Springs, Flings and Disks
Planetary Nebulae as Astrophysical MHD Laboratoies

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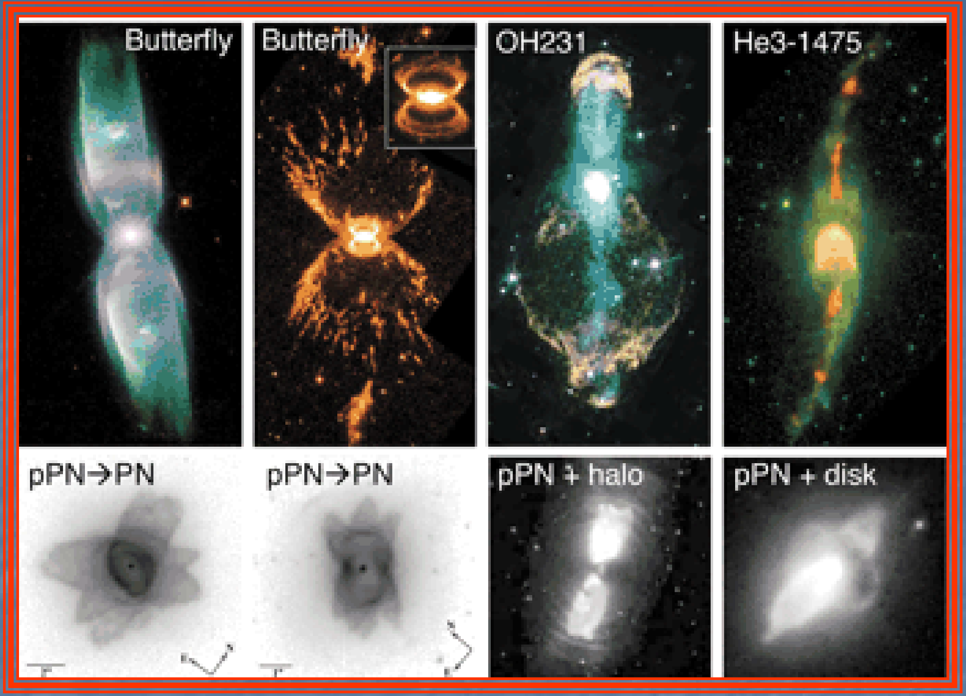
Why not HD for PNe? Why MHD?

- Hydrodynamic Models can not easily recover morphologies
  - Multi-polar geometries
  - Point symmetry geometries
- Central stars -> hard X-rays imply fields (Kastner et al, Chu et al)
  - X-rays too hard to be thermal
  - Thus…X-rays are the result of flares on surface
  - Flares imply strong fields!



PN X-rays (Chu et al)

What is Wrong with Radiation Driven Winds for pPNe?

Momentum Excess in pPNe

Bujarrabal et al 2001

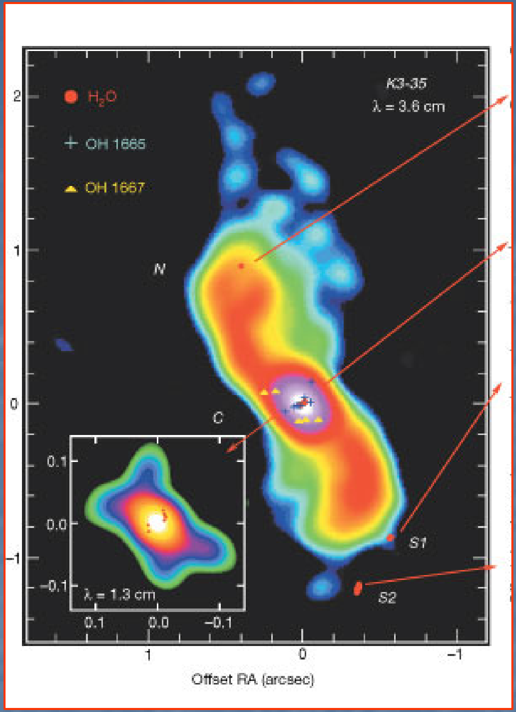
- Outflow shaping begins during proto-PNe stage
  - Acceleration time short (< 100 y?)
- pPNe show pronounced momentum excess!
  - Radiation driving *can not* account for outflows

