Magnetars in Supernova Remnants
&
Magnetars Formation

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Isolated NSs, London, April, 2006
The central question:

What is the origin of the high magnetic fields of magnetars?
Two possible formation scenarios

1. progenitor star has high magnetic field (fossil field hypothesis)

2. - proto-neutron star is rapidly spinning
   - $P < 3 \text{ ms} \ (\sim 3 \text{ ms} \ \text{proto NS convective overturn time})$,
   - convective dynamo → growth of magnetic field to $\sim 10^{15} \text{G}$
   (Duncan & Thompson, 1992)
   C.f.: typical isolated neutron stars have $B \sim 10^{12} \text{ G} \ \text{and} \ P_i \sim 10 \text{ ms}$

Problems for rapid spinning scenario:

- If magnetars are from massive stars stellar winds may have removed most angular momentum
- Simulations don’t show enough differential rotation
  (Fryer & Warren 2004)
The Fossil Field Hypothesis

• Similar distributions B-fields of White Dwarfs and Neutron stars (Ferrario & Wikramsinghe 2006)
• F&W: B-field variation reflects variation in the ISM
• High B-field WD/NSs should have slow rotation (rotational coupling of wind/core through B-field)
• But: giant flare of SGR1806 suggests even higher internal field: $B_{\text{int}} > 10^{16}$G
  (e.g. Stella et al. 2006)
Implications of ms proto-neutron stars
(c.f. Duncan&C.Thompson '92, T.Thompson et al. '04, Allen&Horvath '04)

- Dynamo results in magnetars fields on time scales of $\tau_d < 10$ s
- $B \sim 10^{15}$G magnetic breaking $\tau_B < 400$ s $(10^{15}$ G/B$)^2(P/1\text{ms})^2$
  (upper limit, as propellor effect gives more rapid slow down)
- Short time scale suggests spin-down energy absorbed by supernova
- For $P \sim 1$ ms, rotational energy $E_{\text{rot}} \sim 3 \times 10^{52}$ erg
- If all $E_{\text{rot}}$ converted to magnetic energy: $<B_{\text{NS}} > \sim 3 \times 10^{17}$ G
- If $<B_{\text{NS}} > \sim 10^{15-16}$ G, magnetars may power hypernovae
  (T. Thompson et al. 2004)

Can be tested with X-ray data of supernova remnants!
Association of SNRs and magnetars

- 8 AXPs/4 SGRs known
- 1 SGR associated with supernova remnant:
  - N49/SGR0526-66 (LMC)
- 3 AXPs associated with SNRs:
  - Kes 73/1E1841-045 (~7 kpc)
  - CTB109/1E2259+586 (~3 kpc)
  - G29.6+0.1/AX J1845.0-0258 (~3 kpc)
Deriving the explosion energy

- At late times evolution is assumed to be self-similar (Sedov):
  \[ r^5 = 2.02 \, E_k \, t^2/\rho_0, \quad v_s = 2/5 \, r/t \]
- Density low → time dependent ionization (NEI) → \( n_e \, t \)
- From X-ray data: \( n_e \, t, \, kT \, (= 3/16 \, <m> \, v_s^2) \),
  emission measure (\( \int n_e n_H dV \)), and radius
  Sufficient to determine energy, age, density
  (e.g. Hamilton et al. '83, Jansen&Kaastra '93, Borkowski et al.'01)
- Some redundancy from observations, e.g. age: \( t=2/5 \, r/v \), or \( n_e \, t \)
- Potential caveat: \( kT \) (electrons) ≠ \( kT \) (protons)
- However, equilibration is also dependent on \( n_e \, t \)
  (incorporated in some spectral mode codes)
- Spectral codes: XSPEC (Hamilton/Borkowski), SPEX (Kaastra, Mewe)
- Method used by e.g. Hughes et al. '98 for LMC SNRs: \( E = 0.5-7 \, foe \)
• CTB 109 (1E2259+586): complex morphology
• AXP showed SGR-like burst
• Very long spindown age: 220 kyr

\[ E_0 = (0.7 \pm 0.3) \times 10^{51} \text{ erg} \]
from literature
(Sasaki et al. '04)
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**N49/SGR 0526-66**

