X-ray emission from isolated pulsars

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First seen neutron stars...

OPTICAL

1942: Crab pulsar

The “south, preceding star” V≈16 at the center of the Crab Nebula (Baade 1942, Minkowsi 1942)
First seen neutron stars...

- X-RAYS
  - 1962: Sco X-1 (Giacconi+ 1962)
  - 1964: Tau X-1 (Bowyer+ 1964)
  - 1967 June: Crab PSR at > 20 keV (Fishman+ 1969)

... before the discovery of radio pulsars
Outline

1. NON - THERMAL EMISSION
2. THERMAL EMISSION
3. LINES
4. VARIABILITY

Mainly on results since PNS 2011

My apologies for incompleteness....
Non-thermal emission: basic facts

- Dominates in youngest/most energetic NS
  ...but present in (almost) all NS classes

- Pulsations – Power-law spectra

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Non-thermal emission: basic facts

- Dominates in youngest / most energetic NS...but present in (almost) all NS classes
- Pulsations – Power-law spectra
- Charges accelerated in magnetosphere at the expense of rotational energy
  \[ L_X \approx 10^{-3} \dot{E}_{\text{ROT}} \] (large scatter)
- Synchr. /Curvature radiation + Inv. Compton
Crab PSR: phase-resolved spectroscopy

Same behavior of X-ray and $\gamma$-ray photon index

Subtle correlations with polarization properties

Chandra

Weisskopf+ 2011
Crab SED: nebula and pulsar

Buhler & Blandford 2014

1-10 keV

100 GeV

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The Crab is the best studied PSR...

...but it is not representative of the whole population of X-ray and γ-ray pulsars!

See L. Kuiper talk

Kuiper & Hermsen 2013
Emission in outer magnetosphere favored:

- Lack of super-exponential cut-off expected for magnetic pair production in γ-ray spectra
- Large number of gamma PSR not seen in radio

See Pierbattista and Timokhin talks

2° Fermi PSR Catalog Abdo+ 2013
2. Thermal emission
Thermal emission

- Best observed, e.g., in middle-aged NS and XDINS

- About 40 “coolers” (Vigano’+ 2014):
  - 11 RPP
  - 7 XDINS
  - 4 CCOs
  - 17-18 AXPs/SGRs

(De Luca et al. 2005)
Thermal emission

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- About 40 “coolers” (Vigano’+ 2014):
  11 RPP   7 XDINS
  4 CCOs   17-18 AXPs/SGRs

- Uncertainties / caveats:
  - Ages
  - Distances
  - Atmosphere composition and magnetization
  - Non-uniform sample

- No evidence for fast cooling,
  ....but data do not exclude it

See Page / Reisenegger talks
Fast (?) cooling of NS in Cas A

- No pulsations
  (<12% PF for P > 10 ms)

- C atmosphere, R ≈ 12-15 km → NS
  (Ho & Heinke 2009)

- decrease 4% in T over 10 yrs
  (21% in observed flux)
  delayed thermal relaxation
  (Heinke & Ho 2010)

- triplet-state N superfluid in core
  steep T drop caused by ν emission
  from CPF
  (Shternin+ 2011, Page+ 2011)

- cooling significant only in ACIS-S
  graded mode (which suffers pile-up
  and CTI)
  (Elshamouty+ 2013)
Fast (?) cooling of NS in Cas A

- ACIS-S faint mode in 2006 and 2012 (Posselt+ 2013)

- With C model $\Delta T<1\%$ with significance $<3\sigma$

- No change with H model
Magneto-thermal evolution of INS

Explain variety of INS (timing and radiative properties) by coupled evolution of T and B

Variety of initial B, M and envelope composition

Evolutionary links between different classes

See Pons and Reisenegger talks


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3. X-ray spectral lines
X-ray lines in INS

- A formidable diagnostic tool... (in principle!)

See, e.g., accreting NS, where lines are well established and interpreted as cyclotron resonance features from electrons in $B \approx 10^{12}-10^{13} \, G$ (e.g. Mushtukov talk)

- Lines reported in different classes of isolated NS: (CCOs, XDINSs, AXPs/SGRs, RRAT, RPPs)

→ a variety of different situations and complex (sometimes unclear/controversial) results - no unique interpretation
X-ray lines in INS

CCOs:

- Harmonically-spaced absorption lines in 1E 1207

  \[ P = 0.4 \text{ s}, \quad \dot{P} = 2 \times 10^{-17} \text{ s/s} \]
  (Gotthelf+ 2013)

\[ \Rightarrow \text{ electron cyclotron line in } B \approx 10^{11} \text{ G} \]

- time-variable phase-dependent feature in PSR J0821 (in Pup A)
  emiss. at 0.75 keV or abs. 0.45 keV?
  (Gotthelf & Halpern 2009, De Luca+2012, Gotthelf+ 2013)
X-ray lines in INS

- **XDINS:**
  - Most have broad absorption lines
  - Proton cyclotron lines or atomic transitions in $B \approx 10^{13}$ G
  - No lines in RX J1856

