Magnetic dipole moment of SGRs and AXPs as white dwarf pulsars

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I - SGRs and AXPs: Unusual X-ray Neutron Star Pulsars

II - SGRs and AXPs as fast rotating-powered Magnetic White Dwarf Pulsars

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VI - Conclusions
I- SGRs and AXPs: Unusual X-Ray Pulsars

• Soft Gamma Repeaters (SGR) and Anomalous X-Ray Pulsars (AXP) are very slow rotating pulsars: long Periods $P \sim (2 - 11)$ s. Periods in a narrow range comparing to ordinary pulsars $P \sim (0.001 - 1)$ s.

• Spin-down rates $dP/dt \sim (10^{-13} - 10^{-10})$ s larger than normal pulsar $(10^{-15} - 10^{-14})$ s.

• Isolated stars and only 18 confirmed (9 SGRs and 11 AXPs) comparing with more than 2000 pulsars known.

• Strong outburst of energies $\sim (10^{41} - 10^{43})$ erg. SGRs, giant flares of even large energies $\sim (10^{44} - 10^{47})$ erg.
• High X-ray luminosities $L_x \sim (10^{32} - 10^{36}) \text{ erg/s} >> \text{spin-down rotational energy rate (seen as neutron star pulsars).}$

• A reservoir of energy to explain the X-ray Luminosity: ultra-strong magnetic fields in the interior and at the surface of the star $B \sim (10^{14} - 10^{15}) \text{ G}.$

• MAGNETARS - Magnetic-powered X-Ray pulsars (seen as neutron stars).

• Hot Stars – $T \sim (0.4 - 0.6) \text{ KeV},$ larger than $10^6 \text{ K}.$

• Young Stars – spin-down ages $(10^3 - 10^5) \text{ yr};$ exception the new SGR 0418+5229 with 24 Myr.
**SGRs**

- Recurrent sources of soft gamma ray burst, short times $t \sim 0.1 \text{ s}$ and Energy $E \sim 10^{41} \text{ erg/s}$.
- Occasionally active episodes producing many short X-Ray bursts, lasting weeks or months, separated by quiescent phases of years or decades.
- Intermediate bursts $t \sim 1-40 \text{ s}$, higher energy $E \sim (10^{43}-10^{47}) \text{ erg}$ showing an Hard X-ray emission $T \sim 100 \text{ KeV}$.
- Extremely rare: giant flares $E \sim (10^{44}-10^{47}) \text{ erg}$ ($\sim$ one at each 50 ys). Initial spike $t < 0.1 \text{ s}$ (Hard X-ray) with a long tail $t > 500 \text{ s}$.

**AXPs**

- Similar to SGR but weaker in intensity. No giant flares.
- No recurrent gamma ray bursts.

*McGill catalogue of SGRs&AXPs*


• Magnetars differ from radio pulsars since their internal magnetic field is twisted up to 10 times the external dipole. At intervals, it can twist up the external field, stresses build up in the NS crust causing glitches, flares, and all sort of instabilities.

• The surface of a young magnetar (with age less than a few kyr) is so hot that it glows brightly in X-rays.

• The shifting magnetic field outside the star must drive electrical currents along arched magnetic field lines. The streaming charged particles inevitably impart energy to X-ray photons by scattering against them.

• Streaming charged particles also slam against the star reaching the footpoints of magnetic field lines, heating spots on the surface.

Magnetic instability!

The twisted magnetic lines stress the crust which is not able anymore to respond plastically, then it cracks. e+e- are created and trapped in a fireball (small or large depending on the crack). Depending on how baryon loaded the fireball is it will behave in different manners.

We see in fact flux and spectral changes correlated to the bursting activity, as well as glitches.

II - SGRs/AXPs AS FAST ROTATING -
POWERED MAGNETIC WHITE DWARF
PULSARS
(M. Malheiro, J. A. Rueda and R. Ruffini – PASJ 64, 56 2012)

In this new description several observational properties are easy understood and well explained as a consequence of the large radius of a massive white dwarf that manifests a new scale of mass density, moment of inertia and rotational energy:

I - The existence of stable WDs can explain, the range of long rotation periods \((2 \leq P \leq 12 \text{ s})\) observed in SGRs and AXPs.
II - The long standing puzzle of the energetic balance of the SGRs/AXPs pulsars is solved: the steady X-ray luminosity $L_x$ observed is smaller than the loss of rotational energy of the WD.

III - The large steady luminosity $L_x$ seen of $L_x \sim 10^{35}$ erg/s, for slow pulsars ($\Omega \sim 1$ Hz) is also understood, as a consequence of the large radius of the dense WD that produces a large magnetic dipole moment, in the range of the magnetic white dwarfs.

