Magnetars: the Universe strongest magnets

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Magnetars: the Universe strongest magnets

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and many others

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and INTEGRAL
A bit of history

• **1931** Chandrasekhar argued that WDs collapse at masses $> 1.4 \, M_\odot$. (Chandrasekhar 1931, ApJ)

• **1934** Baade & Zwicky proposed the existence of NS, they predicted their formation due to supernova explosion and their radius of $\sim 10$ km. (Baade & Zwicky 1934, Proc.Nat.Acad.Sci.)

• **1939** Oppenheimer & Volkoff defined the first equation of state for a NS of mass $\sim 1.4 \, M_\odot$, a radius of $\sim 10$ km and a density of $\sim 10^{14} \, \text{gr/cm}^3$ (Oppenheimer & Volkoff, Phys.Rev)

• **1967** Pacini predicted electromagnetic waves from rotating NSs and that such star might be powering the Crab nebula. (Pacini 1967 and 1968, Nature)

• **1967** Hewish & Bell studing interplanetary scintillation observed a periodicity of 1.337s, discovering the first pulsar: PSR 1919+21. (Hewish et al. 1968, Nature)

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The pulsar zoo

Magnetars: B-powered

XDINS: kT-powered

Pulsars and RRATs: rotation-powered

CCOs: kT-powered

Recycled binaries: rotation-powered

(courtesy of C. Espinoza)
The pulsar zoo: B-field estimates

\[ \dot{E}_{\text{rot}} = I_{ns} \Omega_s \dot{\Omega}_s = -\frac{4\pi^2 I_{ns} \dot{P}_s}{P_s^3} \]

\[ P_{\text{dip-rad}} = -\frac{2}{3c^3} |\vec{\mu}_d|^2 = -\frac{2(B_d R_{ns}^3 \sin(1 + \alpha))^2}{3c^3} \left( \frac{4\pi^2}{P_s^2} \right)^2 \]

\[ B_d \approx 3.2 \times 10^{19} \sqrt{\dot{P}_s P_s} \text{ Gauss} \]

Critical Electron Quantum B-field

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

(courtesy of C. Espinoza)
Magnetars: a decade ago…

- Magnetic fields > B critical \( \sim 4.4 \times 10^{13} \) Gauss
- X-ray luminosities exceed rotational power
- Stable soft X-ray pulsars with \( P \sim 5-10 \text{s} \) and \( L_x \sim 10^{34-35} \text{ erg/s} \)
- Radio quiet X-ray pulsars

\[
\begin{align*}
\text{Period Derivative} \left(10^{-13} \text{ s}^{-1}\right) & \quad \text{Period (s)} \\
10^{-4} & \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 1 \quad 10 \quad 100 \quad 1000 \quad 10^4
\end{align*}
\]
- Magnetic fields **NOT** always $> B_{\text{critical}} \sim 4.4 \times 10^{13}$ Gauss
- X-ray luminosities does **NOT** always exceed rot. power
- **NOT** stable soft and hard X-ray pulsars ($P \sim 0.3-10$ s and $L_x \sim 10^{30-35}$ erg/s)
- **NOT** radio quiet, but radio on during transient events

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**Magnetars: now…**

- **Magnetars**
  - Isolated Rotational-Powered Pulsars
  - High-B pulsars
  - XDINS

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**Graphs**

- Period Derivative $(10^{-15} \text{ s}^{-1})$ vs. Period (s)
  - $B_{\text{crit}}$ line
  - Hig-B pulsars
  - XDINS

- X-ray luminosity $(L_x)$ vs. Energy (keV)
  - $L_{\text{rot}} = L_x$ line
**Short bursts**
- the most common
- they last ~0.1s
- peak ~$10^{41}$ ergs/s
- soft $\gamma$-rays thermal spectra

**Intermediate bursts**
- they last 1-40 s
- peak ~$10^{41}$-$10^{43}$ ergs/s
- abrupt on-set
- usually soft $\gamma$-rays thermal spectra

**Giant Flares**
- their output of high energy is exceeded only by blazars and GRBs
- peak energy > $3\times10^{44}$ ergs/s
- <1 s initial peak with a hard spectrum which rapidly become softer in the burst tail that can last > 500s, showing the NS spin pulsations, and quasi periodic oscillations (QPOs)

(Mereghetti 2008, Rea & Esposito 2011 for a review)

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(Kaspi et al. 2003)

(Israel et al. 2008)

(Palmer et al. 2005)
Magnetar outbursts (timescale: months/years)

(updated from Rea & Esposito 2011)

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A 2.4" projected distance translates in a minimum physical separation $d = 0.09+/-0.02$ pc (90% CL) for $D=8.3$ kpc.
Magnetars have highly twisted and complex magnetic field morphologies, both inside and outside the star. The surface of young magnetars are so hot that they are bright in X-rays.

