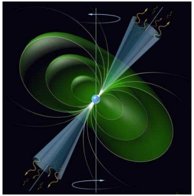
Astrophysics of Neutron Stars : The Magnetic Field

Sushan Konar



Astronomy from Archival Data

An IAU-OAD Project

2020

The Magnetic Field

1. The Glitch
2. The Origin
3. The Transport
4. The Evolution

The Glitch

The Glitch

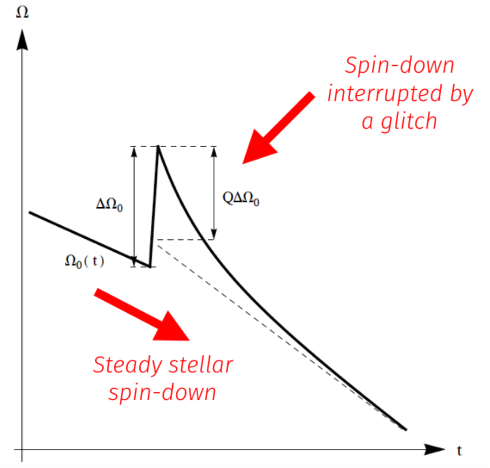


Image credit : Lisa Drummond

The Glitch

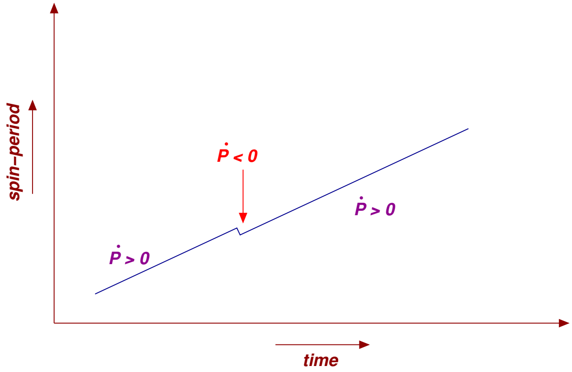


Image credit : Sushan Konar

- sudden decrease in P $(10^{-12} \leq \delta\nu/\nu \leq 10^{-4})$
- followed by a relaxation towards unperturbed P

Statististics of Glitch

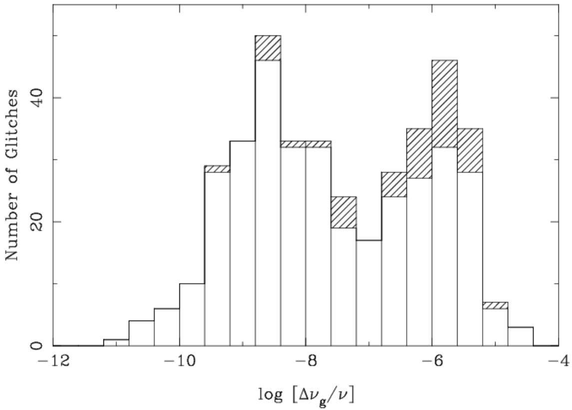
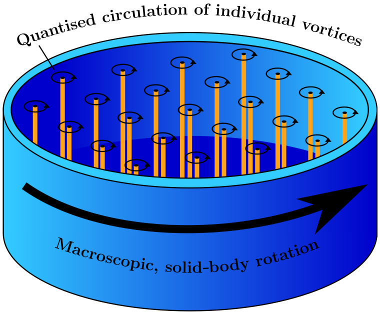


Figure credit : Yu M. et al., MNRAS, 429, 688 (2013)

Neutron Supefluidity



- *rotation by creation of vortices*
- quantum of circulation :
  $I_n = h/2m_n \sim 2 \times 10^{-3}\ cm^2.s^{-1}$
- number of rotational vortices :
  $2\pi R^2 \Omega_{\rm NS}/I_n \sim 2 \times 10^{16}(P/s)^{-1}$

Figure credit : Graber, V. et al., Int.J.Mod.Phys., D26, 08, 1730015 (2017)

Glitch : Crustal Physics

Superfluid Dynamics

- sf spin-down $\rightarrow$ number of rotation vortices $\downarrow$
- vortices pinned to inner crust : $\delta\nu/\nu \lesssim 10^{-3}$
- $(\nu_{\rm SF} - \nu_{\rm NS}) \uparrow \rightarrow$ unpinning
- unpinning $\rightarrow$ angular momentum transfer $\rightarrow$ spin-up

Crust-quake

- spin-down $\rightarrow$ centrifugal force $\downarrow$
- ellipticity change $\rightarrow$ mechanical stress $\uparrow$
- crust cracking $\rightarrow -\delta I/I = \delta\nu/\nu \uparrow$

crustal energy not sufficient?