name	Mass M_{sol}	P = MV (gm cm s^{-1})	E (erg)	$\dot{P}/(L/c)$
CRL 618	.65	$2.1\ 10^{39}$	$1.8\ 10^{45}$	$1.8\ 10^{4}$
CRL 2688	.69	$2.2\ 10^{39}$	$1.7\ 10^{45}$	$2.2\ 10^{4}$
M2-56	.01	$3.0\ 10^{37}$	$2.0\ 10^{44}$	$3.3\ 10^{3}$
Frosty Leo	.36	$8.0\ 10^{38}$	$4.5\ 10^{44}$	$7.0\ 10^{4}$

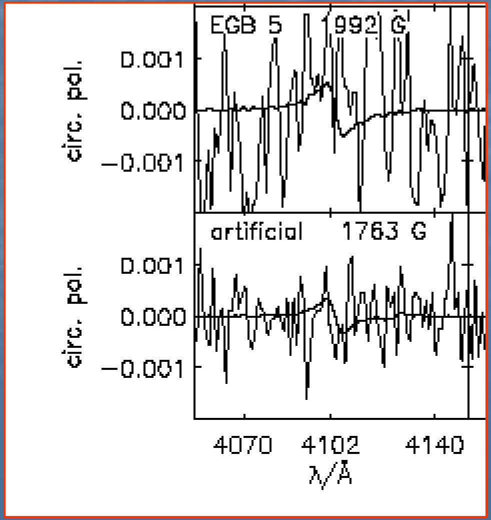
Why MHD for PNe

Magnetic Fields Are Observed in PNe!

- Nebular Gas Maser Emission
  - SiO at smaller scales
  - H_20 at larger scales
  - B ~ G - mG
    - Miranda et al 2001,
- Central Star
  - Circular polarization measurements
  - B ~ kG
    - (Jordan et al 2004)
  - Right size for dynamical launching effects
- Is Evidence for B fields stronger than that for interacting binaries or CE evolution?



PN masers (Miranda et al)



Circ. Polarization (Jordan et al)

Magnetic vs. Binary PNe Shaping? No.Magnetic and Binary Shaping.

(1) Accretion disks require presence of binary companion but….

Jet is *both launched and collimated* by magnetic stresses (Frank & Blackman 04).

"jet driven nebula" = MHD driven nebula

(2) Stellar Dynamo field models (Blackman et al 01a,b, Matt Frank Blackman 05) may require spin-up of outer envelope to maintain/achieve differential rotation

$(\Delta\Omega/\Delta R > 0$ or $\Delta\Omega/\Delta R < 0$ OK)

Thus Binaries provide Ang. Mom. resivior and a source of material for accretion disks, they do not, in themselves, launch or collimate outflows

A Universal Models for Asto Jets: Magneto-rotational Launching (Spring vs Fling)

- Many forms of theory (Blandford & Payne 1985, Pelletier & Pudritz 1992, Shu et al 1994, Lovelace et al)
- Theory/Simulation – different roles of “Fling” (B_p) vs “Spring” (B_ϕ)
- Where:
  - YSOs: protostar + disk
  - AGN: SMBH + disk
  - micro-Quasars: BH + disk
  - GRBs/SNe: proto-neutron star + disk(?)
  - **!! Planetary Nebulae !!**
    - **Post AGB star alone?**
    - **Post AGB star + companion for spin-up**
    - **Post AGB star/Proto-white dwarf + companion disk**

PNe MHD Wind Launching

Version I *Fling* *(B_{pol} dominated)*

- Magnetized Accretion Disk: R*equires binary*
  - Blackman, Frank & Welch 2001, Frank & Blackman 2004

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i) Disk Around Primary (companion disrupted)