- **Magnetars**
  - A few unconfirmed claims in phase-resolved spectra of persistent emission
  - Transient features during (some) bursts ($E \approx 14$ keV)
    - Recently confirmed with NuSTAR
  - Strong phase-dependent line in SGR 0418 ("low Pdot magnetar")
X-ray lines in INS

- RRAT PSR J1819 - absorption line at 1 keV
  (McLaughlin+ 2005, Rea+ 2009, Camero-Arranz+ 2013)

- Normal RPP:
  - PSR J1740+1000  
    phase-dependent line at 0.5-07 keV  
    (Kargaltsev+ 2012)
  - Fermi pulsar PSR J0633+0632  
    (Danilenko talk)
  - Double pulsar PSR J0737-3039  
    (Egron talk)
PSR J1740+1000

(Kargaltsev+ 2012)

\[ P = 154 \text{ ms} \quad P_{\text{dot}} = 2 \times 10^{-14} \text{ s/s} \quad 2\text{BB}+\text{PL spectrum} \]

\[ \tau = 10^5 \text{ yrs} \quad B = 1.8 \times 10^{12} \text{ G} \quad \dot{E}_{\text{ROT}} = 2.3 \times 10^{35} \text{ erg/s} \]

Atomic transitions in Z>2 elements or cyclotron line from electrons at few \( R_{\text{NS}} \) in magnetosphere
Caveat for broad lines in thermal spectra

- Vigano’+ 2014 → Inhomogeneous surface temperature distributions can produce spectra which mimic broad absorption lines

**XDIN RXJ 0806**

**Caveat** for broad lines in thermal spectra.
Absorption line at strongly phase-dependent energy in low-Pdot magnetar SGR 0418 (Tiengo+ 2013)

Spectrum of 1/50 of phase

10 keV  Phased-Energy Image

5 keV

2 keV

Line center varies from 1 to 10 keV in $\Delta\phi \approx 0.1$
Absorption line at strongly phase-dependent energy in low-Pdot magnetar SGR 0418 (Tiengo+ 2013)

- cyclotron line from protons in small-scale loop with $B$ from $\approx 2 \times 10^{14}$ to $\approx 2 \times 10^{15}$ G

wrt dipolar field $B \approx 6 \times 10^{12}$ G (Rea+ 2013)
4. Variability
X-ray variability in INS

- Distinctive property of magnetars
- bursts / flares
- Transients / variable “persistent”

See N. Rea talk

1E1048.5-5937 (Dib et al. 2009)

1E1547.0-5408 (Bernardini et al. 2010)

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X-ray variability in INS

- Distinctive property of magnetars
  - bursts / flares
  - Transients / variable “persistent”

- Seen also in other NS of different classes, e.g.:
  - PSR J1846 (RPP)
  - Kes 75 (Kumar & Safi-Harb 2008)

- RXJ 0720 (XDINS)
- RCW 103

Gayriil+ 2008
X-ray variability in INS

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  - bursts / flares
  - Transients / variable “persistent”

- Seen also in other NS of different classes, e.g.:
  - RXJ 0720 (XDINS)

Hohle+ 2009, 2012
**X-ray variability in INS**

- RXJ 0720 is the only XDINS with confirmed variability.
- Most other XDINS are fainter and/or less observed.
- Except RX J1856 in which small temperature variations could be caused by calibration issues (Sartore+ 2012).

![Graph showing temperature variations](image)
X-ray variability in INS

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Excluding the 2002 point

$\Delta kT < \sim 0.5\%$ and $\Delta f_x < \sim 3\%$
X-ray variability in INS

- Distinctive property of magnetars
  - bursts / flares
  - Transients / variable “persistent”

- Variability seen also in NS of other different classes, e.g.:
  - PSR J1846 (RPP)
  - RXJ 0720 (XDINS)
  - RCW 103

- Possibly all related to dynamic manifestations of magnetic fields

Central source in RCW 103

X-ray variability in INS

Mode-switching radio PSR B0943+10

Bright mode: regularly drifting sub-pulses
Quiescent mode: sparse and chaotic pulses

X-ray properties change with radio mode suggesting global magnetospheric variations (Hermsen+ 2013)

...but see Mereghetti+ 2013 for a different interpretation
ASTRO-H:
- launch in 2015
- soft and hard X-ray telescopes + different detectors to provide wide band coverage
- Calorimeter: $\Delta E \approx 5\ eV$ in 0.3-10 keV band

NICER:
Neutron star Interior Composition ExploreR
- on ISS in 2017
- Mission devoted to NS timing +spectroscopy
A few final remarks

1. NON - THERMAL EMISSION
   - broad-band multi-λ approach fundamental,
   - impressive progress in γ-ray band (models geometry, population)

2. THERMAL EMISSION
   - observations-starved theoreticians...

3. LINES
   - mostly elusive results, but things are changing

4. VARIABILITY
   - magnetic activity not limited to magnetars
   - new great diagnostic tool also for RPP

5. (NEAR) FUTURE
   - try to get more time on XMM/Chandra...
   - Astro-H 2015 ? - NICER 2017 ?