IV – The large dP/dt observed ($10^{-10} - 10^{-13}$ s/s) are also consequence of the large WD magnetic dipole moment, as well of the large radius and the momentum of inertia, and not only of the magnetic field as it is the case for NS in the magnetar model.
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III – MAGNETAR x WHITE DWARF PHYSICAL SCALES

• Morini (1988) and Paczynski (1990) – Massive fast rotating highly magnetized white dwarf for 1E 2259+586 (AXP) at SNR G109.1-1.0 (period of $P = 6.98$ s).

• Kepler frequency $W_k = (G M/R^3)^{1/2} \sim (G \rho)^{1/2}$; $W < W_k$.
  $P \sim 1$ s, the average density $\rho > 10^8$ g/cm$^3$.

• Low density stars cannot spin fast.
  High density and massive white dwarfs: $M = 1.4$ $M_{\text{sun}}$ and maximal radius $R \sim 3000$Km $= 3 \times 10^2 R_{\text{NS}}$.

• Momentum of Inertia $I_{\text{NS}} \sim MR^2 = 10^{45}$ g.cm$^2$
  $I_{\text{WD}} = 10^5 I_{\text{NS}} = 1.26 \times 10^{50}$ g.cm$^2$
Dipole magnetic moment

\[ |\vec{m}| = \frac{B_p R^3}{2}, \]

New scale of magnetic dipole moment

\[ m = \left( \frac{3c^3 I}{8\pi^2} P \dot{P} \right)^{1/2}. \]

White Dwarf

\[ m_{WD} = 1.14 \times 10^{40} (P \dot{P})^{1/2} \text{emu}, \]

\[ B_{WD} = 4.21 \times 10^{14} (P \dot{P})^{1/2} \text{G}. \]

Magnetar

\[ m_{NS} = 3.2 \times 10^{37} (P \dot{P})^{1/2} \text{emu}, \]

\[ B_{NS} = 3.2 \times 10^{19} (P \dot{P})^{1/2} \text{G}. \]
Very Different Magnetic Field Scales

White Dwarfs

\[ B_{WD} = 4.21 \times 10^{14} (P \dot{P})^{1/2} \text{G}. \]

Magnetars

\[ B_{NS} = 3.2 \times 10^{19} (P \dot{P})^{1/2} \text{G}. \]

White Dwarf Model – no more huge magnetic fields, all undercritical !!!
SGRs and AXPs as fast rotating-powered Magnetic White Dwarf Pulsars.

The red points corresponds to recent discoveries of SGR 0418+5729 and Swift J1822.3-1606 with low magnetic field, and the green squares are the AXPs transients.
Outbursts mechanism: change of rotational energy from glitches (spin-up events).

- Conservation of angular momentum (Ruderman, 1969)
  \[
  \frac{d}{dt}(I\Omega) = 0 \Rightarrow \frac{\Delta I}{I} = -\frac{\Delta \Omega}{\Omega} = \Delta \varepsilon, \quad \varepsilon : \text{oblateness parameter} \quad I = I_o (1 + \varepsilon)
  \]

  Crab: \( \Delta \varepsilon = -\frac{\Delta \Omega}{\Omega} \approx 10^{-7} = 2\Delta R/R \Rightarrow \Delta R \approx 0.06\text{cm} \)

  **observable effects from shrinkage of less than 1mm!**
Fig. 6. Timing analysis of the glitch of 1E 2259+586 on June 2002 (from Woods et al. 2004). The vertical axis shows the evolution of the spin frequency and the horizontal axis the date time. The observed fractional change of period is $\Delta P/P \sim -4 \times 10^{-6}$ and the observed energy released during the event is $\sim 3 \times 10^{41}$ erg (Woods et al. 2004). Within the white dwarf model from such a $\Delta P/P$ we obtain $|\Delta E_{\text{rot}}^{\text{WD}}| \sim 1.7 \times 10^{43}$ erg as given by Eq. 9.
Delta $E_{\text{rot}} = -2\pi^2 I (\Delta P/P)/P^2$

**Fig. 2.** Change in the rotational energy $\Delta E_{\text{rot}}$ as a function of the rotational period $P$ of the object for different fractional period changes $\Delta P/P$. The left panel shows the case of neutron stars in the magnetar model and the right panel shows the case of white dwarfs addressed here.
# Observed and Predicted Glitches

Table 2. Glitches and Outbursts of some SGRs and AXPs within the white dwarf model.

