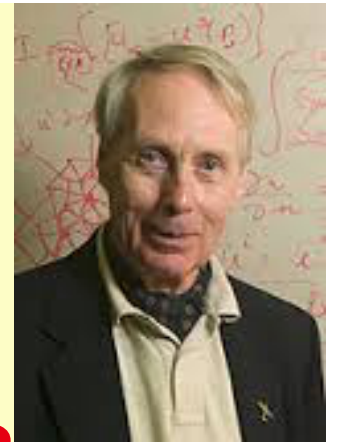
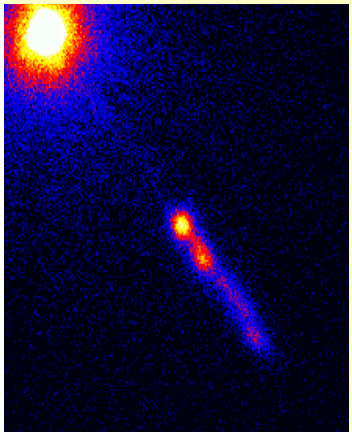


Knots, Tangles and Magnetoluminescence



Roger Blandford
KIPAC
Stanford

**With Yajie Yuan, Jonathan McKinney,
Sasha Tchekhovskoy, Jonathan Zrake, William East**



Antony Jameson





Hardy?

Ramanujan?

Pulsar Wind Nebulae

- eg Crab Pulsar/Nebula
- Spinning Neutron Star
 - 34 ms!
- Polarized inner knot is shock
- γ -ray flares from nebula
- $E_\gamma \sim 400$ MeV -- only
- ~ 5 PeV electrons
- $t \sim$ hrs; $R_{\text{nebula}} \sim 1$ t yrs!

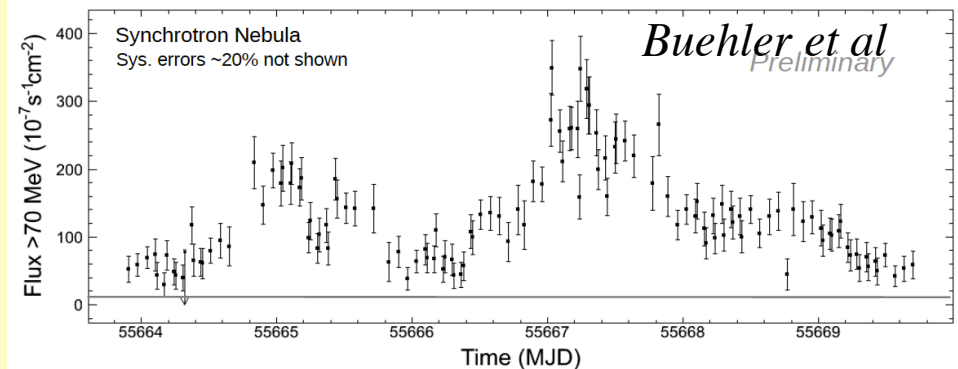


Prostrating myself before your majesty, I hereby report that a guest star has appeared... (This) means that there is a person of great wisdom and virtue in the country. *Yang Wei-ti 1054 AD*



