Exploring Hidden Emission from Neutron Stars

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The neutron star zoo
Hard X-ray pulsar population

- Pulsars seen only in hard X-ray – not at GeV
- 11 “MeV pulsars” are known, $E_{\text{dot}} > 10^{36}$ erg/s
- Emission may probe a different part of the magnetosphere than GeV

![Graph showing the hard X-ray pulsar population with data from Kuiper & Hermsen 2015](image)
Light curves of MeV pulsars

- All MeV pulsars with no Fermi pulsations have broad single peaks – with the exception of J2022+3842

- J1513-5908 and J0540-6919 have Fermi pulsations but very soft SED

Kuiper & Hermsen 2015
Spectra of MeV pulsars

- Broad SED peaking at 1-10 MeV
- No GeV component??

Kuiper et al. 2017
Radiation modeling of MeV pulsars

- Particle trajectories in force-free magnetosphere
- Synchrotron radiation from pairs
- Curvature radiation from primaries
- Emission from 0.7 – 2.0 $R_{lc}$

Harding & Kalapotharakos 2017

Brambilla et al. 2018
Model spectra for MeV pulsars

Harding & Kalapotharakos 2017

Pairs from polar cap,

\[ E_{SR} \propto B_0 B_{LC} \]

Pairs from outer gap,

\[ E_{SR} \propto B_{LC}^{7/2} \]

Measurement of \( E_{SR} \) can locate source of pairs

Peak of synchrotron SED

\[ E_{SR} \approx \gamma_e^2 B_{LC} \]

Synchrotron only!

B1509-58

\( B_0 = 3 \times 10^{13} \text{ G} \)
\( B_{LC} = 8 \times 10^4 \text{ G} \)

J1846-0258

\( B_0 = 9 \times 10^{13} \text{ G} \)
\( B_{LC} = 3 \times 10^4 \text{ G} \)

J1838-0655

\( B_0 = 3.8 \times 10^{12} \text{ G} \)
\( B_{LC} = 1 \times 10^5 \text{ G} \)
MeV pulsars – the tip of the iceberg?

<table>
<thead>
<tr>
<th>name</th>
<th>period (ms)</th>
<th>age (kyr)</th>
<th>$10^3 \log(L_{sd})$</th>
<th>$Fermi\ LAT/Pulsed$</th>
<th>No radio</th>
<th>$B_0 &gt; 10^{13} G$</th>
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<tr>
<td>PSR J0205+6449 (3C58)</td>
<td>65.7</td>
<td>5.4</td>
<td>37.43</td>
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<td>PSR J0534+2200/B0531+21 (Crab)</td>
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</table>

Kuiper & Hermsen 2015
HE spectra of millisecond pulsars

Energetic MSPs have hard, nonthermal X-ray spectra like MeV pulsars

Kuiper & Hermsen 2003
Spectra of millisecond pulsars

Spectra continue to rise toward MeV band!
Gotthelf & Bogdanov 2017

Higher pair energies
Predicted SR spectra peak
~1-10 MeV
Harding & Kalapotharakos 2015
Polarization of pulsar emission

Synchrotron (SR) and curvature radiation (CR)

• Intrinsic polarization fraction

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

\[
\varepsilon \ll \varepsilon_c \Rightarrow 0.5 \quad \varepsilon = \varepsilon_c \Rightarrow 0.75 \quad \varepsilon \gg \varepsilon_c \Rightarrow 1.0
\]

• Position angle

E vector || to electron acceleration vector
Transition between synchrotron and curvature radiation occurs at 10 – 100 MeV in Crab-like pulsars.

- GeV CR: rise in polarization degree and change of PA at transition.
- Determine mechanism of GeV emission!

GeV component is:

- CR? (Kalapotharakos et al. 2014)
- SR? (Cerutti et al. 2016)
- IC? (Lyutinkov 2012)
SR-limited particle acceleration gives universal maximum SR photon energy - applies to Crab PWN

\[ \tau_{SR} = \tau_{acc} \implies E_{\text{max}} = 17 \text{ TeV} B_s^{-1/2} \]

\[ \implies \varepsilon_{SR} \propto E_{\text{max}}^2 B_s = 160 \text{ MeV} \]

For most other PWNe, voltage across open field lines gives the particle energy upper limit, giving SR spectral cutoff in MeV range:

\[ V_{open} = 6 \times 10^{12} eV B_{12} P^{-2} < E_{\text{max}} \]

\[ \implies \varepsilon_{SR} \propto V_{open}^2 B_s = 0.14 \text{ MeV} \left( \frac{L_{SD}}{10^{36} \text{ erg/s}} \right)^{6/5} \left( \frac{\sigma}{1 + \sigma} \right)^{1/2} \tau_{kyr}^{-3/10} \]

Constrain \( B_s \) and wind magnetization \( \sigma \)
Millisecond pulsar Binaries

- Black Widows MSPs with very low-mass binary companions
  - 10 – 80 Jupiter masses ($M_{\odot} \sim 0.01$)
- Pulsar wind ablates companion by exciting stellar winds

Before Fermi launch: 3 Black Widows, 1 Redback
Now: 19 Black Widows, 9 Redbacks – Total of 28!

Redbacks (cousins)
$\sim 0.1 M_{\odot}$ companions
Double-peaked soft X-ray light curves

- Flux minimum around superior (BW)s or inferior (RB)s conjunction
- Spectral indices $\Gamma \sim 1 - 1.5$
- Synchrotron, modulated by Doppler boosting?