<table>
<thead>
<tr>
<th>Date</th>
<th>SGR 0526-66</th>
<th>1E 2259+586</th>
<th>1E 1048.1-5937</th>
<th>SGR 1806-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Energy (erg)</td>
<td>3.6 × 10^{44}</td>
<td>3 × 10^{41}</td>
<td>4.2 × 10^{42}</td>
<td>~ 10^{46}</td>
</tr>
<tr>
<td></td>
<td>1.2 × 10^{-4} (predicted)</td>
<td>4.24 × 10^{-6} (observed)</td>
<td>1.63 × 10^{-5} (observed)</td>
<td>3 × 10^{-3} (predicted)</td>
</tr>
</tbody>
</table>

Predicted Energy (erg) | 3.6 × 10^{44} | 1.7 × 10^{43} | 7.7 × 10^{43} | ~ 10^{46} |

**Notes.** The predicted values of $|\Delta P|/P$ are calculated with Eq. (9) assuming $|\Delta E_{\text{rot}}^{W}$| equals the observed energy of the burst event. The predicted values of the energy released in the burst event is calculated with Eq. (9) using the observed fractional change of rotational period $|\Delta P|/P$. 
In the last years, two SGRs with low magnetic field were discovered, SGR 0418+5729 and Swift J1822.3-1606 (see N. Rea et al. 2010, 2012).

- SGR 0418+5729 with Period $P = 9.04$ s with a low surface magnetic field $B = 7 \times 10^{12}$ G.
- Large spin down: $dP/dt = 5.4 \times 10^{-15}$ s/s.
- Old star among SGRs: characteristic age $t \sim 26$ Myr
- Luminosity $L_x = 6.2 \times 10^{31}$ erg/s
- $L_x \sim 200 \, dE_{rot}/dt$
Massive and Highly Magnetized White Dwarf Pulsars.

- Catalogue of more than 100 isolated massive white dwarfs and 25% are magnetic (M. Nalezyty and J. Madej 2004)
- Four most massive white dwarfs $M > 1.3 \, M_{\odot}$ are magnetic with $B \sim (10^6 - 10^9) \, G$
- Magnetic white dwarfs have higher temperatures $T \sim 10^5 \, K$
- Similar properties of SGR 0418+5729: $P = 33 \, s$, $dP/dt = 5.64 \times 10^{-14} \, s/s$, $L_x \sim 10^{31} \, \text{erg/s} \ (< 4 \, \text{Kev})$, $B = 3 \times 10^8 \, G$, $T \sim 0.5 \, \text{KeV}$, characteristic age $t \sim 9.4 \, \text{Myr}$. 
Massive and Highly Magnetized White Dwarf Pulsars.

- More recently, X-ray multimirror mission (XMM) – Newton satellite had observed a WD pulsar faster (P=13.2 s) than AE Aquarii. Mereghetti et al. 2009 showed that the X-ray pulsator RX J0648.0-4418 is a WD with mass \( M = 1.28 M_{\text{sun}} \) and radius \( R = 3000 \) Km.

- As discussed by Mereghetti et al. 2009, the luminosity of \( L_x \sim 10^{31} \) erg/s is produced by accretion onto the white dwarf of the helium-rich matter from the wind of the companion.

- In this work, we investigate the possibility to describe RX J0648.0-4418 as a rotation powered WD.
Massive and Highly Magnetized White Dwarf Pulsars.

- EUVE J0317-855, a hydrogen-rich magnetized WD discovered as an extreme-ultraviolet (EUV) source by the ROSAT Wide Field Camera and Extreme Ultra-violet Explorer EUVE survey, is another observed WD pulsar candidates.

- Barstow et al. 1995 obtained a period of $P \approx 725$ s, which is also a fast and very magnetic white dwarf with a dipole magnetic field is $B \approx 4.5 \times 10^8$ G, and a mass $(1.31-1.37)M_{\text{sun}}$

- EUVE J0317-855 has a white dwarf companion, but is supposed to be no interaction between them, because of their large separation ($>10^3$ UA).
SIMILARITIES OF SGRs WITH LOW MAGNETIC FIELD AND WHITE DWARF PULSARS

Several features of two SGRs with low magnetic field are very similar to the ones of fast and magnetic white dwarfs recently detected.

