly* support this theoretical consensus
- “Best” evidence for MHD launch: rotation in YSO jets $\lesssim 100$ AU scales. (Bacciotti et al. 2002-05; Coffey et al. 2004,2005; Woitas et al. 2004)
- Does B dominate in propagation region at $r > 50r_{obj}$?
 - YSO and PNe jets: probably flow dominated at $r > 100$ AU
 - AGN (galactic BH engine) and GRB, Microquasar (stellar BH engines) might be B-dominated to large r but how far from engine?

Hsu & Bellan 02

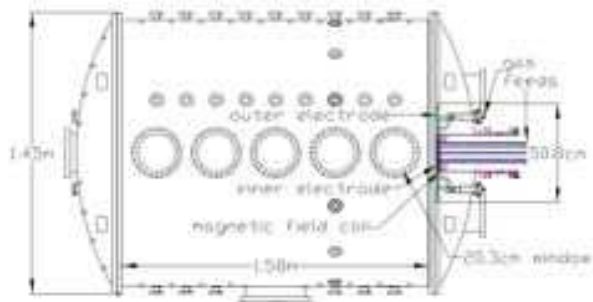


Figure 1. Side-view schematic of vacuum chamber and planar coaxial gun setup.

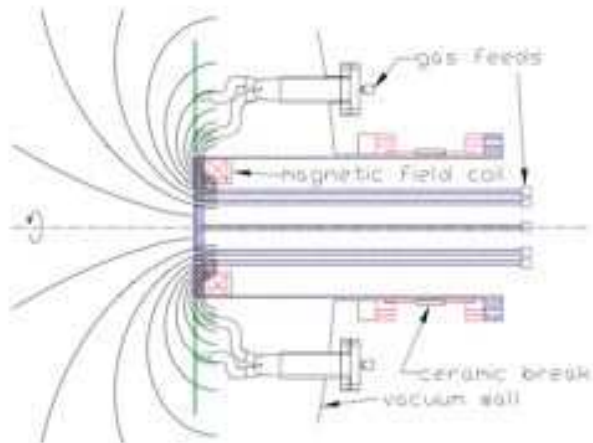


Figure 2. Side-view schematic of planar coaxial gun, including gas feeds, external magnetic field coil, poloidal flux ϕ contours and symmetry axis.

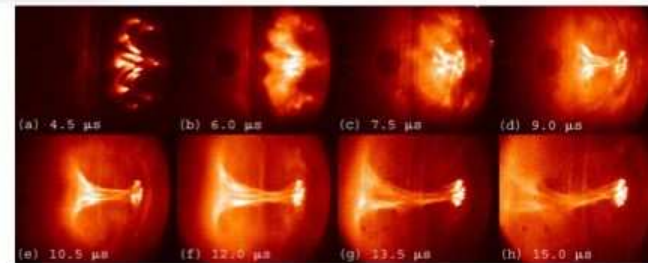


Figure 3. Images of plasma evolution (shot 1210; peak $\alpha_{\text{pl}} \approx 66 \text{ m}^{-1}$) in which a plasma column forms and persists for many Alfvén transit times, illustrating the magnetic topology required for an astrophysical jet.

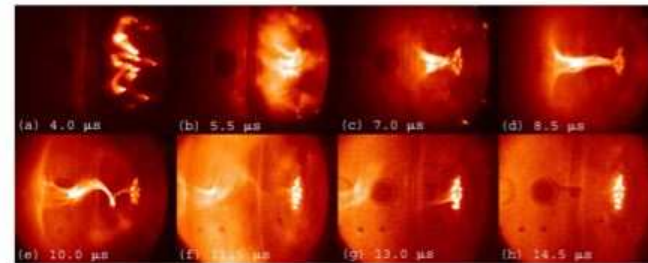


Figure 4. Images of plasma evolution (shot 1233; peak $\alpha_{\text{pl}} \approx 71 \text{ m}^{-1}$) in which a helical instability, probably a current-driven kink, develops on the ideal MHD time-scale, illustrating one possible source of jet internal structure.

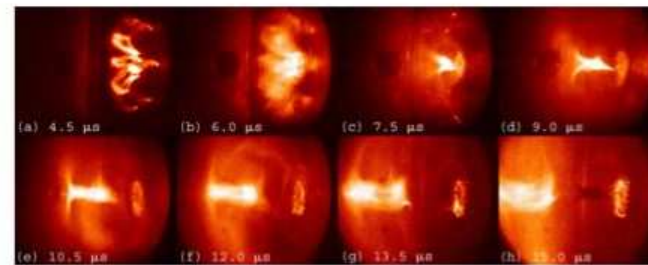
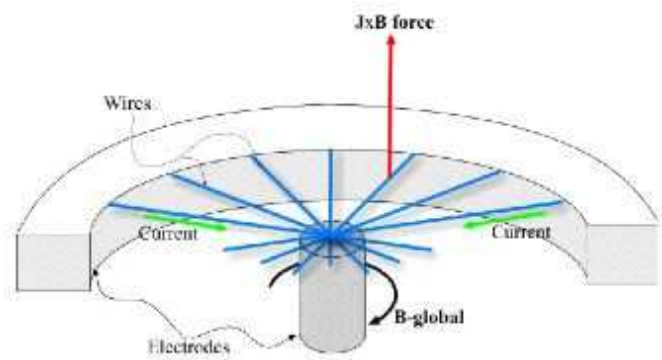
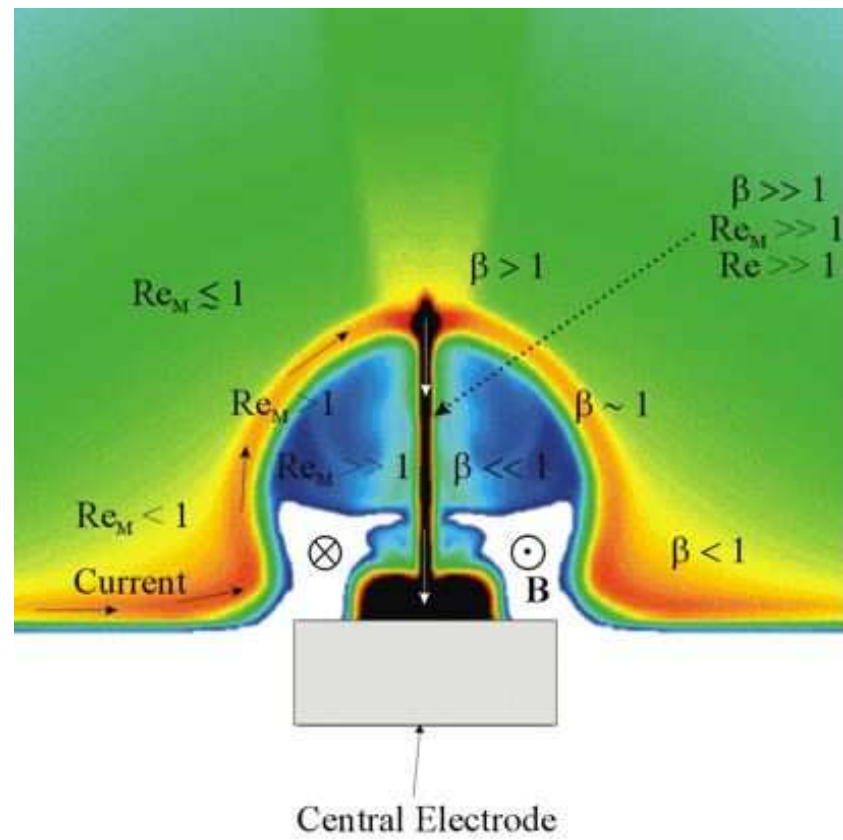


