Title: Mysterious Magnetars: Maximum Stars

Date: Nov 05, 2015 11:00 AM

URL: http://pirsa.org/15110082

Abstract: <p>Magnetars are exceptional neutron stars with the highest magnetic<br>
fields ( 10^15 gauss) in the universe, an unusual quasi steady X<br>
radiation (10^35 ergs/sec) and also produce flares which are some of<br>
the brightest events (10^46 ergs in one fifth of a second) to be<br>
recorded. There is no satisfactory model of magnetars.<br>
The talk will cover neutron stars and a new model for the origin of<br>
the magnetic fields in which magnetars arise from a high baryon<br>
density ( phase transition) magnetized core which forms when they are<br>
born. The core magnetic field is initially shielded by the ambient<br>
high conductivity plasma. With time the shielding currents dissipate<br>
transporting the core field out, first to the crust and then breaking<br>
through the crust to the surface of the star. Recent observations<br>
provide support for this model which accounts for several properties<br>
of magnetars and also enables us to identify new magnetars.</p>

# Report

The explosion on the surface of a magnetar, SGR 1806-20, reached Earth from 50,000 light years away.

It was the brightest event known to have impacted this planet from an origin outside our solar system.

The magnetar, which is no more than twenty kilometers (twelve miles) in diameter, released more energy in one-tenth of a second than our sun has released in 100,000 years. A similar blast within ten light years of earth would destroy the ozone layer.

Fortunately, the nearest known magnetar to earth is 1E 2259+586, 13,000 light years (120 exameters) away. SGR 1806-20 is located in the constellation Sagittarius.

# Neutron Star Profile

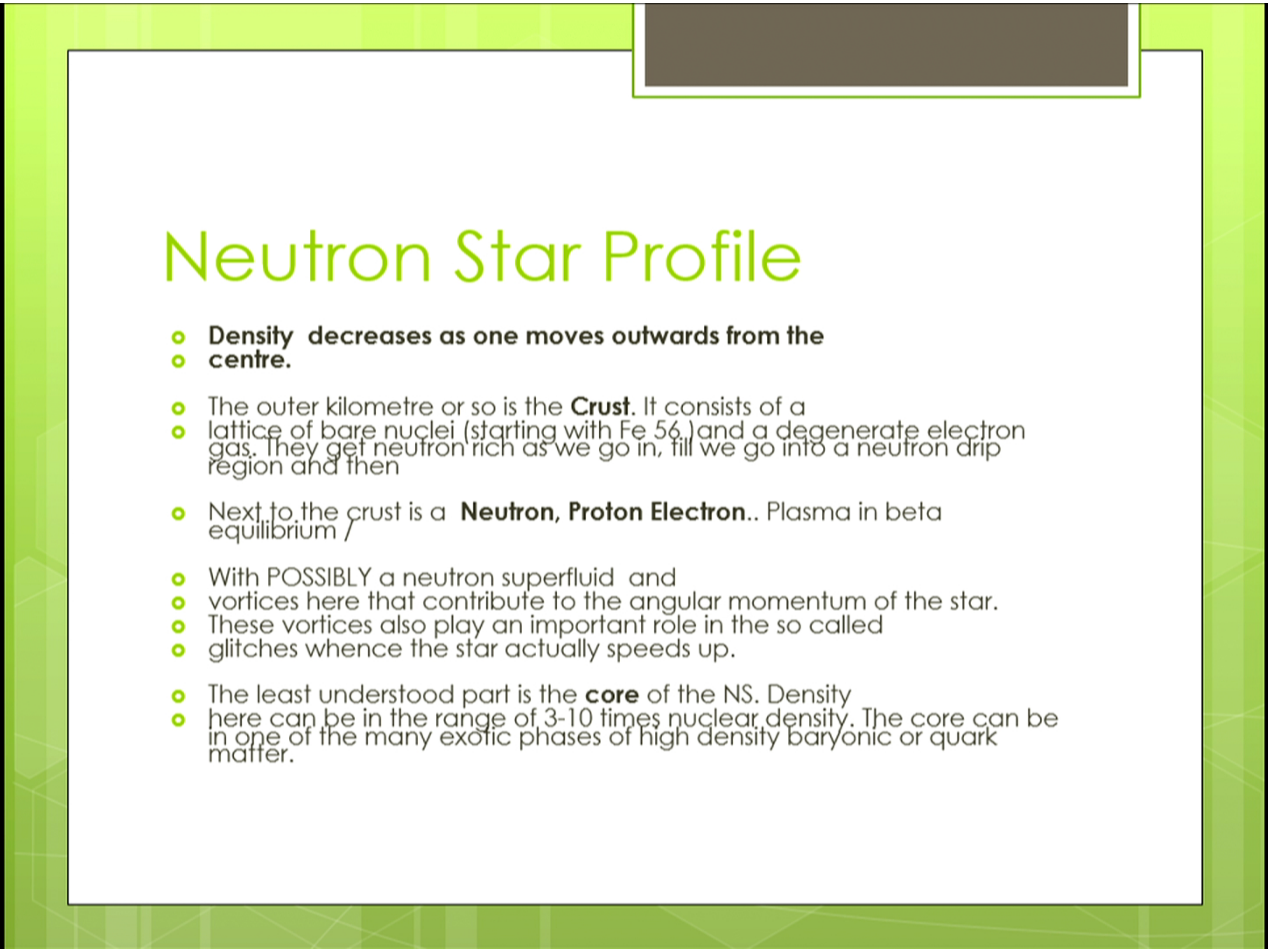
- **Density decreases as one moves outwards from the**
- **centre.**

