Magnetars, the most extreme Neutron Stars. Multiwavelenght emission

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Black Holes, jets and outflows
Kathmandu, Nepal
14-18 Oct 2013

- SGRs/AXPs as “magnetars”, the most extreme compact objects
- Multiband emission mechanisms – from IR to X-rays
- Recent results and newly discovered sources
MAGNETARs: the most extreme NSs

(Isolated) neutron stars where the main source of energy is the (super-strong) magnetic field

Most observed NS have $B = 10^9 - 10^{12} \, G$ and are powered by accretion, rotational energy, residual internal heat

$$B \geq B_{\text{QED}} \approx 4.41 \times 10^{13} \, G : \text{quantum effects important}$$

In Magnetars: external field: $B = 10^{14} - 10^{15} \, G$

internal field: $B > 10^{15} \, G$

Low (dipolar) field magnetars: SGR0418+5279 and SGR1822: still a quite large internal component, >50-100 times larger than $B_{\text{dip}}$

Magnetars are neutron stars with the highest magnetic fields. Those huge fields are believed to form either via alpha-dynamo mechanisms soon after birth or as fossil fields from a very magnetic and massive progenitor.
Neutron star formation & Magnetars

- Strong convection in a rapidly rotating ($P \sim 1$ ms) newborn neutron star generates a very strong magnetic field via dynamo action
  
  (Duncan & Thomson 1992; Thomson & Duncan 1995)

- Probably associated with massive progenitors, $M \geq 25 M_{\text{sun}}$
  
  (Lose et al, 2004; Eikenberry et al, 2005, Gaensler et al 2005)
Young stellar clusters: AXPs-SGRs nests?

If SGR-cluster is confirmed:
1. Progenitor mass is $>20M_{\text{sun}}$
2. Age $< 10^5$ yr
3. High metallicity
SGR 0526-66 / N49

SGR 1900+14/G42.8+0.6

SGR 1806-20/G10.0 0.3

SGR 1627-41 /G337.0-0.1

Kulkarni et al. 2003

Hurley et al. 1999

Kaplan et al. 2002

Woods et al. 1999
How do we measure neutron stars' magnetic fields?

\[
\dot{E}_{\text{rot}} = -\frac{2}{3c^3} |\ddot{m}|^2 = -\frac{2B^2 R^6 \Omega^4 \sin^2 \alpha}{3c^3}
\]

\[
\dot{P} = -\frac{8\pi^2 R_{\text{ns}}^6}{3c^3 I} B_0^2 \sin^2 \alpha
\]
Isolated neutron stars: P-Pdot diagram

\[ P \dot P = \frac{8 \pi^2 R_{ns}^6 B_0^2 \sin^2 \alpha}{3 c^3 I} \]

Critical Electron Quantum B-field

\[ B_{\text{critic}} = \frac{m_e^2 c^3}{e \hbar} = 4.414 \times 10^{13} \text{ Gauss} \]
Magnetars general properties

- Two classes of sources: AXPs and SGRs (now unified?)
- bright X-ray pulsars in quiescence: \( L_x \sim 10^{33}-10^{36} \) erg/s
- strong soft and hard X-ray emission
- pulsed fractions ranging from \( \approx 2-80\% \)
- large outbursts, X-gamma rays activity. Bursts and flares with duration from subms to several tens of seconds, (3) giant flares - output of high energy only exceeded by blazars and GRBs
- rotating with periods of \( \approx 2-12 \) s
- period derivatives of \( \approx 10^{-13}-10^{-11} \) s/s
- magnetic fields of \( \approx 10^{14}-10^{15} \) Gauss
- glitches and timing noise
- faint infrared/optical emission (\( K \approx 20 \); sometimes pulsed and transient)

\[\text{see Woods & Thompson 2006, Mereghetti 2008, Rea & Esposito 2011 for a review}\]
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<th>Source</th>
<th>P (s)</th>
<th>Pdot (s/s)</th>
<th>Hard-X</th>
<th>Short bursts</th>
<th>Outbursts</th>
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Soft X-ray spectra

- 0.5 - 10 keV emission well represented by a blackbody plus a power law

- Long term spectral evolution, with correlation among some parameters (as spectral hardening, luminosity, spin down rate...)

