Magnetars

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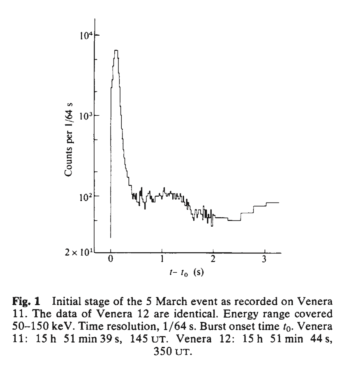
Abstract

What is the origin of neutron star magnetic fields ? Although the fossil field hypothesis (i.e. the amplification of the neutron star progenitor field by flux conservation) would be the simplest mechanism, it seems unlikely to explain the existence of magnetars, which are a peculiar type of neutron stars endowed with unusually strong dipolar magnetic fields. Their intensity is currently deduced from stellar spin-down rate measurements and estimated to be in the order of 10^{15} G, which makes them the strongest magnetic fields ever observed in the Universe. Understanding the formation process of magnetars is of particular importance, since they are believed to power a variety of outstanding explosive events observed with ongoing and future transient surveys (SVOM).

1. Historical context

A new class of galactic high-energy sources:

1979, March 5:



Soft Gamma Repeaters (SGR): detection of an enormous flare with a 8 s pulsation decaying flux strongly suggestive of a neutron-star origin, supported by its association with supernova remnants (Mazets *et al.*, ApJ).

1981: Anomalous X-ray pulsars (AXP): observation of bright X-ray pulsations at few-second periods with luminosity greater than could be explained via rotation power, and without any accreting companion.

1992: Duncan & Thompson, *Formation of very strongly magnetized neutron stars: implications for gamma-ray bursts* $\Longrightarrow$ "Detection of long-period pulses from an isolated neutron star would provide evidence for an extremely strong dipole field, although a measurement of the period derivative would be needed for corroboration."

1996: Thompson & Duncan, *SGRs as very strongly magnetized neutron stars* $\Longrightarrow$ "The identification of the AXPs with isolated magnetars leads to the prediction that these sources will eventually emit SGR bursts and perhaps extremely luminous superbursts similar to the March 5 event."

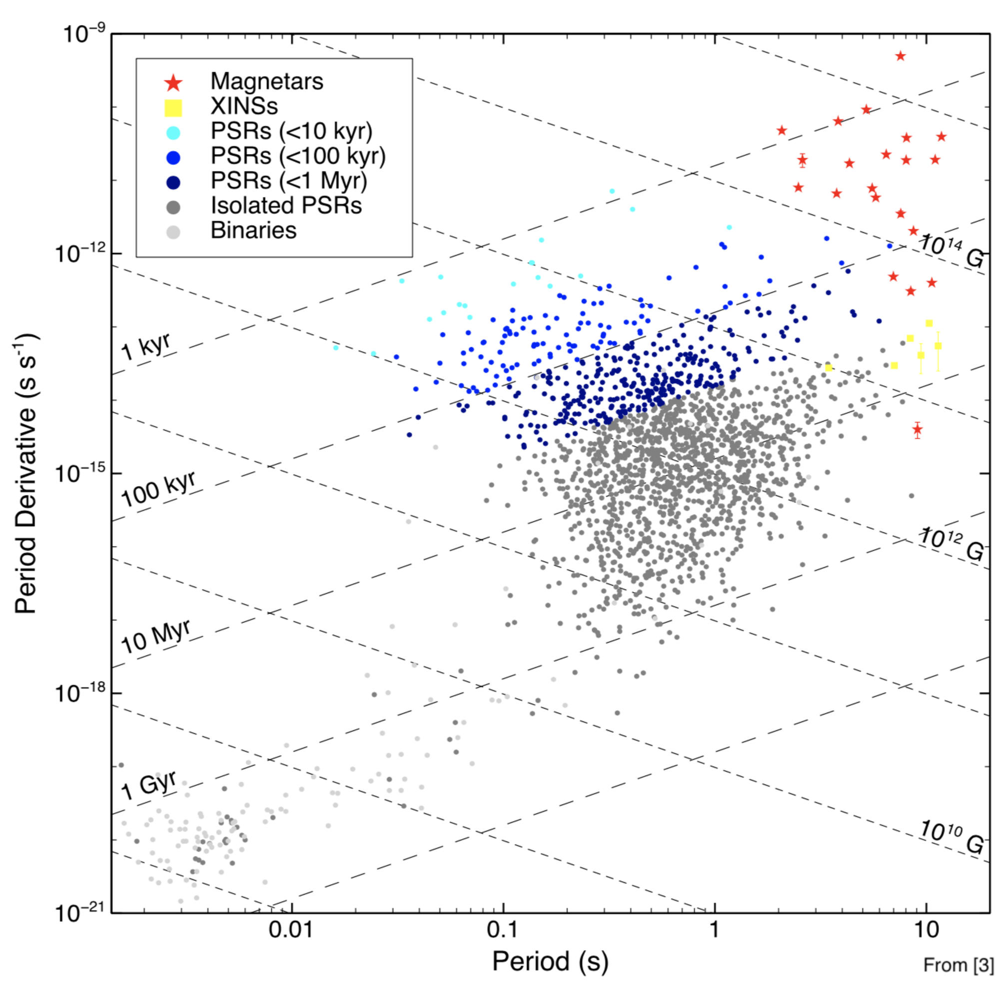
1998: Kouveliotou *et al.* $\Longrightarrow$ "Our observations demonstrate the existence of 'magnetars', neutron stars with magnetic fields about 100 times stronger than those of radio pulsars, and support earlier suggestions that SGR bursts are caused by neutron-star 'crust-quakes' produced by magnetic stresses. The 'magnetar' birth rate is about one per millennium."

