Soft γ-ray pulsar population

- Pulsars seen only in hard X-ray but not with Fermi
- 11 “MeV pulsars” are known, $\dot{E} > 10^{36}$ erg/s
- Emission may probe a different part of the magnetosphere than GeV
- Look for high energy spectral cutoff

Kuiper & Hermsen 2015
High energy emission models

Inclination angle
Observer angle
Rotation axis
Open magnetic field lines
Radio/Polar cap beam
Current sheet/Striped wind
Slot gap
Gamma rays
Outer gap
Magnetic axis

\[ \Omega \cdot \mathbf{B} = 0 \]
MHD pulsar magnetosphere

- Contain open and closed field regions
- Contain different signs of charge
- Current sheet forms along spin equator
- Current flows out of polar regions and returns along equatorial current sheet

Kalapotharakos et al. 2012  
Color: charge density, Streamlines: magnetic field
X-ray/soft $\gamma$-ray radiation from pairs

Polar cap pair cascade

Outer gap pair cascade

Thermal X-ray

Harding et al. 2008

Tang et al. 2008
MeV $\gamma$-rays are a signature of the pair spectrum.
Spectral model for Crab pulsar

\[ \alpha = 45^0, \zeta = 60^0, M_\oplus = 3 \times 10^5 \]

Radiation from outer magnetosphere and current sheet

Harding & Kalapotharakos 2015
Model for Crab-like pulsar B0540-69

Harding & Kalapotharakos 2015

$\alpha = 45^0, \zeta = 70^0, M_+ = 3 \times 10^5$

Twin J0537-6910 is an MeV pulsar – not a $\gamma$-ray pulsar

Is lack of CR component for MeV pulsars due to different viewing angle?
HE spectra of millisecond pulsars

Kuiper & Hermsen 2003
Spectral models for MSPs

Harding & Kalapotharakos 2015

$\alpha = 45^0$, $\zeta = 80^0$

High

$B_{LC} = 7.3 \times 10^5$ G

$L_R = 1210$ mJy kpc$^2$

Small

$R_{LC} = 1.4 \times 10^7$ cm

$\alpha = 75^0$, $\zeta = 70^0$

High

$B_{LC} = 1 \times 10^6$ G

$L_R = 6000$ mJy kpc$^2$

Small

$R_{LC} = 7.6 \times 10^6$ cm

SR spectra peak ~1-10 MeV

SSC peak ~ 100 GeV but lowered by KN reductions
Polar cap pair cascade spectra

Pair cascade photon spectra have HE turnovers below 100 MeV

Look for turnovers at 10 – 100 MeV

Timokhin & Harding 2015

Emission appears from 100 keV – 100 MeV
Polar cap emission – hints from Fermi?
PSR J1813-1246 – polar cap emission?

Marelli et al. 2014  Fermi and XMM

γ-rays from current sheet

X-rays from PC cascade
Spectrum shown cutoff ~ 10-100 MeV
Polarization of pulsar emission

Synchrotron (SR) and curvature radiation (CR)

• Polarization degree

\[ p(\varepsilon) = \frac{P_2(\varepsilon) - P_1(\varepsilon)}{P_2(\varepsilon) + P_1(\varepsilon)} = \frac{K_{2/3}(\varepsilon/\varepsilon_c)}{\int_{\varepsilon/\varepsilon_c} K_{5/3}(x)dx}, \]

\[ \varepsilon << \varepsilon_c \Rightarrow 0.5 \]
\[ \varepsilon = \varepsilon_c \Rightarrow 0.75 \]
\[ \varepsilon >> \varepsilon_c \Rightarrow 1.0 \]

• Position angle

CR: E vector || to electron acceleration vector

SR: E vector is perpendicular to B and electron acceleration
Phase-averaged polarization

Transition between synchrotron and curvature radiation occurs at 1 – 100 MeV in Crab-like pulsars
Look for drop in polarization degree at transition
Emission sky maps

Pulsar inclination

Slot gap

Outer gap

Current sheet (Petri 2011)
Crab pulsar: models vs. data

Observed optical

Crab Pulsar

Slot gap model
$\alpha=70^\circ, \zeta=50^\circ$

Polar cap model
$\alpha=7^\circ, \zeta=12^\circ$

Outer gap model
$\alpha=50^\circ, \zeta=100^\circ$

Striped wind model
$\alpha=60^\circ, \zeta=60^\circ$

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• Light curve undergoes shape between 100 keV and 50 MeV

• Bridge emission is highest around 500 keV

• Polarization measurements may show emission mechanism transition
Energy-dependent polarization

Slot gap

0.1 – 10 MeV

Position angle

Pol. fraction

Phase

Takata et al. 2007

Outer gap

20 - 100 keV

Harding & Kalapotharakos 2016
Magnetar quiescent emission

Low-energy thermal plus hard high-energy components up to 200 keV
Seen by INTEGRAL (den Hartog et al. 2008)

AXP 1RXS J170849-400910

AXP 4U 0142+61
Magnetar quiescent emission theory

Cyclotron resonant upscattering and pair/splitting cascade
Baring & Harding (2004), Beloborodov (2013)
Magnetars – signature of photon splitting?

- Photon splitting threshold at lower energy than pair production threshold

Look for 100% polarization near the cutoff
Summary

• Rotation-powered pulsars
  – Young ‘MeV’ pulsars
  – Millisecond pulsars
  – Polar cap emission
  – Polarization – SR-CR transition, pol. vs. phase

• Magnetars
  – Cutoff in quiescent hard component
  – Photon splitting signature: 100% polarization at cutoff