(Soker, Livio, Reyes-Ruiz & Lopez)

Energy and Momentum Budgets Work Out

$$E = \int \frac{1}{2}\dot{M}_w u_\infty^2 dt \approx 1.3\times 10^{44}\ erg \left[1-\left(\frac{1\ yr}{t}\right)^{1/4})\right]$$

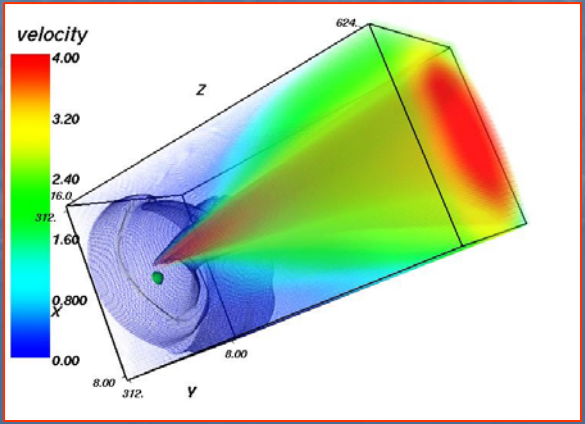
$$\Pi = \int \dot{M}_w u_\infty dt \approx 1.8\times 10^{37}\ erg\ cm\ s^{-1} \left[1-\left(\frac{1\ yr}{t}\right)^{1/4}\right]$$

Frank & Blackman 04

ii) Disk Around Companion

(Soker, Livio)

