Magnetars: Pion Condensates in the Sky?

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Some References

- N.D. Hari Dass and V. Soni, Mon. Not. Royal Astron. Soc., 425, 1558-1566 (2012).
- H.B. Nielsen and V. Soni, Phys. Lett. B726, 41-44 (2013).

Neutron Stars

- *Nuclear density* $\rho_0 \simeq 2.8\ 10^{14} gm/cm^3$. Equivalently $n_0 \simeq 0.17 nucleons/fermi^3$.
- Stable neutron stars can have masses in the range 0.1 solar mass to 2 solar masses.
- Most observed pulsars have masses about 1.4 solar masses.
- Neutron stars produced in core collapse are expected with this mass.
- Heavier neutron stars are believed to be as a result of acretion later on.
- Typical radii of NS are 10 - 20 kms.
- Neutron stars can be thought of as giant nuclei with $A \simeq 10^{57}$!

Neutron Star Structure

- Density ρ decreases as one moves outwards from the centre.
- The outer kilometre or so is the Crust. It consists of a lattice of bare nuclei and a degenerate electron gas.
- Next to the crust is a superfluid layer and vortices here contribute to the angular momentum of the star.
- These vortices also play an important role in the so called glitches whence the star actually speeds up.
- The least understood part is the core of the NS. Density here can be in the range of 3-10 times nuclear density. It is also very hot. The core can be in one of the many exotic phases of high density baryonic and/or quark matter.

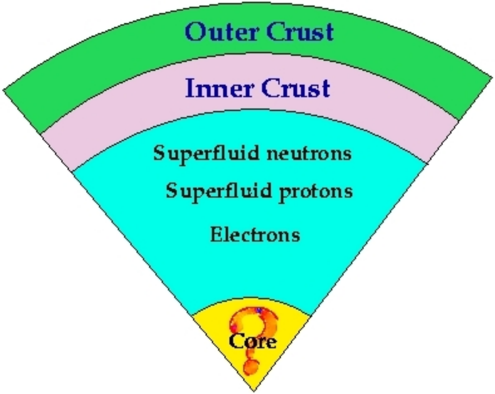

Figure: Neutron star interrior.

Other Important Properties

- The electron densities in the core and the region upto the crust are very high $\simeq 10^{36}/cm^3$ and the electrical conductivity is $\simeq 10^{28}$.
- Newly born Ns are rapidly rotating with periods of tens of milliseconds.
- This can be understood from angular momentum conservation.
- The progenitor star typically has surface magnetic fields $\simeq$ Gauss.
- As shown by Woltjer, flux conservation during collapse amplifies these to the typical neutron star surface fields of $\simeq 10^{12}$ G. We shall call these fossil or inherited fields.
- The magnetic fields make conductivity highly anisotropic.

Pulsars

- Such rapidly rotating stars with magnetic dipole moment radiate.
- The radiation is expected to be beamed from the magnetic poles.
- To a distant observer this radiation will appear pulsed.

Pulsars.

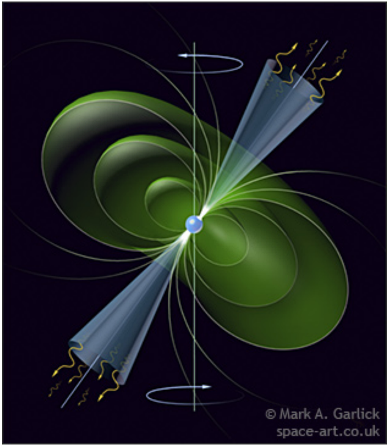

Figure: A Pulsar.

Magnetic Dipole Radiation

- The power radiated

$$\frac{2}{3}\,\omega^4\,\frac{B^2\;R^6}{c^3}$$

- The rate of rotational energy loss

$$\dot{E}_R = I\omega\dot{\omega}$$

- Spin-down rate

$$\dot{P} = \frac{2}{3}\frac{4\pi^2}{P}\frac{B^2 R^6}{c^3\;I} \qquad \tau_{SD} = \frac{P}{2\dot{P}}$$

- An important relation (using $R = 10$ Km, $I = 10^{45} gmcm^2$)

$$P\dot{P} = 9.75\;10^{-38} B^2$$

Supernova Remnants(SNR).