Glitch : Crustal Physics

Superfluid Dynamics

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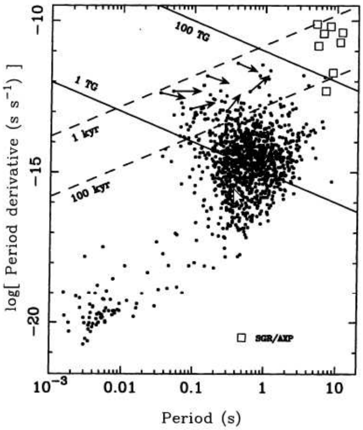
Glitch : New Directions?

Young glitching pulsars to Magnetars?



Lyne et al., 2004

Glitch Phenomenology

Trigger :

- catastrophic vortex unpinning
- thermal pulse due to star-quake
- crust cracking due to magnetic stresses

Summary :

- likely two different origins for glitches
- relation between glitch & flux expulsion
- multiple glitch : pulsar $\Rightarrow$ magnetar

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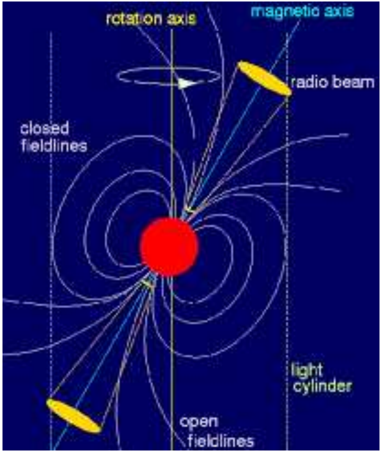
The Origin

Dipolar Field

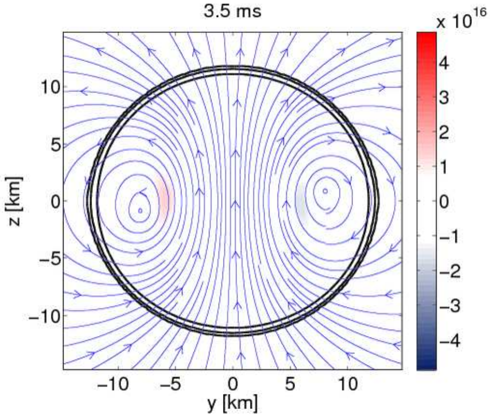


- $B_{\rm surface} \sim 10^{8} - 10^{15}$ G
- $P_{\rm spin} \sim 10^{-3} - 10^{1.5}$ s

$B_{\rm light-cylinder}$ has a wide range.

Figure credit : Jodrell Bank Observatory

Internal Configuration



Ciolfi, R., Astron. Nachr., 335, 624, (2014)

Internal Configuration

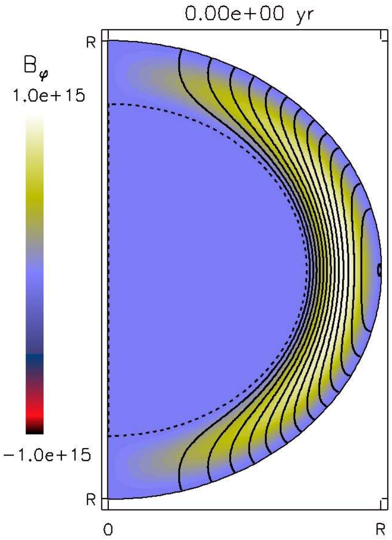


Figure credit :
Geppert U. et al. ASP Conf.Ser., 466, 107 (2012)