- The outer kilometre or so is the **Crust**. It consists of a
- lattice of bare nuclei (starting with Fe 56 )and a degenerate electron gas. They get neutron rich as we go in, till we go into a neutron drip region and then

- Next to the crust is a **Neutron, Proton Electron**.. Plasma in beta equilibrium /

- With POSSIBLY a neutron superfluid and
- vortices here that 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. The core can be in one of the many exotic phases of high density baryonic or quark matter.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# Neutron Star Properties

- Radius ~ 10 KM
- Density 10^15 gm/cc ~ 1baryon / Fermi^3
- The electron densities in the core are very high ' 10^36/cc and the electrical conductivity is ' 10^28 (CGS).
- **Birth**
- Pulsar Fields
- The progenitor star (Radius ~10^6km) typically has surface magnetic fields of 1-10 Gauss.
- Collapse : High conductivity -> Flux conservation ( ~4 π R^2 B) amplifies surface B ~ 10^12(11) Gauss.
- We shall call these fossil or inherited fields.
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- An important relation (using $R = 10$ Km, $I = 10^{45} gmcm^2$)

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

# Magnetars: A New Class of Neutron Stars

- Their surface magnetic fields are much larger than those of pulsars i.e ' 10^14–10^15 G. These are the largest ever observed fields.
- They have with periods P ~ 5s -12 s. ( >pulsars)
- Unlike Pulsars they have strong steady X-ray emission :
- 10 ^34 ergs/sec.
- Unlike Pulsars they exhibit bursts of energy called flares:
- 10^41 -10^46 ergs

Unlike pulsars ( 10^6 yr ) Magnetar Ages - 10^4 years

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

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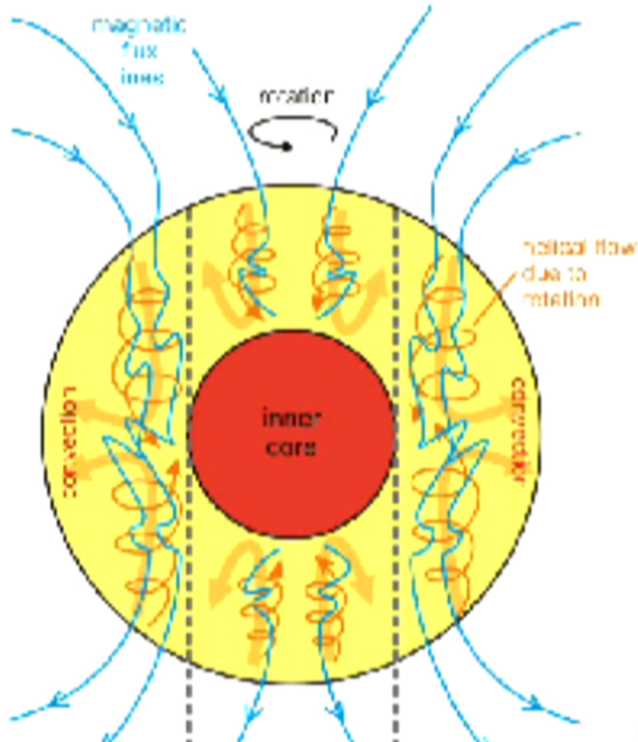
# Dynamos.


