Abstract: The nature of an unusual class of cosmic X-ray source, dubbed "Anomalous X-ray Pulsars," was a mystery since 1982 when the first example was discovered. In this talk, I will show the recent observational evidence that unambiguously links them with another equally exotic class of object, the explosive "Soft Gamma Repeaters." The evidence to date strongly supports the picture that both are "magnetars:" isolated young neutron stars having surface magnetic fields ~1000 times greater than those in conventional neutron stars.
Magnetars: The High-Magnetic-Field Puzzle

Vicky Kaspi
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November 8, 2006
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Canada Foundation for Innovation
Summary

- Observational Properties of Isolated Neutron Stars
  - “Conventional” wisdom: Radio Pulsars
  - Soft Gamma Repeaters
  - Anomalous X-ray Pulsars
  - The Case for Magnetars
  - New: Transient Magnetars
  - Magnetar birthrate
  - Connection with Radio Pulsars
GOAL

Identify Observational Manifestations of Neutron Stars
Why Study Neutron Stars?

- unique because extreme yet observable:
  - extreme gravity: General Relativity matters
    - 1993 Nobel Prize for Test of General Relativity
  - extreme density: fundamental physics via equation of state of dense matter
  - extreme magnetic fields: fundamental physics via QED, $B > B_{QED} = 4.4 \times 10^{13} G$
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BLACK HOLES MAY BE CLEAN...
BUT NEUTRON STARS CAN BE SEEN.
Crab Nebula
Crab Nebula

Near center of Crab is a neutron star: a pulsar.

The Crab pulsar pulsates 30 times every second! 🎧

this time sequence lasts 0.033 seconds!
Pulsars

Beam of radiation
Rotation axis
Concentration of electrons
Magnetic axis
Magnetic field lines
Basic Neutron Star Facts

typical neutron star mass:
1.4 solar masses
   — about a half-million
      Earths!

typical neutron star radius:
10 km
Basic Neutron Star Facts

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fastest known pulsar rotates
642 times per second!
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716!!! (Hessels et al. 2006)
Basic Neutron Star Facts

typical neutron star mass: 1.4 solar masses
– about a half-million Earths!
typical neutron star radius: 10 km
fastest known pulsar rotates 642 times per second! 716!!! (Hessels et al. 2006)

1.4 times the mass of the Sun, crushed into the size of a city, rotating like a household blender!
More Pulsar Basics

- spin characterized by spin period $P$
  steady spin down due to magnetic braking

$$P(t) = P(t_0) + \dot{P}(t - t_0) + \ldots$$

$\dot{P} > 0$
NB – Radio pulsar steady spin-down behavior very different from accreting neutron stars which generally spin up or show large torque reversals.
Pulsar Basics continued...

\[ E = \frac{d}{dt} \left( \frac{1}{2} I \omega^2 \right) = I \omega \ddot{\omega} = 4\pi^2 I \frac{\dot{P}}{P^3} \]

\[ \tau_c = \frac{P}{2 \dot{P}} \]

\[ B = 3.2 \times 10^{19} \left( \frac{\dot{P}}{P^3} \right)^{1/2} \]
Pulsar Basics continued...

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\[ B = 3.2 \times 10^{19} \left( \frac{P \dot{P}}{G} \right)^{1/2} \]

Assumes magnetic dipole braking in a vacuum
P-Pdot Diagram

main radio pulsar population
P-Pdot Diagram

main radio pulsar population

millisecond radio pulsars
P-Pdot Diagram

- young radio pulsars
- main radio pulsar population
- millisecond radio pulsars
Soft Gamma Repeaters

- sources of rare, brief, intense, repeating soft gamma ray and x-ray bursts
- 5 examples known: 4 in Galactic Plane, 1 in Large Magellanic Cloud
- 3 giant flares seen: March 5, 1979, August 27, 1998, December 27, 2004
March 5, 1979: SGR 0526-66

Mazets et al. 1979
KONUS on Venera
50-150 keV

From SNR N49 in LMC
March 5, 1979: SGR 0526-66

total energy $> 5 \times 10^{44}$ erg

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Soft Gamma Repeaters

- sources of rare, brief, intense, repeating soft gamma ray and x-ray bursts
- 5 examples known: 4 in Galactic Plane, 1 in Large Magellanic Cloud
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\[ L > 10^6 L_{\text{Eddington}} \]

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From SNR N49 in LMC

For one moment, this source’s flux greatly dominated entire cosmic hard X-ray flux!
August 17, 1998: SGR 1900+14

SGR 1900+14 flare

Intensity

Time

~5 minutes

Hurley et al. 1999
Blast from the past. High-energy photons erupted from a neutron star in Aquila roughly 20,000 years ago, only to smash into Earth last August. They then bloated our ionosphere, temporarily weakening radio transmissions that travel from Hawaii to Colorado and are reflected by the ionosphere en route. Courtesy Michael Johnson, Stanford University.
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~100 times more luminous than any Galactic transient yet seen!