Fermi

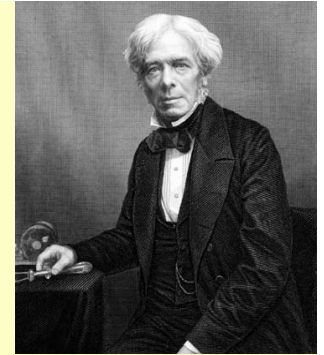
Antony



Rapid flux variability <1h

Unipolar Induction

EMF from spinning magnetized body

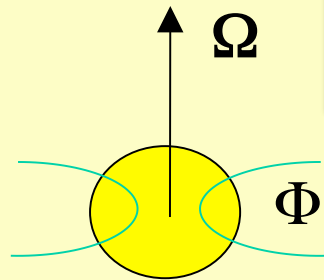


$$V \sim \Omega \Phi \sim E_{\max}/e$$

$$I \sim (V / Z_0)$$

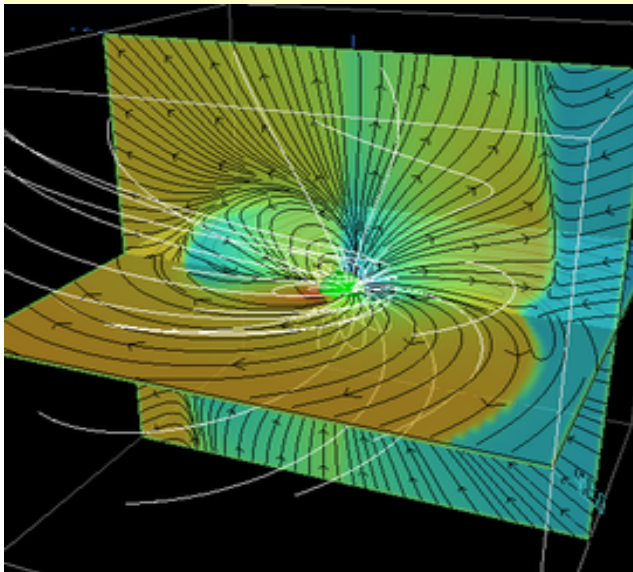
$$Z_0 \sim 100\Omega$$

$$P \sim VI \sim (V^2/Z_0)$$

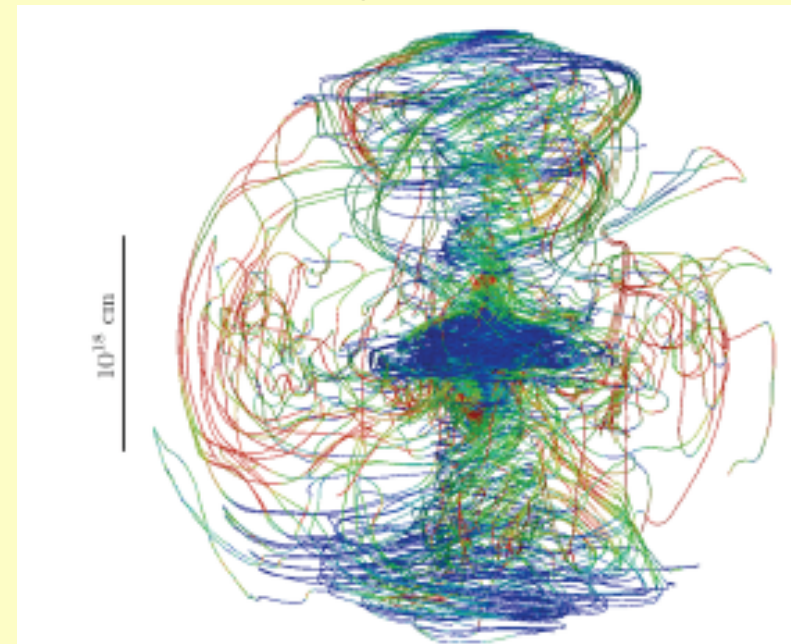


Sun - $V \sim 100$ MV, $I \sim 1$ GA, $P \sim 100$ PW
Crab - $V \sim 30$ PV, $I \sim 300$ TA, $P \sim 10^{31}$ W

Spitkovsky



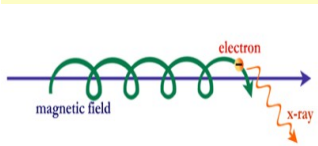
Porth



Antony Jameson

Crab Flares

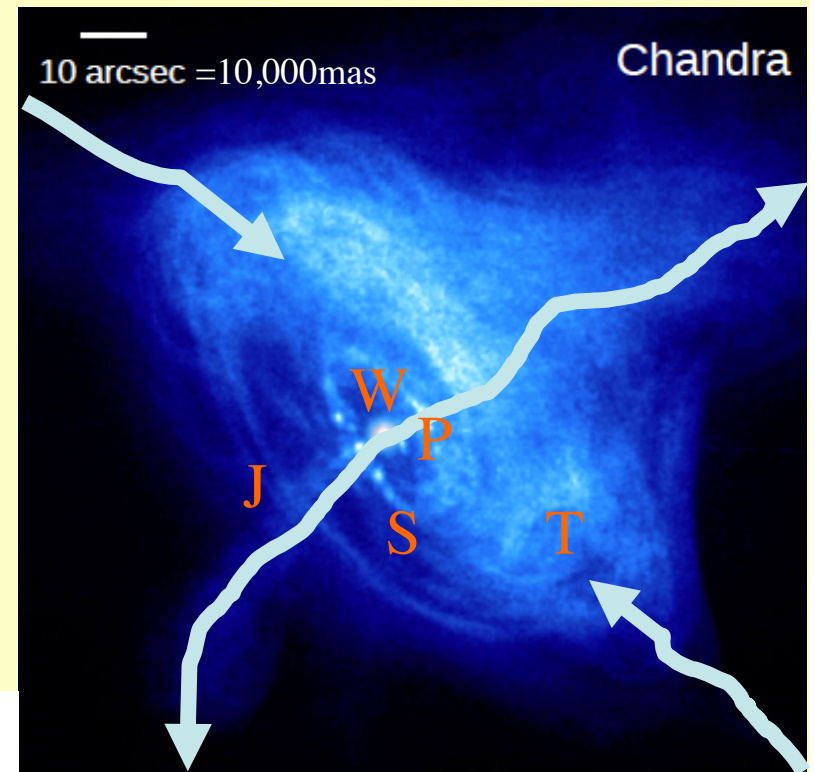
- GeV Crab flares appear to be synchrotron radiation by PeV electrons in mG fields
- Challenge to classical electrodynamics
- Similar problems in other sources



$$\vec{a}_L = \frac{e}{m} \left(\frac{\vec{E}}{c} + \hat{u} \times \vec{B} \right)$$

$$\frac{d\vec{u}}{dt} = \vec{a}_L - \frac{2r_e}{3c} \gamma^2 a_{L\perp}^2 \hat{u}, \quad \frac{d\vec{x}}{dt} = \hat{u}$$

$$a_{L\perp}(\vec{x}, \hat{u}) = \frac{e}{m} B_e = \frac{e}{m} \left[B_{\perp}^2 + \left(\frac{E_{\perp}}{c} \right)^2 - 2 \frac{\vec{E} \times \vec{B} \cdot \hat{u}}{c} \right]^{1/2}$$



