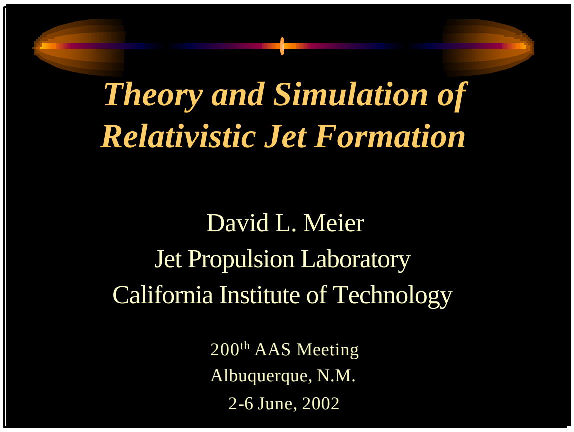

Theory and Simulation of Relativistic Jet Formation

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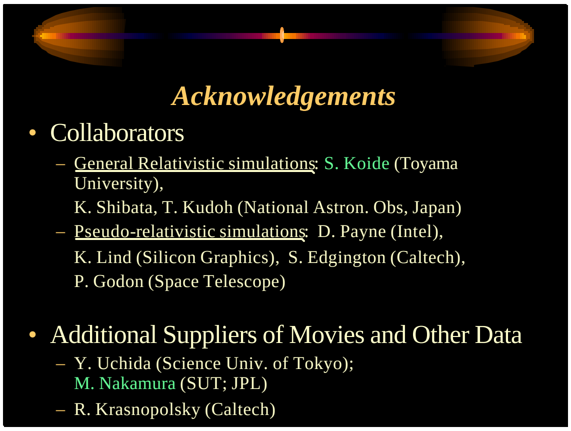
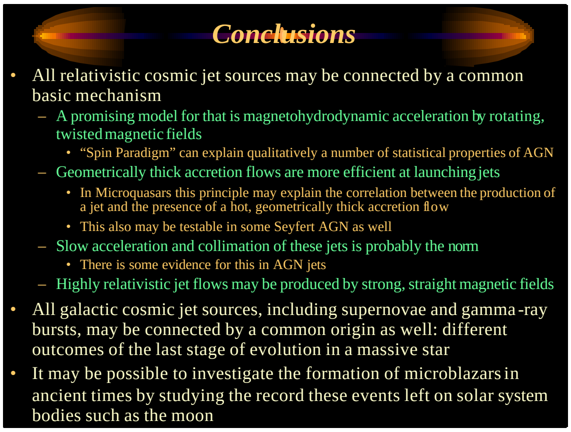
200th AAS Meeting
Albuquerque, N.M.
2-6 June, 2002



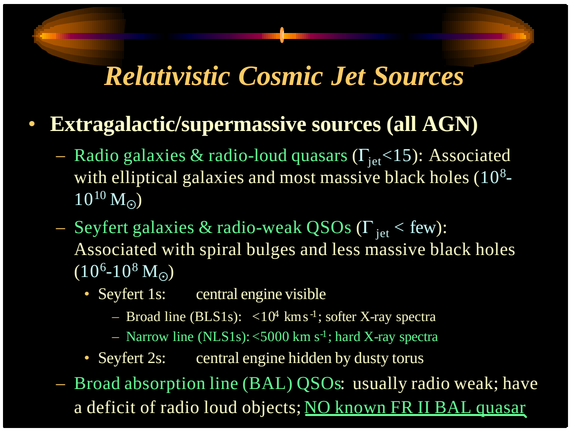
Acknowledgements

- Collaborators
  - General Relativistic simulations: S. Koide (Toyama University), K. Shibata, T. Kudoh (National Astron. Obs, Japan)
  - Pseudo-relativistic simulations: D. Payne (Intel), K. Lind (Silicon Graphics), S. Edgington (Caltech), P. Godon (Space Telescope)
- Additional Suppliers of Movies and Other Data
  - Y. Uchida (Science Univ. of Tokyo); M. Nakamura (SUT; JPL)
  - R. Krasnopolsky (Caltech)



