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Chiral anomaly effects in pulsar magnetospheres*

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*For more details see [Gorbar & Shovkovy, arXiv:2110.11380]

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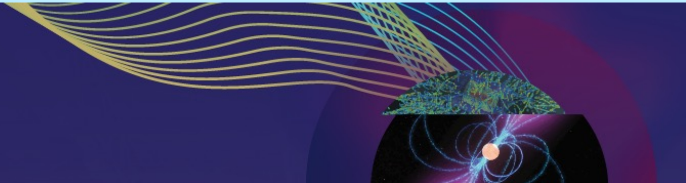
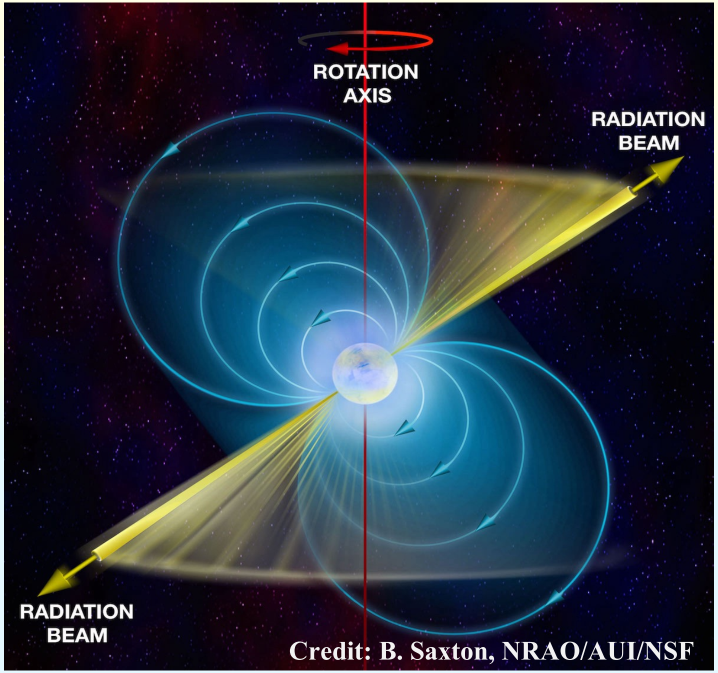


Neutron stars

- **Neutron stars** are laboratories of matter under extreme conditions

[Baade & Zwicky, *Proc. Nat. Acad. Sci.* **20**, 259 (1934)]
[Hewish, Bell, Pilkington, Scott & Collins, *Nature* **217**, 709 (1968)]

- **Neutron** stars (pulsars) are
  - rapidly rotating ($P \sim 1$ ms to 10 s)
  - very dense ($n \lesssim 10^{18}$ kg/m^3)
  - strongly magnetized ($B \sim 10^8$ to 10^{15} G)
- The pulsar **magnetosphere** is made of **hot** plasma ($T \lesssim 10$ MeV)



- **Main claim**: anomalous **chiral plasma** can be produced in the magnetosphere and can affect the pulsar activity

What is chiral plasma?

- Relativistic plasma is **chiral** if it can allow a chiral asymmetry with $n_L \neq n_R$ to exist on macroscopic time/distance scales
- Evolution of $n = n_R + n_L$ and $n_5 = n_R - n_L$ is governed by the continuity equations

$$\frac{\partial n}{\partial t} + \vec{\nabla} \cdot \vec{j} = 0$$

and

chiral anomaly

$$\frac{\partial n_5}{\partial t} + \vec{\nabla} \cdot \vec{j}_5 = \boxed{\frac{e^2 \vec{E} \cdot \vec{B}}{2\pi^2}} - \Gamma_{\mathrm{m}} n_5$$

where the chirality flip rate is $\Gamma_{\mathrm{m}} \propto \alpha^2 T (m/T)^2$, provided $T \lesssim m/\sqrt{\alpha}$

Pulsar magnetosphere

- Pulsars have highly conducting magnetospheres (their specific plasma composition is irrelevant here)
- The co-moving **electric field** in the rotating magnetosphere is