1 lt hr = 3 mas

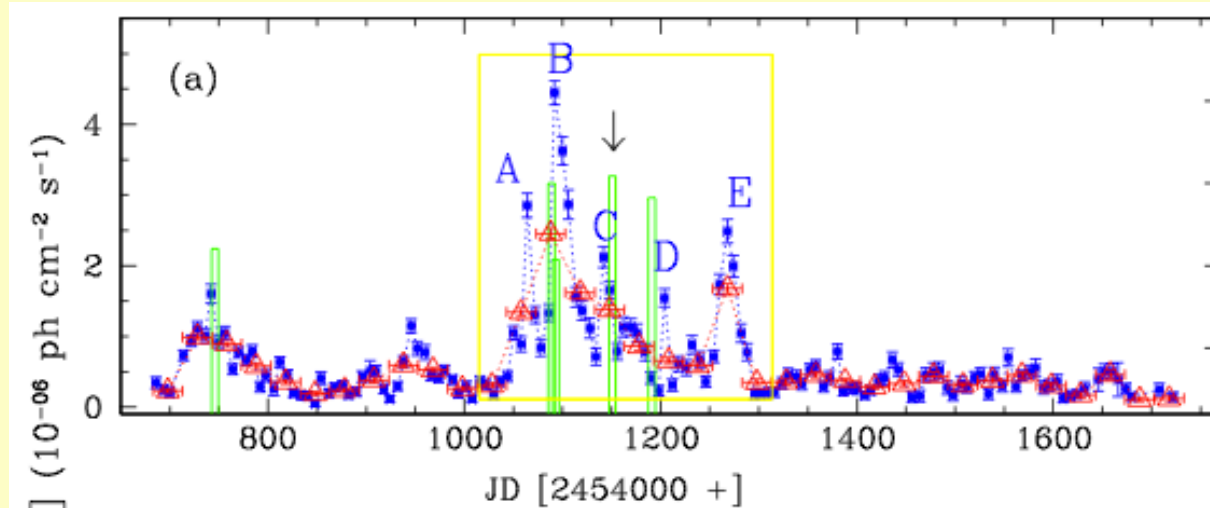
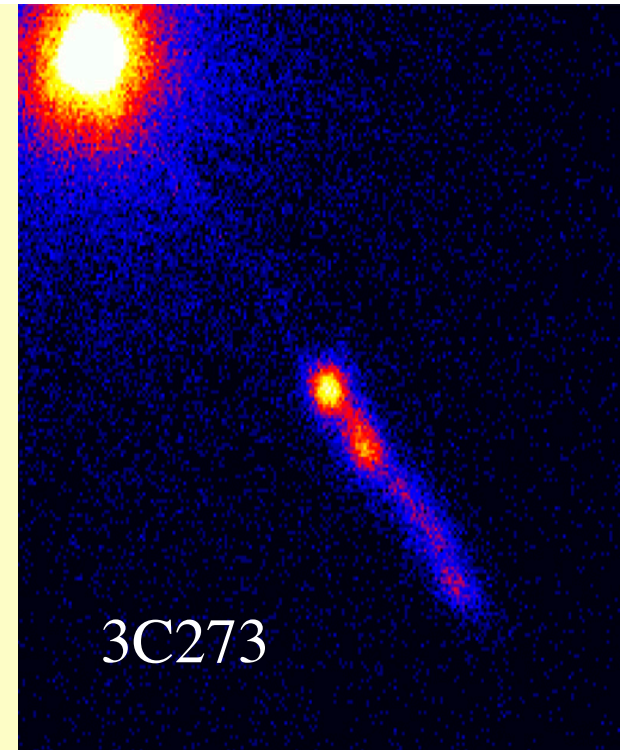
Larmor radius = $60\gamma_9 B_{-7}^{-1}$ mas

Maximum energy $\sim \alpha^{-1} m_e \sim 100$ MeV if $E \sim B$

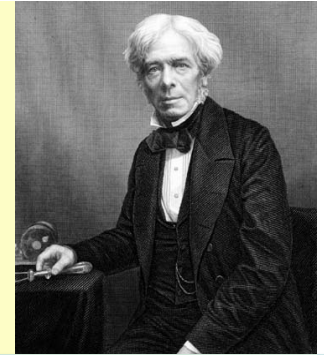
Cool in 10⁶!

Quasar Jets

- eg 3C 273
- $10^9 M_{\odot}$ Spinning Black Hole
- γ -rays from relativistic jet
- $E_{\gamma} \sim 15 \text{ GeV}$
- $t \sim 10 \text{ hr}$, $R_{\text{jet}} > 30 \text{ lt yr}$