Figure: Ring Nebula.

Magnetars: A New Class of Neutron Stars

- Their surface magnetic fields are much larger than those of pulsars i.e $\simeq 10^{14-15}$ G.
- These are the largest ever observed fields.
- They are much more slowly rotating with periods $P \simeq 5$s.
- There is evidence that they are much hotter and also more massive than Pulsars.
- They have a considerable steady X-ray emission.
- Unlike Pulsars they exhibit bursts of energy release called flares

Flares and Varieties of Magnetars

- These flares can be extremely energetic with energies $\simeq 10^{42-46}$ ergs.
- Anomalous X-ray Pulsars(AXP) have small flares.
- Soft Gamma Repeaters(SGR) have large flares.

Tsunami Day Magnetar Flare.

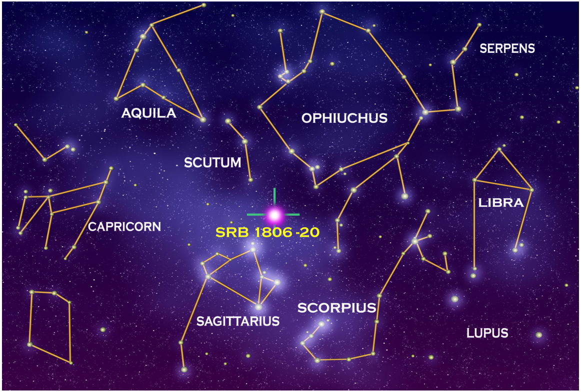

Figure: Massive Flare on 27 Dec 2004.

Tsunami Day Magnetar Flare

- In tenth of a second it put the equivalent of Sun's energy output in 150,000 years.
- Total energy $\simeq 10^{46}$ ergs.
- It disturbed the atmosphere of the earth.
- Even the part that bounced off the Moon lit up the upper atmosphere.
- Only the fact that it was 50000 light years away saved the Earth from a major catastrophe.

What supplies the energy in flares and steady X-emission?

- Rotational ($\frac{1}{2}\ I\,\omega^2$) is too meagre to source these.
- Duncan & Thomson suggested that the source is instead the magnetic energy.
- Another issue to settle is the source of the extraordinarily large magnetic fields in Magnetars.
- The origin of these fields is clearly not the same as the Pulsar magnetic fields.
- They suggested the Dynamo Mechanism, more precisely Secondary Dynamo Mechanism.
- Actually even the question of how Earth generates and sustains its magnetic field is quite a challenging one!

Difficulties with the Dynamo Mechanism

- To efficiently magnify pulsar fossil fields to Magnetar fields, P must be of the order of a ms.
- This requires massive progenitors which supports the fact that magnetars are more massive.
- But simulations show that even with very massive progenitors its hard to get P that small.
- The dynamo model would imply that magnetars acquire their large fields almost immediately after their birth and magnetic activity too starts promptly.

The Magnetar Age Crisis

- There is an independent and direct way of establishing the age of a Neutron Star.
- Its birth must coincide with the Supernova explosion and the age of the associated SNR must, if magnetic activity starts immediately upon birth, match the spin-down age.
- Observationally there appears to be a systematic offset of some 10,000 years between the SNR age, which is older, and the magnetar spin-down age.
- This is illustrated by an analysis made by Leahy et al, shown in the next figure.
- The dynamo mechanism has no way of explaining such an offset.

Observational Evidence for Age Crisis.

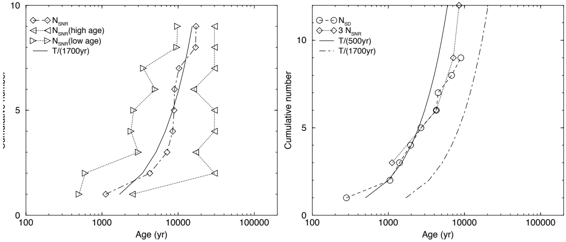

Figure: Leahy Analysis for Age Crisis.