Their internal magnetic field is twisted up to 10 times the external dipole. At intervals, stresses build up in the crust which might cause glitches, flares...

Magnetar magnetospheres are filled by charged particles trapped in the twisted field lines, interacting with the surface thermal emission through resonant cyclotron scattering.

(Thompson & Duncan 1993; Thompson, Lyutikov & Kulkarni 2002; Fernandez & Thompson 2008; Nobili, Turolla & Zane 2008a,b)
1. Magnetars can be radio pulsar during outbursts.

2. A “normal” X-ray pulsar showed magnetar activity.

3. Magnetars were discovered having also low B-field.
Low magnetic-field magnetars: SGR0418+5724

Magnetic field was: $B < 7.5 \times 10^{12} \text{ G}$

$P = 9.1 \text{s}$
$P < 6 \times 10^{-15} \text{ s/s}$

Low magnetic-field magnetars: we have three now!

\[
\begin{align*}
B &= 6.2 \times 10^{12} \text{ G} \\
B &= 2.3 \times 10^{13} \text{ G} \\
B &< 4 \times 10^{13} \text{ G}
\end{align*}
\]

**SGR 0418+5729**

Esposito et al. 2010, MNRAS
Rea et al. 2010, Science

**Swift 1822-1606**


**3XMM 1852+0033**

We are filling the gap around the critical B-field

Magnetars

PSR 1846-02

Swift 1822.3-1606

3XMM 1852+0033

SGR 0418+5729

XDINS

Isolated Rotational-Powered Pulsars

Period (s)

Period Derivative (10^{-13} \text{ s s}^{-1})

B_{\text{critic}}
No critical B-field is in place between magnetars and pulsars

1- No critical field!
2- A continuum of Rotational and B-dominated pulsars
Magneto-thermal evolutionary models

Thermal evolution: energy balance equation

\[ C_v e^{\Phi(r)} \frac{\partial T}{\partial t} + \nabla \cdot (-\hat{k} \cdot \nabla (e^{\Phi(r)} T)) = e^{2\Phi(r)} Q \]

Magnetic evolution: Hall induction equation

\[ \frac{\partial B}{\partial t} = - \nabla \times \left\{ \eta \nabla \times (e^\gamma B) + \frac{c}{4\pi e n_e} \left[ \nabla \times (e^\gamma B) \right] \times B \right\} \]

Electrical resistivity: strongly depends on T

(Aguilera et al. 2008; Pons et al. 2009; Vigano' et al. 2013)
A unified scenario for different neutron star classes

(Vigano', Rea, Pons, Perna, Aguilera & Miralles 2013, MNRAS)
A unified scenario for different neutron star classes

Normal Pulsar
Initial conditions:
\[ B_{\text{dip}} \sim 10^{13} \, \text{G} \] (white lines)
\[ B_{\text{int}} \sim 10^{14} \, \text{G} \] (colors)

Very Magnetic
Initial conditions:
\[ B_{\text{dip}} \sim 10^{14} \, \text{G} \] (white lines)
\[ B_{\text{int}} \sim 10^{15} \, \text{G} \] (colors)

Extremely Magnetic Pulsar
Initial conditions:
\[ B_{\text{dip}} \sim 10^{15} \, \text{G} \] (white lines)
\[ B_{\text{int}} \sim 10^{16} \, \text{G} \] (colors)

During the outburst peak it showed a phase variable absorption feature. Different geometries can be envisaged, but our toy-model shows that the hypothesis of proton cyclotron resonant scattering in a magnetar loop is a viable scenario.

\[ E_{\text{cycl},p} = 0.6 \times B_{14} \text{ keV} \Rightarrow B \sim (2-20) \times 10^{14} \text{ G} \]

Magnetars... are starting to show up everywhere!!!