Figure 6. Images of plasma evolution (shot 1181; peak $\alpha_{\text{pl}} \approx 129 \text{ m}^{-1}$) in which the plasma detaches from the electrodes, illustrating the possibility of field-line opening in disc coronae.



4mm



AGN Unified Model

(e.g. Urry & Padovani 1995)

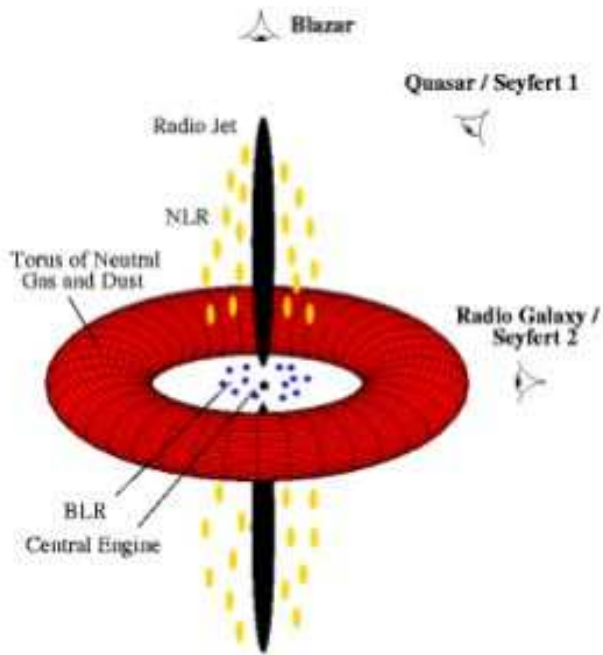
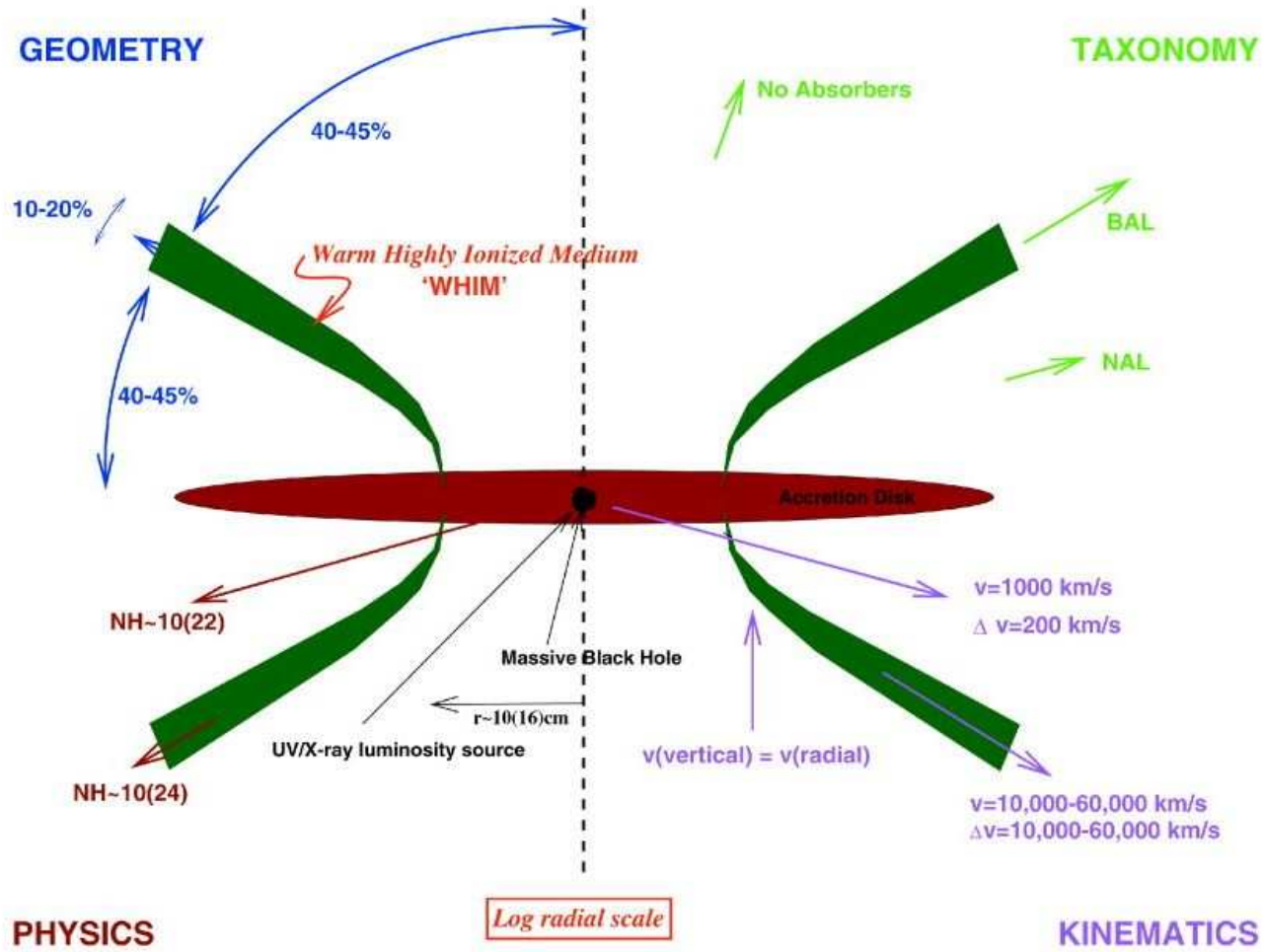