- Non-spherical, SNR-cloud interaction
  - (e.g. Park et al. '03)
- Distance $\sim 50$ kpc
- Radius = 10 pc
- Spindown age: 1900 yr
- Connection SGR/SNR requires $\sim 1000$ km/s kick
  - (Gaensler et al '01)
- Spectral modeling indicates:
  - $kT = 0.5$ keV $\rightarrow V_s = 700$ km/s
  - $n_e \cdot t = 3 \times 10^{12}$ cm$^{-3}$s
  - $n_e = 3$ cm$^{-3}$
  - mass = 320 M$_{\odot}$

\[ E_0 = (1.3 \pm 0.3) \times 10^{51} \text{ erg} \]
\[ t = 6300 \pm 1000 \text{ yr} \]
(see also Hughes et al. '98)
Kes 73/1E1841-045

- Spherical morphology
- Distance $\sim$ 6-7.5 kpc (HI abs.)
- Radius = 4 pc
- Spin down age: 4500 yr
- Spectral modeling:
  - $kT = 0.7$ keV $\rightarrow V_s = 800$ km/s
  - $n_e t = 4 \times 10^{11}$ cm$^{-3}$s
  - $n_e = 3$ cm$^{-3}$
  - mass = 29 M$_{\text{sun}}$
  - no overabundances

$E_0 = (0.5 \pm 0.3) \times 10^{51}$ erg
$t = 1300 \pm 200$ yr

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Isolated NSs, London, April, 2006
**Was Kes 73’s progenitor a massive star?**

- Spectral models give different abundances
- SPLEX program gives best fits, but consistent with solar abundances!!
- Not consistent with young SNR with oxygen rich ejecta!! (c.f. Cas A, G292+1.8)
- Suggest hydrogen rich envelope, i.e. progenitor MS mass of < 20 M_{\odot}
- Suggests not all magnetars come from the most massive stars?
- Contrary to some evidence for SGRs (Gaensler)
- Could there be a difference between AXPs and SGRs?

<table>
<thead>
<tr>
<th>Model</th>
<th>Kes 73</th>
<th>2 NEI</th>
<th>Sedov</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM (10^{12} cm^{-5})</td>
<td>26.9 ± 3.1</td>
<td>16.4 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>kT_e (keV)</td>
<td>0.63 ± 0.06</td>
<td>0.72 ± 0.3</td>
<td></td>
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<tr>
<td>n_{oe} (10^{11} cm^{-3}s)</td>
<td>3.1 ± 0.8</td>
<td>4.6 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>EM (10^{12} cm^{-5})</td>
<td>2.0 ± 0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kT_{2e} (keV)</td>
<td>2.26 ± 0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n_{oe} (10^{11} cm^{-3}s)</td>
<td>0.47 ± 0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>(1)</td>
<td>(1)</td>
<td></td>
</tr>
<tr>
<td>Ne</td>
<td>(1)</td>
<td>(1)</td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>1.13 ± 0.13</td>
<td>1.95 ± 0.15</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>1.09 ± 0.07</td>
<td>1.7 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>1.12 ± 0.06</td>
<td>1.6 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>Ar</td>
<td>1.02 ± 0.18</td>
<td>1.1 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>1.84 ± 0.42</td>
<td>0.77 ± 0.33</td>
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<tr>
<td>Fe</td>
<td>0.42 ± 0.15</td>
<td>4.3 ± 0.7</td>
<td></td>
</tr>
<tr>
<td>N_H (10^{21} cm^{-2})</td>
<td>27.3 ± 0.6</td>
<td>31.2 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>Fit range (keV)</td>
<td>0.8–8.0</td>
<td>0.8–8.0</td>
<td></td>
</tr>
<tr>
<td>C-statistic/d.o.f.</td>
<td>186/110</td>
<td>956/468</td>
<td></td>
</tr>
</tbody>
</table>
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Comparison of two models