- Coalescence of compact binaries
- Super Luminous supernovae
- Gravitational waves
- ULXs
- Gamma Ray Bursts
- Super Giant Fast X-ray Transients

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Magnetars birth rate and magnetic field distribution at birth

Pulsars Population Synthesis Models using: radio pulsars and all different isolated X-ray pulsar population, comprising magnetars for the first time

$B_0 < 10^{15} \text{ G}$

1- Galactic Pulsar distribution of initial B fields cannot be a single Gaussian, and cannot exceed $10^{15} \text{ G}$ (in dipole)!

2- ~40% of the pulsar population is born with fields between $10^{14}-10^{15} \text{ G}$

(Gullon, Pons, Vigano, Rea, Perna, Miralles 2015, MNRAS)
Magnetars and Gamma-ray Bursts

- Simulating 100 SN-Type-GRBs in 1 Myr in the Milky Way we would expect to have now \( \sim 25 \) “observable” magnetars.

- HOWEVER, the expected X-ray luminosities and spin period distribution of these GRB-magnetars CANNOT be reconciled with what observed in our magnetars.

There should exist in Nature “magnetars” and “super-magnetars” if the GRB-magnetar scenario is correct in its present form.
Conclusions

- Magnetars are unique laboratories to study the effects on matter embedded in extreme magnetic fields.

- The different classes of neutron stars can be unified in a simple scenario invoking field decay and thermal evolution in objects with different initial B-field strength, configuration and age.

- The intensive follow-up of magnetar outbursts is giving every day new key discoveries, as the low field magnetars and the Galactic center magnetar.

- Population synthesis models considering for the first time all neutron star classes, including magnetars, hint to a limiting B-field at birth of $\sim 10^{15}$ Gauss.

- This limit in the B-field at birth shows that if the GRB-magnetar model is correct, there might be “magnetars” and “super-magnetars” with different origins.
BACK UP SLIDES!
GENERAL
3. Gamma-ray Bursts

GRBs may be powered by a millisecond highly magnetized pulsar.

Collapsar model for Long-GRBs

Binary mergers for Short-GRBs

(Usov 1992; Zhang & Meszaros 2002; Duncan & Thompson 1992; Dai et al. 2006; Metzger 2009; Metzger et al. 2011)
3. First multi-band Population Synthesis modelling

- Age uniformly chosen in $[0, 500 \text{ Myr}]$
- Spatial location related to OB associations of massive stars $\rightarrow$ Disk (spiral arms) + height.
- Initial velocity (“kick”) due to supernova explosion ($v \sim 500 \text{ km s}^{-1}$)
- $P_0$ and $\log B_0$ from normal distributions
- Initial inclination angle $\chi_0$ (rotational and magnetic axis) randomly selected.
- Evolution dictated by magneto-rotational models.
- Tested vacuum magnetosphere and with plasma, secular alignment or not.

B-field decay models $\rightarrow$ Monte-Carlo Simulations $\rightarrow$ 2D Kolmogorov-Smirnov test

(Fauscher-guitierre & Kaspi 2006; Gonthier et al. 2009; Popov et al. 2010, Pierbattista et al. 2012; Gullon et al. 2014)

(Gullon, Pons, Miralles, Vigano’, Rea, Perna 2015)
3. First multi-band Population Synthesis modelling

- If the origin of B-field is attributed to MHD instabilities (i.e. any dynamo process related to convection), one should expect a saturation when the B-field becomes dynamically relevant to suppress the instability.

A bi-modal distribution is preferred to explain the pulsar population + magnetars!

- This might be explained by different progenitors: binaries versus isolated? GRB-SN versus normal CC-SN?

(Gullon et al. 2015)
3. Galactic magnetars and Gamma-ray Bursts

We fitted with a plateau model all Swift GRBs (Long and Short) from launch till August 2014.

3. Galactic magnetars and Gamma-ray Bursts

We derive $B_0$ and $P_0$ for all GRBs with Swift X-ray plateaus well fit with a magnetar spin-down model.

$$T_3 \simeq \tau_{sd} = 2.05 \left( I_{45} B_{p,15}^{-2} P_{ms}^2 R_6^{-6} \right)$$

$$L_{49} \simeq L_{sd} = \left( B_{p,15}^2 P_{ms}^{-4} R_6^6 \right)$$

$$B_{0_{p,15}}^2 \simeq 4.2025 I_{45}^2 R_6^{-6} [L_{sd,49} \ast \epsilon / (1 - \cos \theta)]^{-1} \tau_{sd,3}^{-2}$$

$$P_{0_{-3}}^2 \simeq 2.05 I_{45} [L_{sd,49} \ast \epsilon / (1 - \cos \theta)]^{-1} \tau_{sd,3}^{-1}$$

(Usov 1992; Zhang & Meszaros 2002)

How these $B_0$ and $P_0$ compare with the Galactic population of magnetars we know of?