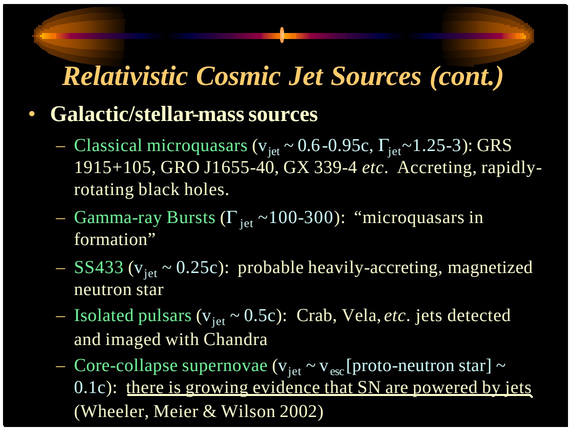
Conclusions

- All relativistic cosmic jet sources may be connected by a common basic mechanism
  - A promising model for that is magnetohydrodynamic acceleration by rotating, twisted magnetic fields
    - “Spin Paradigm” can explain qualitatively a number of statistical properties of AGN
  - Geometrically thick accretion flows are more efficient at launching jets
    - In Microquasars this principle may explain the correlation between the production of a jet and the presence of a hot, geometrically thick accretion flow
    - This also may be testable in some Seyfert AGN as well
  - Slow acceleration and collimation of these jets is probably the norm
    - There is some evidence for this in AGN jets
  - Highly relativistic jet flows may be produced by strong, straight magnetic fields
- All galactic cosmic jet sources, including supernovae and gamma-ray bursts, may be connected by a common origin as well: different outcomes of the last stage of evolution in a massive star
- It may be possible to investigate the formation of microblazars in ancient times by studying the record these events left on solar system bodies such as the moon



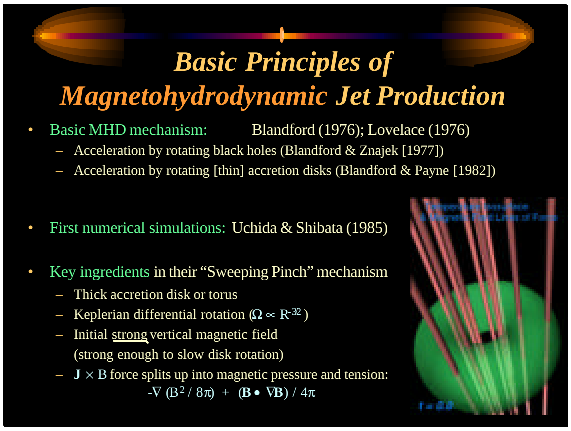
Relativistic Cosmic Jet Sources

- **Extragalactic/supermassive sources (all AGN)**
  - Radio galaxies & radio-loud quasars ($\Gamma_{jet}<15$): Associated with elliptical galaxies and most massive black holes (10^8-10^{10} $M_\odot$)
  - Seyfert galaxies & radio-weak QSOs (Γ_{jet} < few): Associated with spiral bulges and less massive black holes (10^6-10^8 $M_\odot$)
    - Seyfert 1s: central engine visible
      - Broad line (BLS1s): $<10^4$ km s^{-1}; softer X-ray spectra
      - Narrow line (NLS1s): <5000 km s^{-1}; hard X-ray spectra
    - Seyfert 2s: central engine hidden by dusty torus
  - Broad absorption line (BAL) QSOs: usually radio weak; have a deficit of radio loud objects; NO known FR II BAL quasar



Relativistic Cosmic Jet Sources (cont.)