First 0.2 s contained same energy as Sun radiates in 250,000 yr.

Suggests GRB relevance…

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Soft Gamma Repeaters cont...

- much more common are small bursts
- tend to occur in bunches — active periods last weeks, recur on timescales of years
- burst durations \( \sim 100 \text{ ms} \)

Gogus et al. 2001
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Soft Gamma Repeaters cont...

- much more common are small bursts
- tend to occur in bunches
  - active periods last weeks, recur on timescales of years
- burst durations ~100 ms

Gogus et al. 2001
Soft Gamma Repeater cont...

GRs
Soft Gamma Repeaters cont...

- X-ray pulsations in quiescence from 2(3) SGRs
  - SGR 1806-20: $P=7.5$ s, spinning down
  - SGR 1900+14: $P=5.2$ s, spinning down
Soft Gamma Repeaters cont...

- X-ray pulsations in quiescence from 2(3) SGRs
  - SGR 1806-20: $P=7.5$ s, spinning down
  - SGR 1900+14: $P=5.2$ s, spinning down
- steady spin down reminiscent of behavior seen in young radio pulsars
\[ B = 3.2 \times 10^{19} \sqrt{\dot{P} P G} \]

P-Pdot Diagram

- SGRs
- main radio pulsar population
SGRs as Magnetars

Spin-down cannot power emission... need new mechanism

Duncan & Thompson, Paczynski (1992); Thompson & Duncan (1995,6):

- Need large B field to spin down neutron star to 8 s in SNR age, ~10 kyr (N49 in LMC)
  
  • Similar periods seen in 2 other sources; spin down later confirmed directly

- Need magnetar field to confine energy in tails of giant bursts
  
  • evidence from relative burst, tail durations and energies, light curve
SGRs as Magnetars, cont...

- Need energy source for flares
  - Given giant outburst energies, need magnetar field to yield enough magnetic energy
- For B-field decay on relevant time scales, need magnetar strength B fields (Goldreich & Reisenegger 1992)
- Quiescent emission can also be powered by magnetic field, via internal heating, external currents
“A magnetar is a star designed by a committee of physicists, each trying to outdo the other.”

Roger Blandford, April 2005
SGRs as Magnetars continued...

- huge magnetic field decays, heats interior, causes stresses on crust which occasionally cracks or deforms to cause bursts
- small scale deformations:
  - small bursts
- large scale deformations:
  - large bursts
SGRs as Magnetars continued...

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Anomalous X-ray Pulsars

- 7(8) known
- all but 1 in Galactic Plane (|b| < 1 deg), 1 in SMC
- some in SNRs → young sources
- P=6-12 s, all spinning down
- pulsed fractions 0.1-0.7

1E 1841-045 in Kes 73

“anomalous” as energy source unclear: X-ray luminosity much too high to be rotation-powered...
AXP Models, historically

- **Accretion-powered I**: accreting from companion star (1982-1996)
  - No evidence for companion
  - LMXB in SNR??
- **Accretion-powered II**: accreting from "fall-back" disk (e.g. Chatterjee, Hernquist & Narayan 1999; Yavuz & Alpar 2003)
- **Magnetars**: "quieter" form of SGR: same spin periods, spin-down rates, X-ray luminosities, comparable spectra (Thompson & Duncan 1995)
RXTE Monitoring of AXPs

- Long-term project, since 1996
- Weekly/monthly snapshot monitoring of 5 AXPs
- ~1 Ms/yr: large project
- Monitor spin behavior, flux, pulse profile

PCA instrument: 2-60 keV X-rays in 1 degree FOV.
AXPs Generally Rotationally Stable

**HE 2259+586**

<table>
<thead>
<tr>
<th>Year</th>
<th>Modified Julian Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>50500, 51000, 51500</td>
</tr>
<tr>
<td>1998</td>
<td>52000</td>
</tr>
<tr>
<td>1999</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td></td>
</tr>
</tbody>
</table>

**Residual (ms)**

**Residual (periods)**

Phase-coherent timing.

