The properties of magnetized nuclear matter and its influence on the behaviour of magnetars

JPW Diener, FG Scholtz

National Institute for Theoretical Physics, Stellenbosch

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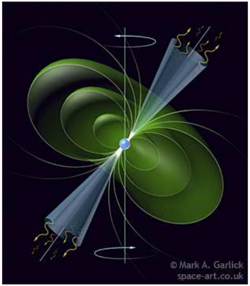
Neutron stars, pulsars and magnetars

Neutron stars are formed in core-collapse supernovae and in general have

- radii $\sim$ 10 km,
- masses $\sim 1.4\ M_\odot$,
- densities $\sim 10^{14}$g/cm^3,
- with surface magnetic fields of
  - pulsars: 10^8 - 10^{13} G
  - magnetars: 10^{14} - 10^{15} G.

Pulsars are rapidly rotating, radio-emitting neutron stars with

- rotation periods of milliseconds to seconds, and
- sudden increases in period observed ("glitches").



Pulsar illustration by Mark Garlick

Neutron stars, pulsars and magnetars continued

Magnetars are highly magnetised neutron stars.

- They are observed as AXPs and SGRs which can emit sudden burst of high energy radiation.
- Magnetic fields in the interior are projected to reach up to 10^{18} - 10^{19} G.
- Magnetars also glitch and often the glitches are accompanied by radiative events.
- Recently one (1E 2259+586) has also been observed to have an anti-glitch.

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LETTER

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An anti-glitch in a magnetar

R. F. Archibald[1], V. M. Kaspi[1], C. -Y. Ng[1,2], K. N. Gourgouliatos[1], D. Tsang[1], P. Scholz[1], A. P. Beardmore[3], N. Gehrels[4] & J. A. Kennea[5]

R. F. Archibald *et al.*, Nature **497**, 591 (2013)

Neutron star equation of state (EoS) aka the star's guts

Key to understanding neutron star behaviour is knowing its EoS.
To describe the EoS all fundamental forces have to be considered:

- nuclear interactions,
- gravity, and
- electromagnetic interactions.

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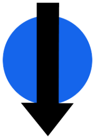
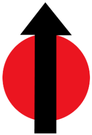


Proton/neutron with magnetic dipole moment pointing down.



Proton/neutron with magnetic dipole moment pointing up.

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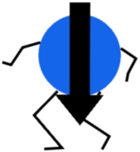

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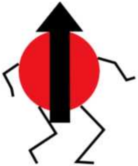

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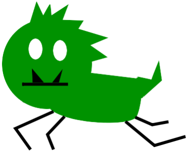

Gravity always is pulling (chasing) matter together.

  Due to the large masses and distances gravity bound the system since the nuclear interaction is short ranged.

- electromagnetic interactions.

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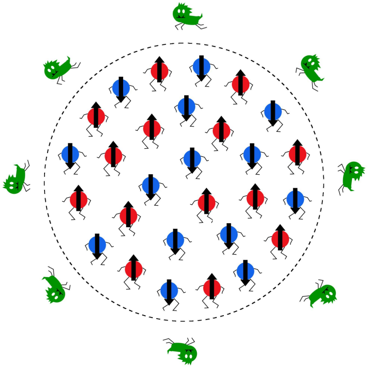

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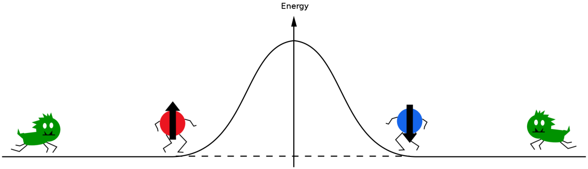
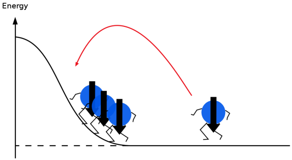
  Unmagnetized protons and neutrons have continuous energy levels.



Particles can be anywhere on the energy slope, but cannot be next to each other.

Adding particles to the system higher energy states have to be occupied.