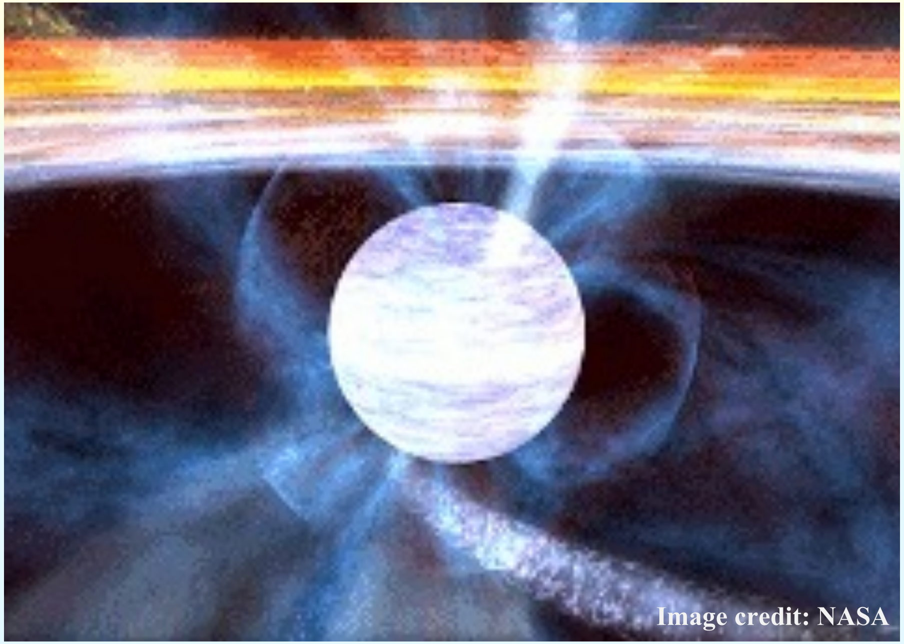
$$\vec{\boldsymbol{E}}' = \vec{\boldsymbol{E}} + \frac{\vec{\boldsymbol{\Omega}}\times\vec{\boldsymbol{r}}}{c}\times\vec{\boldsymbol{B}} = 0$$

implying that $E_{\|}=0$

- Intermittent gaps with $E_{\|} \neq 0$ develop due to charge/current starvation

[Ruderman & Sutherland, Astrophys. J. **196**, 51 (1975)]

- Background photons induce e^{+}-e^{-} plasma and close the gap



Pulsar gap parameters

- Estimate of the gap size and the electric field

  [Ruderman & Sutherland, Astrophys. J. **196**, 51 (1975)]

$$E_{\|} \simeq Bh/R_{LC}$$

where $R_{LC} = c/\Omega$ is the radius of light cylinder and

$$h \simeq 3.6\ \mathrm{m} \left(\frac{R}{10\ \mathrm{km}}\right)^{2/7} \left(\frac{\Omega}{1\ \mathrm{s}^{-1}}\right)^{-3/7} \left(\frac{B}{10^{14}\ \mathrm{G}}\right)^{-4/7}$$

The field scales with pulsar parameters as follows

$$E_{\|} \approx 2.7\times10^{-8} E_c \left(\frac{R}{10\ \mathrm{km}}\right)^{2/7} \left(\frac{\Omega}{1\ \mathrm{s}^{-1}}\right)^{4/7} \left(\frac{B}{10^{14}\ \mathrm{G}}\right)^{3/7}$$

where $E_c = m_e^2/e = 1.3 \times 10^{18}$ V/m

Chiral charge production

- When $E_{\parallel} \neq 0$, the chiral charge production is governed by

$$\frac{\partial n_5}{\partial t} \cancel{+ \vec{\nabla} \cdot \vec{j}_5} = \frac{e^2 \vec{E} \cdot \vec{B}}{2\pi^2} - \Gamma_{\mathrm{m}} n_5$$