2. Current overview

The dipolar model:

- magnetic field intensity $B \propto \sqrt{\dot{P}P} \sim 10^{15}$ G
- characteristic age $\tau_c \propto P\dot{P}^{-1} \sim 10^3$ yr
- spin-down luminosity $\dot{L}_{sd} \propto \dot{P}P^{-3} \sim 10^{33}$ erg s^{-1}

The $\dot{P} - P$ diagram:



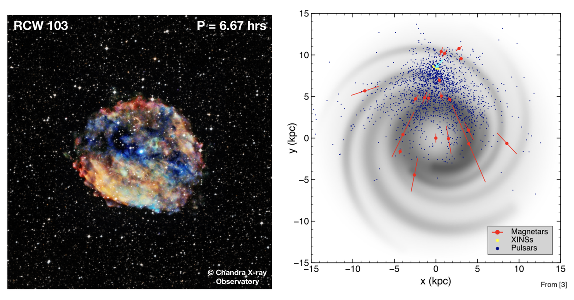
From [3]

Legend:

XINSs:	"X-ray isolated neutron stars", characterised by low X-ray luminosities, long periodicities and the lack of a radio counterpart
PSRs:	radio pulsars (rotation powered pulsars)
Binaries:	pulsar with a binary companion (white dwarf, neutron star)