FIG. 1—A schematic diagram of the current paradigm for radio-loud AGN (not to scale). Surrounding the central black hole is a luminous accretion disk. Broad emission lines are produced in clouds orbiting above the disk and perhaps by the disk itself. A thick dusty torus (or warped disk) obscures the broad-line region from transverse lines of sight; some continuum and broad-line emission can be scattered into those lines of sight by hot electrons that pervade the region. A hot corona above the accretion disk may also play a role in producing the hard X-ray continuum. Narrow lines are produced in clouds much farther from the central source. Radio jets, shown here as the diffuse jets characteristic of low-luminosity, or FR I-type, radio sources, emanate from the region near the black hole, initially at relativistic speeds. For a $10^8 M_{\odot}$ black hole, the black hole radius is $\sim 3 \times 10^{13}$ cm, the accretion disk emits mostly from $\sim 1-30 \times 10^{14}$ cm, the broad-line clouds are located within $\sim 2-20 \times 10^{16}$ cm of the black hole, and the inner radius of the dusty torus is perhaps $\sim 10^{17}$ cm. The narrow-line region extends approximately from $10^{18}-10^{20}$ cm, and radio jets have been detected on scales from 10^{17} to several times 10^{24} cm, a factor of ten larger than the largest galaxies.

Elvis (2000)



AGN Jets:

- Relativistic (superluminal motion; 1-sided jets); typically $\Gamma \lesssim 30$, though degeneracies. Flows collimated up to $\sim 300\text{kpc}$; Radio, X-ray, Opt, γ -ray,
- Radiation pressure from extended base cannot supply needed anisotropic momentum for relativistic jets. “Compton drag”.
- Magnetic domination in source is natural theoretical alternative
- Evidence for accretion+coronal paradigm in X-rays supports role of B-fields and some dissipation in engine.

- Polarized radio emission down to sub pc scales; Rapid variabilites in radio down to 20 min in Mk 421 (e.g. Gaidos et al. 96; Cui 04); Flaring.
- $T_b \sim 10^{11}(F/1\text{Jy})(\lambda/\text{cm})^2(d/\text{Mpc})^2(1+z)^{-2}(t_{var}/\text{sec})^{-2}\gamma^{-3}(1-\beta\cos\theta)^{-3}\text{K}$
Above this temp, inverse Compton cooling produces large X-ray fluxes not detected. (e.g. Wegner & Witzel). Relativistic motion, coherent emission, scintillation, or some combination of the above. (10^{21} brightness temps require too-high gammas.)
- Shorter intraday variability in blazars; Mk 421; 3C279; larger Γ in Blazars and BL Lacs.

Beyond launch region: magnetic domination is debated

- to parsec scales? ($\sim 10^5 r_g$)
- to kiloparsec scales? ($\sim 10^8 r_g$)
- to few 100 kpc scales? ($\lesssim 10^{10} r_g$)

Essential problem: proton content, and thermal particle vs. magnetic energy density is hard to constrain

Types of constraints: polarization, inertial/morphological, spectral
need more.

Parsec Scale ($\sim 10^5 r_g$) AGN Jets

- VLBI polarization measured in a number of sources.e.g. 3C 273
- not inconsistent with magnetic helix; (is helix moving ?)
- \mathbf{e} not necess. \perp to \mathbf{B}_J . For relativistically moving helix; toroidal jet field enhanced in lab frame. (Lyutikov et al.03,04: “..observers should report \mathbf{e} .”)
- evidence for change in polarization orientation and RM across pc scale jets; consistent with helix (Asada et al; Lyutikov et al)
- e.g. Gabudza 03: \mathbf{e} remains \parallel to jet even as jet follows bends; arguably suggestive of magnetic rather than shock structure; alternating \parallel, \perp along jet
- **However**: unconstrained parameters: (emissivity distribution, field strength variation, jet direction wrt sight line, γ , helix motion)
- Conical + planar shocks can give similar polar.; Cawthorne 90;Hughes 05
- (Pariev 05; per. comm.) Observed synchrotron emissivity contrast between supposed shocked regions and unshocked regions predicted to be (Jones 88) $\sim (p_d/p_u)^{5/2}$ for nearly adiabatic hydro shock lab frame (upstream frame). Stronger contrast than seen in radio, but in optical (?)
- [Implications of mechanism for particle acceleration needs work.]
- [Form./propag. of knots in PFDO, MHD, HD (Nakamura & Meier; Hardee)]