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- Age uniformly chosen in → [0, 1 Myr]
- Spatial location related to OB associations of massive stars → Disk (spiral arms) + height.
- Initial velocity ("kick") due to supernova explosion (v ~ 500 km s⁻¹)
- B₀ from GRBs distributions + Po from correlation
- Initial inclination angle χ₀ (rotational and magnetic axis) randomly selected.
- Evolution dictated by magneto-rotational models.

Radio Pulsars

Magnetars from GRB distribution

B-field decay models —> Monte-Carlo Simulations of Pulsar Population

(Gullon et al. 2014, 2015)

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Numbers ok! Simulating 100 GRBs leaving behind a stable magnetar in the past Myr in our Galaxy, correcting for selection effects we would see ~25 objects, compatible with the Galactic population of magnetars.

Properties NOT OK! HOWEVER, their current X-ray luminosities and spin period distribution CANNOT be reconciled with what observed in our magnetars!

→ B0 fields required for GRBs are WAY too large!

3. GRB-magnetars vs Galactic magnetars: conclusions

Our Galactic magnetars DOES NOT come from Gamma-ray bursts!

How many GRB-magnetars can we have in the Milky Way but missing them for selection effects?

a) Two kind of magnetar progenitors are assumed, GRB-ones being different from Galactic magnetar ones (i.e. Metallicity differences?)

a) The No. of stable magnetars produced in the Milky Way via a GRB in the past Myr should be about < 16

- Magnetars are unique laboratories to study the effects on matter embedded in extreme magnetic fields.

- The different classes of neutron stars can be unified in a simple scenario invoking field decay and thermal evolution in objects with different initial B-field strength, configuration and age.

- Our intensive follow-up of magnetar outbursts is giving everyday new key discoveries, as the Galactic center magnetar and the low-B magnetars.

- Population synthesis models considering for the first time all neutron star classes, including magnetars, hint to a limiting B-field at birth of $\sim 10^{15}$ Gauss.

- This limit in the B-field at birth shows that if the GRB-magnetar model is correct, there might be “magnetars” and “super-magnetars” with different origins.
** SN explosions and rates**
Study the neutron star population of our Galaxy and B-field distribution at birth, is crucial for SN simulations and rates. SNe should be able to form obliquously strong internal B.

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

** Gamma-ray bursts**
GRBs are believed to be strongly connected with the formation of magnetars. We are about to show that the ms-magnetar model is not consistent as it is, with the Galactic population of magnetars.

** 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.
Magnetar birth: formation

There are big uncertainties on how these huge fields are formed…

- via dynamos in the stellar core
- as fossil fields from a magnetic progenitor
- from massive star binary progenitors
- Connection with Gamma-Ray Bursts???

Observationally…

- Proper motions for ~6 objects: 200-300 km/s range
- A few magnetars coincident with massive star clusters
- One case a wind blown bouble observed in radio
- One case a run-away star close-by is detected.
- ~6 confirmed SNRs, 3 more possibly associated

(Thompson & Duncan 1993; Ferrario & Winkramasinge 2006; Clark et al. 2014)
2. How do we discover magnetars

No physical distinction between Anomalous X-ray Pulsars, Soft Gamma Repeaters, and Transient Magnetars: all showing all kind of magnetar-like activity.

- Bright X-ray pulsars with 0.5-10 keV spectra modelled by a thermal plus a non-thermal component

- Short X/gamma-ray bursts (at the beginning thought to be GRBs)

- Bright X-ray transients!

(Mereghetti 2008, Rea & Esposito 2011 for a review)
2. Magnetar birth: formation...connected with GRBs?

Some GRBs are believed to form and be powered by a millisecond highly magnetized pulsar: i.e. Millisecond-magnetars

(Usov 1992; Zhang & Meszaros 2002; Metzger et al. 2011;)
2. Magnetar flaring activity: quasi-periodic oscillations

(Israel et al. 2005; Stromayer & Watts 2006)
2. Where do we observe twisted magnetospheres

Thermal

\[ \sigma_{\text{ROS}} \sim \left( \frac{R_s}{r_e} \right) \sigma_T \sim 10^3 \sigma_T \]
\[ R_s \sim 8 R_{\text{seq}} \left( \frac{B_{\text{seq}}}{B_{\text{seq}}^0} \right)^{1/3} \left( \frac{1\text{keV}}{k\omega_e} \right)^{1/3} \]

~10^{44} \text{ erg}

~10^{42} \text{ erg}

(Pons & Rea 2012)

(Rea, Zane, Lyutikov, Turolla 2008)

(Israel et al. 2008)

(Palmer et al. 2005)
2. Magnetar outburst mechanisms: crustal heating

Varying the injected energy

Standard candles!