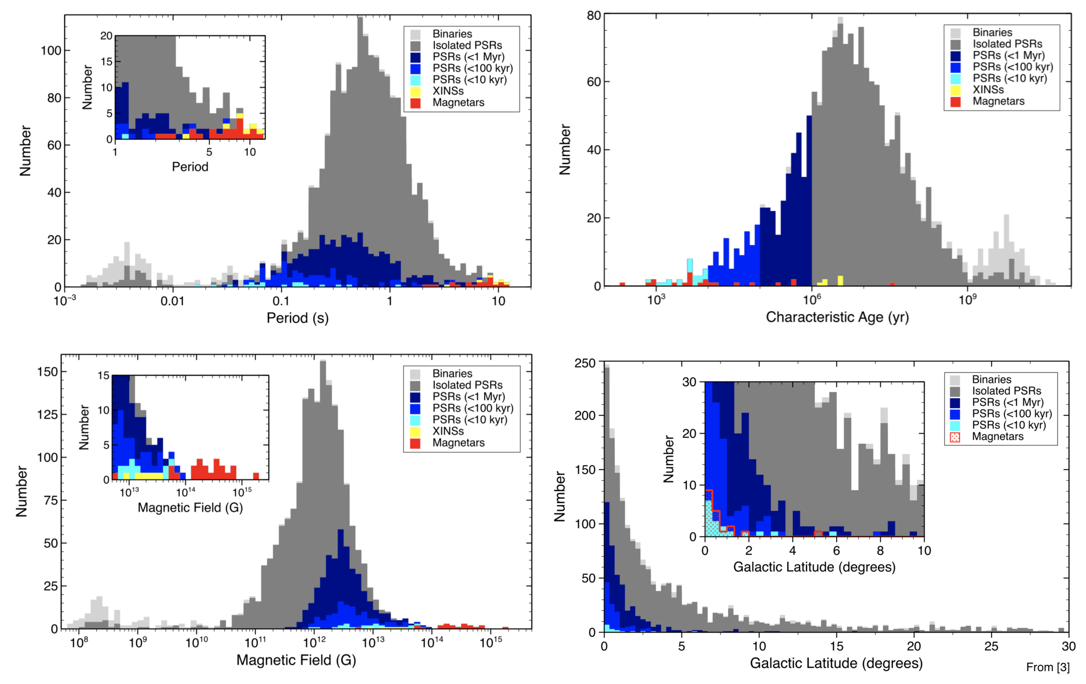
3. Magnetar characteristics

- **Distribution**



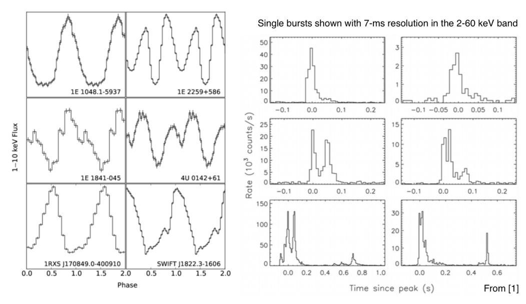
– scale height: 20 pc
– proper motion: 200 km s^{-1}
– associated with supernova remnants (~ 10 out of 23)

- **Statistical properties**



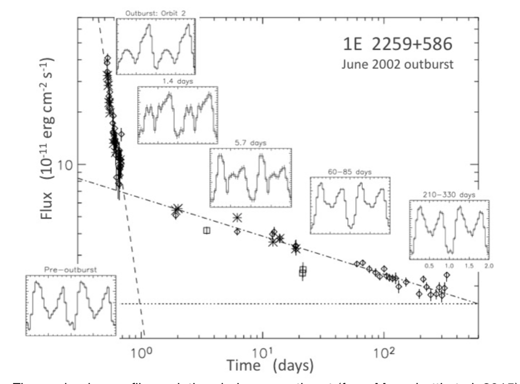
From [3]

- **Pulses and chaotic short bursts**



– diverse pulse profiles
– $\tau_{burst} \sim 100$ ms
– large spectrum in burst rates

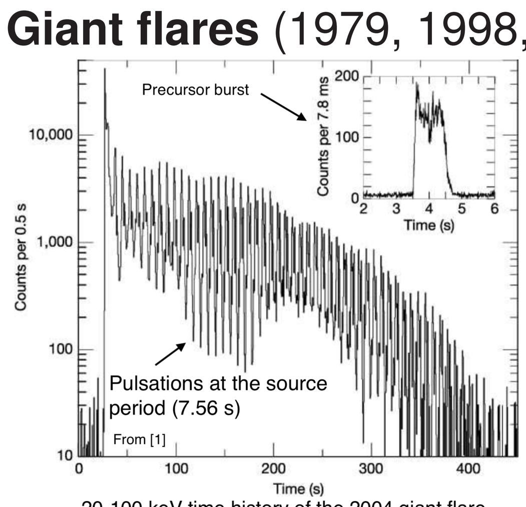
- **Outbursts:** long term flux enhancements



Flux and pulse profile evolution during an outburst (from Mereghetti et al. 2015)

– flux increase up to a factor 10^3
– $\tau_{decay} \sim$ min
– $\tau_{afterglow} \sim$ months to years
– accompanied by multiple short X-ray bursts and timing anomalies (spin-up glitches, or occasional anti-glitches)

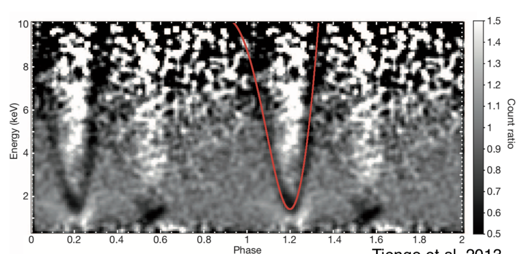
- **Giant flares** (1979, 1998, 2004)



20-100 keV time history of the 2004 giant flare

– most luminous transient yet observed in the Galaxy
– discovery of QPOs (18, 30 and 92.5 Hz) in the tail of the 2004 giant flare could give direct information on the neutron star crust and magnetic field (Israel *et al.*, 2005)