Multipolar Field

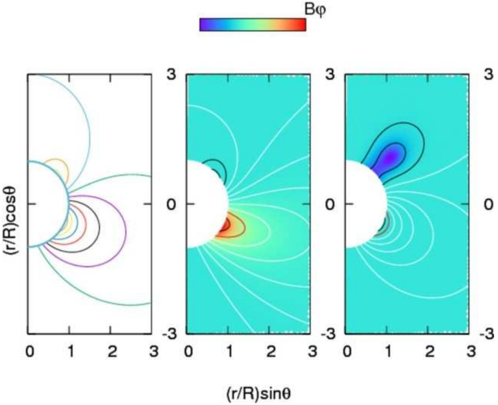
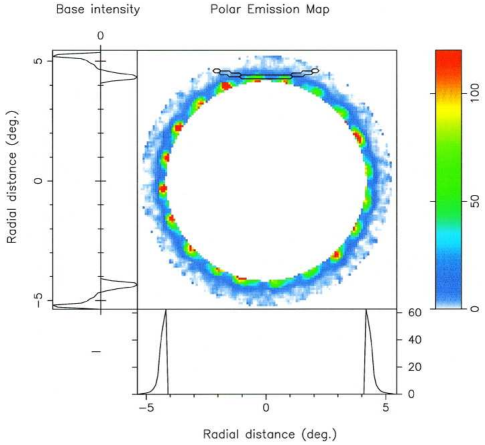


Figure credit : Kojima Y., MNRAS, 477, 3530 (2018)

- pulsar emission

  smaller radius of curvature required
- existence of slow pulsars ($P_s^{\max} = 23.5$ s)
  very strong, twisted surface field
  (*Tan C. M. et al., ApJ, 866, 12 (2018)*)
- indication from magnetar activity

Multipolar Field



- Surface footprints of field
- indication from magnetar activity

Figure credit : Deshpande A. A., Rankin J., ApJ, 524, 1008 (1999)

Magnetic Fields : Measurements

Dipolar Field at large distances.

- Measurements :
  - secular spin-down : $B \propto (P\dot{P})^{1/2}$, only dipolar field
  - channelised accretion : $B \propto \dot{M}^{1/2}$, dipolar field at Alfven radius
  - cyclotron line-emission : total field strength
- Uncertainties :
  - primarily large-scale dipolar field measured
  - no understanding of multipolar structure near surface
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Magnetic Field : Origin

1. Generation in the Core :
   1. fossil field : flux freezing from pre-collapse core field
      $[(R_{\rm progenitor}/R_{\rm NS})^2 \sim 10^{10}]$
   2. magnetized core : spontaneously magnetized state of matter
   3. turbulent dynamo amplification in proto-neutron star core

2. Generation in the Crust :
   1. thermo-electric battery/dynamo in crust
   2. strong toroidal field in deeper regions of crust

None of the proposed processes are problem-free.

Magnetic Field : Location

Location -

- superconducting flux tubes in the core
  [$\phi = hc/2e = 2 \times 10^{-7}$G.cm^2, 10^{31} fluxoids]
- crustal currents
- charged particle currents in the core (n-p-e plasma)

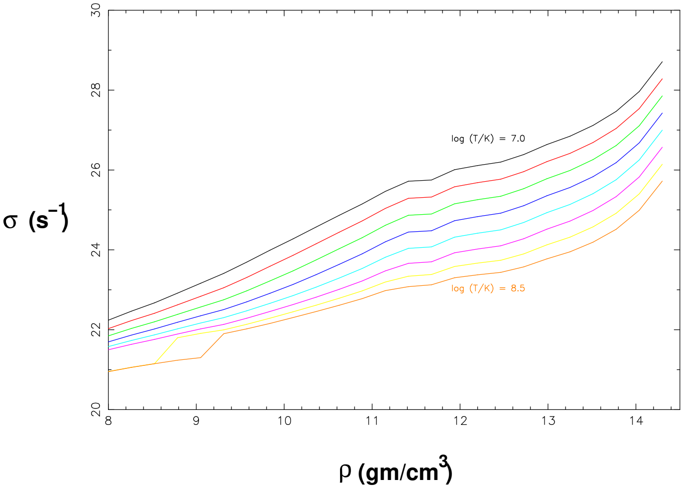
Evolution -

- actual dissipation only in metallic crust

For details see - Konar S., JApA, 38, 47 (2017)