- Also seen during the evolution of “transient” AXPs

AXP 1E1048-5937; from Rea, SZ et al, 2008
- Black, blue, green are taken in 2007, 2005, 2003 (XMM-Newton)
- Red lines: total model, dashed lines: single BB and PL components
Multiband Emission

- INTEGRAL revealed substantial emission in the 20 -100 keV band from SGRs and AXPs
- Hard power law tails, $\Gamma \approx 1$-3
- Hard Emission pulsed
- no relevant emission above the Integral band (spectral break?)
Multiband Emission

Sasamz Mus and Gogus 2011

Integral/Comptel/Fermi SED of 4U0142+61

Also, no detections so far from the Fermi-LAT team (ApJ, 2010)
Multiband Emission

- Also, Optical/IR emission
- Faint K~19-21 and sometimes variable IR counterparts
- Fossil disk or inner magnetosphere?

Durant and van Kerkwijk 2005

(VLT-UT4 NAOS-CONICA Ks-filter)

(Israel et al. 2010)
How magnetar persistent emission is believed to work?

Magnetars have magnetic fields twisted up, inside and outside the star.

Magnetar magnetospheres are filled by charged particles
- interacting with the surface thermal emission through resonant cyclotron scattering.
- Producing curvature radiation

High energy photons interacting with B and produce pairs

(Thompson & Duncan 1992; 1993; Thompson, Lyutikov & Kulkarni 2002; Pons & Rea 2012)
A POSSIBLE SCENARIO: A TWISTED MAGNETOSPHERE

A: RCS photons interact with high B-field and generate $e^\pm$ pairs via single photon pair production. $\gamma \approx 1000$
CR in IR/Optical

B: Mildly relativistic electrons slowed down to $\gamma \sim$ a few (Compton drag). Soft X-ray spectra through RCS of surface thermal photons

B+C: $\gamma \sim 10^5$ or more. CR or RCS up to the high energy band (100-1000 KeV) INTEGRAL?
A Monte Carlo Approach

Surface Emission

Magnetosphere setting
(twisted dipole)

Radiative transfer, Monte Carlo code

Predicted spectra, lightcurves, polarization to be compared with X-ray data

GOAL: probe the magnetospheric properties of the neutron star via spectral analysis of X-ray data

(Nobili, Turolla, SZ. 2008a,b; SZ, Rea, Turolla & Nobili, 2009)
XSPEC Implementation and fit of all magnetars spectra (<10 keV)
SZ, Rea, Turolla and Nobili MNRAS 2009

fit with NTZ model only

$\chi^2 = 1.21 \ (101)$

$\chi^2 = 1.16 \ (81)$

CXOU J0100-7211

$\chi^2 = 0.97 \ (197)$

$\chi^2 = 1.21 \ (101)$

1RXS J1708-4009

$\chi^2 = 1.04 \ (152)$

SGR 1900+14

$\chi^2 = 0.99 \ (135)$

1E 1841-045
- Major source of uncertainty is the nature/velocity distribution of scattering particles and the global topology of the B-field.

- Particularly crucial when trying to simulate the Hard X-ray Spectra (50-200 keV), since hard X-rays may be emitted from huge portions of the magnetosphere!

- Detailed simulations of these spectra still unavailable.
Hard X-ray emission

Need to break the degeneracy..

