Understanding the Pulsar Multipolar Field Structure through NICER and Fermi data

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Outline

• Non-dipolar magnetic fields
  -NICER results (J0030+0451)

• MCMC, Field Degeneracies

• γ-rays
  -FERMI data, FF & dissipative simulations

• Summary, Future Steps

**NICER results**

**Riley et al. (2019)**

\[ M = 1.34M_\odot \]
\[ R = 12.71\, \text{km} \]
\[ \zeta = 53.85^\circ \]

- 2 hotspots
- same temperatures

**Miller et al. (2019)**

\[ M = 1.49M_\odot \]
\[ R = 13.64\, \text{km} \]
\[ \zeta = 47.38^\circ \]

- 2 hotspots
- same temperatures
- + 3 hotspots

**Thermal X-ray LC Bogdanov et al. (2019)**

- ~20 parameters

**Strong evidence for multipolar magnetic field**

**Hot spots are based on pre-selected shape patterns unrelated to magnetic field structures**
Non-Dipolar Fields
Offset Dipole + Offset Quadrupole

Static Vacuum Field (SVF)

11 parameters
Non-Dipolar Fields
Offset Dipole + Offset Quadrupole

Central dipole → offset dipole + offset quadrupole

SVF

11 parameters
We developed a **GR-code (GIKS)** that follows the photon trajectories in the full **Kerr-metric**  
Kalapotharakos et al. 2021, see Psaltis & Johannsen 2012

We use Kerr metric, but Schwarzschild metric would be adequate for PSR J0030 spin rate  

\[ N = 2.5 \times 10^6 \]

**Mathematica, Parallel, Pleiades NASA supercluster**

Assumptions  
\( M_*, r_*, \zeta \) from Miller et al. 2019 and Riley et al. 2019
The reconstruction of X-ray LCs (i.e., the intensity at each phase) requires the incorporation of the Doppler boosting and an atmosphere model.

Miller et al. 2019 and Riley et al. 2019 used the same atmosphere model (i.e., pure $H^+$) even though they used slightly different energy channels.

Atmosphere Model

$I = \mathcal{F}(\vartheta_z, E)$

$I \propto \cos^n(\vartheta_z)$

Assuming the Riley et al. HSs, we were able to reproduce the X-ray LC for $n \approx 1$

Assuming the Miller et al. HSs, we were able to reproduce the X-ray LC for $n \approx 0.65$
Atmosphere model

\[ I = \mathcal{F}(\theta_z, E) \]
\[ I \propto \cos^n(\theta_z) \]

For the Riley et al. HSs, we were able to reproduce the X-ray LC for \( n \approx 1 \).

For the Miller et al. HSs, we were able to reproduce the X-ray LC for \( n \approx 0.65 \).

\[ \zeta = 53.85^\circ \]
We developed a parallel MCMC code implementing the *stretch move* (Goodman & Weare 2010, Foreman-Mackey et al. 2013) ensemble method.
Magnetic Field Solutions

Highest likelihood

\[ \chi_r^2 = 0.66 \]
Demonstration
Degeneracies?

Highest likelihood

Different field configuration

Highest likelihood

$$\chi_r^2 = 0.78$$
Degeneracies?

SVF, Riley et al., 2019 fixed parameters

11 parameters

8 parameters

6 parameters

$B_{surf}$

$\cos \theta_z$
Degeneracies?

SVF, Miller et al., 2019 fixed parameters

8 parameters

6 parameters

11 parameters
Degeneracies?

<table>
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<tr>
<th>Quantity</th>
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<th>$RV_{31}$</th>
<th>$RV_{41}$</th>
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</table>

SVF model highest likelihood parameters
Realistic FF field structures

The consensus is that the $\gamma$-rays are mainly produced outside the LC in the equatorial current sheet (ECS).

**FF, Dissipative, PIC**
Contopoulos & Kalapotharakos 2010
Bai & Spitkovsky 2010
Cerutti et al. 2016
Philippov & Spitkovsky 2018

Success in reproducing Fermi gamma-ray LCs and spectra
Realistic FF/Dissipative Simulations lifting the field degeneracies

Fermi data
Model

FF, Riley et al., 2019 fixed parameters
3D FF field structure
γ-ray emission and X-ray thermal emission
Polar cap Asymmetries
Return vs. Direct Current

Pair production
Rocket effect
Summary

• The NICER thermal X-ray LC motivated us to study multipolar (D+Q) field structures in MSPs, which led to the discovery of degenerate solutions.
• Comparing the model γ-ray LCs to the Fermi one lifts the degeneracies.

Future

• A complete study, (i.e., MCMC exploration), which will incorporate all the related problem parameters ($M_*, r_*, \zeta, T$), atmosphere model, energy channels, & γ-ray LCs.

Impact

Self-consistent $M_*, r_*$, and magnetic field determination (EoS)
Internal magnetic fields
Pair production in MSPs
Validation of the pulsar γ-ray emission model
Rocket effect
Extend the study to all the NICER MSPs