magnetic
flux
lines
rotation
helical flow
due to
rotation
inner
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convection
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# Difficulties with the Dynamo Mechanism

- To amplify pulsar fossil fields to Magnetar fields,P must be of the order of a **1** millisec.
- This requires **massive progenitors** which supports the fact
- that magnetars are more massive. But
- **Simulations(Heger etal Ap J 626 2005) and**
- **Explosion energgies (J. Vink and L. Kuiper, MNRAS 370,2006))**
- show that even with very massive progenitors its hard to get P <~5 millisec.
- In the dynamo model, magnetars acquire their large fields almost immediately after their birth and magnetic dipole radiation starts promptly.This implies that the spin-down age $\tau = P/(2dP/dt)$ is a good measure of the age of a magnetar. **BUT**

## Observational Evidence for Age Crisis.

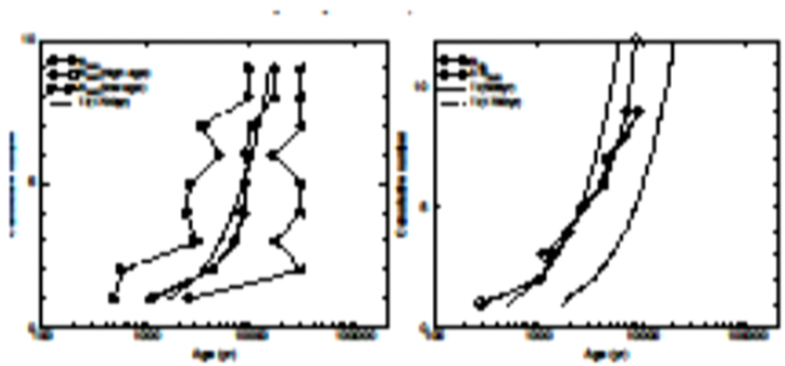
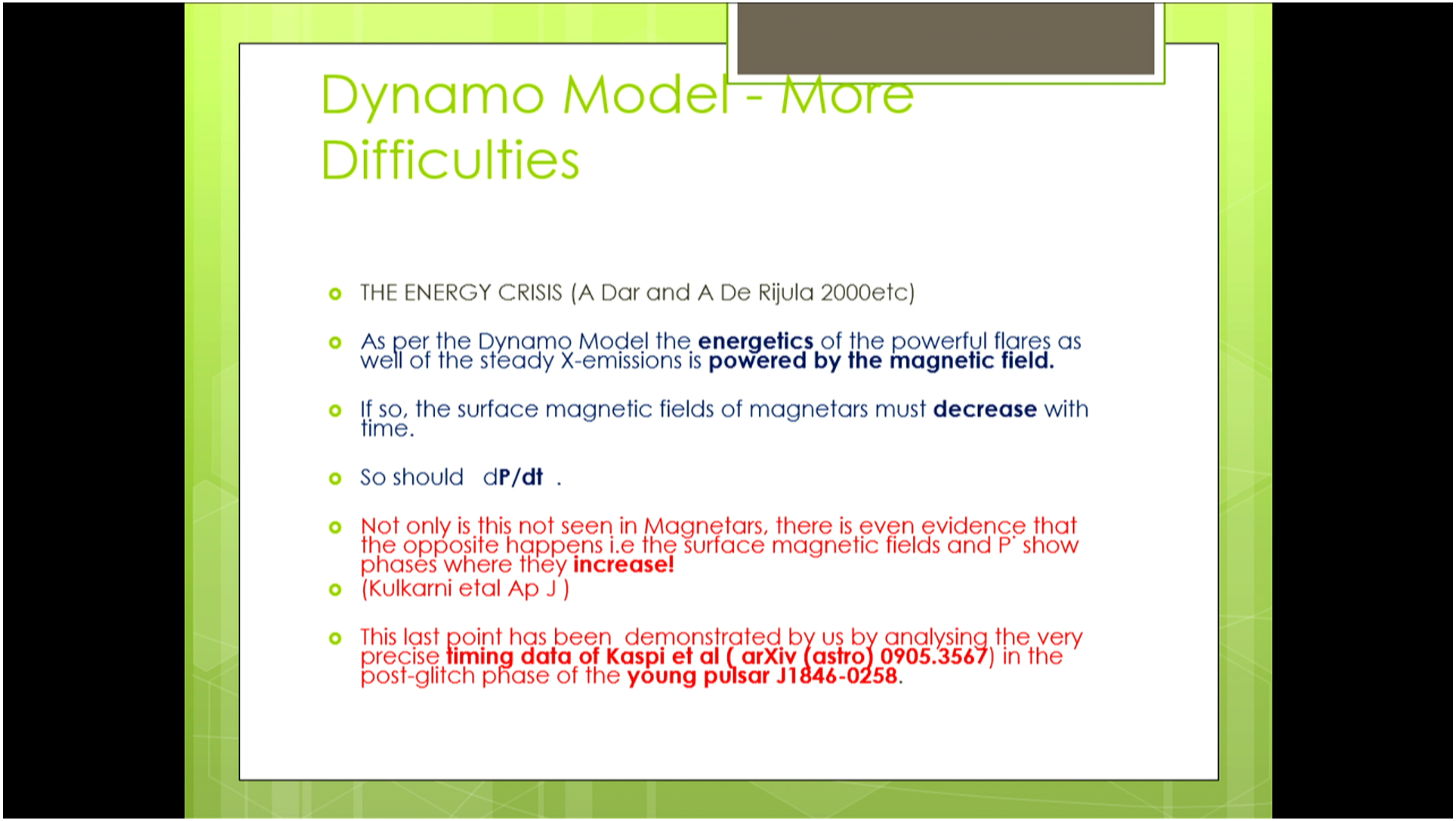