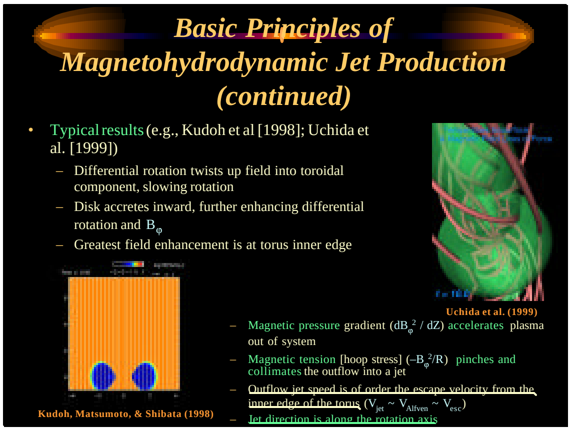
- **Galactic/stellar-mass sources**
  - Classical microquasars (v_{jet} ~ 0.6-0.95c, Γ_{jet}~1.25-3): GRS 1915+105, GRO J1655-40, GX 339-4 *etc*. Accreting, rapidly-rotating black holes.
  - Gamma-ray Bursts (Γ_{jet} ~100-300): “microquasars in formation”
  - SS433 (v_{jet} ~ 0.25c): probable heavily-accreting, magnetized neutron star
  - Isolated pulsars (v_{jet} ~ 0.5c): Crab, Vela, *etc*. jets detected and imaged with Chandra
  - Core-collapse supernovae (v_{jet} ~ v_{esc}[proto-neutron star] ~ 0.1c): there is growing evidence that SN are powered by jets (Wheeler, Meier & Wilson 2002)



Basic Principles of Magnetohydrodynamic Jet Production

- Basic MHD mechanism: Blandford (1976); Lovelace (1976)
  - Acceleration by rotating black holes (Blandford & Znajek [1977])
  - Acceleration by rotating [thin] accretion disks (Blandford & Payne [1982])
- First numerical simulations: Uchida & Shibata (1985)
- Key ingredients in their “Sweeping Pinch” mechanism
  - Thick accretion disk or torus
  - Keplerian differential rotation ($\Omega \propto R^{-32}$)
  - Initial strong vertical magnetic field (strong enough to slow disk rotation)
  - **J** × B force splits up into magnetic pressure and tension:

$$-\nabla (B^2 / 8\pi) + (\mathbf{B} \bullet \nabla \mathbf{B}) / 4\pi$$



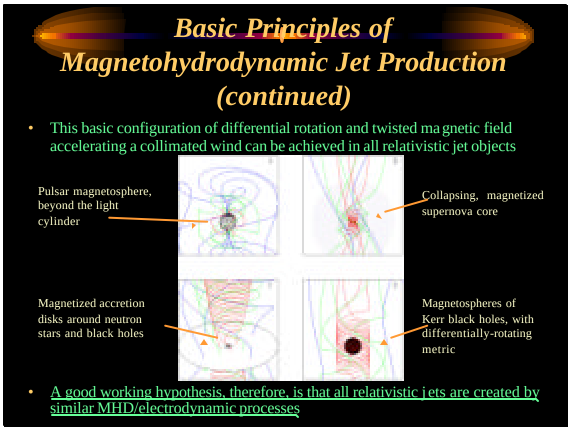
Basic Principles of Magnetohydrodynamic Jet Production (continued)

- Typical results (e.g., Kudoh et al [1998]; Uchida et al. [1999])
  - Differential rotation twists up field into toroidal component, slowing rotation
  - Disk accretes inward, further enhancing differential rotation and B_φ
  - Greatest field enhancement is at torus inner edge

Kudoh, Matsumoto, & Shibata (1998)

Uchida et al. (1999)

  - Magnetic pressure gradient (dB_φ^2 / dZ) accelerates plasma out of system
  - Magnetic tension [hoop stress] ($-B_\varphi^2/R$) pinches and collimates the outflow into a jet
  - Outflow jet speed is of order the escape velocity from the inner edge of the torus ($V_{jet} \sim V_{Alfven} \sim V_{esc}$)
  - Jet direction is along the rotation axis



Basic Principles of Magnetohydrodynamic Jet Production (continued)

- This basic configuration of differential rotation and twisted magnetic field accelerating a collimated wind can be achieved in all relativistic jet objects