Varying initial quiescent luminosity

All magnetars are transient!

(Pons & Rea 2012; Rea & Pons 2015 in prep)
2. Magnetar birth: what can their SNRs tell us?

Kes73 → 1E 1841-045  
CTB109 → 1E 2259+586  
N49 → SGR 0526-66 (LMC)  
Kes75 → PSR 1846-0258

Magnetar SNRs are similar in energetics, ionization states and detectability, to normal pulsar SNRs.

2. Magnetar flaring activity: the Earth perspective

(Palmer et al. 2005)

(Manda & Balasis 2006, Geophysical Journal)
3. The Galactic Center magnetar: SGR 1745-2900

(Rea et al. 2013)

- Radio pulsed emission at DM=1750+/-50 pc cm\(^{-3}\) (the highest ever detected for a radio pulsar)

- Thermal spectrum: 0.95 keV cooled down to 0.85 keV plus faint non-thermal component

- Tiny (~1km) hot spot which temperature cools down very slowly

- Column density \(N_h = 0.98(4) \times 10^{23} \text{ cm}^{-2}\)

- Slow flux decay, a factor of 2-3 in one yr.

(Coti Zelati et al. 2015)

\[ P \approx 3.76 \text{ s} \]
\[ P_{\text{dot}} \approx 0.4 - 6.6 \times 10^{-12} \text{ s/s} \]
\[ B_{\text{dip}} \approx 2 \times 10^{14} \text{ G} \]
\[ L_{\text{sd}} \approx 5 \times 10^{33} \text{ erg/s} \]
\[ \tau_c \approx 9 \text{ kyr} \]
3. The Galactic Center magnetar: SGR 1745-2900

Proper motion from VLBA observations

Transverse velocity of 236+/-11 km/s at a position angle 22+/-2 deg East-of-North

Fraction of bound orbits from Monte Carlo N-body simulations

90% probability on average of being bound to the SMBH if born within 1 parsec.

Depending on eccentricity and semi-major axis, it can have an orbital period from a minimum of 500 yr to several kyrs.
3. The Galactic Center magnetar: SGR 1745-2900

**Crustal cooling?**

Bad modelling when injecting an energy of $10^{45-46}$ erg in the inner crust ($\rho_{IN} < \rho < \rho_{OUT}$)

Better modelling if plasmon and synchrotron neutrino emissions are switched off...BUT they should be at work!

Pons & Rea 2012

**Bombardment by magnetospheric currents?**

Currents in a bundle of twisted field lines keep slamming on to the NS surface and form a hot spot

The bundle untwists, the hot spot cools and shrinks

$L \propto A_b^{1.2}$

$L \propto A_b^2$

Beloborodov 2009

(Coti Zelati et al. 2015)
2. Not rotational power nor accretion powered
BACK UP SLIDES!
PASTA
X-ray pulsars are NOT biassed

- There are no theoretical or observational biases in the X-ray band for discovering slow X-ray pulsars!
Magnetic field decay drives spin period evolution

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2. Magnetars outburst rates

(Perna & Pons 2011; Pons & Perna 2011; Vigano’ et al. 2013)
- Changing the B-field configuration: large differences between pure crustal and core fields

(Pons, Vigano' & Rea 2013 Nature Physics 9, 431)
2. Magnetar outburst mechanisms: eventually crustal heating

1. **Internal source of heat:** Magnetic fields evolve in the crust and dissipates energy. This changes the stress balance. When the crustal shear breaking strength is exceeded by magnetic stress, the crust breaks, and elastic/magnetic energy is released.

2. **External source of heat:** Magnetic bundles are ubiquitous in magnetars. They can form and dissipate on timescales of months/years. They cause strong particles outflows, and slamming particles heating the magnetar surface.

(Thompson et al. 2002; Beloborodov 2007; Perna & Pons 2011; Pons & Rea 2012; Paffrey, Beloborodov & Hui 2013)
What is the crustal impurity: $Q_{imp}$

At densities $> 10^{13}$ gr cm$^{-3}$ nuclei are favoured in pasta shapes (rods, slabs, bubbles).