Dynamo Model - More Difficulties

- As per the Dynamo Model the energetics of the powerful flares as well of the steady X-emissions is powered by the magnetic field.
- If so, the surface magnetic fields of magnetars must decrease with time.
- So should $\dot{P}$.
- This further implies that the spin-down age $\tau_{SD} = \frac{P}{2\dot{P}}$ is a good measure of the age of a magnetar.
- Not only is this not seen in Magnetars, there is even evidence that the opposite happens i.e the surface magnetic fields and $\dot{P}$ show phases where they increase!
- This last point has been explicitly demonstrated by us by analysing the very precise timing data of Kaspi et al in the post-glitch phase of J1846-0258.

Our Model: A Pion Condensed Core

- When baryon density exceeds 3 times nuclear density, it becomes favourable for the formation of a neutral pion condensate core. This introduces an additional term in the strong interaction hamiltonian (see next slide)

  $$\frac{G_A}{2}\,\vec{q}\cdot\vec{\sigma}\;\tau_3$$

  where $\vec{q}$ is the Pion wave-vector, σ the nucleon spin and τ the isospin ($\tau_3 = -1$ for neutrons).
- This shows that in the neutral pion condensate phase it becomes energetically favourable for all neutron spins, and hence all the magnetic moments, to align antiparallel to $\vec{q}$.
- The energy released is considerable i.e about 30 MeV per neutron. We have argued that this is sufficient to take care of all the energetics.
- The aligned magnetic moments produce an enormous magnetic field, which is estimated in the next frame.

π_0-condensate transitions: some details

- A good way to understand this transition is to look at the Chiral Sigma Model coupled to nucleons(quarks).
- This is described by the celebrated Gell Mann - Levy model:

$$\begin{aligned}\mathcal{L} &= -\bar{\psi}\{D + g(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi})\}\psi - \frac{1}{2}\{\partial_\mu\sigma^2 + \partial_\mu\vec{\pi}^2\} \\ &- \frac{\lambda}{4}\{\sigma^2 + \vec{\pi}^2 - f_\pi^2\}^2 - f_\pi^2\, m_\pi^2\,\sigma\end{aligned}$$

- For a translationally noninvariant pion-condensed configuration

$$<\sigma>= f_\pi\ \cos\vec{q}\cdot\vec{r} \qquad <\pi_3>= f_\pi\ \sin\vec{q}\cdot\vec{r} \qquad <\pi_{1,2}>= 0$$

the Hamiltonian becomes:

$$H = \frac{1}{2}f_\pi^2 + f_\pi^2 m_\pi^2(1 - \cos\vec{q}\cdot\vec{r}) + \psi^\dagger\{\frac{p^2}{2m_N} + g_A\,\vec{q}\cdot\vec{\sigma}\tau_3\}\psi$$

Consequences

- This leads to

$$E(\vec{q}) - E(\vec{q}=0) = \frac{1}{2} f_\pi^2\, q^2 - \frac{g_A}{2}\, n\, q$$

- Minimising this with respect to q yields

$$q = \frac{g_A}{2 f_\pi^2}\, n$$

- which leads to

$$E(q) - E(0) = -\frac{g_A^2}{8 f_\pi^2}\, n^2$$

Estimate of the aligned magnetic moments

- At 5 times nuclear density of $10^{15} gm/cm^3$ there are some $6\ 10^{38}$ neutrons.
- Each has a magnetic moment $\mu_N \simeq 2 \cdot \frac{e\hbar}{2m_N c} \simeq 10^{-23}$.
- This translates to a magnetic moment density $\mathbf{m} \simeq 6 \cdot 10^{15}$ and a uniform core field of $\simeq 5 \cdot 10^{16}$ G.
- Unlike magnetic fields produced by currents this field is virtually indestructible.
- Caveats: Our common thesis adviser, Raymond Sawyer (also the original discoverer of pion condensation), has pointed out that this single particle picture is too simple-minded.

Estimates...

- When filled over the fermi sea, he pointed out that magnetisation vanishes!
- I subsequently showed that this result is very general.
- But Holger Bech Nielsen and Soni have now argued that if one treats the constituent masses correctly, there is net magnetisation.
- I would say that the issue needs a very careful review.

Time evolution of Magnetic Fields in Our Model.