<table>
<thead>
<tr>
<th></th>
<th>SGR 0418+5729</th>
<th>Swift J1822.3-1606</th>
<th>AE Aquarii</th>
<th>RXJ 0648.0-4418</th>
<th>EUVE J0317-855</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ (s)</td>
<td>9.08</td>
<td>8.44</td>
<td>33.08</td>
<td>13.2</td>
<td>725</td>
</tr>
<tr>
<td>$\dot{P}$ ($10^{-14}$)</td>
<td>&lt; 0.6</td>
<td>8.3</td>
<td>5.64</td>
<td>&lt; 90</td>
<td>-</td>
</tr>
<tr>
<td>Age (Myr)</td>
<td>24</td>
<td>1.6</td>
<td>9.3</td>
<td>0.23</td>
<td>-</td>
</tr>
<tr>
<td>$L_X$ (erg/s)</td>
<td>$\sim 6.2 \times 10^{31}$</td>
<td>$\sim 4.2 \times 10^{32}$</td>
<td>$\sim 10^{31}$</td>
<td>$\sim 10^{32}$</td>
<td>-</td>
</tr>
<tr>
<td>$B_{WD}$ (G)</td>
<td>$&lt; 9.83 \times 10^7$</td>
<td>$3.52 \times 10^8$</td>
<td>$\sim 5 \times 10^7$</td>
<td>$&lt; 1.45 \times 10^9$</td>
<td>$\sim 4.5 \times 10^8$</td>
</tr>
<tr>
<td>$m_{WD}$ (emu)</td>
<td>$2.65 \times 10^{33}$</td>
<td>$0.95 \times 10^{34}$</td>
<td>$\sim 1.35 \times 10^{33}$</td>
<td>$3.48 \times 10^{34}$</td>
<td>$1.22 \times 10^{34}$</td>
</tr>
</tbody>
</table>
Green cross points - X-ray pulsars. The two blue circle points - SGR 0418+5729 and Swift J1822.3-1606 considering neutron stars and white dwarfs parameters. The black full point are: RX J0648.0-4418, AE Aquarii and EUVE J0317-855. And all the other points points are polar and isolated white dwarfs (see Terada et al. 2008d, for details of these points).
Magnetic dipole moment \( m \sim (10^{34} - 10^{36}) \text{ emu} \)

- Because of the small radius of the fast and massive white dwarf comparing to normal WD, the large magnetic field of the SGRs/AXPs as white dwarfs generated a magnetic dipole moment \( m (10^{34} - 10^{36}) \text{ emu} \), exactly in the range of \( m \) for isolated and polar magnetic white dwarfs.

- The values for \( m \sim (10^{33} - 10^{34}) \text{ emu} \) of the two SGRs with low B, are exactly at the same order of the three white dwarf pulsars observed, and in the lower values of the observed isolated and polar white dwarf magnetic dipole moment range.
VI - Conclusions

- The large steady X-ray emission $L_x \sim 10^{35}$ erg/s observed in the SGRs/AXPs is now well understood as a consequence of the fast white dwarf rotation ($P \sim 10$ s), since the magnetic dipole moment $m$ is at the same scale as the one observed for the very magnetic and not so fast WDs.

- This supports the description of SGRs/AXPs as belonging to a class of very fast and magnetic massive WDs perfect in line with recent astronomical observations of fast white dwarf pulsars.
Hard and soft short Bursts of SGR 1806-20

Fig. 5  Short bursts from SGR 1806–20 observed with the IBIS instrument on board INTEGRAL (from Götz et al. 2004). Top panels light curves in the soft energy range $S = 15–40$ keV. Middle panels light curves in the hard energy range $H = 40–100$ keV. Bottom panel hardness ratios, defined as $(H - S)/(H + S)$, showing that spectral evolution is present in some burst.
Two intermediate bursts of SGR 1900+14

Fig. 9  Light curves of two intermediate flares from SGR 1900+14. Top panel August 29, 1998 (RXTE, 2–90 keV, from Ibrahim et al. (2001)). Bottom panel April 18, 2001 (BeppoSAX GRBM, from Guidorzi et al. 2004)
Three giant flares: SGR 0526-66, SGR 1900+14, and SGR 1806-20

Fig. 7 Light curves of the three giant flares from SGRs. Top panel SGR 0526–66 (Venera data in the 50–150 keV range, from Mazets et al. 1982), middle panel SGR 1900+14 (Ulysses data in the 20–150 keV range, courtesy K. Hurley), bottom panel SGR 1806–20 (INTEGRAL SPI/ACS at E > 80 keV, from Moregheiti et al. 2005). The initial peaks of the flares for SGR 0526–66 and SGR 1806–20 are out of the vertical scale.
Prediction of spin-down lower limit of SGR 0418+5729

\[
\frac{L_x P^3}{(4 \pi^2 I)} < \frac{dP}{dt} < 6.0 \times 10^{-15} \text{ s/s}
\]

\[
dP/dt > 1.18 \times 10^{-16} \text{ s/s}
\]

- Lower limit for Surface Dipolar Magnetic Field.

\[
1.05 \times 10^8 \text{ G} < B < 7.47 \times 10^8 \text{ G}
\]