Unipolar Induction



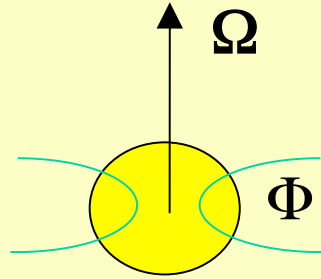
EMF from spinning magnetized body

$$V \sim \Omega \Phi \sim E_{\max} / e$$

$$I \sim (V / Z_0)$$

$$Z_0 \sim 100 \Omega$$

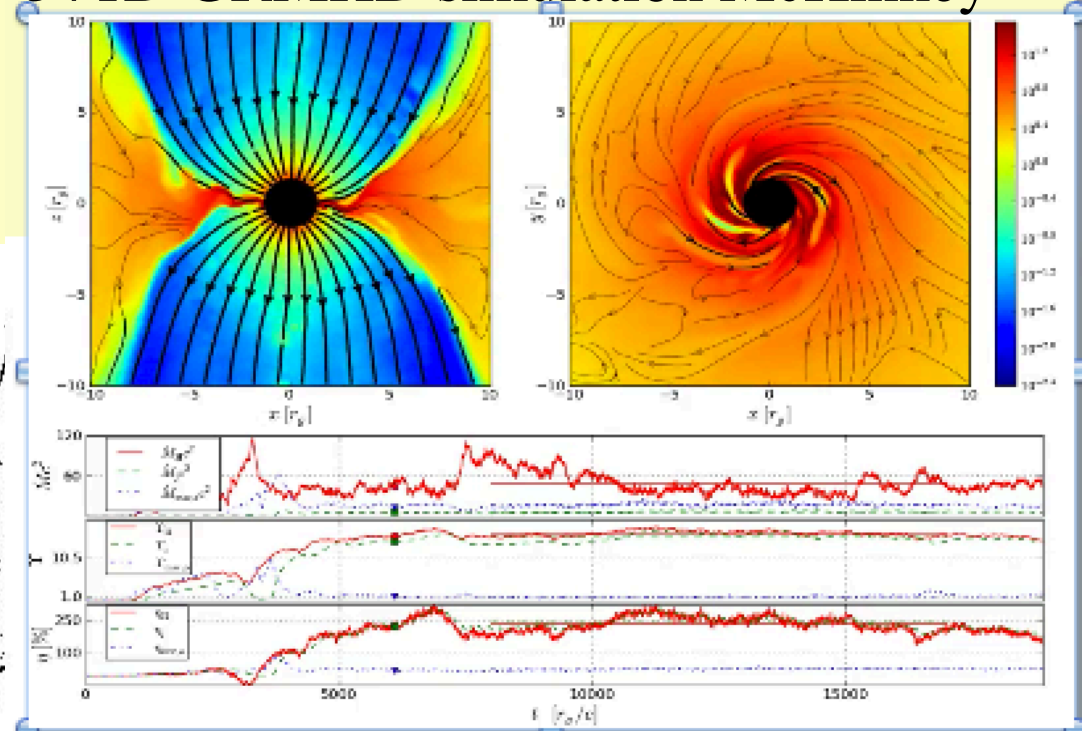
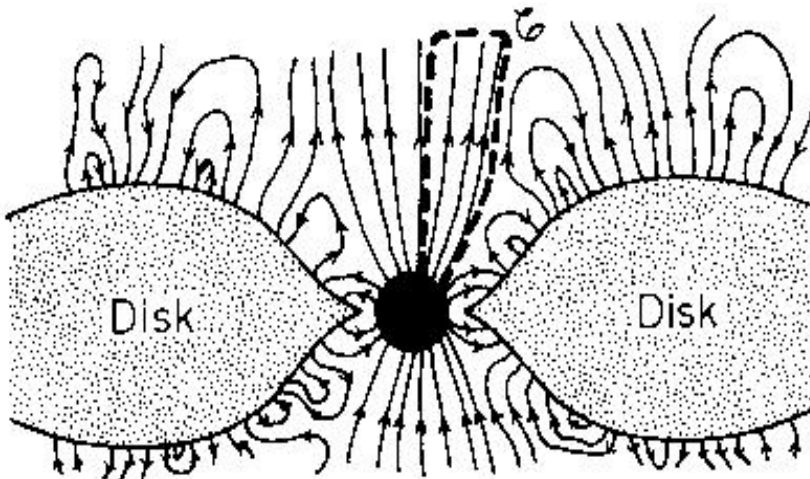
$$P \sim VI \sim (V^2 / Z_0)$$

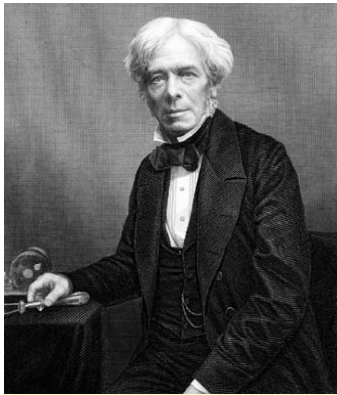


Sun - $V \sim 100$ MV, $I \sim 1$ GA, $P \sim 100$ PW
 Crab - $V \sim 30$ PV, $I \sim 300$ TA, $P \sim 10^{31}$ W
 AGN - $V \sim 1$ ZV, $I \sim 10$ EA, $P \sim 10^{40}$ W
 GRB - $V \sim 0.1$ YV, $I \sim 1$ ZA, $P \sim 10^{44}$ W

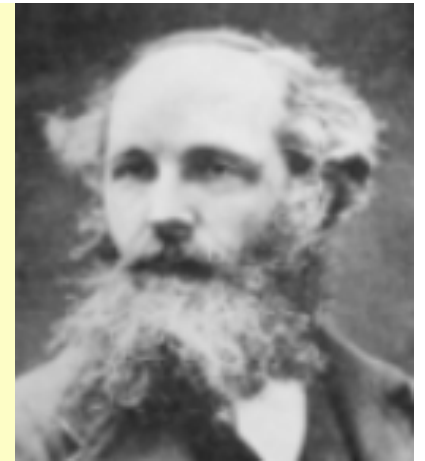
3+1D GRMHD simulation McKinney

Spinning Black Hole





Let there be Light

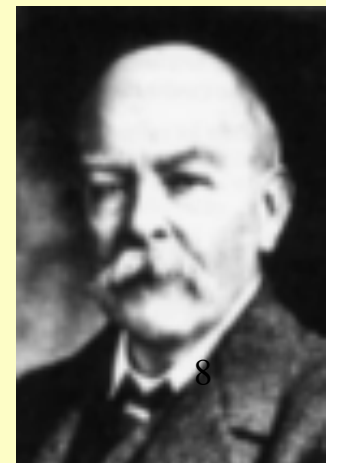


- Faraday
- Maxwell
- Initial Condition
- Definition

$$\begin{aligned}\frac{\partial B}{\partial t} &= -\nabla \times E \\ \frac{\partial E}{\partial t} &= \nabla \times B - j \\ \nabla \cdot B &= 0 \\ \nabla \cdot E &= \rho\end{aligned}$$