- **Outburst spectral features**



Tiengo et al. 2013

– absorption line is interpreted as a proton cyclotron feature
– suggests a strong multipolar surface field, whereas a weak dipolar component is derived from timing parameters

4. Field amplification

- **The fossil field hypothesis:** this simple scenario based on flux conservation ($B \propto \rho^{2/3}$) seems to be ruled out for magnetars because (a) only the core of the progenitor collapses to form a proto-neutron star (b) the number of main-sequence progenitors with strong enough magnetic field (10 kG) is too small (Spruit, 2009; Mereghetti *et al.*, 2015).
- **Proto-neutron star dynamos**, either driven by
  – differential rotation (Akiyama *et al.*, 2003)
  – turbulent convection [4]
- **Order of magnitudes** characterising the parameter regime of a proto-neutron star convective dynamo (based on the neutrino viscosity)

$$Rm = \frac{UL}{\eta} \sim 10^{17} \Longrightarrow \text{ quintessential fast dynamo !}$$

$$Pm = \frac{\nu}{\eta} \sim 10^{13}\,, \qquad Re = \frac{UL}{\nu} \sim 10^{4}\,,$$

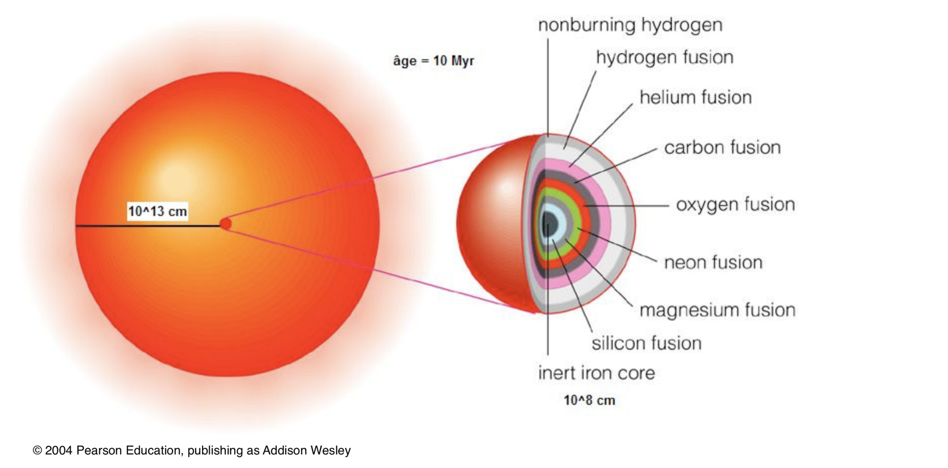
$$Pr = \frac{\nu}{\kappa} \sim 0.1\,, \qquad Ro = \frac{U}{\Omega d} \sim 1\,,$$

$$E = \frac{\nu}{\Omega d^2} \sim 10^{-4}\,.$$

Remark: the seed field is *not* infinitesimal.

5. Proto-neutron star stage

Structure of a massive star (10-30 $M_\odot$)



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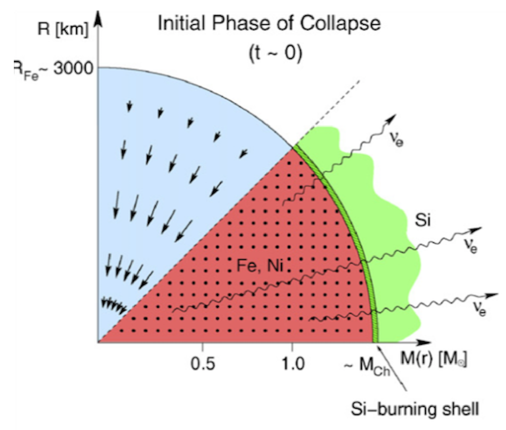
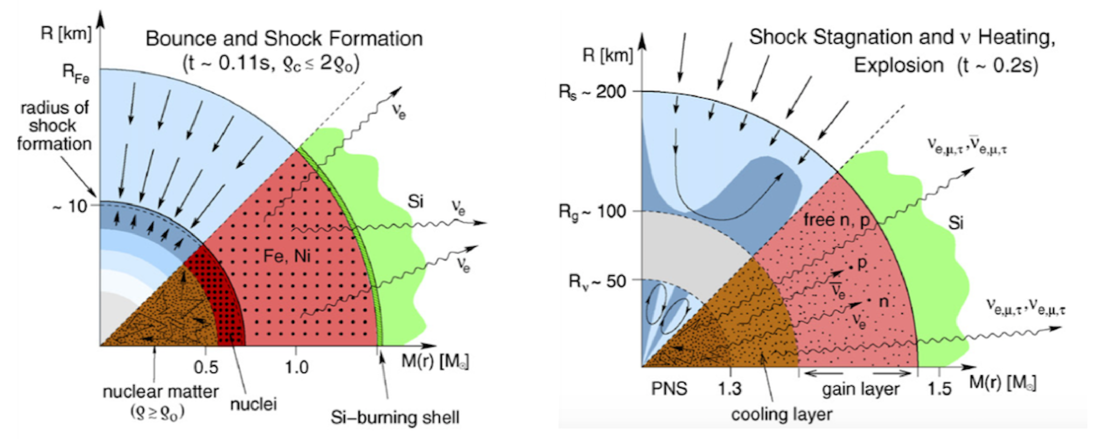