- As the core magnetic moment and the core field builds up, Lenz currents also rise and shield this field.
- Hence till these currents dissipate there will be no surface magnetic field apart from the fossil field.
- As the shielding currents dissipate the magnetic field in the interrior starts increasing till it reaches the fully relaxed configuration due to the core moment produced by strong interactions.
- This naturally leads to a delay in the onset of magnetar activity and explains the age crisis.
- It also predicts phases when the surface field and $\dot{P}$ increase in conformity with observations.
- This behaviour is symbolically displayed in the next two figs.

Time evolution of magnetar magnetic fields in our model.

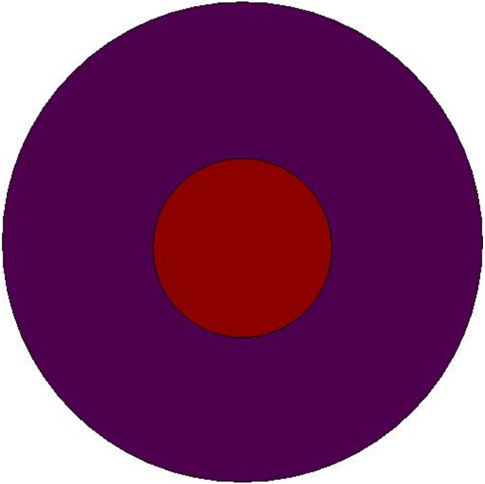

Figure: Early Magnetic Field Configuration.

Time evolution of magnetar magnetic fields in our model.

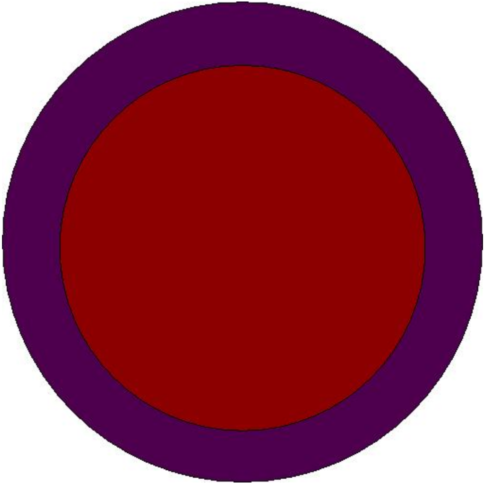

Figure: Late Magnetic Field Configuration.

Time Scales of Field Evolution.

- How exactly the shielding currents dissipate is an extremely interesting problem.
- The time scale for Ohmic Dissipation is estimated at 10^{11} years and is therefore totally irrelevant.
- There is a dissipation mechanism called Ambipolar Diffusion whose time scale is given by

  $$t_{ambi} \simeq 10^4 \; B_{16}^{-2} \; T_{8.5}^{-6}$$

  years. This, for the likely parameters of our model, works out to about 10,000 years.
- This nicely matches the offset characterising the age crisis.
- The physics of ambipolar diffusion involves plasma physics, beta equilibrium, condensed matter physics of strongly magnetised media etc...
- During the ambipolar dissipation there will be energy loss from the star in the form of neutrinos, thermal X-rays etc..

The final phase

- In the final phase, the relaxed magnetic field reaches the inner crust.
- The field gradients will be too large for the crust to sustain the magnetic stresses.
- The crust starts cleaving and field lines will start to leak out giving rise to the phase where the surface field starts increasing.
- The interior field is almost uniform.
- In the transition period the exterior field is multipolar.

Cleaving and Cracking Crust.

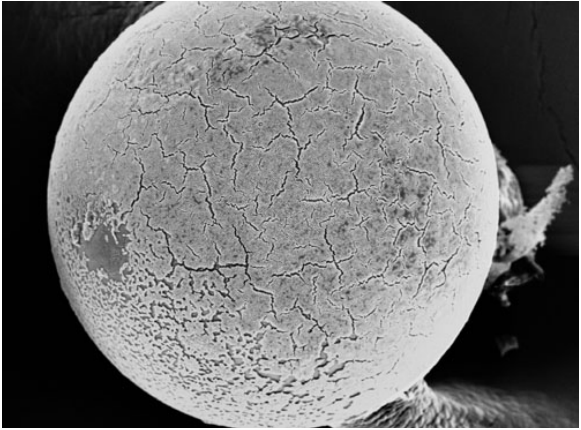

Figure: Crust yielding to Magnetic Stresses.