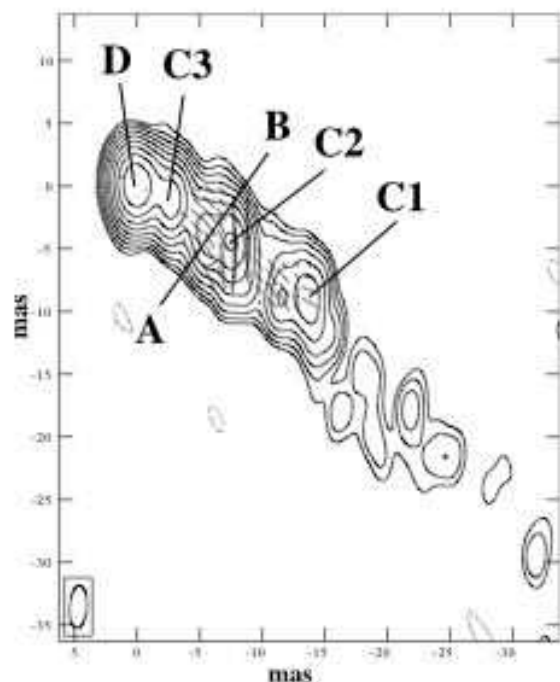


Fig. 2. Distribution of the projected magnetic field of 3C 273 superposed on the contour image of the total intensity at 4.702 GHz. Contours are plotted at $-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512,$ and $1024 \times 19.25 \text{ mJy beam}^{-1}$, which is three-times the r.m.s. noise in the total intensity image. The restored beams is the same as in figure 1. The bars overlaid on the total intensity represent the direction of the projected magnetic field derived from the intrinsic polarization angle, PA_0 (see the text), and plotted where the polarized intensity is greater than 3-times the r.m.s. noise in the polarized intensity at all the frequencies. In C2 a remarkable change is seen in the field direction. The line A-B on C2 shows the position of the cross-cut shown in figure 4.

field is perpendicular to the jet (\perp region) is flatter than that in the region where the magnetic field is parallel to the jet (\parallel region). The fractional polarization is up to 25% in the \perp region, compared to $\sim 10\%$ in the \parallel region. These facts, combined with the presence of the bright peak at the eastern edge of the \perp region, suggest that this region is compressed by the shock front in the jet. The magnetic field direction in the

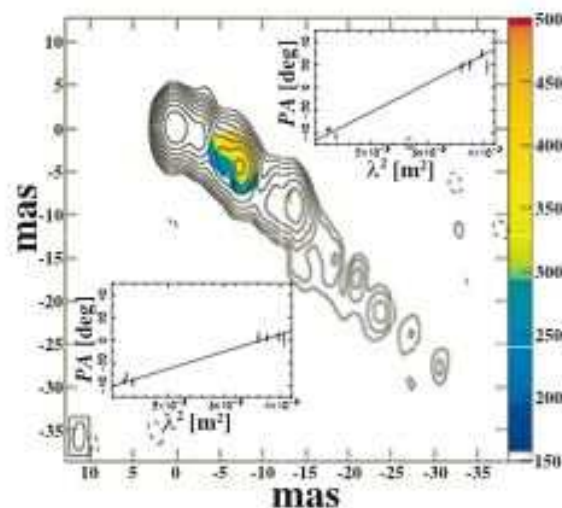
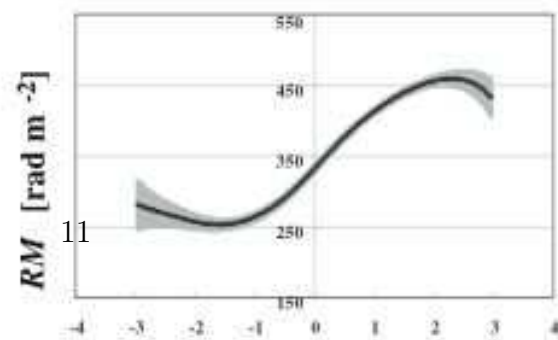


Fig. 3. Distribution of RM (color scale) superposed on the total intensity image at 4.76 GHz seen in figure 2. RMs are plotted in regions where the polarized intensity is greater than 3-times the r.m.s. noise in the polarized intensity, but in C1 RMs are not shown because of a large error due to a low polarized intensity. In C2, the RM distribution is very systematic along the jet, even across the regions of different field directions. This systematic distribution is easily understood by a helical magnetic field. We show plots of PA vs. λ^2 for each side of the jet, where RM is the maximal and minimal points on line A-B in figure 2, showing that the overall data are consistent with the behavior expected for Faraday rotation.