Evolutionary stages of a core-collapse supernova

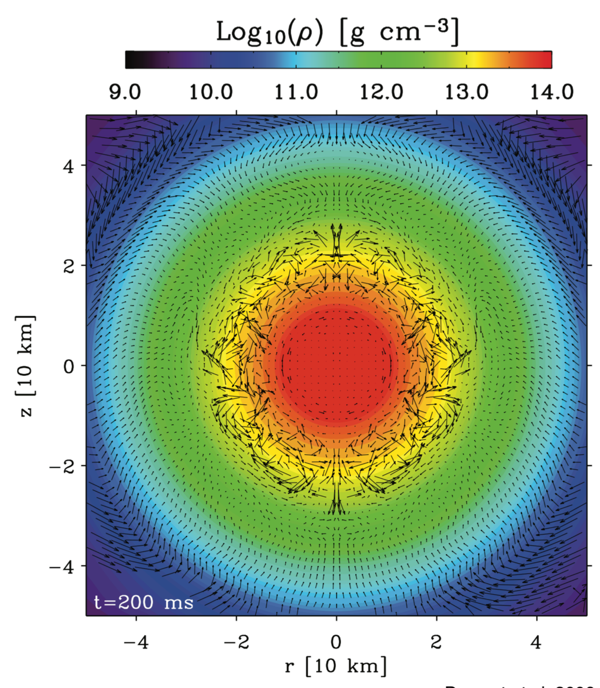
(from Janka *et al.*, 2007)



PNS convection

Right: hydrodynamic simulation of PNS convection showing the density map with the overplotted velocity field (using a diffusion approximation for the neutrino transport).

- Instability develops in a spherical shell between $R \sim 10$ and 30 km.
- Mach number $\lesssim 0.1$.



Dessart et al. 2006

"Thermo-leptonic" convection (Epstein, 1979) sets in according to the Ledoux criterion

$$\frac{dS}{dr} + \left(\frac{\partial S}{\partial Y_l}\right)_{P,\rho} \frac{dY_l}{dr} < 0\,.$$

6. Open questions

- **Initial conditions:** the progenitor mass and rotation period can be constrained by the analysis of the supernova remnant properties, but energetic considerations fail to differentiate supernova forming magnetars from standard supernova forming typical pulsars (Vink & Kuiper, 2006; Sánchez-Cruces, 2017).
- **Magnetic field strength and geometry:** X-ray spectra of neutron stars allow a measurement of magnetic field strengths. In connection to the spin-down limits, certain cases show evidence for a significantly non-dipolar structure of the magnetic field (Güver *et al.*, 2010). Moreover, a high surface dipolar magnetic field is not necessarily required for magnetar-like activity. The magnetar population may thus include objects with a wider range of B-field strengths, ages, and evolutionary stages than observed so far (Rea *et al.*, 2010). High Rossby dynamos ?
- **Birth rate problem:** birth rate estimates of the separate neutron star populations are not consistent with the galactic rate of core-collapse supernova (1.9 ± 1.1 century^{-1}) (Keane & Kramer, 2008).
- **"Grand unification"** of radio pulsars, magnetars and XINs: magneto-thermal evolution model (heating reduces the crust conductivity, leading to the coupled evolution of temperature and magnetic field [1]).

References

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