$Q_{imp} = \langle Z^2 \rangle - \langle Z \rangle^2$: In absence of more detailed calculations, $Q_{imp}$ parametrizes the crystal structure.
Constraining crustal composition

(Pons, Vigano' & Rea 2013 *Nature Physics* 9, 431)
In neutron stars, neutron heavy nuclei are found as relativistic electrons penetrate the nuclei and produce inverse beta decay, wherein the electron combines with a proton in the nucleus to make a neutron and an electron-neutrino:

\[ p + e^- \rightarrow n + \nu_e \]

As more and more neutrons are created in nuclei the energy levels for neutrons get filled up to an energy level equal to the rest mass of a neutron. At this point any electron penetrating a nucleus will create a neutron which will "drip" out of the nucleus. At this point we have:

\[ E_F^n = m_n c^2 \]

And from this point onwards the equation

\[ E_F^n = \sqrt{(p_F^n)^2 c^2 + m_n^2 c^4} \]

applies, where \( p_F^n \) is the Fermi momentum of the neutron. As we go deeper into the neutron star the free neutron density increases, and as the Fermi momentum increases with increasing density, the Fermi energy increases, so that energy levels lower than the top level reach neutron drip and more and more neutrons drip out of nuclei so that we get nuclei in a neutron fluid. Eventually all the neutrons drip out of nuclei and we have reached the neutron fluid interior of the neutron star.
In astrophysics, **nuclear pasta** is a type of degenerate matter found within the crusts of neutron stars. Between the surface of a neutron star and the quark–gluon plasma at the core, at matter densities of $10^{14} \text{ g/cm}^3$, nuclear attraction and Coulomb repulsion forces are of similar magnitude. The competition between the forces allows for the formation of a variety of complex structures assembled from neutrons and protons. Astrophysicists call these types of structures *nuclear pasta* because the geometry of the structures resembles various types of pasta.[1][2]

Nuclear pasta phases are theorized to exist in the inner crust of neutron stars, forming a transition region between the conventional matter at the surface, and the ultradense matter at the core. Towards the top of this transition region, the pressure is great enough that conventional nuclei will be condensed into much more massive semi-spherical collections. These formations would be unstable outside the star, due to their high neutron content and size, which can vary between tens and hundreds of nucleons. This semispherical phase is known as the *gnocchi phase*. 
BACK UP SLIDES!
MAGNETO-THERMAL
3. Magneto-thermal evolutionary models


Thermal evolution: energy balance equation

\[ C_v e^{\Phi(r)} \frac{\partial T}{\partial t} + \nabla \cdot \left( -\kappa \cdot \nabla \left( e^{\Phi(r)} T \right) \right) = e^{2\Phi(r)} Q \]

Magnetic evolution: Hall induction equation

\[ \frac{\partial B}{\partial t} = -\nabla \times \left( \eta \nabla \times (e^\gamma B) + \frac{c}{4\pi e n_e} \left[ \nabla \times (e^\gamma B) \right] \times B \right) \]

Electrical resistivity: strongly depends on T
Neutron star cooling models


Varying masses and microphysics varying $B$-field configuration

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3. Magnetic evolution of neutron stars: toward a unification

(Vigano', Rea, Pons, Perna, Aguilera & Miralles 2013, MNRAS)
3. Magnetars bursting rate

Can a neutron star with $6 \times 10^{12}$ Gauss dipolar field, as the low-B magnetar SGR 0418+5729, show magnetar-like outbursts and flares?

(Perna & Pons 2011; Pons & Perna 2011; Vigano’, Rea, Pons, Perna, Aguilera & Miralles 2013)
3. Magneto-thermal evolutionary models

- Neutron star model (structure, EOS)

- Thermal evolution (energy balance equation): standard theory of cooling of NSs

- Magnetic field decay and Joule heating.

- Magnetic field evolution in the crust: Hall induction equation

- Magnetic field evolution in the core: ambipolar diffusion? superconducting fluid dynamics, interaction between fluxoids and vortices? (Elfritz et al. 2015 in prep)

- Microphysics ingredients (thermal conductivity, electrical resistivity, neutrino emission processes, …)

- Elastic/plastic properties of the crust: shear modulus, breaking strength (Horowitz+: crust is much stronger than though !). Necessary to understand starquake activity.