Lyutikov, Pariev, Gabuzda 2003,2004

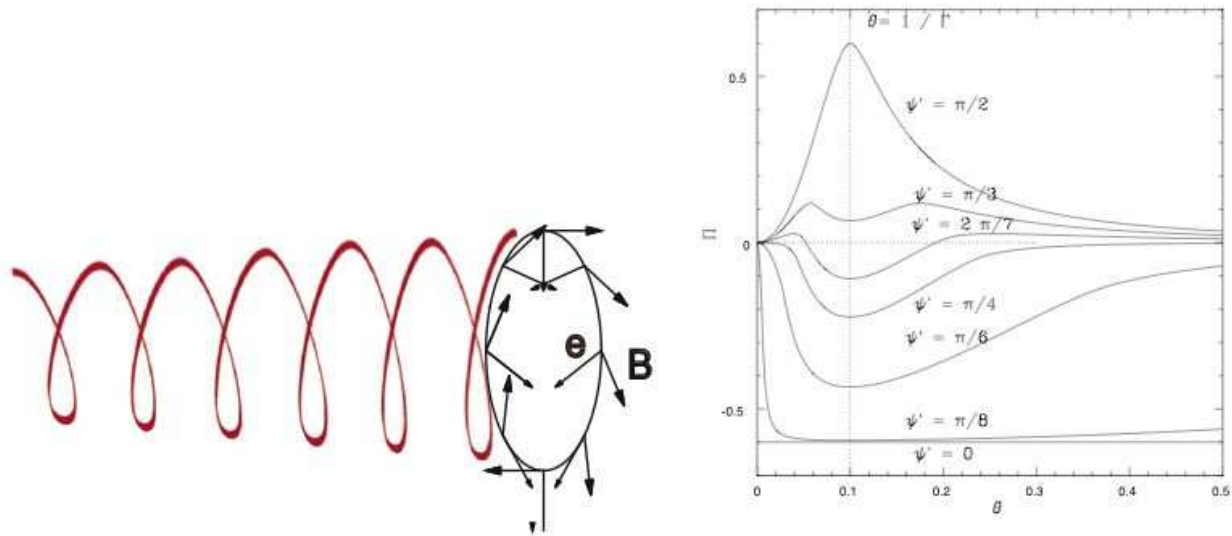


Fig. 1. (a) Example of observed electric field in the wave and magnetic field for helical field with $\psi' = \pi/4$, $\Gamma = 2$, $\theta_{ob} = \pi/3$.(b) Polarization fraction for unresolved cylindrical shell as a function of the observer angle θ for $p = 1$, $\Gamma = 10$ as a function of the pitch angle ψ' . Positive values indicate polarization along the jet, negative — polarization orthogonally to the jet.

Jets on Kiloparsec Scales (more ambiguities)

- Tavecchio et al. 2004: kpc jets “simple” extension of kpc scales (Chandra obs.) same ambiguities apply.
- Optical knots typically show more contrast than radio knots. (Sparks et al. 1996 for M87)
- Bicknell and Begelman (96): detailed model of kpc emission with equipartition $40\mu\text{G}$ fields + shocks. Appeal to helical K-H modes to produce oblique shocks, but need ambient medium to be < 100 times the density of jet.
 - larger scale $> kpc$ lobes are overpressured and under-dense with respect to ISM.
 - claimed knots are transient overpressures from shocks. no need for B-fields to collimate.
- Reynolds et al. argue that M87 is pair dominated; based on (1) estimates of total integrated jet power (to get density; lower for protons) (2) synch self absorption x-ray flux limits to get upper limits on γ_{min} from $F \propto n\gamma_{min}$ (3) absence of observed synch cutoff at 100GHz

- **Important:** questionable *minimum pressure* arguments are often used in the analysis of AGN jets which gives equipartition between magnetic and synchrotron emitting particle energy densities.
- Need constraints that do not invoke such minimum pressure.
- Fabian et al. (2002) argue that X-ray obs of kpc holes in Perseus cluster from 3C 84 are not magnetically dominated, and fields are subequipartition.

BUT: (1) Assumed balance between cavity, and x-ray surrounding gas pressures and (2) that there is no local reacceleration of particles within cavities.

→ Maybe both (1) and (2) are incorrect:

→ e.g. Reacceleration, is needed in a range of sources where synchrotron life times are much shorter than travel distances (e.g. 3C 33 Meisenheimer and Roser 86; kpc scale optical synch emission).

Jet Radio Lobes (50-100s of kpc)

- Interesting evidence for ordered magnetic fields (Kronberg; Clarke..)
- Faraday rotation shows constant sign in some sources for scales $\sim 100kpc$ in cluster radio sources
- Colgate et al. emphasize the importance
- $30\mu G$ fields, 10^{59-60} ergs of mag energy
- $20-30\mu G$ fields, 10^{60} ergs of mag energy; 1% of the BH rest mass for $10^8 M_{\odot}$ hole.

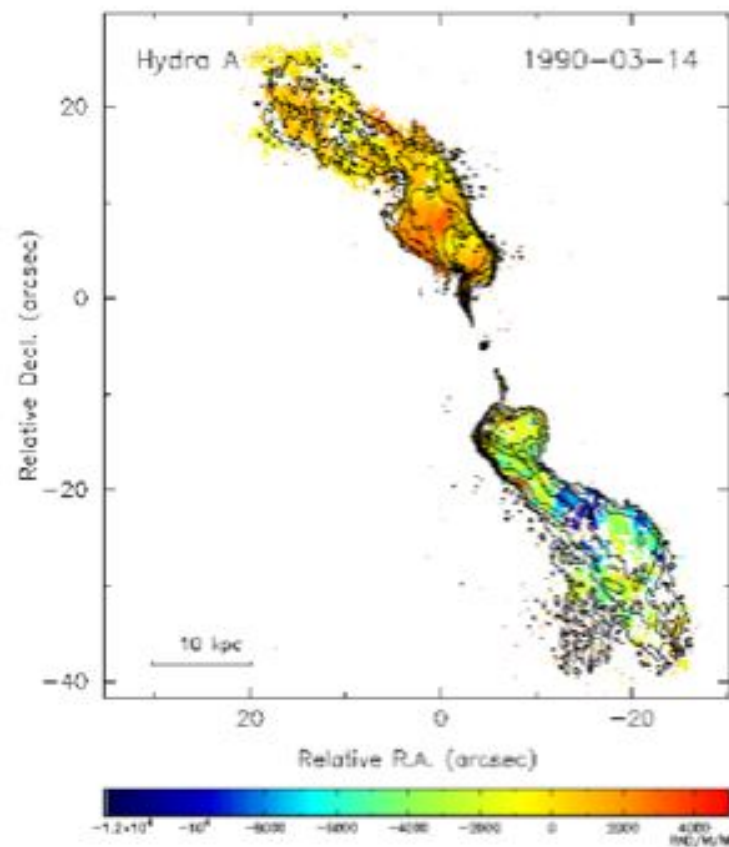


Fig. 1.— Faraday rotation measure map of Hydra A in color with total intensity contours overlaid (Taylor & Perley 1993). The northern lobe is mainly positive (field toward observer) while the southern lobe is mainly negative (field away from observer) indicating organized structures on scales of 50 kpc. The map also shows small scale fluctuations on scales of 5 – 10 kpc, indicating the presence of a tangled field component.