Outflow modified jet/wind interaction

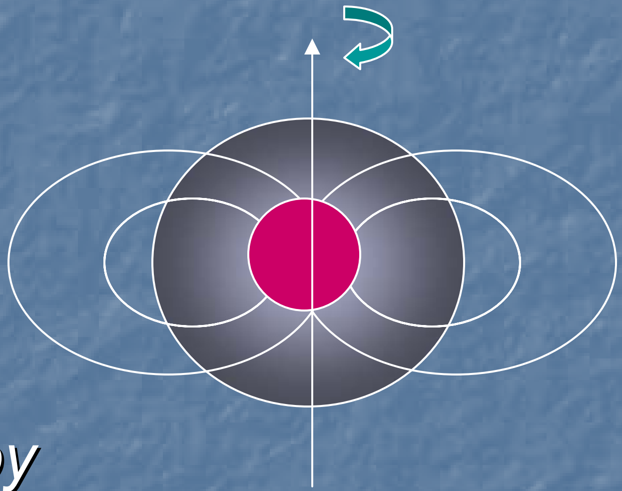


Garica-Arrendondo & Frank 04

PNe MHD Wind Launching

Version II *Spring (B_ϕ dominated)*

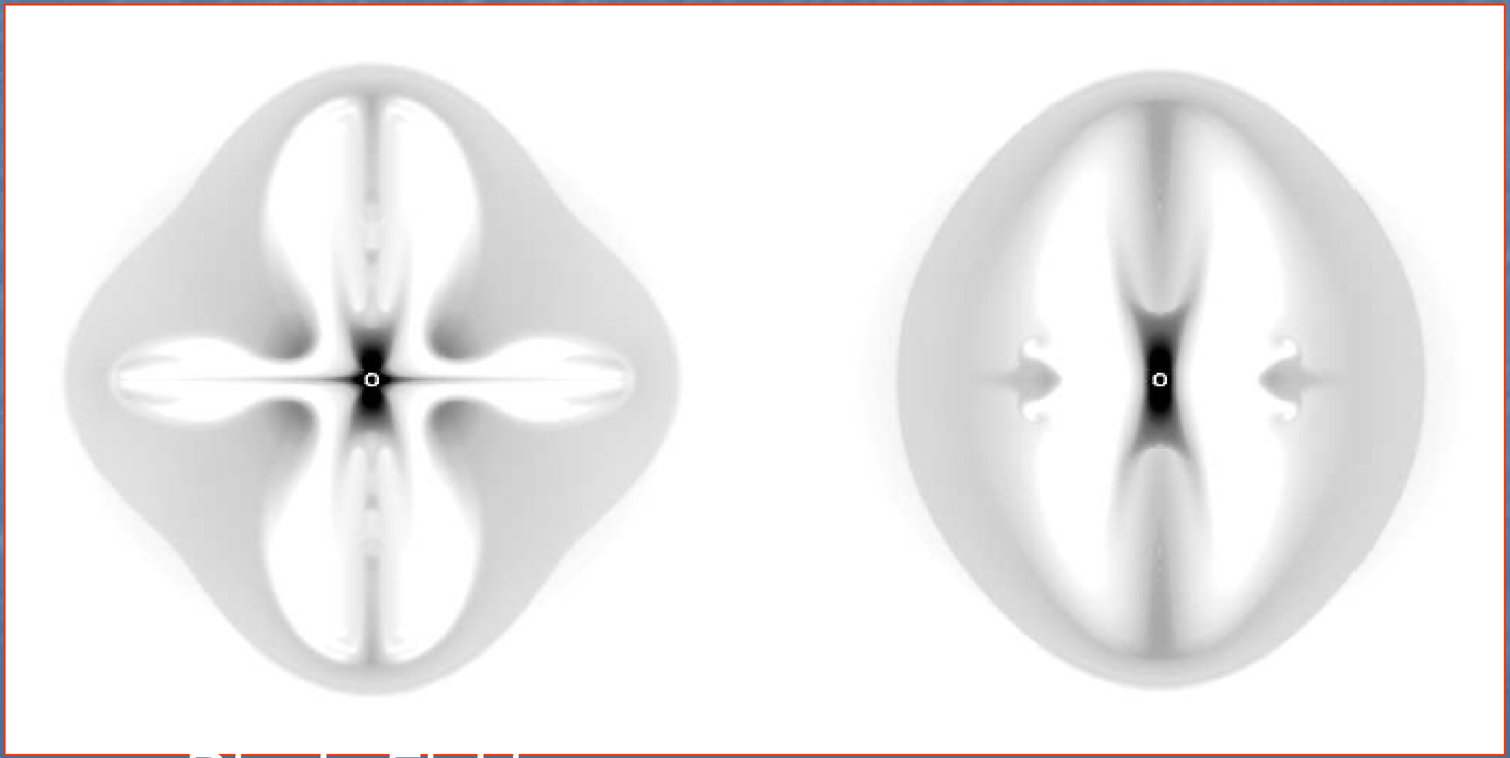
Blackman et al Nature 2001
Matt, Frank & Blackman 2004, 2005



- Rapidly Rotating Magnetized Core
- *Rotating AGB star*
  core + envelope
- *Core shrinks/Envelope expands*
  -> $\Delta\Omega$
- *$\alpha-\Omega$ interface dynamo (Maintained by Binary?)*
- *Remove envelope via normal AGB wind*
- *Toroidal field unwinds*
  - *magnetic explosion*

RESULTS I: Field Geometry and Morphology

- Outflow shape dependent on field due to location of max B_ϕ
- Both dipole and split monopole make polar jets
- Dipole field creates equatorial excretion disks (Egg Neb?)