Gavriil & VK 2002
AXPs Generally Rotationally Stable

\[ \text{4U 0142+61, } \]
\[ \text{RXS J1708-4009, } \]
\[ \text{1E 1841-045 too} \]

\[ \text{Phase-coherent timing.} \]
AXPs Generally Rotationally Stable

4U 0142+61, RXS J1708-4009, 1E 1841-045 too

* Renders accretion models unlikely.
* Makes glitch detection easy.

Phase-coherent timing.
Evidence for AXPs being Magnetars

- AXP X-ray luminosity requires energy source
- B-field implied by $P$, $dP/dt$ is magnetar-strength
- Similar X-ray spectra to SGRs in quiescence
  - Thermal ($kT \sim 0.4$ keV) + Non-thermal (photon index $\sim 2-4$
- AXPs exhibit SGR-like X-ray bursts
  - Now seen in 4 AXPs
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Major Outburst from 1E 2259+586

on June 18, 2002, during RXTE observations, major bursting detected from 1E 2259+586

80 bursts detected in 15 ks observations; wide range of burst peak fluxes, fluences, rise times, durations, morphologies.
P-Pdot Diagram

SGRs, AXPs
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persistent flux pulsed flux

VK et al 2003
Longer Term 1E 2259+586 Pulsed Flux History

~20x increase in pulsed flux at time of outburst; simultaneous glitch, pulse profile changes, spectral changes

Woods et al. 2004
Evidence for AXPs being Magnetars

- AXP X-ray luminosity requires energy source
- B-field implied by P, dP/dt is magnetar-strength
- Similar X-ray spectra to SGRs in quiescence
- AXPs exhibit SGR-like X-ray bursts

AXPs, SGRs share a common nature, as predicted uniquely by the magnetar model.
Transient Magnetars

• SGR 1801-23 seen once, never again
• 2 likely AXPs discovered in “outburst”: AX J1845-0258, XTE J1810-197
  – Quiescent luminosities > 10-100x lower than in outburst
  – No accompanying outburst detected (but easily could have been missed)
  – J1845-0258 seen in 1993 only; today >>100 times fainter (Tam et al. 2006)
Transient AXP

- 5.5 s X-ray pulsar seen by RXTE in Jan 2003.
- spinning down regularly but noisily
- magnetar strength field inferred
- Quiescent spectrum thermal, kT~0.18 keV, from archival data
- 4 SGR-like bursts seen

Ibrahim et al. 2004
Gotthelf et al. 2004
Woods et al. 2005
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- 4 SGR-like bursts seen

**How many more out there??**

Ibrahim et al. 2004
Gotthelf et al. 2004
Woods et al. 2005
How Many Magnetars in Milky Way?

- past studies of SGR bursts suggested 10 active magnetars (Kouveliotou et al. 1993); AXPs double this
- AXP transients suggest many more...
- Cappellaro et al 1997: Galactic core-collapse SNe every 50-125 yr
- Lyne et al. 1998: radio pulsar born every 60-330 yr
- if magnetar, radio pulsar birth rates comparable, and if magnetars “live” 10 kyr, could be >150 potentially active in Galaxy
- some evidence magnetars come from massive stars (Gaensler et al. 05, Muno et al. 05); if so, birthrate reduced
The Radio Pulsar Connection

Radio pulsars

- Is B distribution bi-modal?
- Is there overlap in spin properties?
  - YES! Overlap in P/Pdot space and AXPs show timing noise and glitches, like young radio pulsars

Magnetars
P-Pdot Diagram

- SGRs, AXPs
- Radio Pulsars
The Radio Pulsar Connection

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Magnetars

- Is there overlap in radiative properties?
  - Radio pulsations from AXPs? YES!
Radio Pulsations from an AXP!

- **XTE J1810-197**
- Very flat spectrum
- Brightest “radio pulsar” at 22 GHz... why?
- Very variable radio emission... why?
- No radio emission from other AXPs seen
- Related to transient nature? Small number statistics?

