Topological Currents in Neutron Stars

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1. **Introduction**
    - What is a topological current?
    - Why do we expect them in neutron stars?
2. **Estimating the magnitude of the current.**
3. **Applications in neutron stars**

What is a topological vector current?

They are non-dissipative currents that appear due to topological effects.

Can be derived using

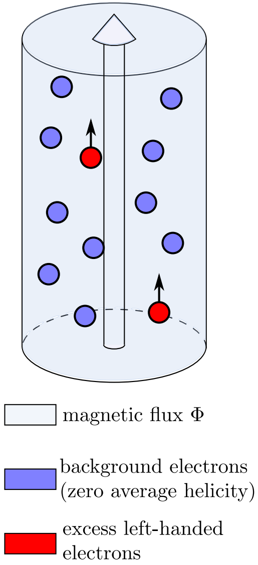
- anomalous effective lagrangians[1]
- index theorems[2]

Topological vector currents have the form

$$\langle j \rangle = (\mu_l - \mu_r)\frac{e\Phi}{2\pi^2}\,.$$

Φ = magnetic flux

$\mu_{l/r}$ = left and right handed electron chemical potential.



[1] Son and Zhitnitsky, hep-ph/0405216 (2004)

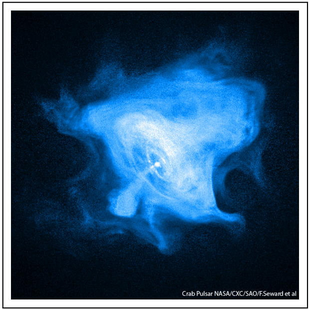
[2] Metlitski and Zhitnitsky, hep-ph/0505072 (2005)

Why do we expect currents in Neutron Stars?

Basic neutron star properties are,

- radius $R \sim 10$ km.
- cold $T_{\rm star} \sim 10^9$ K $\ll T_{\rm Fermi} \sim 10^{12}$ K.
- large magnetic field $B \sim 10^{12}$ G. *
- dense 10^{14} g/cm$^3 \to \mu_e \sim 80$ MeV. *
- equilibrium processes break P symmetry, e.g., *

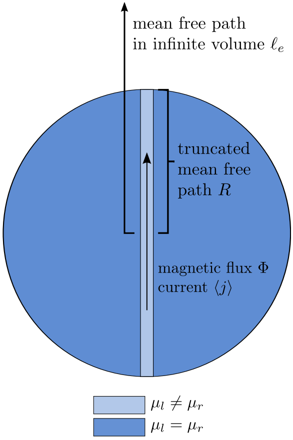
$$n + n \longrightarrow n + p + e^- + \bar{\nu}_e$$
$$n + p + e^- \longrightarrow n + n + \nu_e$$



* All the requirements for the current exist.

Estimating the magnitude of the current

1. Finite system, electrons not in equilibrium
   - the mean free path of electron with respect to weak interaction $\gg R$.
   - electron leaves the star before it decays.
2. Equation from earlier is too idealised and magnetic flux structure is non-trivial.
3. Assume the magnetic field is uniform,
   - calculate the creation rate of electrons with parity P for entire star $w/\Omega \cdot V_{star}$
   - normalise to the number of vortices N_v



We arrive at,

$$\langle j \rangle = P_{asym}(B, \mu, T) \frac{w(B, \mu, T)}{\Omega} \frac{V_{star}}{N_v}$$

How big is the current?

The dominant electron producing process is widely debated. Calculate them all.

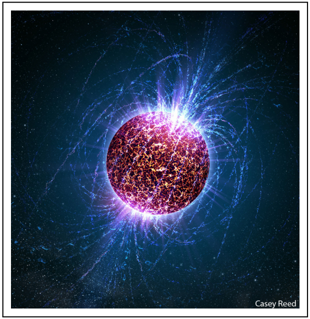
Kaon condensate, Quarks, and Direct Urca

$$\langle j \rangle \sim 10^{-9} \left(\frac{T}{10^9 \ \mathrm{K}} \right)^5 \mathrm{MeV}$$

Modified Urca

$$\langle j \rangle \sim 10^{-14} \left(\frac{T}{10^9 \ \mathrm{K}} \right)^7 \mathrm{MeV}$$

per quantum unit of flux
(or per single type-II vortex).



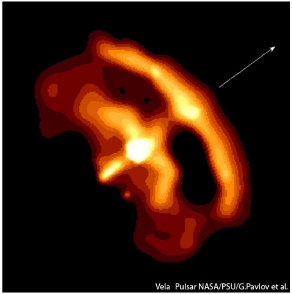
Applications: Neutron Star Kicks

Neutron stars have been "kicked";

- progenitor has proper motion ~ 30 km/s.
- neutron star motion ~ 200 km/s, with some > 1000 km/s.

Electrons exit star and transfer momentum

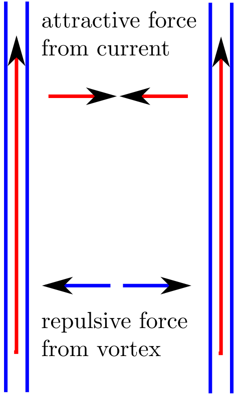
- $1000 \left(\frac{T}{10^9\ \mathrm{K}}\right)^5$ years to reach 1000 km/s
- neutron stars have thick crusts, quarks stars have thin crusts
  $\Rightarrow$ may be a way to tell them apart
- there is now an extra cooling mechanism



Applications: Precession

Neutron stars precess

- the angle of precession conflicts with type-II vortices.
- a current $j > \frac{1}{4e\lambda}$ running along type-II vortices makes them act like type-I[3]
- at $T \sim 5 \cdot 10^9$ K the current can satisfy this inequality
- may be too hot for superconductivity, thus no vortices.



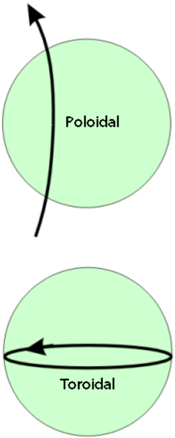
current running along type-II vortices

[3] Charbonneau and Zhitnitsky, astro-ph/0701308 (2007)

Applications: Toroidal Magnetic Field

Neutron stars have large poloidal magnetic fields $B \sim 10^{12}$ G.

- for stability a toroidal field of the same order is needed
- at $T \sim 10^8$ the modified Urca current induces $B \sim 10^{13}$ G (this includes correction for Meissner effect)
- other currents produce giant fields 10^{19} G (almost completely destroys superconductivity)



Conclusion

If there is one fact to take away from this and tell your friends it is,

> A current travels along the magnetic field in neutron stars.