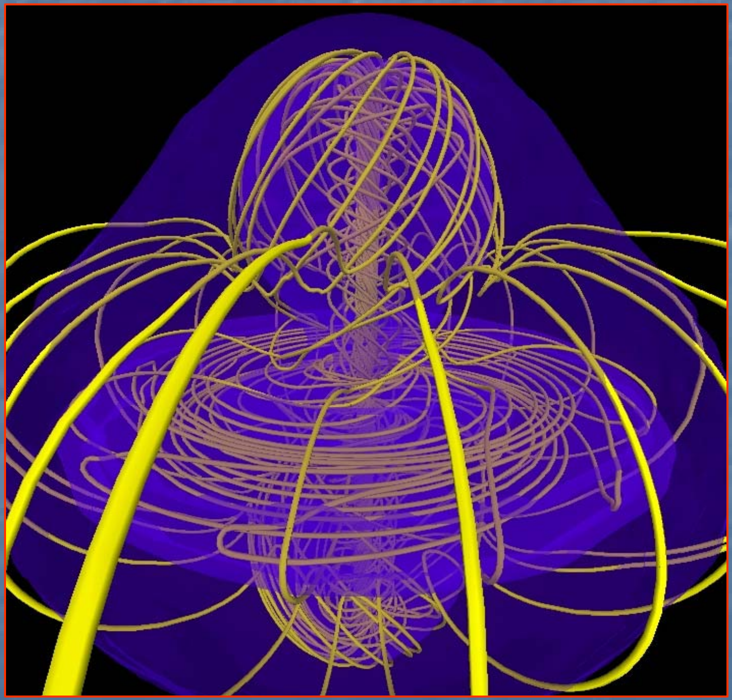
Dipole Field

Split Monopole Field

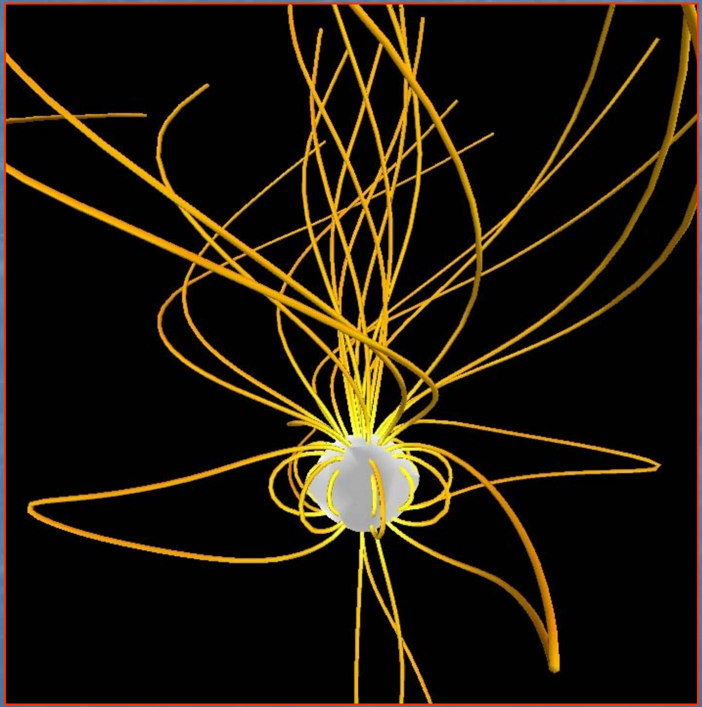
RESULTS II: Field Topology

- Rotation takes initially polodial field (B_p) and creates toroidal field (B_ϕ)
- Magnetic pressure ($B_\phi^2/8\pi$) drives off envelope
- Note strong winding along axis and equator