- **Chirality flipping** tends to wash away the chiral charge produced by the **anomaly**
- In the steady-state,

$$n_5 = \frac{e^2}{2\pi^2 \Gamma_{\mathrm{m}}} \vec{E} \cdot \vec{B}$$

- For the electron-positron plasma, the chirality flipping rate is

$$\Gamma_{\mathrm{m}} \simeq \frac{\alpha^2 m_e^2}{T} \quad (T \lesssim m_e/\sqrt{\alpha}) \quad \text{or} \quad \Gamma_{\mathrm{m}} \simeq \frac{\alpha\, m_e^2}{T} \quad (T \gg m_e/\sqrt{\alpha})$$

[Boyarsky, Cheianov, Ruchayskiy, Sobol, Phys. Rev. Lett. **126**, 021801 (2021)]

Time scales

- The gap formation time

$$t_h \sim h/c \sim 10^{-8}\ \mathrm{s}$$

- Timescale for chiral charge production

$$t^\star \sim 1/\Gamma_\mathrm{m} \sim 10^{-17}\ \mathrm{s}$$

- Since

$$t_h \gg t^\star,$$

the chirality production is nearly instantaneous

Estimate for n_5 in magnetars

- The estimate for the chiral charge reads

$$n_5 \simeq \frac{e^2 E_\parallel B}{2\pi^2 \Gamma_m} \simeq 1.5 \times 10^{-5}\ \mathrm{MeV}^3 \left(\frac{T}{1\ \mathrm{MeV}}\right) \times \left(\frac{R}{10\ \mathrm{km}}\right)^{2/7} \left(\frac{\Omega}{1\ \mathrm{s}^{-1}}\right)^{4/7} \left(\frac{B}{10^{14}\ \mathrm{G}}\right)^{10/7}$$

- The corresponding chiral chemical potential is

$$\mu_5 \simeq \frac{3 n_5}{T^2} \simeq 4.6 \times 10^{-5}\ \mathrm{MeV} \left(\frac{T}{1\ \mathrm{MeV}}\right)^{-1} \times \left(\frac{R}{10\ \mathrm{km}}\right)^{2/7} \left(\frac{\Omega}{1\ \mathrm{s}^{-1}}\right)^{4/7} \left(\frac{B}{10^{14}\ \mathrm{G}}\right)^{10/7}$$

Chiral magnetic effect

- Nonzero μ_5 and $\vec{B}$ modify the local **current density**,

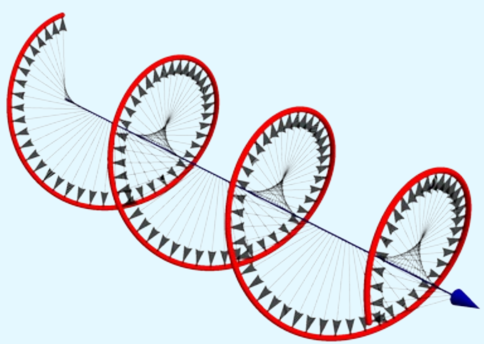
$$\vec{j} = \boxed{k_\star \vec{B}} + \sigma \vec{E}$$

chiral magnetic effect

where $k_\star = \dfrac{2\alpha\mu_5}{\pi}$ encodes the **chiral magnetic effect**

- Maxwell's equations for **helical** eigenmodes ($\lambda = \pm$) reduce to

$$\frac{d\mathbf{B}_{\lambda,k}}{dt} = \frac{1}{\sigma}\left(\boxed{\lambda k_\star k} - k^2 - \frac{\partial^2}{\partial t^2}\right)\mathbf{B}_{\lambda,k}$$



- The corresponding **frequency** solutions read

$$\omega_{1,2} = -\frac{i}{2}\left(\sigma \pm \sqrt{\sigma^2 + 4k(\boxed{\lambda k_\star} - k)}\right)$$

Chiral plasma instability

- For a highly conducting plasma ($\sigma \to \infty$)

