High-energy pulsar models: Developments and new questions

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HE Pulsars - a Diverse Population

Fermi LAT 2nd Pulsar Catalog (2PC)

- 117 high-confidence > 0.1 GeV pulsars
- 3 years of Fermi LAT data
- 50% of these discovered by Fermi!
- 3 even groups: MSPs, young RLPs, young RQPs

See D Smith’s talk

Preliminary

Preliminary
HE Pulsars - a Diverse Population

**Fermi LAT 2nd Pulsar Catalog (2PC)**
- Multiband profiles
- Energy spectra
- Off-peak emission
- Unseen pulsars
- Luminosities

See D Smith’s talk
Light Curve Classes

1. $\gamma$-ray peak(s) lag main radio peak
   - Young pulsars & MSPs
   - “Class I”

2. $\gamma$-ray peaks aligned with radio peaks
   - *Nearly* exclusive to MSPs
   - “Class II”

3. $\gamma$-ray peak(s) lead main radio peak(s)
   - Exclusive to MSPs
   - “Class III”

*2nd Fermi LAT Pulsar Catalog (Abdo et al., submitted)*
*Venter et al. (2012)*
Magnetospheric Structure
Different Regimes

Vacuum retarded dipole (VRD) (Deutsch 1955)
No charges, no currents

Force-free magnetosphere (Spitkovsky 2006)
No particle acceleration

Non-ideal MHD magnetosphere (Kalapotharakos et al. 2011, Li et al. 2011)
Charges, currents + acceleration!

\[ \vec{E} \cdot \vec{B} \neq 0 \]
\[ E_{||} = 0 \]

\( \gamma \)-ray light curves and phase-resolved spectroscopy will help to constrain \( B \)
Geometric Light Curve Modelling
Traditional Accelerator Geometries

Gaps represent deviations from force-free conditions

Daugherty & Harding (1996)
Cheng et al. (1986)
Romani (1996)
Arons & Scharlemann (1979);

$$\nabla \cdot E_\parallel = -4\pi (\rho - \rho_{GJ})$$

$$\rho_{GJ} \approx \frac{\vec{\Omega} \cdot \vec{B}}{2\pi c}$$

SG: $r_{cyl} < 0.95 R_{LC}$
TPC: $r_{cyl} < 0.75 R_{LC}$
PSPC Geometry

Pair-starved case (unscreened PC model)

Muslimov & Harding (2004)
Venter et al. (2009)
Altitude-Limited Geometries

Developed to explain phase-aligned LCs

Venter et al. (2012)
Radio Beam Geometry

Single-altitude conal radio beam

Harding et al. (2007); Gonthier (2004)
Frequency-dependent cone width of Mitra & Deshpande (1999)

Total flux:
\[ S(\theta, \nu) = F_{\text{cone}} e^{- (\theta - \bar{\theta})^2 / \omega_e^2} \]

Cone radius:
\[ \rho_{\text{cone}} = 1.24^{\circ} r_{\text{KG}}^{0.5} P^{-0.5} \]

Cone position:
\[ \bar{\theta} = (1.0 - 2.63 \delta_w) \rho_{\text{cone}} \]

Cone width:
\[ \omega_e = \delta_w \rho_{\text{cone}} \]

Emission altitude:
\[ r_{\text{KG}} \approx 40 \left( \frac{\dot{P}}{10^{-15} \text{ S s}^{-1}} \right)^{0.07} P^{0.3} \nu_{\text{GHz}}^{-0.26} \]
TPC Phaseplot as Function of $\alpha$
Light Curve Calculation
Light Curves as Function of $\zeta$
Atlas of Light Curves ($\alpha, \zeta$)

Venter et al. (2009)

Radio
$\gamma$-ray
Example Best-fit MSP Profiles

Outer gap and Two-pole caustic models

“Class I”

Johnson et al. (2013)
MSPs: Geometric LC Fitting

• γ-ray and radio LC fits for 40 MSPs in 2PC (Johnson et al. 2013)
  ✓ 27 class I – best fit by TPC (15) or OG (12); need mix of these two models
  ✓ 6 class II – best fit by aITPC (1), aLOG (4), or laSG (1)
  ✓ 7 class III – best fit by PSPC model

• Classes
  ✓ No clear separation of classes
  ✓ Class II – low $P$; Class III – low $B_{LC}$

• Trends
  ✓ Broad distribution of $\alpha$, larger $\zeta$
  ✓ Larger $\alpha$ for OG: visibility
  ✓ TPC: smaller $\alpha$ for larger $E_{dot}$
    (larger $|\beta|$)
  ✓ Class II emission altitudes: Radio more limited, higher up, contained within γ-ray region (within errors)
  ✓ Clustering around $\eta = 10\%$
    $L_g \sim E_{dot}; f_\Omega < 1$ for TPC / OG
Young Pulsars: Geometric LC Fits