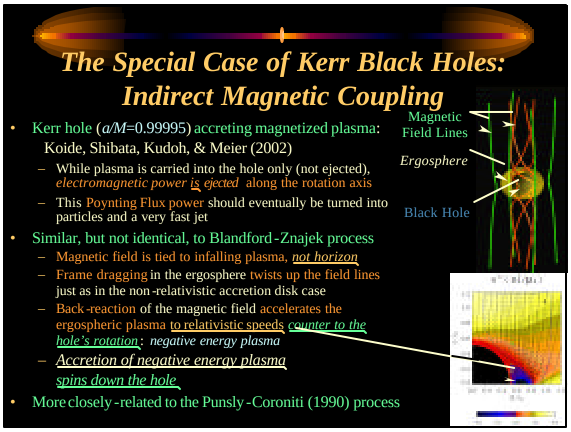
Pulsar magnetosphere, beyond the light cylinder

Collapsing, magnetized supernova core

Magnetized accretion disks around neutron stars and black holes

Magnetospheres of Kerr black holes, with differentially-rotating metric

- A good working hypothesis, therefore, is that all relativistic jets are created by similar MHD/electrodynamic processes



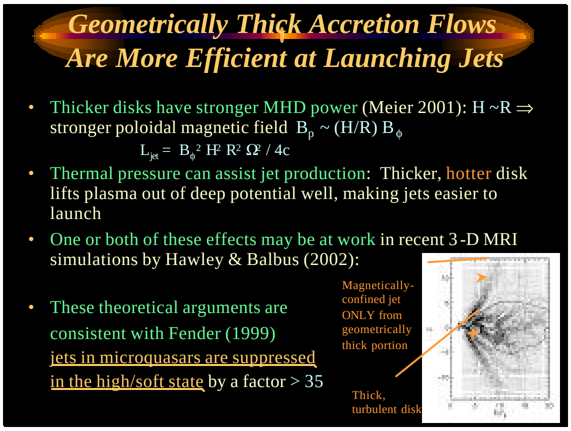
The Special Case of Kerr Black Holes: Indirect Magnetic Coupling

- Kerr hole (a/M=0.99995) accreting magnetized plasma: Koide, Shibata, Kudoh, & Meier (2002)
  - While plasma is carried into the hole only (not ejected), *electromagnetic power is ejected* along the rotation axis
  - This Poynting Flux power should eventually be turned into particles and a very fast jet
- Similar, but not identical, to Blandford-Znajek process
  - Magnetic field is tied to infalling plasma, *not horizon*
  - Frame dragging in the ergosphere twists up the field lines just as in the non-relativistic accretion disk case
  - Back-reaction of the magnetic field accelerates the ergospheric plasma to relativistic speeds *counter to the hole's rotation*: *negative energy plasma*
  - *Accretion of negative energy plasma spins down the hole*
- More closely-related to the Punsly-Coroniti (1990) process

"Spin Paradigm" Qualitatively Explains Many Statistical Properties of AGN

(Wilson & Colbert 1995; Blandford 199?; Meier 1999; Baum et al 2002)

- Difference between radio loud and quiet quasars (RL=Kerr BH; RQ=Schwarzschild BH)
- Cosmic evolution of radio sources (rapid BH spindown [~10^8 yr] plus spin-up by mergers)
- Why powerful radio galaxies occur primarily in giant ellipticals (only ones merging and spinning back up)
- Why central cluster galaxies are primarily FR Is (no comparable hole with which to merge to extreme Kerr)
- Why most massive holes appear to be radio loud (always occur in central cluster galaxies and always harassed by mergers)