The Radio Pulsar Connection

Radio pulsars

- Is B distribution bi-modal?
- Is there overlap in spin properties?
  - **YES!** Overlap in P/Pdot space and AXPs show timing noise and glitches, like young radio pulsars

Magnetars

- Is there overlap in radiative properties?
  - Radio pulsations from AXPs? **YES!**
  - Anomalous X-ray emission from high-B radio pulsars?
# High-B Radio Pulsars

<table>
<thead>
<tr>
<th>Name</th>
<th>P (s)</th>
<th>Pdot</th>
<th>B (G)</th>
<th>D (kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1119-6127</td>
<td>0.4</td>
<td>4.1e-12</td>
<td>4.1e13</td>
<td>8.4</td>
</tr>
<tr>
<td>J1718-3718</td>
<td>3.4</td>
<td>1.6e-12</td>
<td>7.4e13</td>
<td>4.9</td>
</tr>
<tr>
<td>J1734-3333</td>
<td>1.2</td>
<td>2.3e-12</td>
<td>5.2e13</td>
<td>7.4</td>
</tr>
<tr>
<td>J1814-1744</td>
<td>4.0</td>
<td>7.4e-13</td>
<td>5.5e13</td>
<td>9.8</td>
</tr>
<tr>
<td>J1819-1458</td>
<td>4.3</td>
<td>5.7e-13</td>
<td>5.0e13</td>
<td>3.6</td>
</tr>
<tr>
<td>J1846-0258*</td>
<td>0.3</td>
<td>7.1e-12</td>
<td>4.8e13</td>
<td>19</td>
</tr>
<tr>
<td>J1847-0130</td>
<td>6.7</td>
<td>1.3e-12</td>
<td>9.3e13</td>
<td>8.4</td>
</tr>
</tbody>
</table>
PSR J1119-6127:
Radio Pulsar/Magnetar Link?

- $P=0.4\,\text{s}$, $B=4.1\times10^{13}\,\text{G}$, $D=8.4\,\text{kpc}$
- $\tau=P/2P=1.7\,\text{kyr}$
- At center of SNR G292.2-0.5
- SNR X-ray detected by XMM (Gonzalez et al, 2005)
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PSR J1119-6127:

- 50 ks XMM-Newton observation of pulsar
- X-ray pulsations detected at radio period
- Pulsations only seen for E<2.0 keV: **thermal emission** (youngest!)
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- Pulsations only seen for E<2.0 keV: **thermal emission** (youngest!)

**Pulsed Fraction:** (74 +/- 14) %

Gonzalez et al. 2005
PSR J1119-6127:

- Surface thermal emission, from initial cooling, should have:
  - Sinusoidal pulse profile from GR light bending
  - Low pulsed fraction, <37% for passively cooling neutron star with high B, no hot spots (Dedeco & Psaltis 2004)
- Here, pf=74+/−14%, profile non-sinusoidal
- AXPs have high pulsed fractions, non-sinusoidal profiles...
PSR J1119-6127:

- Blackbody temperature high:
  \[ T = 2.4^{+0.3}_{-0.2} \times 10^6 \text{ K} \]
PSR J1119-6127:

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  \[ T = 2.4^{+0.3}_{-0.2} \times 10^6 \text{ K} \]

Of known young (<2 kyr) rotation-powered pulsars, this is the hottest by far.
PSR J1119-6127:

- Blackbody temperature high:
  \[ T = 2.4^{+0.3}_{-0.2} \times 10^6 \text{ K} \]

Of known young (<2 kyr) rotation-powered pulsars, this is the hottest by far.

Quiescent Magnetar??
Summary I

- Of 6 high-B radio pulsars studied in X-rays:
  - All are >order-of-magnitude underluminous relative to magnetars with similar B
  - One has “anomalous” X-ray emission: PSR J1119-6127

- Estimated B field unreliable by factor of <2 (Spitkovsky 2006)

- Need sudden switch to magnetar for >B_{critical}

- Or, magnetars have higher-order multipoles that are irrelevant to spin-down

- Or, there’s another hidden parameter... Mass? Envelope composition? Age?
Summary II

- AXPs, SGRs share common nature
- Magnetar model accounts for most observables: bursts, flares, pulsations, spin-down, spectra
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• AXPs, SGRs share common nature
• Magnetar model accounts for most observables: bursts, flares, pulsations, spin-down, spectra
• Open issues:
  – Can we find direct evidence for the high magnetic field?
  – What differentiates AXPs from SGRs? Age? B?
  – What is the origin of AXP, SGR spectra?
  – Where are the old magnetars? INSs?
  – Why are some magnetars quiescent?
  – What fraction of NSs are magnetars?
  – What is the origin of the magnetic field?
  – What is the connection between AXPs and high-B radio pulsars?
  – Do magnetars form from massive stars?