- 78 young pulsars from 2PC (36 RQ + 40 RL)
- γ-ray: PC, SG, OG, 1PC; Radio: cone + core
- Joint fits

PC: low $\alpha$ and $\zeta$
- Outer-magnetosphere: high $\alpha$ and $\zeta$

Pierbattista et al. (2013)
Young Pulsars: Geometric LC Fits

- $\gamma$-ray only vs. $\gamma$-ray + radio LC fits: Underestimation of $\alpha$ and $\zeta$

- $f_\Omega$ values:
  PC low; SG ~ 1; OG ~ 0.5 – 0.8; OPC ~ 0.8 – 0.9

- $L_\gamma \sim E_{\text{dot}}^{0.5}$

- PC : SG : OG = 16% : 39% : 45% - need some “hybrid” geometry

Pierbattista et al. (2013)
Annular Gap Geometry

Gaussians for emissivity in longitudinal (peaking close to NCS) and transverse directions

Intermediate-altitude, single-pole model

Qiao et al. (2004, 2007)
Du et al. (2010)

(Striped wind: see talk by Pétri)
Annular Gap Model LC Fits

Core + annular gap (altitude-dependent)

Vela (Du et al. 2011)

MSPs (Du et al. 2013)

~R_{LC}

A. Core

J0101-6422

J0437-4715
Global magnetospheres: Force-free solutions
Force-Free Magnetic Field Solutions

- Contain open and closed field regions (blue lines)
- Contain different signs of charge
- Global current flows out of polar regions and returns along equatorial current sheet (yellow arrows)

Contopoulos et al. (1999)
Spitkovsky (2006)
Timokhin (2006)

Color: charge density, Streamlines: magnetic field

\[ \overrightarrow{E} \cdot \overrightarrow{B} = 0 \]
LCs in TPC / Force-Free Magnetic Field

- PC larger than in vacuum retarded dipole
- Suppresses caustic formation in inner magnetosphere
- Not many double-peak profiles

Bai & Spitkovsky (2010)
LCs in OG / Force-Free Magnetic Field

- A large fraction of open field lines does not cross the null charge surface
- Only single-peaked profiles produced under general conditions

Bai & Spitkovsky (2010)
LCs in SL / Force-Free Magnetic Field

- Separatrix layer model: $\gamma$-ray emission originates on thin layer on open field lines just inside separatrix (current sheet) that bounds open flux tube

- Two strong caustics due to “sky map stagnation” (since force-free solution asymptotically approaches split monopole)

Bai & Spitkovsky (2010)
Global magnetospheres: Dissipative solutions
Magnetospheres with Finite Conductivity

As conductivity increases:

• Charge and current density increase

• Current sheet becomes stronger

• Field lines become straighter

• Spin-down power increases

Kalapotharakos, Kazanas, Harding & Contopoulos (2012)
LCs from Resistive Magnetospheres

$\alpha = 90^0$

Kalapothearakos et al. (2012)

- The resistive solutions of lowest $\sigma$ are closest to the VRD
- Distinct progression in LC shapes as $\sigma$ increases
- Increasing $\sigma$: the peaks are shifted to larger phase; broadening
- Highest $\sigma$ – value closest to FF case
LCs from Dissipative Magnetospheres

$\alpha$: inclination angle  $\zeta$: observer angle

$\sigma$ variable

$E_\parallel = 0$ below  
$r = 0.9 \, R_{LC}$

Most emission from current sheet near light cylinder

Kalapotharakos et al. (2013)
$\Delta-\delta$ Trend Revisited

Kalapotharakos et al. (2013)

Fermi 1st Pulsar Catalog (Abdo et al. 2010)

Preliminary
$\Delta - \delta$ Trend Revisited

$r < 0.9 \ R_{LC}$: force-free
$r > 0.9 \ R_{LC}$: finite, high $\sigma$

Kalapotharakos et al. (2013)

Fermi 1st Pulsar Catalog
(Abdo et al. 2010)
Phase-resolved Spectroscopy
Phase-resolved Spectroscopy

- Vela & Crab: peaks softer than bridge
- P2 has higher $E_{\text{cut}}$ than P1
- "Dipping" behaviour of $E_{\text{cut}}$ in Geminga’s peaks, P1 of Crab; rising of $E_{\text{cut}}$ in Vela’s peaks
- Reflecting local changes in $B$, $\rho_c$ or $E_\parallel$?

DeCesar et al. (2013)
Phase-resolved Spectroscopy

Does $E_{\text{cut}}$ variation map magnetic field curvature vs. phase?