Geometrically Thick Accretion Flows Are More Efficient at Launching Jets

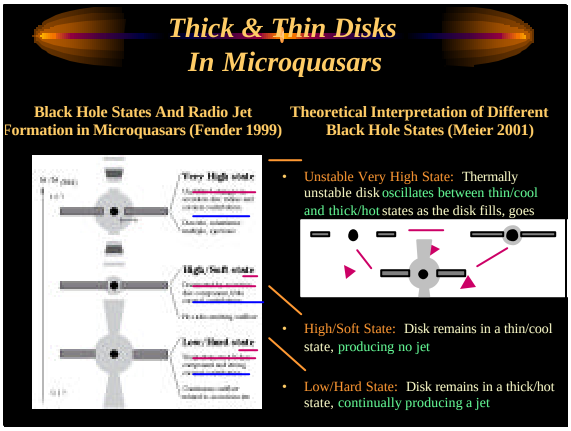
- Thicker disks have stronger MHD power (Meier 2001): $H \sim R \Rightarrow$ stronger poloidal magnetic field $B_p \sim (H/R)\, B_\phi$

$$L_{jet} = B_\phi^2\, H^2 R^2\, \Omega^2 / 4c$$

- Thermal pressure can assist jet production: Thicker, hotter disk lifts plasma out of deep potential well, making jets easier to launch
- One or both of these effects may be at work in recent 3-D MRI simulations by Hawley & Balbus (2002):
- These theoretical arguments are consistent with Fender (1999) jets in microquasars are suppressed in the high/soft state by a factor > 35

Magnetically-confined jet ONLY from geometrically thick portion

Thick, turbulent disk

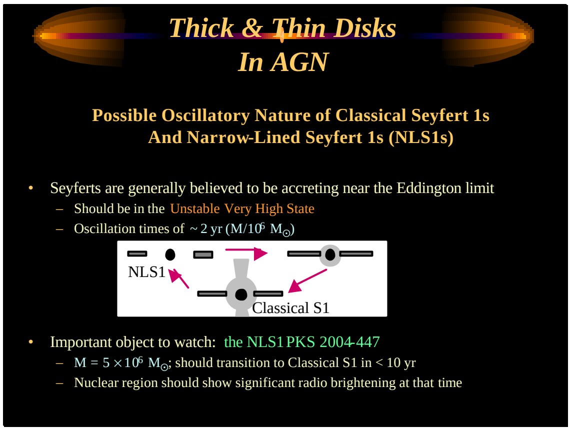


Thick & Thin Disks In Microquasars

Black Hole States And Radio Jet Formation in Microquasars (Fender 1999)

Theoretical Interpretation of Different Black Hole States (Meier 2001)

- Unstable Very High State: Thermally unstable disk oscillates between thin/cool and thick/hot states as the disk fills, goes
- High/Soft State: Disk remains in a thin/cool state, producing no jet
- Low/Hard State: Disk remains in a thick/hot state, continually producing a jet

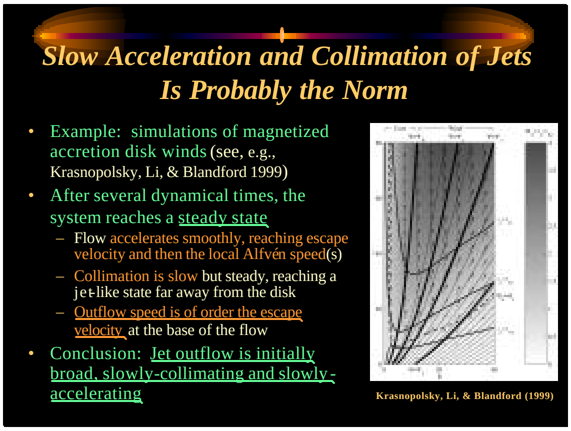


Thick & Thin Disks In AGN

Possible Oscillatory Nature of Classical Seyfert 1s And Narrow-Lined Seyfert 1s (NLS1s)

- Seyferts are generally believed to be accreting near the Eddington limit
  - Should be in the Unstable Very High State
  - Oscillation times of ~ 2 yr ($M/10^6\ M_\odot$)