Transport Properties

Electrical Conductivity



Electrical conductivity (σ) in the crust

$\sigma \uparrow$ with $\rho \uparrow$

$\sigma \downarrow$ with $T \uparrow$

Figure credit : Sushan Konar

Electrical Conductivity : Impurity

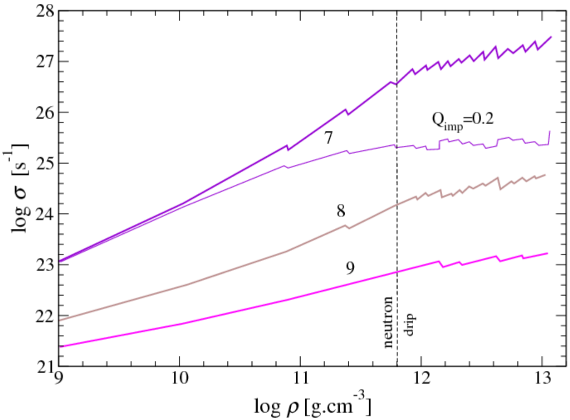


Figure credit : Chamel N., Pawel H., LRR, 11, 1 (2008)

Thermal Conductivity

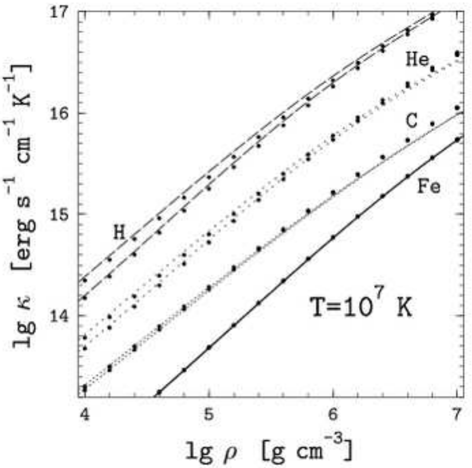
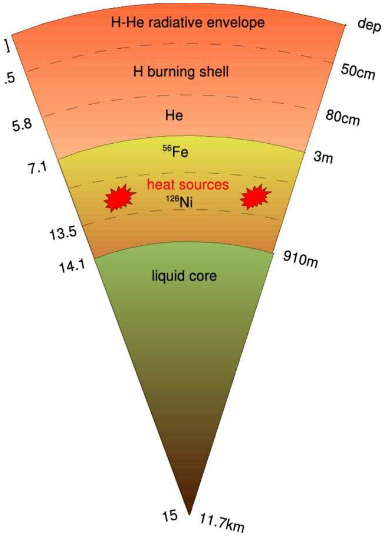


Figure credit : Chamel N., Pawel H., LRR, 11, 1 (2008)

Accreting Neutron Star



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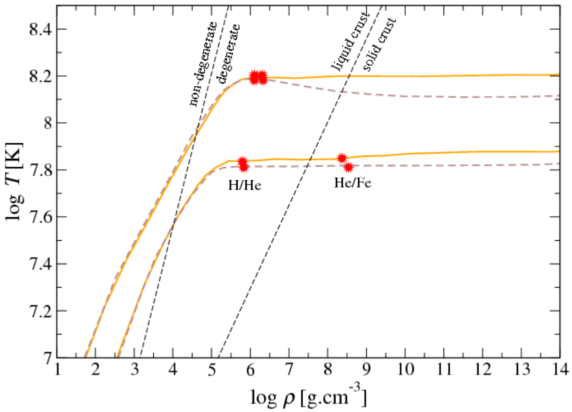
Heated Crust



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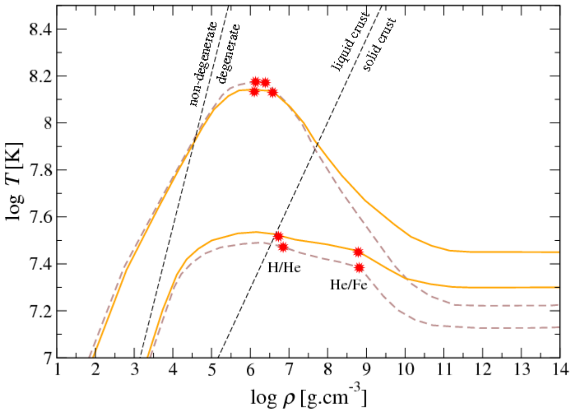