Constraints on Blazar Power from
Multiwavelength Spectral Modeling;
Ghisellini
& Celotti 2002

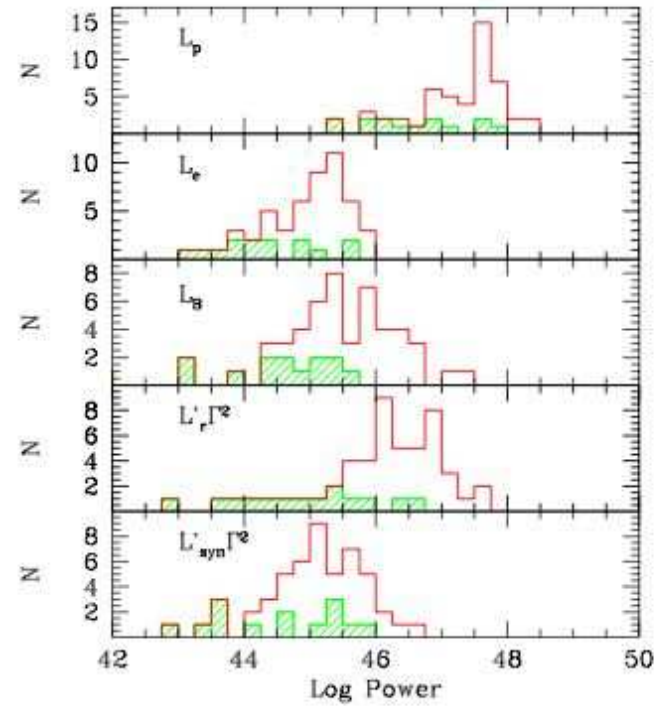


Figure 2. Histograms of powers estimated for flat spectrum radio loud quasars and BL Lac objects (the latter ones represented by shaded areas). Powers are in erg s^{-1} . $L'_i \Gamma^2$ and $L'_{syn} \Gamma^2$ represent the total and the synchrotron radiative power dissipated in the jet, respectively (where Γ is the bulk Lorentz factor), while L_e , L_p and L_B indicate the kinetic powers associated with the electron component, the proton component (assuming one proton per electron), and the power transported as Poynting flux, respectively. The relative quantities are estimated by modeling the observed SED of blazars as due to synchrotron and inverse Compton emission from a homogeneous one-zone region (see Ghisellini et al., 1998 for details on the model). From Celotti & Ghisellini, in prep.

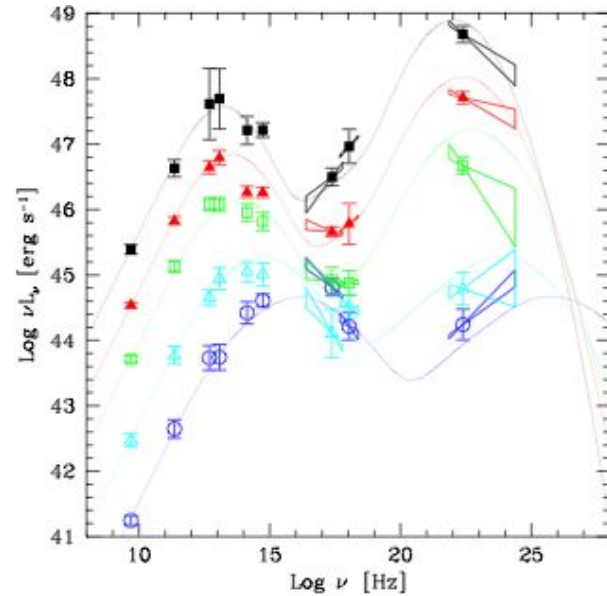


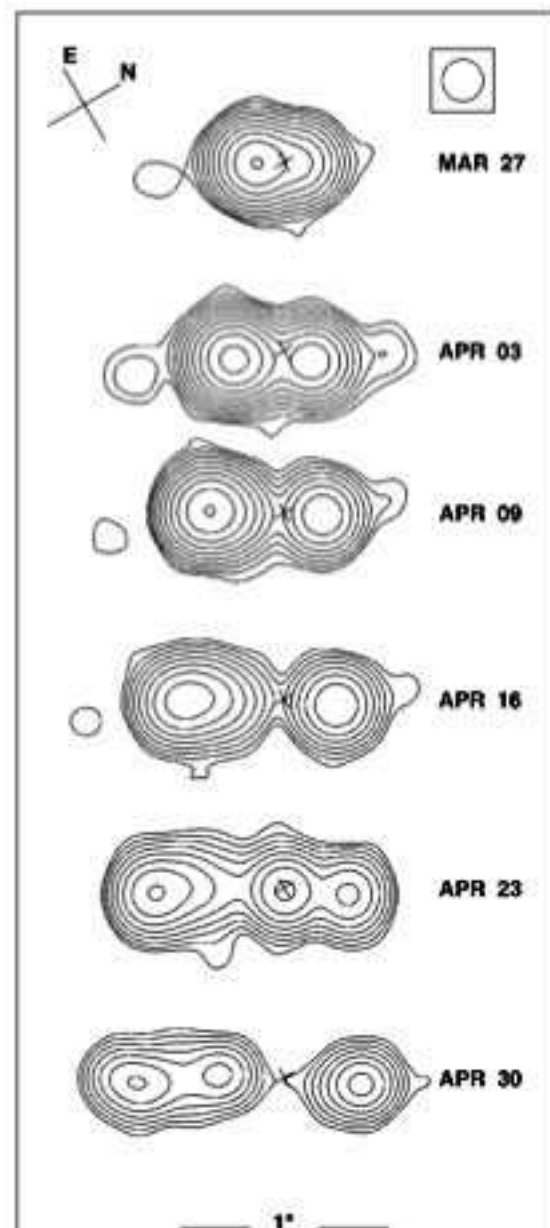
Figure 1. Averaged SED of blazars. The data in each band are the result of averaging over a number of sources, belonging to the 1 Jy complete sample of BL Lacs, the Einstein SLEW survey sample of BL Lacs and the 2 Jy complete sample of blazars, for a total of over 100 sources. The sources have been divided into 5 bins of increasing radio power, thought to be representative of the bolometric one. See Fossati et al. (1998) and the additional new collection of hard X-ray data in Donato et al. (2001). The solid curves correspond to a phenomenological description of the average SED which is based on only one parameter (which can be the bolometric power, the peak synchrotron frequency or the radio power, which are related with one another through simple relations), as discussed originally in Fossati et al. (1998) and slightly modified by Donato et al. (2001).