Direct Evidence for Field Increase

- The object J1846-0258 has been conventionally considered to be a rotation powered pulsar.
- Its $P \simeq 326ms$. and inferred field is $5 \cdot 10^{13}$ G.
- But it has a very high X-ray luminosity more characterstic of magnetars.
- Recently Gavrill et al reported a glitch accompanied by a flare in this object.

A glitch.

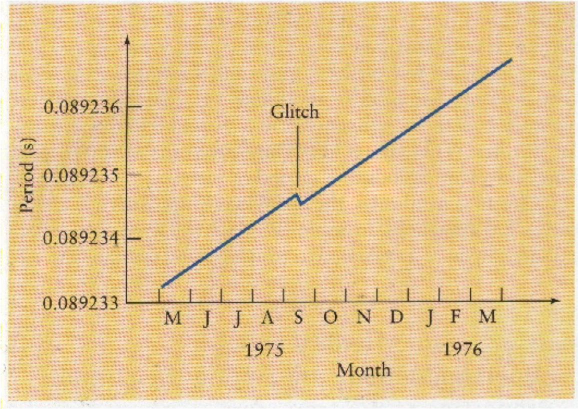

Figure: Glitches in Neutron Stars.

Post-glitch Timing Analysis of J1846-0258

- Kaspi et al carried out a very precise timing analysis of this object in the post-glitch period.
- Immediately after the glitch the stars behaviour is very complex.
- Very elaborate models for post-glitch behaviour have been proposed by Alpar, Anderson, Pines and Shaham.
- There is a good fit for an exponential decay of post glitch effects with a characterstic timescale of 127 days.
- Even after 920 days there was a persistent change in $\dot{P}$ which translates to an increase in magnetic field of about 1% per year.
- An effect with such a magnitude has never been reported in pulsars before.

Timing The Object J1846-0258.

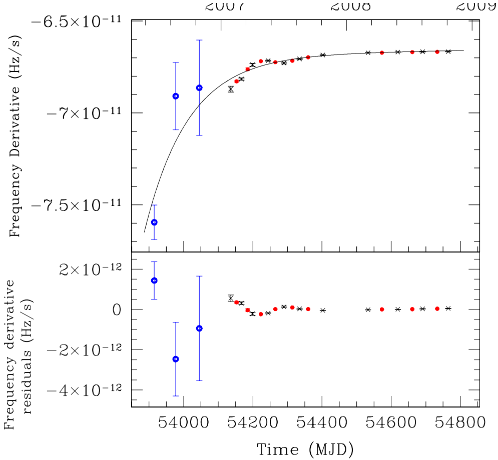

Figure: High Precision Timing Analysis of J1846-0258.

Comparison with other glitching pulsars

Table: Comparison of persistent $\Delta\dot{\Omega}/\dot{\Omega}$ of PSR 1846-0528 with those in some large-glitch pulsars.

Name	Length	τ_d	Persistent $\Delta\dot{\Omega}/\dot{\Omega}$	Source
1846-0528	920 d.	127 d.	$5.5 \cdot 10^{-2}$	Timing Data
0355+54	77 d.	44 d.	$6 \cdot 10^{-3}$	Timing Data
Vela	–	–	$3 \cdot 10^{-4}$	Breaking Index

Other explanations.

- A positive second time derivative of the moment inertia, but it is difficult to imagine any physical mechanism for that.
- A positive rate of change of the angle between the magnetic axis and the rotation axis; but no change in the consequent pulse profile has been observed.
- Plasma distortions of magnetic fields; but that would also lead to a huge increase in particle luminosity which has not been seen.
- So it is safe to ascribe this to an increase in surface magnetic field, which is what our model predicts.

Conclusions

- The first task is to critically address the magnetisation issue in pion condensates.
- Another important task is to understand better the mechanisms and time scales for surface activity.
- A careful numerical simulation of ambipolar diffusion is of great importance.
- An estimate of neutrino emission is also very important both from the theoretical and observational perspectives.