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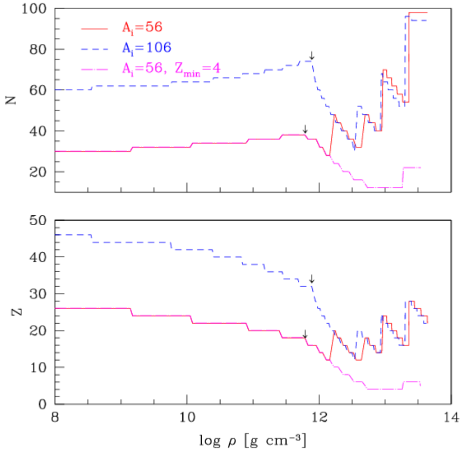
Accreted Crust



Chamel N., Pawel H., LRR, 11, 1 (2008)

The Evolution

Induction Equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \frac{\mathbf{c^2}}{\mathbf{4}\pi} \nabla \times (\frac{\mathbf{1}}{\sigma} \nabla \times \mathbf{B}) \quad (1)$$

σ - electrical conductivity
v - velocity of material movement

field evolution = flux transport + Ohmic diffusion $(\tau_{\rm diff} \sim \frac{4\pi\sigma L^2}{c^2})$

$$\sigma = \sigma(\rho, Z, A, T, Q)$$

NS Parameters : ρ, Q

Isolated Neutron Star

- Spin-Down :
  - spin-down $\rightarrow$ expulsion of rotational vortices
  - inter-pinning $\rightarrow$ expulsion of magnetic fluxoids
- Field Evolution
  - flux-expulsion $\rightarrow$ flux deposition at core-crust boundary
  - flux in metallic crust $\rightarrow$ Ohmic dissipation
  - Hall transport & ambipolar diffusion in metallic crust
- Glitch induced Field Evolution
  - increased magnetic stress at core-crust boundary
  - crust-cracking $\rightarrow$ expulsion of magnetic fluxoids

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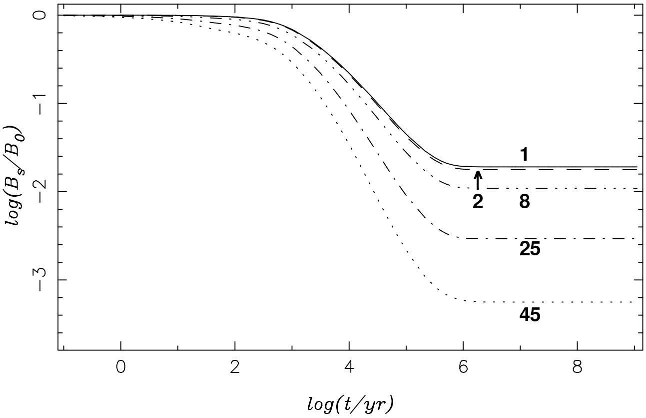
Ohmic Dissipation



evolution of surface field (poloidal)
(numbers indicate order of multipole)

Figure credit : Mitra D., Konar S., Bhattacharya D., MNRAS, 307, 459, (1999)

Accreting Neutron Star

- spin-down induced flux-expulsion followed by Ohmic dissipation
  Jahan-Miri M., ApJ, 532, 514 (2000)
- enhanced Ohmic dissipation in accretion heated crust
  Konar S., JApA, 38, 47 (2017)
- diamagnetic screening followed by re-emergence
  Cumming Al, Zweibel E., Bildsten L., ApJ, 557, 958 (2001)
- burial through fallback hyper-critical accretion followed by re-emergence
  Bernal C. G., Page D., Lee W. H., ApJ, 770, 12 (2013)

Multipolar Fields

Multipole Mixing :

$$\mathbf{B} = \mathbf{B}_{\mathrm{p}} + \mathbf{B}_{\mathrm{t}}, \tag{2}$$

$$\mathbf{B}_{\mathrm{p}} = B_r \mathbf{e}_r + \mathbf{B}_\theta \mathbf{e}_\theta, \tag{3}$$