  Field driven to pole and equator by early B_ϕ pressure gradients

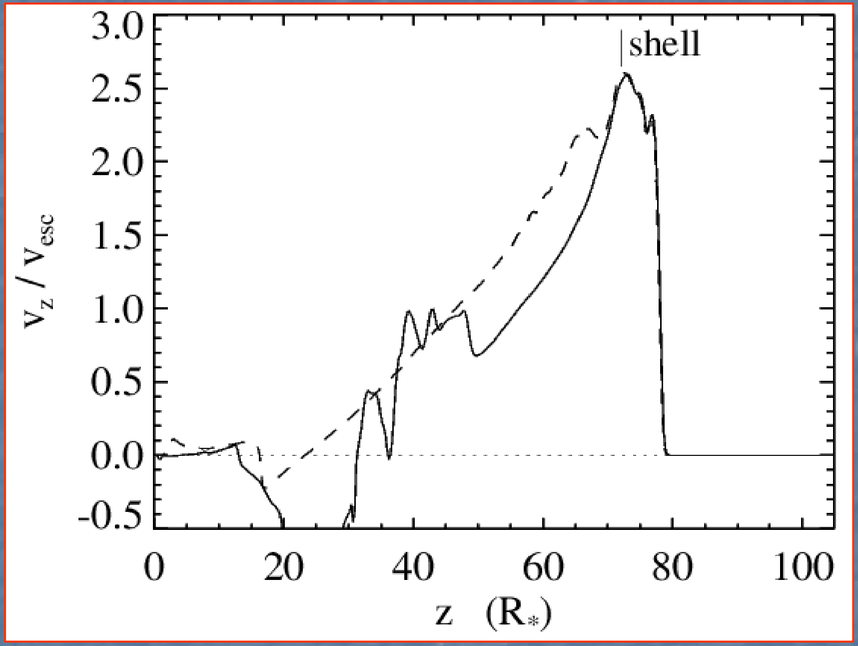


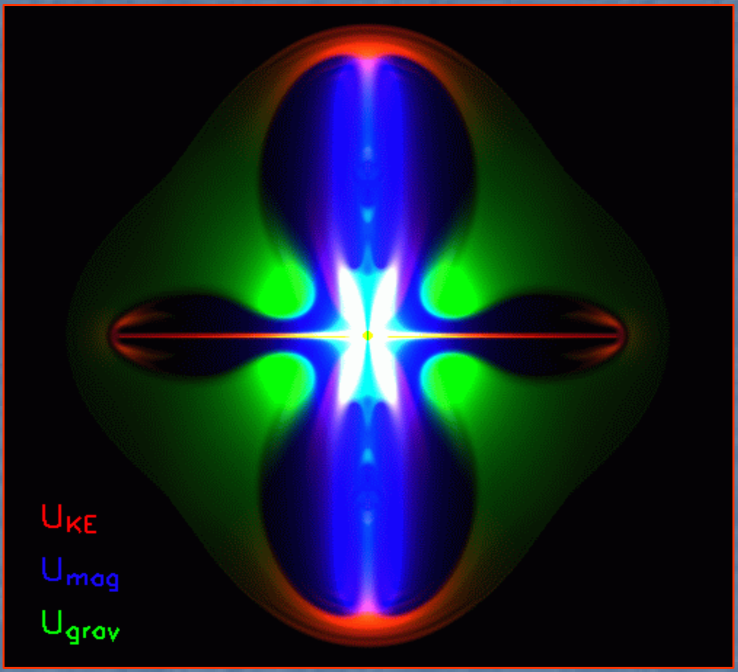
Dipole Field Far View



Dipole Field Near View

RESULTS III: Acceleration and Energetics



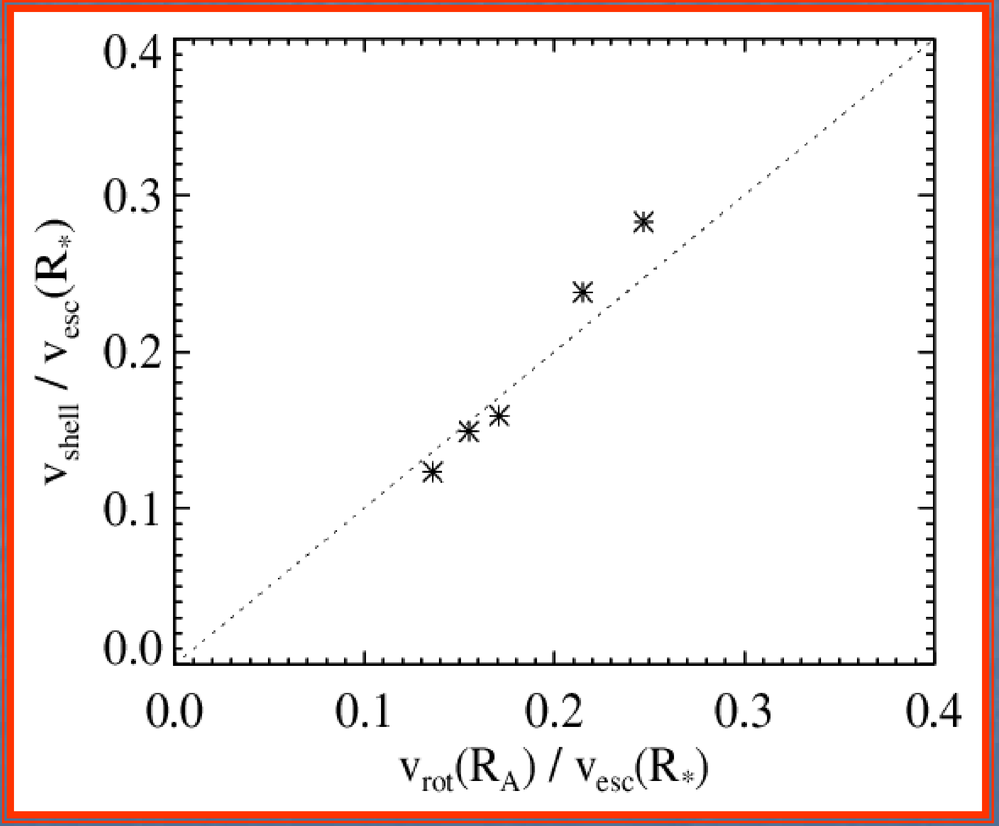


- We do get an OUTFLOW
- Polar shell exceeds local escape speed after 6 t_{rot}

- Polar and equatorial shells KE dominated,
- Polar interior **Poynting Flux Dominated**. (Important for new class of GRB models)

RESULTS IV: Acceleration and Initial Conditions

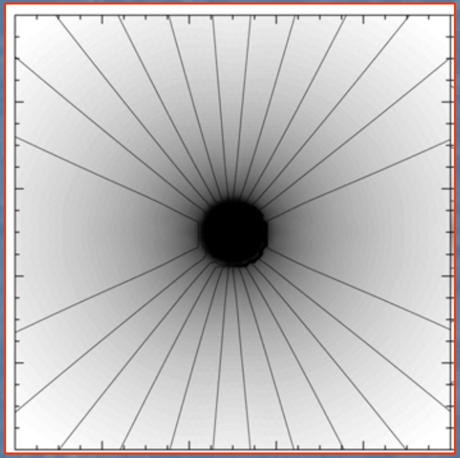
- 5 models with different initial rotation rates for star.
