“Invisible” Magnetic Fields of Neutron Stars

1. Constrain crustal B field from X-ray light curve modeling
   NS in Kes 79

2. B Field evolution in NS crust: Hall drift and crust breaking
   Smooth vs episodic dissipation of B fields
   (pulsars vs magnetars?)

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Magnetic Fields of Isolated NSs

Have been inferred by

- P, Pdot
- Spectral lines (+ interpretation)
- Energetics argument (e.g., SGR flares)

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This Talk:

Lightcurve of surface emission provides constraint on hidden crustal B-field

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- X-ray pulsar (P=0.1 s) in SNR (age 7 kyr)
- $P, \dot{P} \Longrightarrow B_{\rm dipole} = 3 \times 10^{10}\,{\rm G}$
- $L_{\rm spindown} \ll L_{\rm X\ ray}$
- Pulse fraction ~60%

QuickTime™ and a
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Puzzles: How to produce hot spots?
Can 60% pulse fraction be produced?

A natural solution: Large B field in crust .….

Modeling of light curve of magnetic NS

-- Divide NS surface into many patches, each has its own $(T_{\rm eff}, \mathbf{B})$

-- Add up emission from all patches (including light bending)

-- Require atmosphere model for each patch $(T_{\rm eff}, \mathbf{B})$

This is not practical…

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Temperture-Template Full Transport (TTFT) method:

(Shabaltas & DL 2011)

-- At a given patch, take $T = T_0 F(\tau)$

-- Using exact magnetic radiative transfer eqn to obtain $T_0 \leftrightarrow T_{\rm eff}$

-- Can then use the resulting $T(\tau)$ $(\text{for } T_{\rm eff})$ and exact transfer eqn to compute radiation intensity.

T templates provided by Wynn Ho

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A physical model for hot spots and lightcurve of NS in Kes 79

-- Poloidal field (consistent with measured dipole)

-- Toroidal field inside the crust

$$B_\phi(r,\theta) \sim B_0 f(\theta)$$

$$f(\theta) = \frac{\sin^2\theta}{\sin^2\theta + \sin^2\theta_0}$$

-- Anisotropic heat conduction
in crust (Potekhin et al. 2003)
==> $T_{\rm eff}(\theta)$
(Two opposite hot spots)

QuickTime and a decompressor are needed to see this picture.

-- Use TTFT method to compute
atmosphere emission;
Add up patches to get lightcurve

10°

40°

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4×10^{14} G

40°

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4×10^{13} G

Crustal toroidal field

> a few x 10 G is needed to produce high pulse fraction (>60%)

(Full magnetic transport is important even for B_{dipole} is a few 10^{10}G)

Shabaltas & DL 11

Summary (I)

- Advocate a practical method (TTFT) for computing emission from whole surface of magnetic NS

  -- adequate for lightcurve modeling

- From modeling X-ray lightcurve using TTFT ==>

  NS in Kes 79 has crustal toroidal field > a few 10 G, much stronger than observed dipole field.

  -- Robust result: conservative assumption about field topology…

  -- Such field can last a few 10^4yrs, but not much longer…

Evolution of Magnetic Field in NS Crust

Two modes of field dissipation:

Smooth vs Episodic => Pulsars vs Magnetars?

Basic Idea:

In NS crust, Hall drift makes B field develop sharp features/gradients ("current sheets")…

Two things can then happen:

(1) Ohmic decay ("smooth" evolution)

(2) As B field becomes cuspy, it exerts stress on the crust, leading to crust breaking ("episodic" evolution)

Which one occurs first? Depends on B field strength…

Hall Drift of B Field in NS Crust:

Jones 88, Urpin & Shalybkov 91, Goldreich & Reisenegger 92, …

Electron drift velocity: $\mathbf{v}_e = -\frac{\mathbf{J}}{ne} = -\frac{c}{4\pi ne}\nabla \times \mathbf{B}$

B-field evolution:

$$\begin{aligned}\frac{\partial \mathbf{B}}{\partial t} &= \nabla \times (\mathbf{v}_e \times \mathbf{B}) \\ &= -\nabla \times \left[\frac{c}{4\pi ne}(\nabla \times \mathbf{B}) \times \mathbf{B}\right]\end{aligned}$$

Including Ohmic dissipation:

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left[\frac{c}{4\pi ne}(\nabla \times \mathbf{B}) \times \mathbf{B}\right] + \eta \nabla^2 \mathbf{B}$$

Hall drift of B-field leads to sharp features (current sheets)

Toy Model (Vainshtein et al.~2000)

"Plane-Parallel" NS: $n = n(z), \quad \mathbf{B} = B(x)\,\hat{y}$

$$==> \frac{\partial B}{\partial t} = \underbrace{\left[-\frac{d}{dz}\left(\frac{c}{4\pi n e}\right) B \right]}_{V_H \sim \frac{c}{4\pi n e H_z} B} \frac{\partial B}{\partial x}$$

"Burger's eqn"

$(H_z = \text{density scale height})$

Hall timescale: $t_H \sim l / V_H$

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Ohmic timescale: $t_{\rm Ohm} \sim l^2 / \eta$

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The same happens (exactly) for spherical NS with pure toroidal fields

(Reisenegger et al. 2007)

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Crust Breaking due to magnetic stress

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$$\mathbf{F}_B \sim \frac{\mathbf{B}\cdot\nabla\mathbf{B}}{4\pi} \sim \frac{B^2}{4\pi l}$$ (non-compressional part)

$$\mathbf{F}_{\rm shear} = \nabla\cdot\sigma, \qquad \sigma_{ij} = \mu(\xi_{i;j} + \xi_{j;i})$$

==> QuickTime and a decompressor are needed to see this picture. (equilibrium strain)

QuickTime and a decompressor are needed to see this picture. $\sim 10^{-3} - 0.1$ (cf. C. Horowitz)

==> $$l_{\rm break} \sim H_z \left(\frac{B}{B_\mu}\right)^2$$

$$B_\mu \sim (4\pi\mu\theta_{\rm max})^{1/2} \sim 2\times 10^{15}\left(\frac{\theta_{\rm max}}{0.1}\right)^{1/2}\,{\rm G}$$

Two modes of B-field dissipation

- Hall effect makes B field increasingly cuspy, until reaching the scale

$$l_H \sim \frac{H_z}{\omega_c \tau} \sim \left(\frac{10^{11}\ \mathrm{G}}{B} \right) H_z$$

at which it Ohmic dissipates smoothly

- When field scale reaches

$$l_{\mathrm{break}} \sim H_z \left(\frac{B}{B_\mu} \right)^2$$

the crust will break ==> field dissipates episodically

$$\text{Transition at} \quad B \sim 7 \times 10^{13} \left(\frac{\theta_{\mathrm{max}}}{0.1} \right)^{1/3} \mathrm{G}$$

(depending on crust density)

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Complications

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Hall #1: ==> Cascade $B_l \sim l^{2/3}$ (EMHD: Biskamp et al. 99)
(will not lead to crust breaking ==> no magnetar bursts?)

Hall #2: ==> Develop localized cuspy features
(can lead to crust breaking)

-- Simulations by Pons & Geppert (2010) suggest cuspy features can form (??)
-- May also depend on field topology ("shape") in crust, not just strength

Summary (II): Two modes of B-field dissipation

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- **Caveats:** Does EMHD turbulence kill it? May depend on B field shape