$$\nabla^2 A = j$$

=> Maxwell Tensor, Poynting Flux



Force-Free Condition

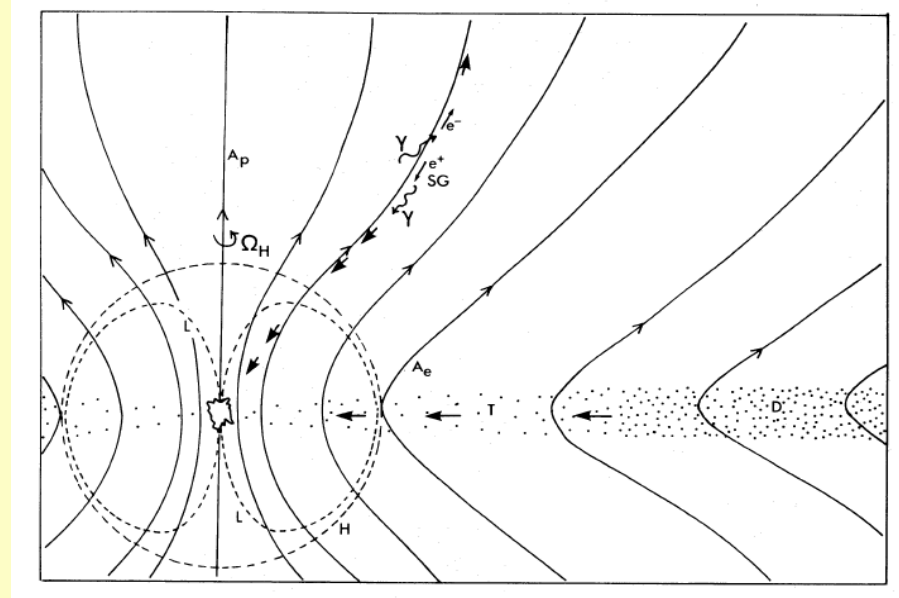
$$\rho E + j \times B = 0 \Rightarrow E \cdot B = E \cdot j = 0$$

$$j = \frac{(\nabla \cdot E)E \times B + (B \cdot \nabla \times B - E \cdot \nabla \times E)B}{B^2}$$

- Ignore inertia of matter $\sigma = U_M/U_P \gg \Gamma^2, 1$
- Electromagnetic stress acts on electromagnetic energy density
- Fast and intermediate wave characteristics, evolutionary

Force-Free Electrodynamics in Black Hole Spacetime

- $\mathbf{F} \cdot \mathbf{J} = 0 \Leftrightarrow \text{div } \mathbf{T}^{\text{EM}} = 0$
 - Pair production necessary
- $F^{\mu\nu}_{;\nu} = J^\mu$
 - $\xi_{\phi,t} \Rightarrow$ Conserved \mathbf{F}, \mathbf{G}
 - $\mathbf{I}(\Phi), \mathbf{V}(\Phi), \mathbf{\Omega}(\Phi)$
- Horizon boundary conditions
 - EM finite for infalling observer
 - Energy outflow in non-rotating frame
 - Energy inflow in rotating frame



$$\Delta G \Omega_H = \Delta G \Omega_L + I^2 \Delta R_H + I^2 \Delta R_L$$

$$\Omega = \frac{\Omega_H \Delta R_L + \Omega_L \Delta R_H}{\Delta R_L + \Delta R_H}$$

MagnetoHydroDynamics

- Relativistic Force-Free treatment

- No inertia

- Relativistic MHD

- Maxwell + Inertia + Pressure

- Collisionless plasma has anisotropic pressure tensor

$$\rho \mathbf{a} = \rho \mathbf{g} - \nabla \cdot \mathbf{P} + \rho_e \mathbf{E} + \mathbf{j} \times \mathbf{B}$$

- Can connect to Drifting Orbit Representation

- $P_{\parallel} \sim n^2 B^{-1}$; $P_{\perp} \sim n B^{1/2}$... changes dynamics, stability, waves...

- Space, time, greater than gyro scales

$$\nabla \cdot (T^{EM} + T^F) = 0$$

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$$\Rightarrow \mathbf{j}_{\perp} = \frac{P_{\parallel} \mathbf{B} \times (\mathbf{B} \cdot \nabla) \mathbf{B}}{B^4} - \left[\nabla \times \left(\frac{P_{\perp} \mathbf{B}}{B^2} \right) \right]_{\perp} + \frac{P_{\perp} \mathbf{B} \times \nabla B}{B^3} + \frac{\rho_e \mathbf{E} \times \mathbf{B}}{B^2} + \rho \frac{\mathbf{g} \times \mathbf{B}}{B^2} + \rho \frac{\mathbf{a} \times \mathbf{B}}{B^2}$$

curvature

magnetization

gradient

$\mathbf{E} \times \mathbf{B}$

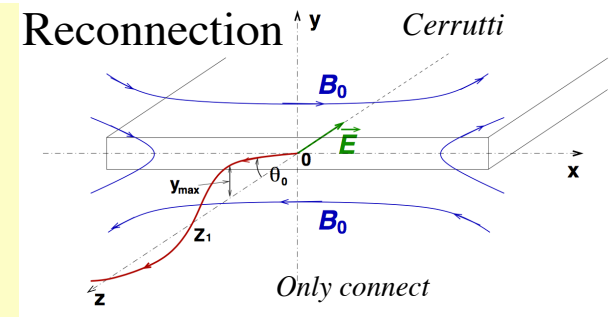
gravity acceleration

Knots and Tangles

- **Knots - links**
 - Reconnection to tie and untie
 - Acceleration in a small volume
 - Slow process, lower energy particles
 - Shocks also accelerate
- **Tangles - braids, hitches...**
 - Sudden transition to lower energy state
 - $E > c B?$; runaway acceleration
 - Volumetric process
 - Magnetic energy \rightarrow electrons \rightarrow γ -rays
 - Implosion, chain reaction?
 - Small fraction of average power