Figure: Leahy Analysis for Age Crisis.



Dynamo Model - More Difficulties
THE ENERGY CRISIS (A Dar and A De Rijula 2000etc)
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 dP/dt .
Not only is this not seen in Magnetars, there is even evidence that the opposite happens i.e the surface magnetic fields and P' show phases where they increase!
(Kulkarni etal Ap J )
This last point has been demonstrated by us by analysing the very precise timing data of Kaspi et al ( arXiv (astro) 0905.3567) in the post-glitch phase of the young pulsar J1846-0258.

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## THE MAGNETIZED CORE

This introduces an additional term in the strong interaction hamiltonian
$-\mathbf{\Sigma}.\mathbf{q}\ \tau 3$
where ~**q** is the Pion wave-vector, **Σ** the neutron spin-operator and τ3 the 3 component of the isospin.

This shows that in the neutral pion condensate phase it becomes energetically favourable for all neutron ( or u quark ) spins, and

**hence all the magnetic moments, to align antiparallel (parallel) to ~q.**
(F. Dautry and E Nyman , Nuc. Phy. A319 1979 for Nucleon matter
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Note that the minimization yields the a condensate wave vector q, that is proportional to the baryon density, n .

The negative condensate term is proportional to, n^2, whereas the kinetic energy term for the nucleons goes as, n^5/3. As the density goes up the negative condensate term dominates leading to a phase transition to the neutral pion condensed groundstate.

The strong interaction Phase Transition to the neutral pion condensate brings down the energy per baryon, E_B, by 20~30 Mev/ baryon

# Estimate of the aligned magnetic moments

- At 5 times nuclear density of 10^15 gm/cm3 there are some 10^38 neutrons per cc.
- Each has a magnetic moment
  μn = 2 · eh/2m_n c 10^(−23) (CGS).
- This translates to a magnetic moment density
- **m** = 6 · 10^15, and a uniform core field of 5 · 10^16 G.
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# Time evolution of Magnetic Fields in Our Model – Magnetzed Core.

- As the core magnetic moment and the core field builds up, ( eg islands in a first order transition) it gets oriented by the inherited/ fossil field
- **The high conductivity plasma generates Lenz currents to shield this field.**
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# ENERGY BUDGET

- I)The strong interaction Phase Transition to the neutral pion
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- So for a core of , R ~2km and density 10^39 baryons/cc

- Net energy reduction is 10^50 ergs

- II) Magnetic energy of the, R ~2km,core with B ~ 10^16 gauss
- ` E_m ~10^47(48) ergs

- III) Net energy IN SHIELDING CURRENTS > E_m

- IV) Net energy from Xray emission of 10^36 ergs per second for
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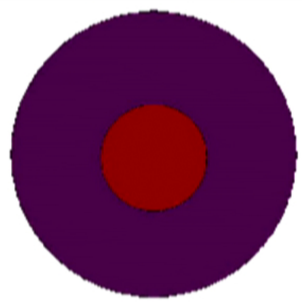

Figure: Early Magnetic Field Configuration.