- Co-rotation point = last point where magnetic field can keep gas rotating with star (approx Alfven point R_A)
- We find tight correlation of final outflow speed with rotation velocity at co-rotation point (R_A)
- Note: This is very different from usual magneto-rotational results. Outflow not proportional to V_{esc}
- *Outflow taps rotational energy via magnetic field!*



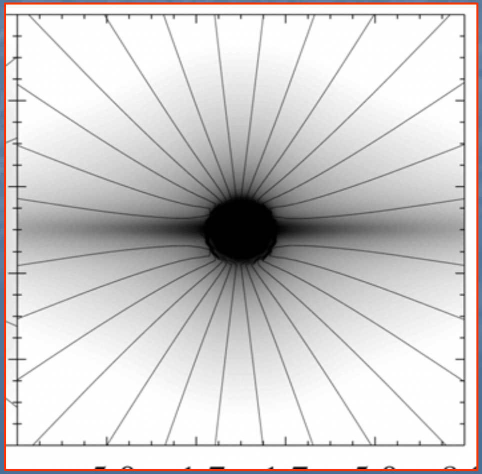
Wind Shaping During AGB Phase

Matt & Balick 2001

- Wind shaping occurs via streaching of dipole field lines.
- Current sheets develop leading to magnetic forces
- Result: Toroidal density distributions