Spectral model code: SPEX (2NEI)
Gives ~solar abundances

Spectral model code: XSPEC (Sedov)
Gives overabundances, but does fit as well

XMM-Newton (MOS 1+2)
Potential Caveats

- Some SNRs in the Sedov phase, but in “ejecta phase”
  Only issue for Kes 73:
  - M rather low (argues against Sedov phase)
  - but abundance (sub)solar (against ejecta phase)
  - more elaborate models (Truelov&McKee ‘99) confirm E<0.5 foe
- Strongly non-uniform density structure
- Very efficient cosmic ray acceleration may have drained energy
- Additional energy ejected in form of jet
  - hard to confine jet for a long time
  - no morphological evidence for jet in 3 SNRs
  - jet only seen in Cas A

But...

Caveats apply also to ordinary SNRs, which have similar measured energies
Cassiopeia A

- Cas A: central compact object is potential magnetar (evidence for big SGR-like?- flare in ±1950, Krause et al '05)
- Not in Sedov phase, but measured shock velocity of 5000 km/s
- Evidence for jet/counter jet, mini GRB? (Vink '03, Hwang et al. '04)
- Energy in jets 1 - 5x10^{50} erg
- Jets enriched in Si/S, some Fe, no Ne, Mg
- Suggest more efficient burning

\[ E_0 = (2-2.5) \times 10^{51} \text{ erg} \]
\[ t = 330 \text{ yr} \]
Conclusions

Presence of magnetar does not imply hypernova remnant!

- Magnetar hosts Kes 73, N49 and CTB109 are not more energetic than other supernova remnants.
- Typical energies of $\sim 0.5 - 2 \times 10^{51}\text{erg}$, so additional energy from magnetic breaking: $< 10^{51}\text{erg}$
- Equating energy to rotational energy gives: $P_i > 5 (E/10^{51})^{1/2}\text{ms}$
  (with $P_i$ spin after formation of magnetar)
- No evidence that proto-NSs of magnetars had $P \sim 1\text{ms}$
Discussion: explanations of results

1. Plausible formation scenario:
   Progenitor's magnetic field instead of angular momentum determines magnetic field of neutron star/magnetars
   (c.f. Ferrario's & Wickramasinghe 2006, B-field distribution in WDs vs NSs)

2. Angular momentum is taken away before magnetic braking:
   - spin energy is completely converted to magnetic energy
     \[ \text{interior } \langle B \rangle \sim 3 \times 10^{17} \text{ G } > B_{\text{bip}} \sim 10^{15} \text{ G} \]
   - excess spin energy is lost through gravitation radiation
     - most plausible way: NS deformation due to high B-field
       \( B_{\text{int}} > 5 \times 10^{16} \text{ G}, B_{\text{bip}} \sim 10^{14} \text{G}, \) Stella et al. 2005
   - magnetic field is buried for some time preventing breaking
     but expect presence of pulsar wind nebula!

3. Magnetic field amplification is still possible around \( P \sim 5 \text{ ms} \)
How likely are points 2 & 3?
The case of Kes 73/1E1841-045

- According to this study: $T=1300$ yr, $P_{\text{psr}}=11.8$ s
- Magnetic braking, current $B = 7 \times 10^{14}$G
- Needed to go from $\sim 5$ ms to 11.8 s: $B_p = 1.6 \times 10^{15}$G
- Gravitational radiation only dominant for very fast periods ($\sim \Omega^5$)
- After having reached 10 ms magnetic braking more dominant
- Expect a fossil pulsar wind nebula in radio (not X-rays: losses)
- Instead: AXP is inside hole in radio emission
- AXP born with $P > 1$ s?
- Or AXP PWN quenched by some phenomenon (high B-field, early/fast formation inside ejecta)

Kriss et al. 1985