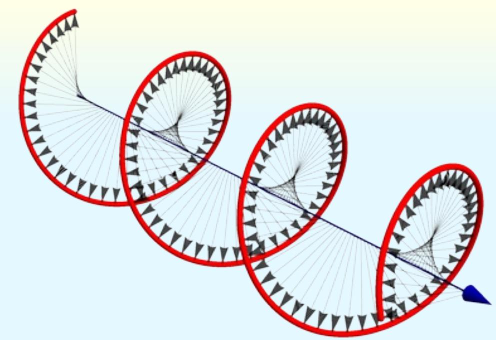
$$\omega_{1,2} \simeq \begin{cases} -i\left(\sigma + \frac{k(\lambda k_\star - k)}{\sigma}\right) \\ i\frac{k(\lambda k_\star - k)}{\sigma} \end{cases}$$

- While mode #1 is **damped** by charge screening:

$$B_{k,1} \propto B_0 e^{-\sigma t},$$

- Mode #2 is **unstable** for $k < \lambda k_\star$:

$$B_{k,2} \propto B_0 e^{+tk(\lambda k_\star - k)/\sigma}$$



- The estimate for $k_\star$ reads

$$k_\star \simeq 2.2\times 10^{-7}\ \text{MeV}\left(\frac{T}{1\ \text{MeV}}\right)^{-1}\left(\frac{R}{10\ \text{km}}\right)^{2/7}\left(\frac{\Omega}{1\ \text{s}^{-1}}\right)^{4/7}\left(\frac{\text{B}}{10^{14}\ \text{G}}\right)^{10/7}$$

Physical parameters

- Numerical estimates of the key physical parameters

B	10^{12} G	10^{13} G	10^{14} G	10^{15} G
h	50 m	13.4 m	3.6 m	0.97 m
$\frac{E_\parallel}{E_c}$	3.8×10^{-9}	1.0×10^{-8}	2.7×10^{-8}	7.3×10^{-8}
$\frac{\boldsymbol{E} \cdot \boldsymbol{B}}{E_c B_c}$	8.6×10^{-11}	2.3×10^{-9}	6.2×10^{-8}	1.7×10^{-6}
$\frac{n_5}{m_e^3}$	1.6×10^{-7}	4.3×10^{-6}	1.1×10^{-4}	3.1×10^{-3}
$\frac{\mu_5}{m_e}$	1.2×10^{-7}	3.4×10^{-6}	9.0×10^{-5}	2.4×10^{-3}
$\frac{k_\star}{m_e}$	5.8×10^{-10}	1.6×10^{-8}	4.2×10^{-7}	1.1×10^{-5}

where $B_c = m_e^2/e = 4.4 \times 10^{13}$ G and $E_c = m_e^2/e = 1.3 \times 10^{18}$ V/m

Observational consequences

- Chiral plasma produces **helical** (circularly polarized) **modes** with frequencies

$$0 \lesssim \omega \lesssim k_\star$$

- For magnetars, these span **radio frequencies** and may extend to the **near-infrared** range
- The energy estimate is $\Delta\mathcal{E} \sim \mu_5^2 T^2 h^3$,

$$\Delta\mathcal{E} \simeq 2.1 \times 10^{25}\ \mathrm{erg} \left(\frac{T}{1\ \mathrm{MeV}}\right)\left(\frac{R}{10\ \mathrm{km}}\right)^{6/7} \times \left(\frac{\Omega}{1\ \mathrm{s}^{-1}}\right)^{-9/7}\left(\frac{B}{10^{14}\ \mathrm{G}}\right)^{2/7}$$

- It may be sufficient to feed the **fast radio bursts** (FRB)

Summary of results

- **Chiral charge** production can be substantial in gap regions of strongly magnetized pulsar magnetospheres
- The chiral charge should trigger a **plasma instability** and emission of helical waves in radio to infrared range
- The corresponding chiral anomalous physics can be connected with the observed fast radio bursts
- For quantitative effects, however, further detailed studies are needed

Outstanding problems

- Interplay of chiral charge and e^+-e^- pair **production** induced by energetic photons
- The **chiral flip rate** in a magnetic field (any suppression compared to $B = 0$ case?)
- Self-consistent **simulation** of chiral plasma in the gap regions
- The **energy transfer** mechanism from unstable helical modes to observable emission