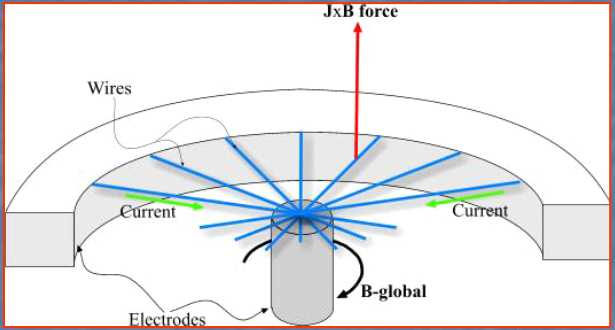
Weak field



Strong field

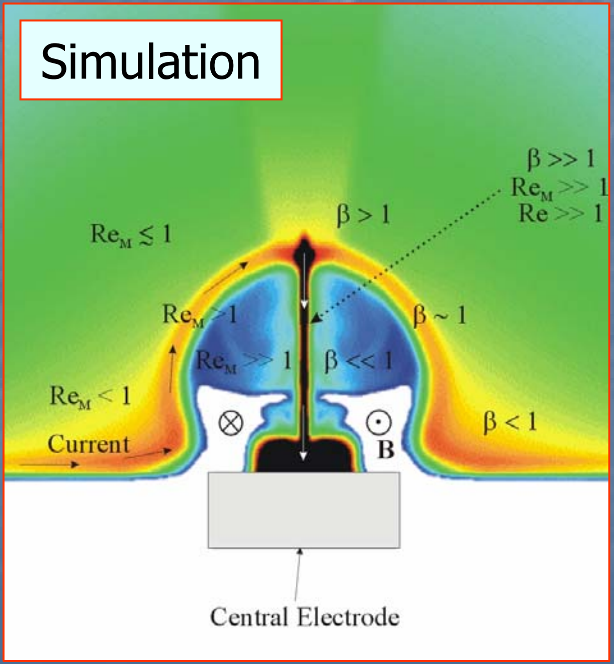
Laboratory MHD Jet Experiments

Lededev…, Frank, Blackman *et al* 2005

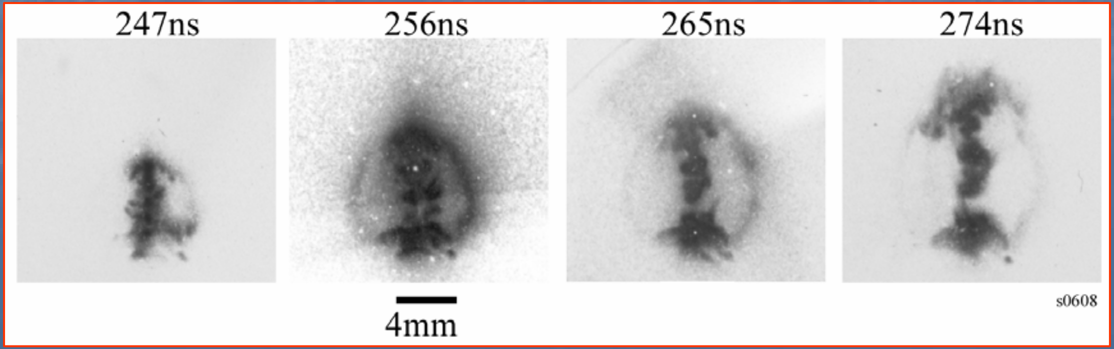


Can now make B dominated flow in Lab!

- MAGPIE Pulsed Power machine: 16 wire radial array.
- Global B_ϕ below wire
- Wires ablate plasma "atmosphere"
- Wires break B_ϕ "inflates" magnetic outflow and collimates axial jet



Experiment: Soft X-ray Images



Conclusions

- Magneto-rotational models maturing for PNe/pPNe.
- Observations of B fields in pPNe and PNe make these systems laboratories for study of astrophysical MHD/Jet launching.
- Magneto-rotational simulations reveal physics applicable to variety of objects (GRB/SNe, YSOs)
- (new) HEDLA experiments can create “pPNe-like” B_ϕ dominated outflows/jets