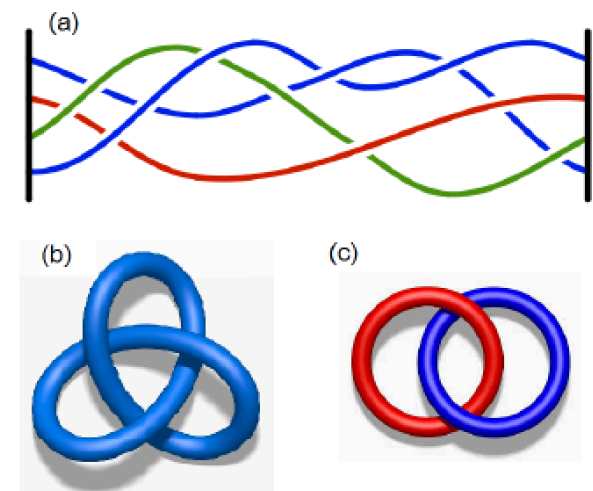
14 xi 2014

Antony Jameson



Alexander the Great
slices Gordian Knot
(accompanied by
electrical storm!)

Alexander (1928): $t+t^{-1}$ etc

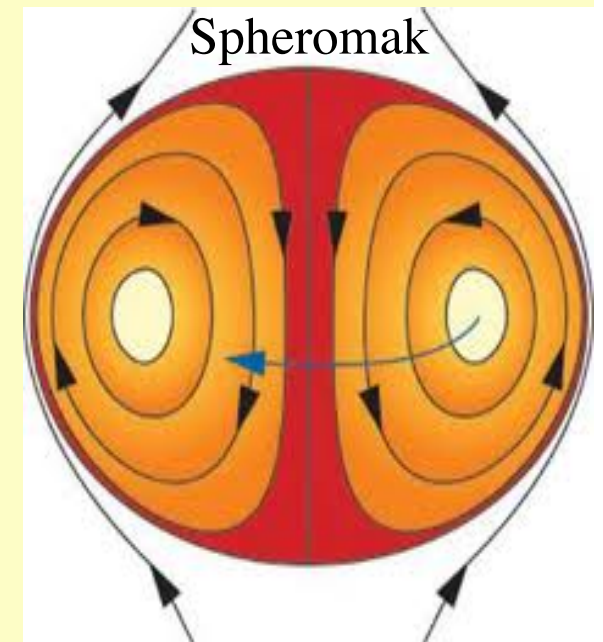
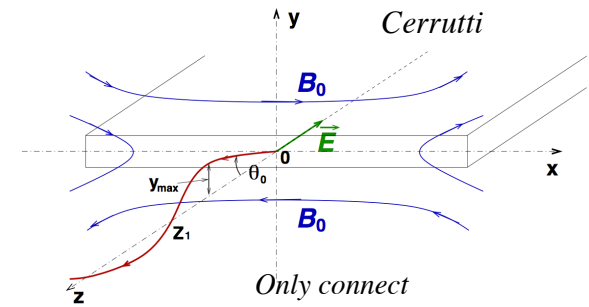


Knots and Tangles

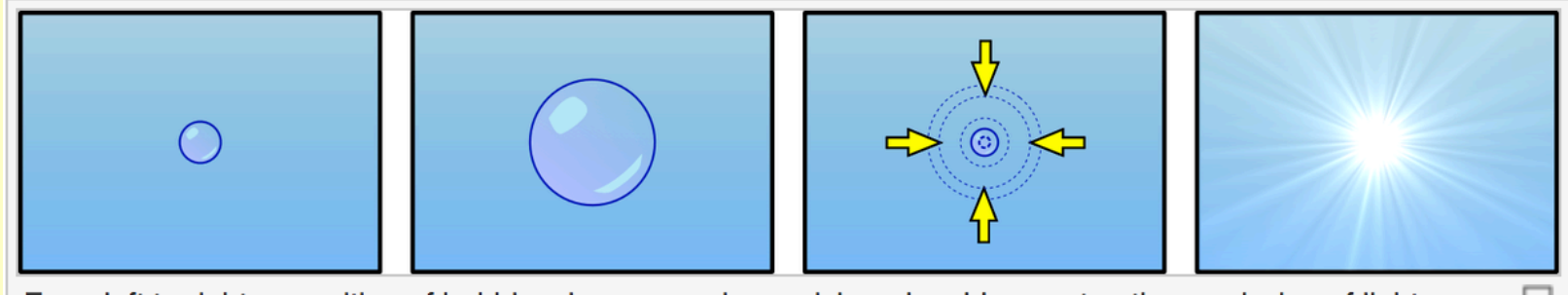
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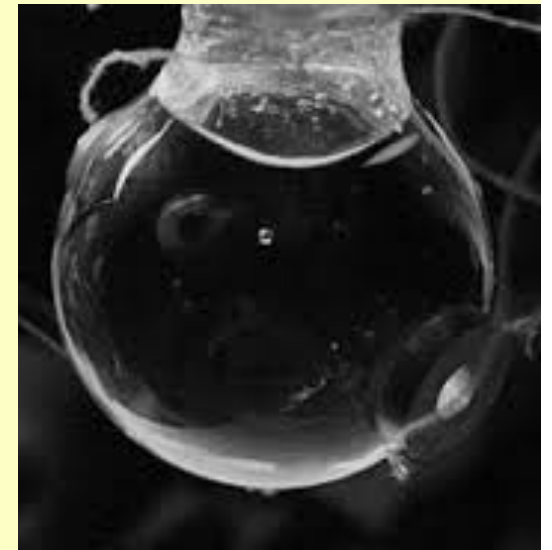
Sonoluminescence