$$\mathbf{B}_{\mathrm{t}} = B_\phi \mathbf{e}_\phi. \tag{4}$$

$$\frac{\partial \mathbf{B}_{\mathrm{p}}}{\partial t} = \nabla \times (\mathbf{v}_{\mathrm{tr}} \times \mathbf{B}_{\mathrm{p}}) + \frac{\mathbf{c}}{4\pi \mathbf{e}} \nabla \times \left(\frac{\mathbf{1}}{\mathbf{n}} (\nabla \times \mathbf{B}_{\mathrm{t}}) \times \mathbf{B}_{\mathrm{p}} \right) - \frac{\mathbf{c}^2}{4\pi} \nabla \times \left(\frac{\mathbf{1}}{\sigma} \nabla \times \mathbf{B}_{\mathrm{p}} \right) \tag{5}$$

$$\frac{\partial \mathbf{B}_{\mathrm{t}}}{\partial t} = \nabla \times (\mathbf{v}_{\mathrm{tr}} \times \mathbf{B}_{\mathrm{t}}) + \frac{\mathbf{c}}{4\pi \mathbf{e}} \nabla \times \left(\frac{\mathbf{1}}{\mathbf{n}} (\nabla \times \mathbf{B}_{\mathrm{p}}) \times \mathbf{B}_{\mathrm{p}} \right) + \frac{c}{4\pi e} \nabla \times \left(\frac{\mathbf{1}}{\mathbf{n}} (\nabla \times \mathbf{B}_{\mathrm{t}}) \times \mathbf{B}_{\mathrm{t}} \right) - \frac{\mathbf{c}^2}{4\pi} \nabla \times \left(\frac{\mathbf{1}}{\sigma} \nabla \times \mathbf{B}_{\mathrm{t}} \right). \tag{6}$$

Material Transport / Hall Term : Multipole Mixing

Polar Cap Accretion

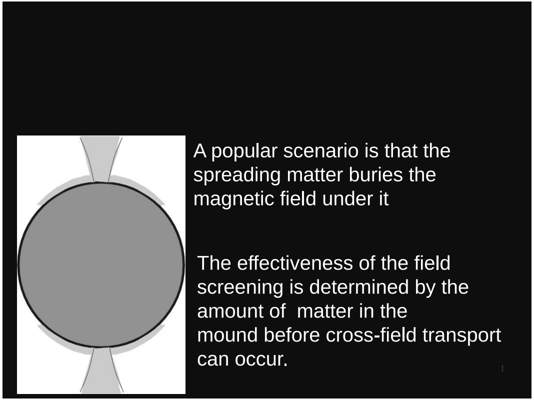
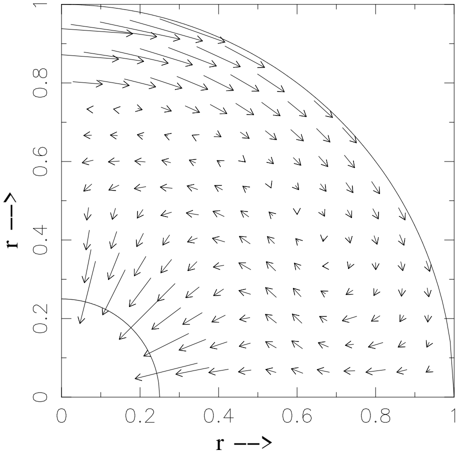


Figure credit : Dipanjan Mukherjee

- material accumulation confined by magnetic stresses
- material sinks & flows side-wise for $P_{\rm column} \gtrsim P_{\rm mag.}$

Flow Pattern

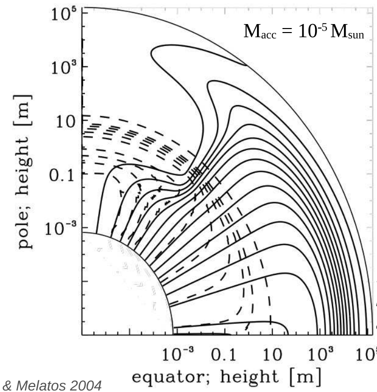


flow velocity

- *equator-ward* in topmost layer
- *counter-flow* in intermediate layers
- *radial* in deeper layers

Figure credit : Arnab Rai Choudhuri, Sushan Konar

Field Distortion



Scaled problem

Instabilities not accounted for

Payne & Melatos 2004

Figure credit : Payne D. J. B, Melatos A., MNRAS, 351, 569 (2004)

Multipolar Field : Outlook

- initial toroidal fields
- generation of higher multipoles/toroidal fields by accretion material flow
- final resultant field structure - observational indication

Inter-pinned Superfluids