- Coupled spectral and timing simulations

- More sensitive hard X-rays observations: PPS, detailed of the spectral turn-over soft/hard X-rays: Astro-H, LOFT?
“Magnetar activity” (bursts, outbursts, …) detected so far only in high-B sources ($B_p > 5 \times 10^{13} \text{ G}$):

AXPs+SGRs (☆)
PSR J1846-0258, PSR J1622-4950 (☆)
SGR 0418+5729 and SGR1822-1606

- SGR 0418+5729: 2 bursts detected on 2009 June 05 with Fermi/GBM, spin period of 9.1 s with RXTE within days (van der Horst et al. 2010)
  - \( \dot{P} \sim 5.14 \times 10^{-15} \) s/s
  - \( B_p = 7 \times 10^{12} \) G
  (Rea, SZ et al. 2013)

- SGR1822-1606: Latest discovered magnetar, outburst in July 2011
  - Monitored with Swift, RXTE, Suzaku, XMM-Newton and Chandra

- It is clear that the dipolar B value is not enough to explain the variety in phenomenology: why some “high B” pulsars do not display bursts, while some “low field” SGRs do?

(Rea, SZ et al 2012)
SGR 0418+5729 and SGR1822-1606
A Magnetar at Work

- What really matters is the internal toroidal field $B_\varphi$

- A large $B_\varphi$ induces a rotation of the surface layers

- Deformation of the crust $\Rightarrow$ fractures $\Rightarrow$ bursts/twist of the external field

Can we have a large $B_{tor}$ associated with a low dipolar $B_p$?
Calculation of magnetic stresses acting on the NS crust at different times (Perna & Pons 2011; Pons & Perna 2011)

Max stress sustained by the crust as in Chugunov B Horowitz 2010

Activity strongly enhanced when $B_{\text{tor},0} > B_{\text{p},0}$

$B_{\text{tor},0} = 2.5 \times 10^{16} \text{ G}$
$B_{\text{p},0} = 2.5 \times 10^{14} \text{ G}$

$B_{\text{tor},0} = 8 \times 10^{14} \text{ G}$
$B_{\text{p},0} = 1.6 \times 10^{14} \text{ G}$
“low-field” SGRs as Old Magnetars
(Turolla, SZ et al. 2011, Rea, SZ et al. 2012)

- Low dipole field ($B < 7.5 \times 10^{12} \, G$)
- Large age (> 1-20 Myr)
- Weak bursting activity (only 2 faint bursts)

• 2D simulations of NS magneto-thermal evolution:
  - $P$, $\dot{P}$ and $B_p$ from magneto-rotational evolution
    - age = 1.6 Myr of SGR 1822
    - age = 29.5 Myr for SGR 0418
    - $B_{\text{tor}}$ 10-100 times larger than $B_{\text{dip}}$
SGR0418+5729
Phase-energy image

67ks XMM observation taken in Aug 2009 (after the outburst of June 2009)

Normalized to the phase-averaged spectrum and the energy-integrated pulse profile

(Tiengo, SZ et al, Science, 2013)
A simple proton cyclotron model

- Different geometries can be envisaged

- **PROTON CYCLOTRON** resonant scattering in a **MAGNETAR LOOP** is a viable scenario
Is the line visible in other observations?

- Detected also in RXTE data!
  - line visible up to ~10 keV
  - line was already present at the onset of the outburst
• The X-ray spectrum of SGR 0418+5729 shows an **ABSORPTION LINE** with strong energy **VARIABILITY** with phase, **UNPRECEDENTED** among neutron stars (including accreting pulsars)

• A natural interpretation as **PROTON CYCLOTRON line** implies magnetic fields $>2 \times 10^{14} \text{ G}$ (B in the loop varies between $2 \times 10^{14} \text{ G}$ and $10^{15} \text{ G}$) ⇒ additional confirmation of magnetar nature of SGR 0418+5729 and of the overall **MAGNETAR MODEL**

• The much lower dipolar component of the magnetic field inferred from low spin-down rate and the line phase variability can be explained only with strong **MULTIPOLAR** magnetic field components (complex B-topology is a key ingredient of the **MAGNETAR MODEL**
Most powerful magnetic field in universe that is 20 trillion times stronger than a fridge magnet

The strongest magnetic field in the universe has potentially been discovered — a dead star that packs the equivalent mass of our sun into an area just 12 miles across.

SGR 0418+5729

Astronomers discover an insanely strong magnetic field

The dead core of a once massive star is producing one of the most powerful magnetic fields ever recorded by scientists. Measuring a mere 12 miles across, the “magnetar” is exerting a force 20 trillion times stronger than a fridge magnet.