- Put everything in a numerical code. Results from simulations.
How does temperature affect the $B$ field evolution?

- In a real NS, the crust is solid. It is appropriate to describe it as a Hall plasma, where ions have very restricted mobility and only electrons can move freely through the lattice.
- The proper equations are Hall MHD. If ions are strictly fixed in the lattice, the limit is known as EMHD (electron MHD).
- There are two basic wave modes: in the homogeneous limit (constant electron density), whistler or helicon waves, and also Hall drift waves in the inhomogeneous case.
- Transition from diffusive to hyperbolic regime depends on temperature.

Hall induction

$$\frac{\partial B}{\partial t} = -\nabla \times \left( \eta \nabla \times (e^\gamma B) + \frac{c}{4\pi n e n_e} [\nabla \times (e^\gamma B)] \times B \right)$$

Electrical resistivity strongly depends on $T$.
### Neutrino processes in the crust

<table>
<thead>
<tr>
<th>Process</th>
<th>$Q_\nu$ [erg cm$^{-3}$s$^{-1}$]</th>
<th>Onset</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Core</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified URCA ($n$-branch)</td>
<td>$8 \times 10^{21} R_n^{MU} n_p^{1/3} T_9^8$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Modified URCA ($p$-branch)</td>
<td>$8 \times 10^{21} R_p^{MU} n_p^{1/3} T_9^8$</td>
<td>1</td>
<td>$Y_p^c = 0.01$</td>
</tr>
<tr>
<td>N-N Bremsstrahlung</td>
<td>$7 \times 10^{19} R_{nn} n_n^{1/3} T_9^8$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>N-N Bremsstrahlung</td>
<td>$1 \times 10^{20} R_{np} n_p^{1/3} T_9^8$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>e-p Bremsstrahlung</td>
<td>$7 \times 10^{19} R_{pp} n_p^{1/3} T_9^8$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Direct URCA</td>
<td>$2 \times 10^{17} n_B^{-2/3} T_9^8$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td><strong>Crust</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pair annihilation</td>
<td>$e^- e^+ \rightarrow \nu \bar{\nu}$</td>
<td>$9 \times 10^{20} F_{pair}(n_e, n_e^+)$</td>
<td>4</td>
</tr>
<tr>
<td>Electron decay</td>
<td>$e^- \rightarrow e^- \nu \bar{\nu}$</td>
<td>$1 \times 10^{20} I_{pl}(T, y_e)$</td>
<td>5</td>
</tr>
<tr>
<td>Bremsstrahlung</td>
<td>$\nu \rightarrow \nu \nu \bar{\nu}$</td>
<td>$3 \times 10^{12} L_{eA} Z \rho_o n_e T_9^6$</td>
<td>6</td>
</tr>
<tr>
<td>N-N Bremsstrahlung</td>
<td>$7 \times 10^{19} R_{nn} n_n^{1/3} T_9^8$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Core and crust</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPBF</td>
<td>$\bar{B} + B \rightarrow \nu \bar{\nu}$</td>
<td>$1 \times 10^{21} n_p^{1/3} F_{AB} T_9^7$</td>
<td>7</td>
</tr>
<tr>
<td>Neutrino synchrotron</td>
<td>$9 \times 10^{14} S_{A_1 B_1 C_1} B_{13}^2 T_9^5$</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.3:** Neutrino processes and their emissivities $Q_\nu$ in the core and in the crust, taken from Aguilera et al. 2008. The third column shows the onset for some processes to operate (critical proton fraction $Y_p^c$). We indicate the normalized temperature $T_9 = T/10^9$ K; detailed functions and precise factors can be found in the references (last column).
Figure 4.7: Neutrino emissivities in the crust and in the core at the four indicated temperatures, with the chosen equation of state and superfluid gaps (see text), and mass $M = 1.4 \, M_\odot$ (no direct URCA). Lines denote: modified URCA (black solid line), $n$-$n$ Bremsstrahlung (black dots), $n$-$p$ Bremsstrahlung (black dashes), $e$-$p$ Bremsstrahlung (green solid), $e$-$A$ Bremsstrahlung (red solid), plasmon decay (short blue dashes), CPBF (blue long dashes), and $\nu$-synchrotron for $B = 10^{14} \, G$ (red dot-dashed line).
BACK UP SLIDES!
OUTBURSTS
1- Set the stage: derive the steady B-configuration, age, crustal thermal map from P, Pdot, quiescent luminosity. Magneto-thermal evolutionary models!