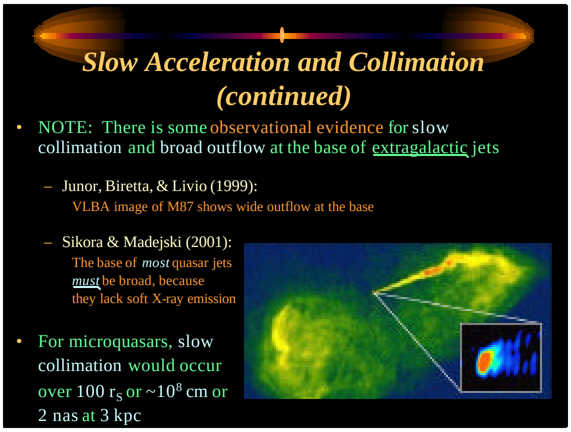
- Important object to watch: the NLS1 PKS 2004-447
  - $M = 5 \times 10^6\ M_\odot$; should transition to Classical S1 in < 10 yr
  - Nuclear region should show significant radio brightening at that time



Slow Acceleration and Collimation of Jets Is Probably the Norm

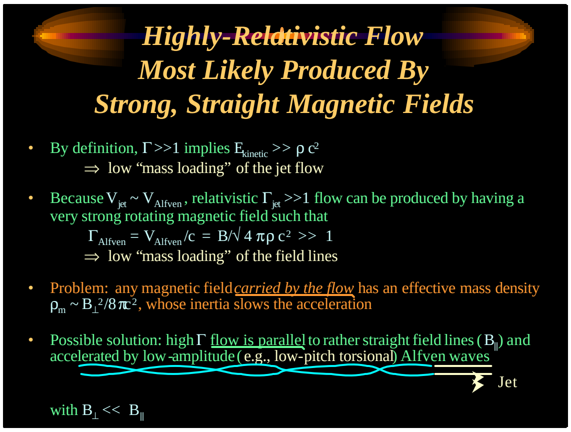
- Example: simulations of magnetized accretion disk winds (see, e.g., Krasnopolsky, Li, & Blandford 1999)
- After several dynamical times, the system reaches a steady state
  - Flow accelerates smoothly, reaching escape velocity and then the local Alfvén speed(s)
  - Collimation is slow but steady, reaching a jet-like state far away from the disk
  - Outflow speed is of order the escape velocity at the base of the flow
- Conclusion: Jet outflow is initially broad, slowly-collimating and slowly-accelerating

Krasnopolsky, Li, & Blandford (1999)



Slow Acceleration and Collimation (continued)

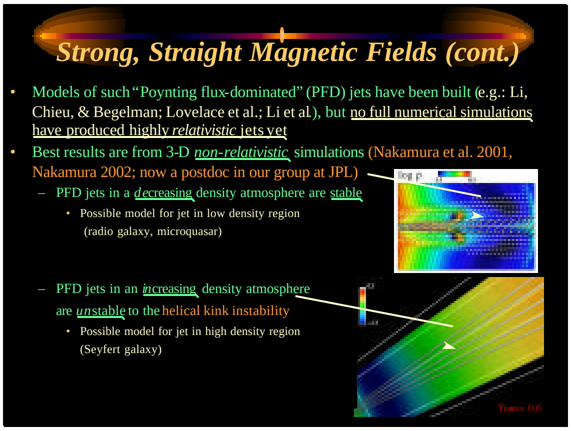
- NOTE: There is some observational evidence for slow collimation and broad outflow at the base of extragalactic jets
  - Junor, Biretta, & Livio (1999):
    VLBA image of M87 shows wide outflow at the base
  - Sikora & Madejski (2001):
    The base of *most* quasar jets *must* be broad, because they lack soft X-ray emission
- For microquasars, slow collimation would occur over 100 r_S or $\sim 10^8$ cm or 2 nas at 3 kpc



Highly-Relativistic Flow Most Likely Produced By Strong, Straight Magnetic Fields