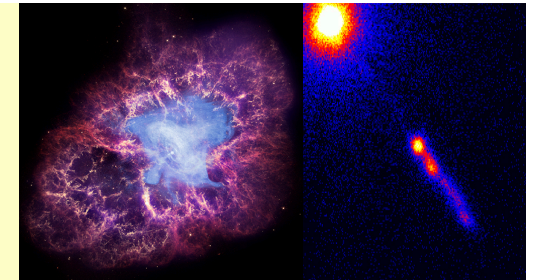
Cavitation -> implosion -> optical (x-ray??) flashes

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho} \left(p_g - P_0 - P(t) - 4\mu \frac{\dot{R}}{R} - \frac{2\gamma}{R} \right)$$

Rayleigh-Plesset equation



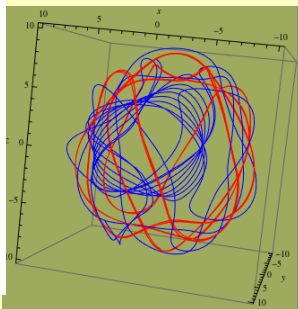
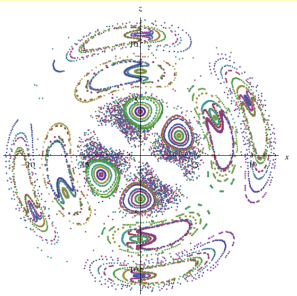
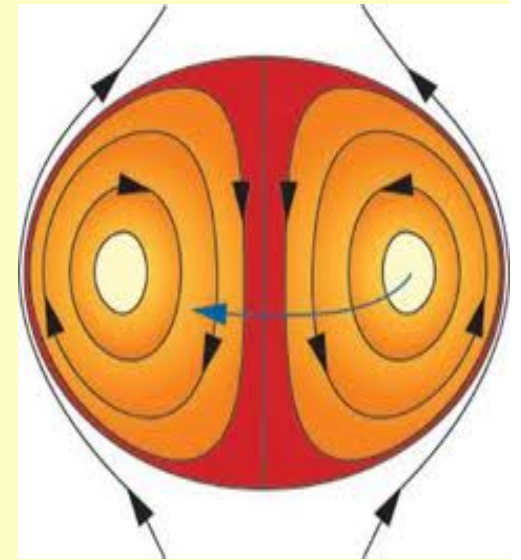
Magnetoluminescence



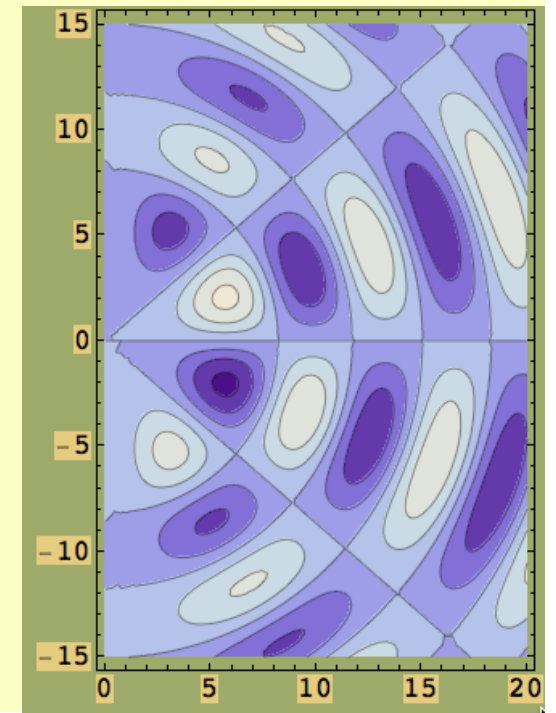
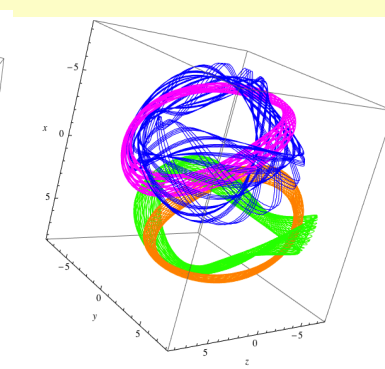
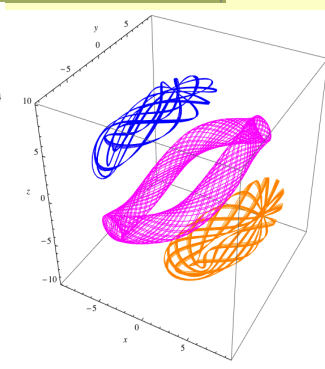
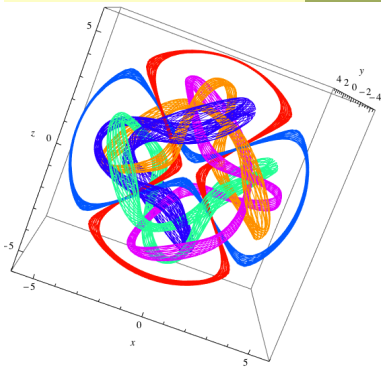
- Topology-preserving re-arrangement of magnetic tangle
- Rapid dissipation of electromagnetic energy
- Relativistic conditions
- Efficient, volumetric particle acceleration of TeV, PeV electrons, positrons
- Prompt synchrotron emission of γ -rays
- Current carried by emitting particles
- Pressure loss \rightarrow non-spherical implosion?