Top image: Artist’s impression of Magnetar SGR 0418+5729. The looping magnetic field runs over a few thousand meter square.
Inferences

SGR 0418+5729 (and SGR 1822-1606) is a low-B source (dipolar B!): more than 20% of known radio PSRs have a stronger $B_p$

Their properties compatible with aged magnetars $\approx 1$ Myr old

A continuum of magnetar-like activity across the $P$-$\dot{P}$ diagram
** SN explosions**
A large number of strong-B neutron stars call for a revision of a key ingredient of the NS formation model: an extreme internal B should then be a common place rather than an exception.

** GW radiation from newly born magnetars**
The GW background radiation produced by the formation of highly magnetic neutron stars is probably underestimated given the recent results.

** Gamma-ray bursts**
If a large fraction of the formed neutron stars have a strong B-field, GRBs caused by the formation of such stars are way more frequent than predicted.

** Massive Stars**
If strong-B neutron stars are formed by the explosion of highly magnetic stars, there should be many more of such stars than predicted thus far.
...nop!!!

Swift/BAT detection of an SGR-like flare from near Sgr A*

on 26 Apr 2013; 02:48 UT

NuSTAR discovery of a 3.76 second pulsar in the Sgr A* region

ATel #5020; Kaya Mori, Eric V. Gotthelf (Columbia University), Nicolas M. Barriere (UC Berkeley), Charles J. Hailey (Columbia University), Fiona A. Harrison (Caltech), Victoria M. Kaspi (McGill University), John A. Tomsick (UC Berkeley), Shuo Zhang (Columbia University)
on 27 Apr 2013; 05:40 UT

Chandra localization of the soft gamma repeater in the Galactic Center region

ATel #5032; N. Rea (CSIC-IEEC), P. Esposito, G. L. Israel (INAF), A. Papitto (CSIC-IEEC), A. Tiengo (IUSS/INAF), F. Baganoff (MIT), D. Haggard (Northwestern/CIERA), S. Mereghetti, M. Burgay, A. Possenti (INAF), S. Zane (MSSL), on behalf of a larger collaboration
on 30 Apr 2013; 21:53 UT
A magnetar within grasp of our SMBH

Rea, SZ et al, 2013
Is SGR 1745-2900 so close to SgrA*?

1. Distance determination from the radio pulsar DM:

Using the Cordes & Lazio (2002) distribution we estimate that a DM=1750 pc cm\(^{-3}\) results in a distance of 8.3 kpc (same as SgrA*). If we assume this distance, a 2.4" projected distance translates in:

\[
d = 0.09+/−0.02 \text{ pc (90\% error).}
\]

2. \(N_H\) difference between the SGR and SgrA*:

Using all possible best fitting continuum, the largest difference between the absorption value of SgrA* and SGR 1745-2900 is < 6x10\(^{22}\) cm\(^{-2}\), that for a particle density of the Central Molecular Zone (~10\(^4\) cm\(^{-3}\)) sets an upper limit on the distance between the two sources

< 2pc (90\% upper limit)
SGR\textsubscript{1745-2900} is a magnetar within 0.07-2 pc from Sgr A*, the closest pulsar to a supermassive black hole.

**Conclusions**

i) it has a \( \sim 90\% \) probability of being in a bound orbit around the SMBH
ii) it might be responsible, or at least partly, for the Fe light echo observed around Sgr A*.

The on-going Chandra/XMM monitoring of this intriguing object will shed light on i) its outburst decay, ii) proper motion, and iii) effects on the dense environment.
Conclusions

Magnetars are intriguing objects, and unique laboratories to test our knowledge on the physics of matter under extreme gravitational and magnetic fields.

We finally understood that behind the powerful magnetar emission there is not just the magnetic strength measured at large scale, but there are other important parameters: i.e. field geometry and evolution.

Many normal pulsars might be hiding a magnetar inside, and may turn out to be active and flaring at any time, with all the due consequences.
THANKS!