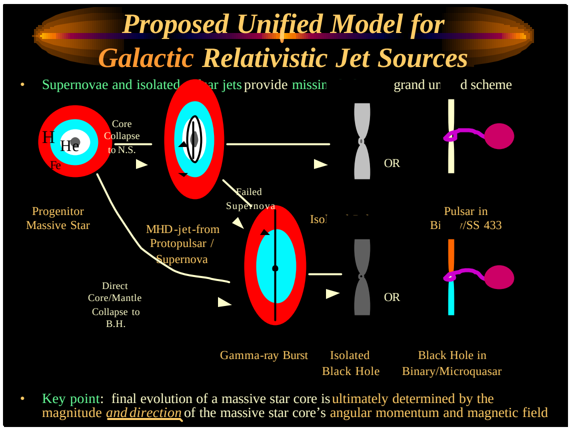
- By definition, $\Gamma \gg 1$ implies $E_{kinetic} \gg \rho c^2$
  $\Rightarrow$ low "mass loading" of the jet flow
- Because $V_{jet} \sim V_{Alfven}$, relativistic $\Gamma_{jet} \gg 1$ flow can be produced by having a very strong rotating magnetic field such that
  $\Gamma_{Alfven} = V_{Alfven}/c = B/\sqrt{4 \pi \rho c^2} \gg 1$
  $\Rightarrow$ low "mass loading" of the field lines
- Problem: any magnetic field *carried by the flow* has an effective mass density $\rho_m \sim B_\perp^2/8\pi c^2$, whose inertia slows the acceleration
- Possible solution: high Γ flow is parallel to rather straight field lines ($B_\parallel$) and accelerated by low-amplitude (e.g., low-pitch torsional) Alfven waves

with $B_\perp \ll B_\parallel$



Strong, Straight Magnetic Fields (cont.)

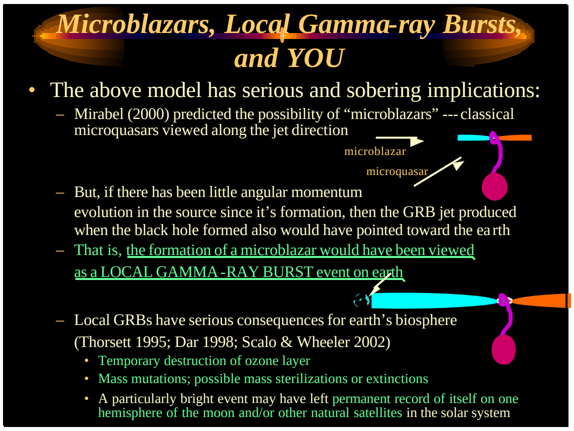
- Models of such "Poynting flux-dominated" (PFD) jets have been built (e.g.: Li, Chieu, & Begelman; Lovelace et al.; Li et al.), but no full numerical simulations have produced highly *relativistic* jets yet
- Best results are from 3-D *non-relativistic* simulations (Nakamura et al. 2001, Nakamura 2002; now a postdoc in our group at JPL)
  - PFD jets in a *de*creasing density atmosphere are stable
    - Possible model for jet in low density region (radio galaxy, microquasar)
  - PFD jets in an *in*creasing density atmosphere are *un*stable to the helical kink instability
    - Possible model for jet in high density region (Seyfert galaxy)



Proposed Unified Model for Galactic Relativistic Jet Sources

- Supernovae and isolated ar jets provide missin grand un d scheme

- Key point: final evolution of a massive star core is ultimately determined by the magnitude *and direction* of the massive star core's angular momentum and magnetic field



Microblazars, Local Gamma-ray Bursts, and YOU

- The above model has serious and sobering implications:
  - Mirabel (2000) predicted the possibility of “microblazars” --- classical microquasars viewed along the jet direction
  - But, if there has been little angular momentum evolution in the source since it’s formation, then the GRB jet produced when the black hole formed also would have pointed toward the earth
  - That is, the formation of a microblazar would have been viewed as a LOCAL GAMMA-RAY BURST event on earth
  - Local GRBs have serious consequences for earth’s biosphere (Thorsett 1995; Dar 1998; Scalo & Wheeler 2002)
    - Temporary destruction of ozone layer
    - Mass mutations; possible mass sterilizations or extinctions
    - A particularly bright event may have left permanent record of itself on one hemisphere of the moon and/or other natural satellites in the solar system