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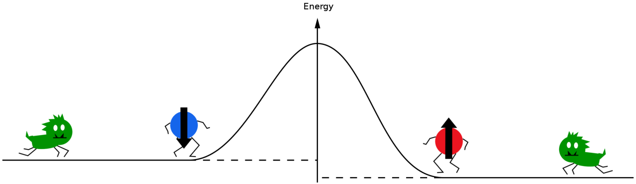
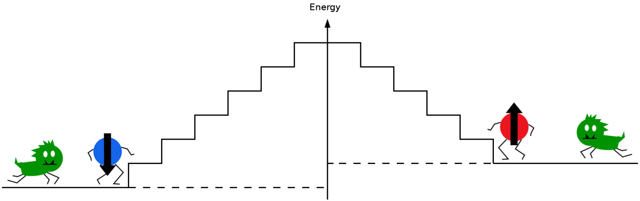
Magnetized neutrons



Magnetized protons



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In neutron stars all interactions have similar or competing length scales. Thus microscopic effects can be imprinted on the macroscopic scale.

Neutron star model

EoS is used to solve the Tolman-Oppenheimer-Volkoff (TOV) equations

$$\frac{dP(r)}{dr} = -G\frac{(\epsilon(r)+P(r))(M(r)+4\pi r^3 P(r))}{r^2(1-2GM(r)/r)}$$

$$\frac{dM(r)}{dr} = 4\pi r^2 \epsilon(r).$$

- General relativistic equations for hydrostatic equilibrium.

It is also used to calculated the moment of inertia of the star

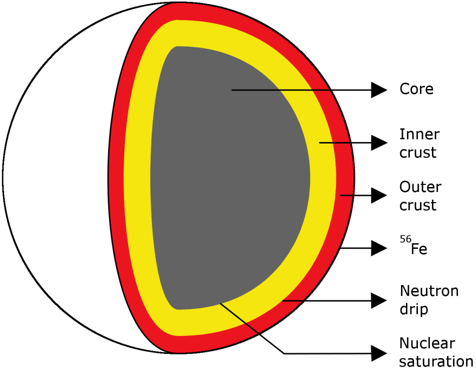
$$I = \frac{J}{\Omega} = \frac{8\pi}{3}\int_0^R r^4 e^{-\nu(r)} \frac{\bar{\omega}(r)}{\Omega} \frac{(\epsilon(r)+P(r))}{\sqrt{1-2GM(r)/r}} dr$$

in the slow rotation approximation.

If the transition density from the core to the inner crust is known, then I of the crust can be calculated.

Neutron star model continued

Very simple model of a neutron star.



Core: Nuclear matter*consisting of protons, neutrons, electrons, and muons magnetized with constant magnetic field.

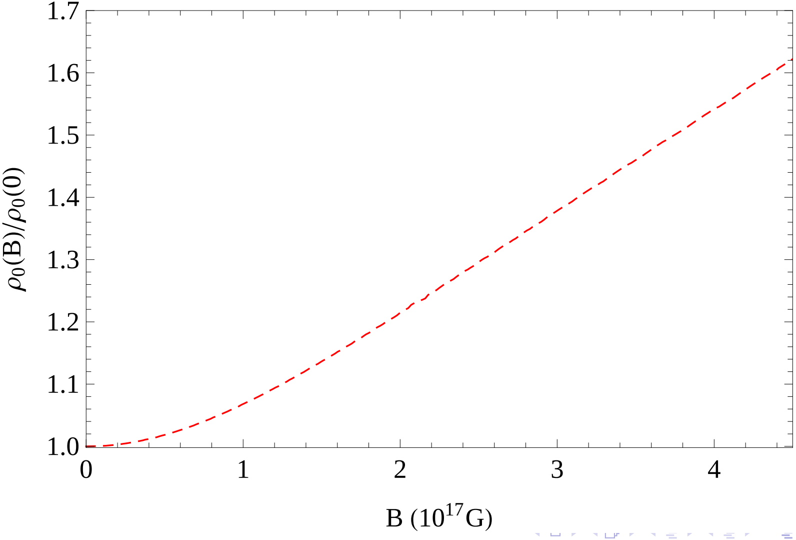
Inner crust: Magnetized polytropic EoS, $P = K\epsilon^{4/3}$.

Outer crust: BPS EoS with crystalline nuclei, assumed to be unmagnetized.

*Charge neutral β-equilibrated nuclear matter described using a relativistic description of baryons interacting via meson exchanges in the mean-field approximation.