B1957+20 Huang et al. 2012

J2129-0429, Roberts et al. 2015

J1723-2837, Hui et al. 2014

J1023+0038, Archibald et al. 2010

J2039-5618, Salvetti et al. 2015
Shock-acceleration maximum energy

PSR J1723-2837 with NuSTAR (Kong et al. 2017)
Emission observed up to 50 keV

J1023+0038 with NuSTAR (Tendulkar et al. 2017)
Emission up to 79 keV

• Magnetic field at shock

\[ B_S \approx \left( \frac{3 \dot{E}_{SD}}{2c} \right)^{1/2} = 22 \left( \frac{\dot{E}_{SD}}{10^{35} \text{ergs}^{-1}} \right)^{1/2} \left( \frac{10^{11} \text{cm}}{r_s} \right)^2 G \]

• If \( E_{\text{max}} \sim 1 \text{ TeV} \), critical energy (Peak of SED) \( \sim 1 - 10 \text{ MeV} \)

Wadiasingh et al. 2017
Transitional MSPs

- 3 tMSPs are known – all redbacks
- In LMXB state,
  - does disk penetrate pulsar magnetosphere to quench pulsar emission? Propeller SSC
  - or not - IC off disk photons
  - Is there a jet?
- In pulsar state,
  - HE spectra cutoff constrains shock acceleration

deMartino et al. 2015
- Six known gamma-ray binaries
- Main emission component either inverse Compton or synchrotron
- Better MeV telescope could decide
- If SR, HE cutoff constrains particle acceleration at shock
- If IC, can probe geometry of binary
Magnetar quiescent emission

Low-energy thermal plus hard high-energy components up to 200 keV

Data from:
INTEGRAL, NuSTAR and Suzaku

Enoto et al. 2017,
Kuiper et al. 2006,
Den Hartog, et al. 2008,
Tendulkar et al. 2015,
Younes et al. 2017
Magnetar quiescent emission theory

Cyclotron resonant upscattering and pair/splitting cascade
Measuring phase-resolved spectra can constrain magnetic field configuration
Baring & Harding (2004), Beloborodov (2013)
Polarization of resonant Compton upscattering

\[ \gamma_e = 10^2, \ B_p = 10 \]

Spectrum is strongly polarized near upper limit (Wadiasingh et al. 2017)

\[ T = 5 \times 10^6 \]
\[ r_{\text{max}} = 4 \]

Expect perpendicular mode to dominate. If maximum particle energy causes cutoff.
Magnetars – signature of photon splitting?

Photon splitting cutoff at lower energy than pair production cutoff

Pair production: $\gamma \rightarrow e^+ e^-$

Photon splitting: $\gamma \rightarrow \gamma \gamma$

Look for 100% parallel polarization near the cutoff
Pulsar/magnetar connection

- Magnetar-like outbursts from rotation-powered pulsars
- Measure evolution of high-energy component – relaxation of toroidal magnetic field?

**J1846-0258 2006 burst**
Kuiper & Hermsen 2009

**J1119-6127 2016 burst**
Archibald et al. 2016
Summary

• Rotation-powered pulsars
  – Young ‘MeV’ and millisecond pulsars
  – Polarization – mechanism of GeV emission

• Magnetars
  – Phase-resolved cutoff in quiescent hard component
  – High polarization at cutoff: photon splitting $||$; max $\gamma$, $\perp$

• Magnetar-like pulsars
  – Evolution of hard spectral cutoff after outburst

• Pulsar wind nebulae, MSP binaries
  – Spectral high-energy cutoff $\rightarrow$ maximum shock acceleration energy
    understanding pulsar wind
# AMEGO at the 231st AAS


<table>
<thead>
<tr>
<th>Day</th>
<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>Monday</td>
<td>11:00 am</td>
<td>Gamma-SIG at 11:00 am (MD Ballroom 3)</td>
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<tr>
<td>Tuesday</td>
<td>5:30 pm</td>
<td>Poster Session at 5:30 pm</td>
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<td><em>MeV Emission from Local Seyfert Active Galaxies</em> (E. Mullin)</td>
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<td>Wednesday</td>
<td>10:00 am</td>
<td>Talk at 10:00 am (Maryland B)</td>
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<td><em>Polarization Observations of Fermi Blazars</em> (B. Rani)</td>
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<td>Wednesday</td>
<td>1:00 pm</td>
<td>Splinter at 1:00 pm (National Harbor 8)</td>
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<td>Astrophysical Extremes and Life Cycles of the Elements (A. Harding, D. Hartmann, J. Racusin, A. Fabian, R. Woolf, &amp; T. Linden)</td>
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<td>Poster Session at 5:30 pm</td>
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<td><em>Fermi-LAT VIP AGN</em> (D. Thompson)</td>
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<td>GRBs and GW Counterparts with AMEGO (J. Racusin)</td>
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<td><em>Neutrino Astrophysics in the MeV Band</em> (R. Ojha)</td>
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<td>Wednesday</td>
<td>9:00 am</td>
<td>iPoster Session at 9:00 am</td>
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<td><em>Development and Testing of the Tracker</em> (S. Griffin)</td>
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<td>5:30 pm</td>
<td>Poster Session at 5:30 pm</td>
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<td><em>Exploring Dark Matter</em> (R. Caputo)</td>
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<td><em>CsI Calorimeter Development for AMEGO</em> (J. E. Grove)</td>
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<tr>
<td>Thursday</td>
<td>2:10 pm</td>
<td>Talk at 2:10 pm (Potomac C)</td>
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<td><em>Advancing the MeV Frontier with AMEGO</em> (D. Hartmann)</td>
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