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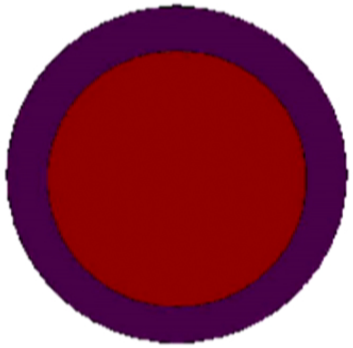

Figure: Late Magnetic Field Configuration.

N.D. Hari Dass Magnetars & Pion Condensates

## 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...
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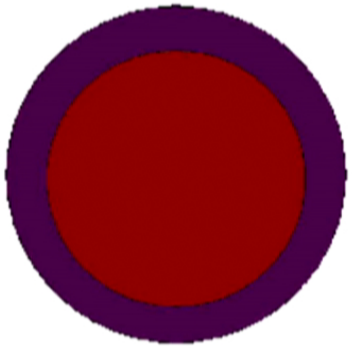

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# The phases

- Phase I
- Via ambipolar diffusion ( P. Goldreich and A Reisenegger, Ap J 395
- 1992) the relaxed magnetic field reaches the inner crust.

- Till then plasma does not allow photon propagation . T > till Neutrino emission is efficient. In this phase the magnetar has no significant EM activity like spin down

- Observational Support II
- In our model THIS IS THE REASON FOR DELAYED AMPLIFICATION AND THE
- RESOLUTION OF THE AGE CRISIS BETWEEN SPIN DOWN AGE AND SNOVA REMNANT ( SNR) AGE

- Phase II
- Once the outgoing field reaches the crust the field gradients will be too
- large for the crust to sustain the magnetic stresses.

- Observational Support III

- The crust starts cleaving and field lines will start to leak out giving rise to the phase where **the surface field starts increasing**.
- **X Radiation and Flares**

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## **Lx** and **Ế$_R$**

- Magnetic Energy in the crust shell , $\Delta R$ =1 Km
- Em ~ 4 π R^2 ΔR B^2     R ~ 10^6 cm
- Spin down age     ζ~ P/ 2( dP/dt)
- dP/dt ~ B^2
- Em/ ζ ~ 2x 10^ (-23) B^4
- B ~ 4 x 10^14 g     **Lx ~ Em/ ζ ~ 5x 10^35 erg/sec**
- **Ế$_R$** ~ 4 π^2 I ( dP/dt)/(P^3)
- **Lx**/ **Ế$_R$** 10 ~ ($B_{13}$)^2 P^2/1000

T.S. Wood and R. Hollerbach arxiv.org/pdf/1501.05149(2015)

K. N. Gourgouliatos and A. Cumming, MNRAS 438, 1618 (2014)

**Their model uses ohmic dissipation and hall drift**

**Lx ~ B ~0.4 x 10^14 g OUTSIDE CRUST -→ 0 INSIDE CRUST**

**GOES TO HALF ITS VALUE IN 0.4 MILLION YEARS**

**Lx ~ 7.5 . 10^(32) ergs/sec**

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## II PREDICTING NEW YOUNG MAGNETARS

- **Direct Evidence for Field Increase**
- **The object J1846-0258 has been conventionally**
- **considered to be a rotation powered pulsar.**

- **Its P = 326ms.**
- **$B = 5 \cdot 10^{13}$ G.**
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- Are all counter to magnetars

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# Post-glitch Timing Analysis of J1846-0258

- Livingstone, Kaspi et al (2010) carried out a very precise timing analysis of this object in the post-glitch period.
- Even after 920 days there was a persistent change in
- $\Delta\dot{\omega} / \dot{\omega} = 5.5\ 10^{-2}$
- which translates via the dipole formula to an increase in magnetic field of about $\Delta B = 0.13 . 10^{13}$ Gauss Or 1% per year.
- **Anomaly**
- **This effect is 10-1000 times in magnitude than in any pulsars**
- More evidence for a potential persistent increase in B is provided by the observed reduction in the braking index for this star, from , **n= 2.65 to 2.16**, after the FLARE, by Livingstone et al (arXiv 2010). Only plausible source is
- **dB/dt >0**