- Ghisellini & Celotti point out that $\Gamma \sim 10 - 20$ even on 100s of kpc scales in the core of blazars to explain X-ray emission via inv Compton scattering off the microwave background.
- Ghisellini & Celotti 98,02 also point out that $\gamma - ray$ variability demands origin of $\gamma - rays$ are at 10^{-2}pc ($\sim 10^4 r_g$) but not much smaller due to pair production opacity.

Lessons from Microquasars (stellar BH accretors) and GRB

- GRS 1915+105 obs. superlum: $\Gamma > 2$, jet power: $\Gamma \lesssim 30$.
- Masses $\sim 10^7, 10^8$ times less than AGN; time scales much shorter.
- “low-hard” state hard: x-rays to 100keV power law; lasts up to months; steady weakly polarized low speed, opt. thick jet; LFQPOs. ($< 60kHz$); inner disk ~ 200 km
- “high-soft” state: thermal emission 1-2keV; weak power law; no steady jet, inner disk at 20 km;
- “very high-soft” state; shows HFQPOs
- bright, transient **relativistic jet** ejections **associated** with hard to soft state transitions
- relativistic ejection up to % 20 polarized; optically thin outflow
- relativistic ejecta form in $t < 1$ day; steady on inner rotation time scales
- x-ray emission shows variabilities from many days down to subsecond time scales. transition from soft to hard state in response to variation in accretion rate could be 100 sec from viscous time scale at 200km.
- linear and circular polarization as complicated as in AGN jets

Figure 2 Pair of radio condensations moving away from the hard X-ray source GRS 1915+105 (Mirabel & Rodríguez 1994). These uniform-weight VLA maps were made at $\lambda 3.5$ -cm for the 1994 epochs on the right side of each map. The position of the stationary core is indicated with a small cross. The maps have been rotated 60° clockwise for easier display. The cloud to the left appears to move away from the stationary core at 125% the speed of light. Contours are 1, 2, 4, 8, 16, 32, 64, 128, 256 and 512 times $0.2 \text{ mJy/beam}^{-1}$ for all epochs except for March 27 where the contour levels are in

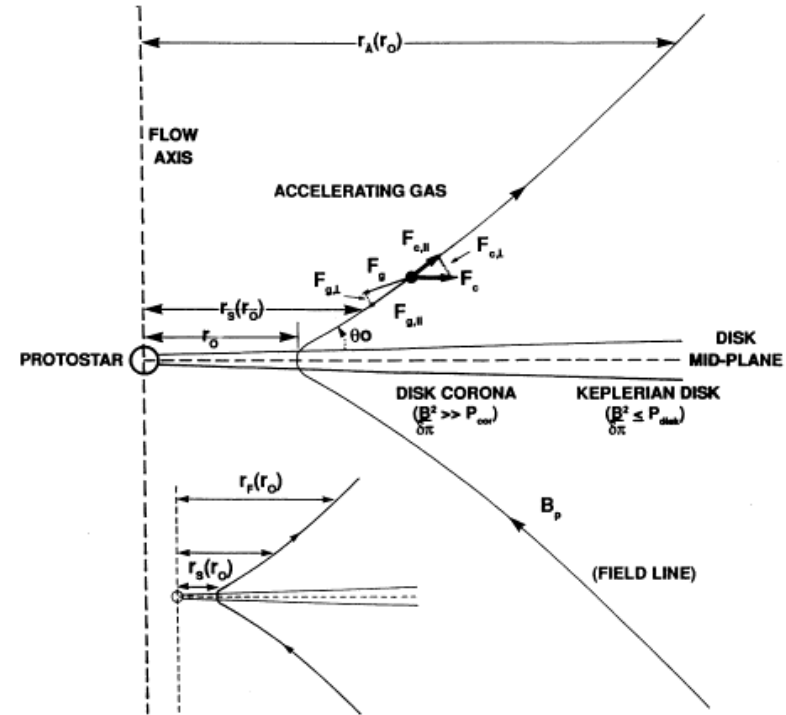
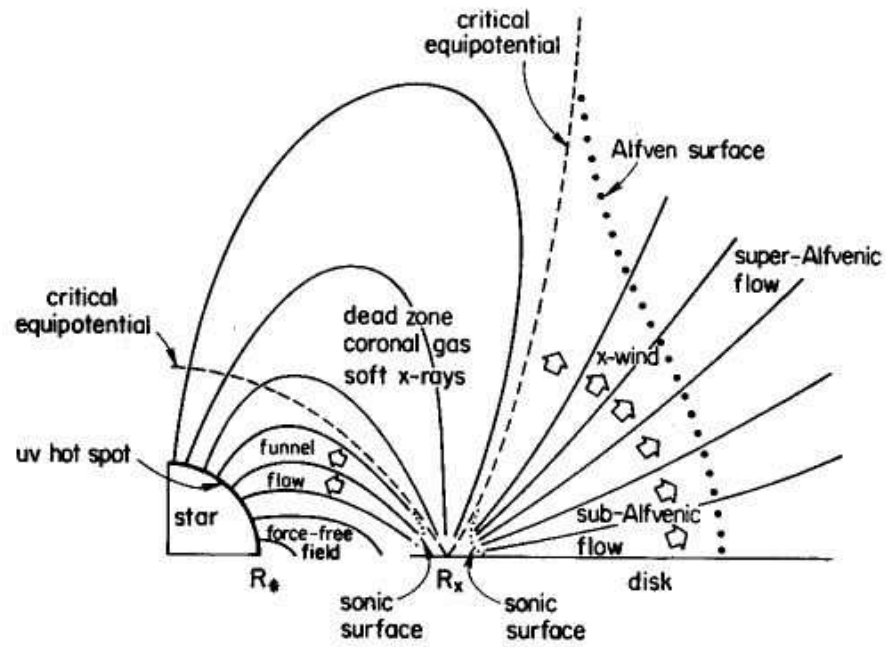