2. A fixed amount of energy is injected in a fraction of the crustal volume. Parameters: rate, energy and volume (depth and angular size).

— We follow the evolution of the thermal structure until it returns to the original state.
2. Low magnetic-field magnetars: outburst modelling

- SGR 0418+5729
- Varying injected energy:
  - $\sim 10^{44}$ erg
  - $\sim 10^{43}$ erg
  - $\sim 10^{42}$ erg
  - $\sim 10^{41}$ erg

- Swift 1822-1606
- Varying initial quiescent luminosity:
  - $\sim 10^{44}$ erg

(Pons & Rea 2012; Rea et al. 2012, 2013)

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Standard Candles!
External surface dipolar field from P and Pdot: $\sim 2 \times 10^{13}$ G. Magneto-thermal state consistent with a 0.5 Myr old magnetar, with crustal toroidal field of $\sim 10^{14}$ G. Outburst due to $4 \times 10^{25}$ erg/cm$^3$ injected in the outer crust on an $\sim 3$ km radius hot spot (total energy $\sim 10^{42}$ erg).
BACK UP SLIDES!
Pop Syth

- Age uniformly chosen in $[0, 500 \text{ Myr}]$
- Spatial location related to OB associations of massive stars → Disk (spiral arms) + height.
- Initial velocity ("kick") due to supernova explosion ($v \sim 500 \text{ km s}^{-1}$)
- $P_0$ and $\log B_0$ from normal distributions
- Initial inclination angle $\chi_0$ (rotational and magnetic axis) randomly selected.
- Evolution dictated by magneto-rotational models.
- Tested vacumm magnetosphere and with plasma, secular alignment or not.

B-field decay models → Monte-Carlo Simulations → 2D Kolmogorov-Smirnov test

(Nanda Rea University of Amsterdam/CSIC-IEEC)

Radio Pulsars

Monte-Carlo simulations

(Gullon, Pons, Rea et al. 2015, submitted)

Nanda Rea  University of Amsterdam/CSIC-IEEC

\[ [\mu_0, \sigma_0, \mu_{B0}, \sigma_{B0}], \alpha, Q_{\text{imp}}, \text{alignment (ON/OFF)}. \]

Best fits for period and B-field distributions at birth for radio pulsars should now be compatible with the other neutron star classes: magnetars, x-ray dim isolated neutron stars, gamma-ray pulsars, etc…

(Gullon, Pons, Rea et al. 2015, submitted)
3. First multi-band Population synthesis modelling

... but none of the Gaussian distributions that best fit the Radio Pulsars population seem to predict correctly the observed samples of the neutron star populations.

(Gullon, Pons, Rea et al. 2015, submitted)

Nanda Rea  University of Amsterdam/CSIC-IEEC
3. First multi-band Population synthesis modelling

A bi-modal distribution does work!
- This might be explained by different progenitors: binaries versus isolated? GRB-SN versus normal CC-SN?

$B_0 < 10^{15}$ G
- If the origin of B-field ia attributed to MHD instabilities (i.e. any dynamo process related to convection), one should expect a saturation when the B-field becomes dynamically relevant to suppress the instability.

(Gullon, Pons, Rea et al. 2015, submitted)
3. Simulation of B-field in proto-neutron stars

- Magnetic field configuration has strong non-dipolar components in every neutron star!

- If the origin of the neutron star magnetic field is attributed to MHD instabilities (any dynamo process related to rotation or convection), one should expect a saturation when the magnetic field becomes dynamically relevant to suppress the instability. We then expect a maximum allowed magnetic field that can be generated this way, which is indeed expected to be of the order of $10^{15}$ Gauss.

(Obergaulinger, Janka & Aloy Toras 2015, MNRAS)
Magnetar general multi-band properties

- X-ray pulsars $L_x \sim 10^{33}-10^{36}$ erg/s
- strong soft and hard X-ray emission
- short X/gamma-ray flares and long outbursts
- pulsed fractions ranging from $\sim 2$-80%
- rotating with periods of $\sim 0.3$-12s
- period derivatives of $\sim 10^{-14}$-$10^{-11}$ s/s
- magnetic fields of $\sim 10^{13}$-$10^{15}$ Gauss
- glitches and timing noise
- faint infrared/optical emission ($K\sim 20$; sometimes pulsed and transient)
- transient radio pulsed emission

(Mereghetti 2008, Rea & Esposito 2011 for a review)