Force-Free Equilibria

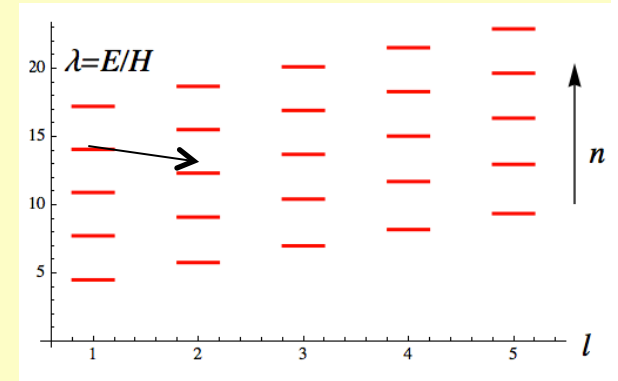
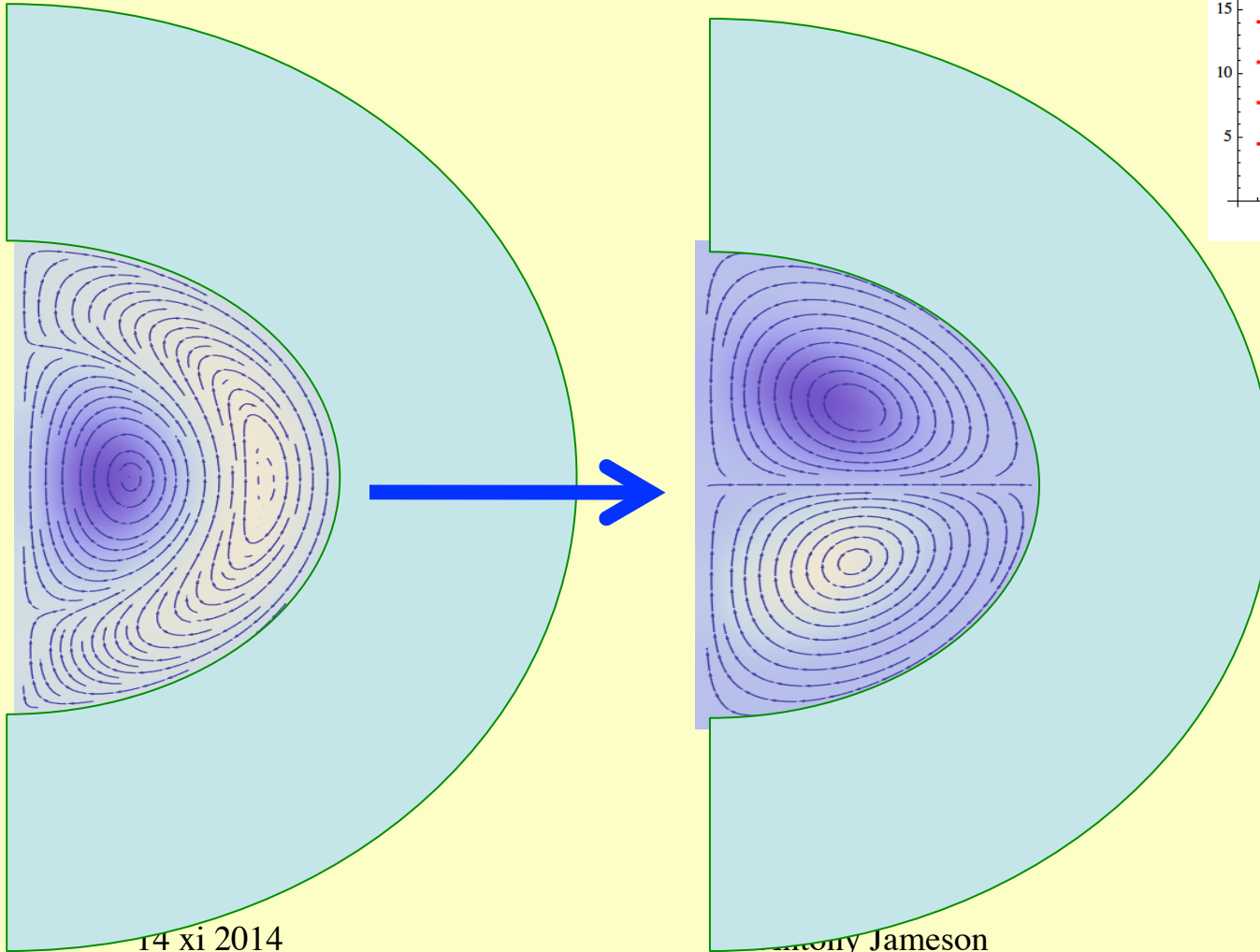
- $B \sim A \sim j \rightarrow$ Helmholtz equation
- Spheromak solutions
 - $n, l, m, s!$
- Two phases
 - Magnetic ropes, confined to nested surfaces
 - Chaotic field
- Connect structural stability to microphysics?



Yuan



Permitted Transition?



Exploring these and other models with RMHD and RFF codes to understand nonlinear evolution

Summary

- New mechanisms needed to account for most dramatic gamma ray flares
- Associated with spinning, magnetized compact objects
- Dissipation of electromagnetic energy
- Steady emission - relativistic reconnection
- Flares - untangling flux tubes?
- Interesting applied math, computing

Happy Birthday!