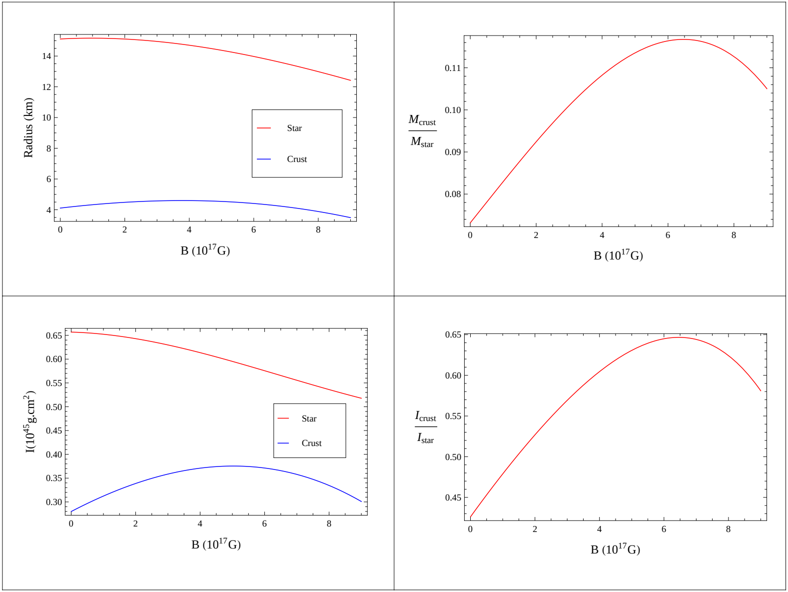
Nuclear saturation density

The nuclear saturation density increases with magnetic field, which implies that the crust will also increase.



Results

For a 1.5 $M_\odot$ neutron star

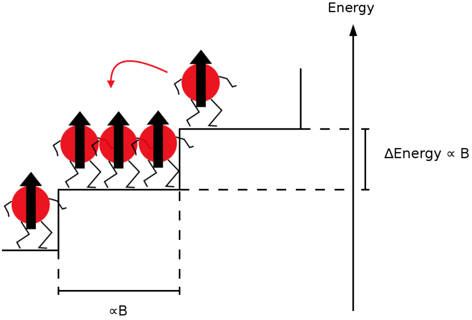


Small changes in the magnetic field in the core.

The magnetic field can undergo sudden changes if a feedback mechanism between the core structure and the magnetic field exists.

One such mechanism is a ferromagnetic phase: the magnetic field stems from particles in the core. As the density increases the system's energy levels have to reconfigure resulting to changes in the magnetic field.

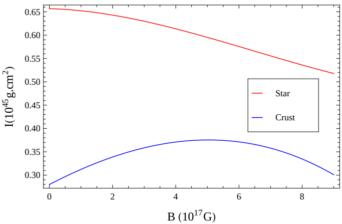
Energy levels depopulate as **B** increases and since the energy levels are discrete the energy jumps.

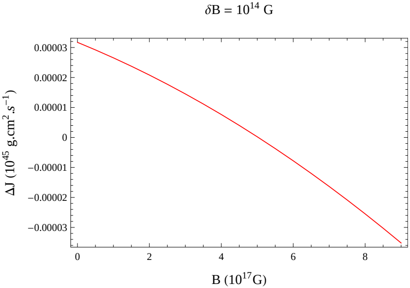


Small changes in the magnetic field in the core.

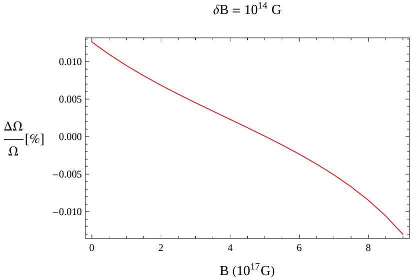
Assuming a weakly coupled, co-rotating core and crust each with angular velocity Ω.

For change in magnetic field of δB the change in crustal angular momentum is $\Delta J_{\text{crust}} = \Omega(I_{\text{crust}}(B + \delta B) - I_{\text{crust}}(B))$.





Transfer of angular momentum between the core and crust of the star for $\delta B = 10^{14}$ G.



Change in the angular velocity of the star for $\delta B = 10^{14}$ G.

Summary

- The magnetic field strengths expected in the magnetar interior can influence the properties of nuclear matter and neutron star matter.
- A sudden change in the interior magnetic field could induce a glitch or anti-glitch in the crust.
- Characteristics of the glitch is sensitive to the parameters of the model of the EoS.
- Neutron stars emit across the electromagnetic spectrum and magnetars have also been observed in the radio frequencies. Therefore find and timing magnetars's emission could lead to better understanding of their glitches and EoS.