- Find $E_{\text{cut}}(\phi)$ from phase-resolved spectroscopy
- Find $\rho_c(\phi)$ from LC fitting (force-free and VRD $B$-fields)
- Assume balance of acceleration and radiation losses
- Assume $E_{\text{cut}} = E_{\text{CR}}$

\[ E_{||} = e \left( \frac{E_{\text{cut}}}{0.32 \lambda_c} \right)^{4/3} \rho_c^{-2/3} \]

DeCesar et al. (2013)
Crab: Constraining $E_{||}$

Maximum / minimum $\rho_c$
Maximum / minimum emission radii

Maximum / minimum $E_{||}$

DeCesar et al. (2013)
Crab: Constraining $B$

$E_{\parallel}/B_{\text{max}} > 1$ not physical

$E_{\parallel} > B$ for VRD but larger radii of curvature (straighter field lines) and larger $B$ near LC give $E_{\parallel} < B$ for FF

Preliminary
Population Synthesis
Initial Population Setup

- Comparing collective properties using population synthesis
- EOS; birth $B$ and $P$ distributions
- Magnetic field decay
- Birth position, kick velocity
- Evolve to obtain $P$, $Pdot$, position, velocity

See also Watters & Romani (2011), Takata et al. (2011)
Geometry, Luminosity, Detection

- Radio core + conal beam; Geometrical gaps: PC, SG, OG, OPC
- Particle luminosity prescription \((L_\gamma \sim w \text{ or } w^3)\); gap widths
- Detection sensitivities
- Efficiency \((L_\gamma = \varepsilon L_p)\): OG \(\sim 1\); SG \(\sim 10\) (V or I); PC \(\sim 1\), OPC \(\sim 0.5\)

Pierbattista et al. (2012)
Spin-down Luminosity Distribution

- All models underpredict number of pulsars with $Edot > 3e35$ erg/s and $t < 100$ kyr
- Predicted population too old and faint
- Evolution modelling needs to be revised
Beaming Correction Factor

- Small decrease in $f_\Omega$ with age / $E_{dot}$: smaller PC
- RQ more dispersed; lower $f_\Omega$: larger $\beta$ (?)
- SG: slight gap evolution with age; radiation large beam
- OG / OPC: $\gamma$-beam goes toward spin equator

\[
\bar{f}_\Omega = \frac{\int_0^\pi \sin \zeta \mathrm{d}\zeta \int_0^{2\pi} n(\phi, \zeta) \mathrm{d}\phi}{2 \int_0^{2\pi} n(\zeta_{obs}, \phi) \mathrm{d}\phi}
\]
$L_\gamma$ vs. Spin-down Luminosity

- Large dispersion in $L_\gamma$ vs. spin-down: cannot discriminate between models
- PC model not luminous enough
- Break in $E_{\text{dot}}^{0.5}$ trend for PC / SG (ineffective screening at low $E_{\text{dot}}$)
- OG: $w$ saturation at low $E_{\text{dot}}$
- Scatter: $f_\Omega$, $w(P, P_{\text{dot}}, \alpha)$

Pierbattista et al. (2012)
Radio-loud vs. Radio-quiet Pulsars

- Cumulative distribution of radio-loud vs. total number of pulsars with $E_{dot}$
- PC: $\sim$constant due to small beams

- All models underpredict this fraction at high $E_{dot}$
- Broader radio beams at higher altitudes for young pulsars?

Pierbattista et al. (2012)
Ravi et al. (2010)
VHE Pulsar Science
Crab Pulsar > 100 GeV

Hirotani outer gap (Aleksic et al. 2011)

- VHE Emission is SSC from pairs
- Uncertain: B-geometry, pairs, SR emissivity
- Possibility of structure in HE spectrum
Crab Pulsar > 100 GeV

Crab phase-averaged spectrum

Annular gap
(Du et al. 2012)

- Primaries: CR, SR
- Secondaries: SR (x2), SSC
- Approximations include PL for 2 pair spectral components, soft-photon SR field; No GR effects
Crab Pulsar > 100 GeV

Slot gap model (Harding 2013)

Pair spectra calculation: PC pair cascades

Preliminary
Crab Pulsar > 100 GeV

Slot gap model (Harding 2013)
(Some) Open Questions

- Rich variety in newly-detected $\gamma$-ray pulsar population

- No overall best-fit geometrical model – may point to hybrid / new geometry

- Preliminary trends seen between geometric / spectral and pulsar parameters

- Force-free vs. conductive magnetospheres – Preferred magnetospheric structure? Current sheet? Magnetic reconnection?

- Behaviour of spectral parameters with phase

- Population synthesis: lack of high-$E_{\text{dot}}$ pulsars? Prescription of $L_{\gamma}$? Beaming? Evolutionary history of pulsars?

- Origin of pulsed TeV photons
THANK YOU!

“You have done wonderful things; Your counsels of old are faithfulness and truth” (Is. 25:1b)