Gamma-Ray Bursts

- indirect evidence for jets
- most relativistic sources in the universe

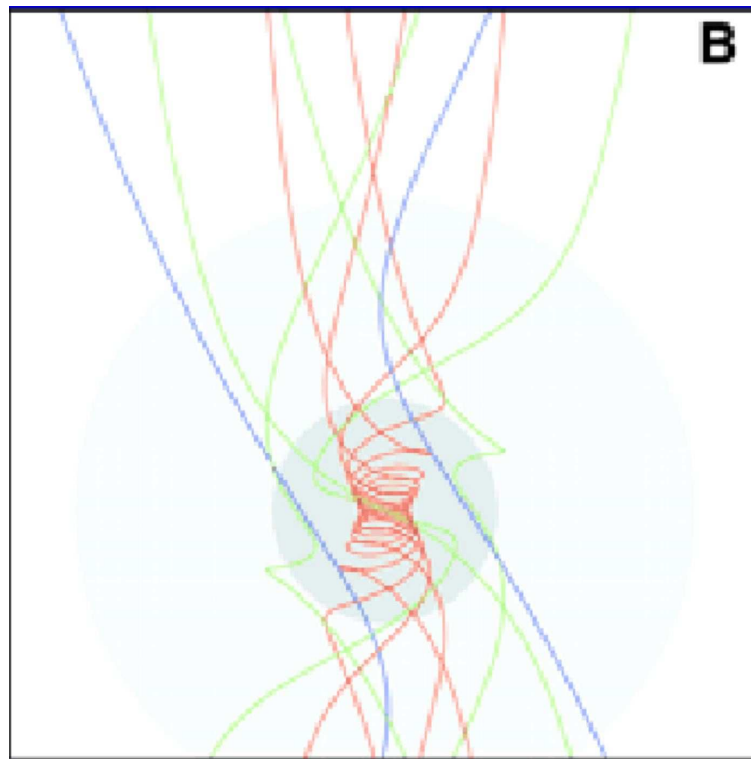
MAGNETIC FLING/ STEADY

(figs from Shu et al. 94; Pelletier & Pudritz 92)

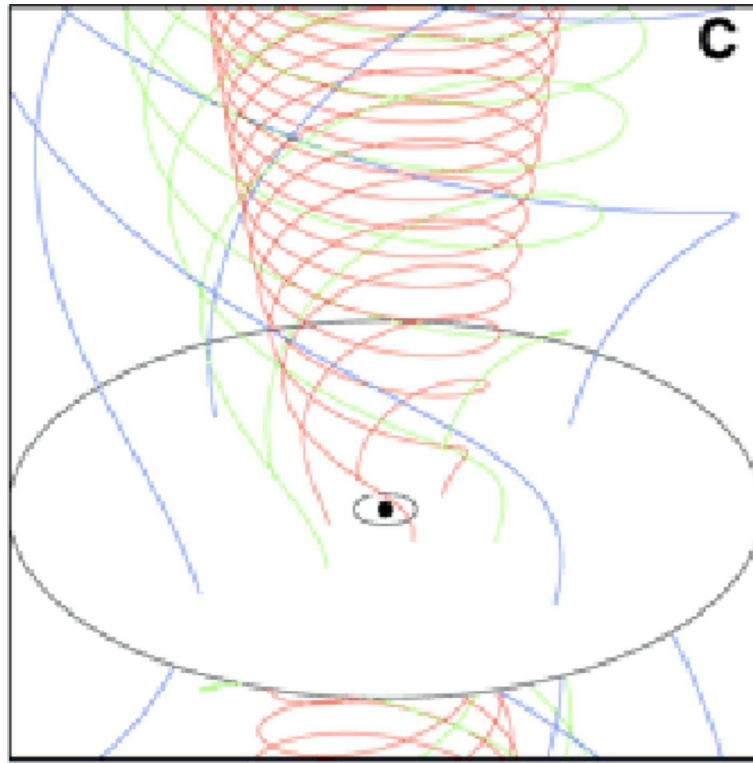


MAGNETIC SPRING EXPLOSION/ TIME-DEPENDENT

(picture from Meier et al. 01; Matt et al. 03; 05)



POYNTING FLUX DOMINATED OR HYBRID



Issues:

- Case for magnetic domination in core $r < 100r_g$ not proven but not disputed.
- Case for magnetic domination on larger scales is more controversial
- “Minimum pressure” argument, which gives near equipartition between mag and relativistic particles often pollutes the estimates
- Lots of ambiguity. Better diagnostics and a real effort for synthesis and review needed.
- Particle acceleration theory is a possibly promising direction: compare shocks to PFDO
- Also, study of instabilities along the jet to distinguish magnetic kinks from K-H case. What moves and what remains fixed?
- Something to learn from microquasars because the time scales are much shorter.
- Inner region of field formation and relaxation is perhaps most accessible from laboratory.
- Must keep in mind the actual mapping of scales from lab $< - >$ simulation $< - >$ experiment.