Magnetars

Brandon Shane, Arya Lakshmanan, Ina Park

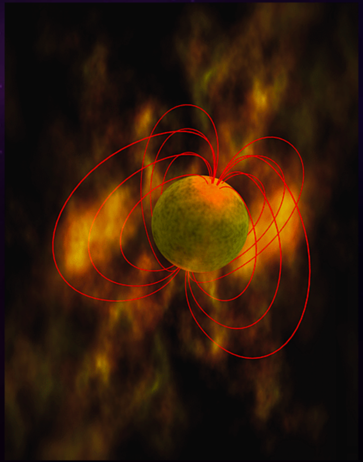
Introduction: What is a Magnetar?

- A Neutron Star +
- Extremely powerful magnetic fields are generated from magnetars
  - Magnetic field strengths near 10^14 - 10^15 G
- They are extremely rare

https://gifer.com/en/gifs/magnetars

Birth of a Magnetar

- Supernova leads to creation of neutron star
- By halving the radius, magnetic flux is quadrupled via conservation of magnetic flux
- Under the right influence of temperature, magnetic field, and spin a magnetic dynamo can form within the middle layers of the star.



https://en.wikipedia.org/wiki/Magnetar

How Does the Magnetar Work?

- Converts heat and rotational energy into magnetic energy and increasing the magnetic field strength of the progenitor star by huge factors
- Interior fluid is a neutron rich, proton superconducting state of matter
    - Superconductor allows for charges to flow with effectively 0 resistance
- The intense spinning of neutron stars makes this magnetohydrodynamic fluid much more effective at generating its dynamo based magnetic field
    - Some theories suggest that magnetars only come from stars with strong magnetic fields.
- Magnetic field strengths near 10^14 - 10^15 G
    - Sun B: 10 G
    - Earth’s B: 0. 25 - 0. 65 G
    - MRI machine B: 15,000 G

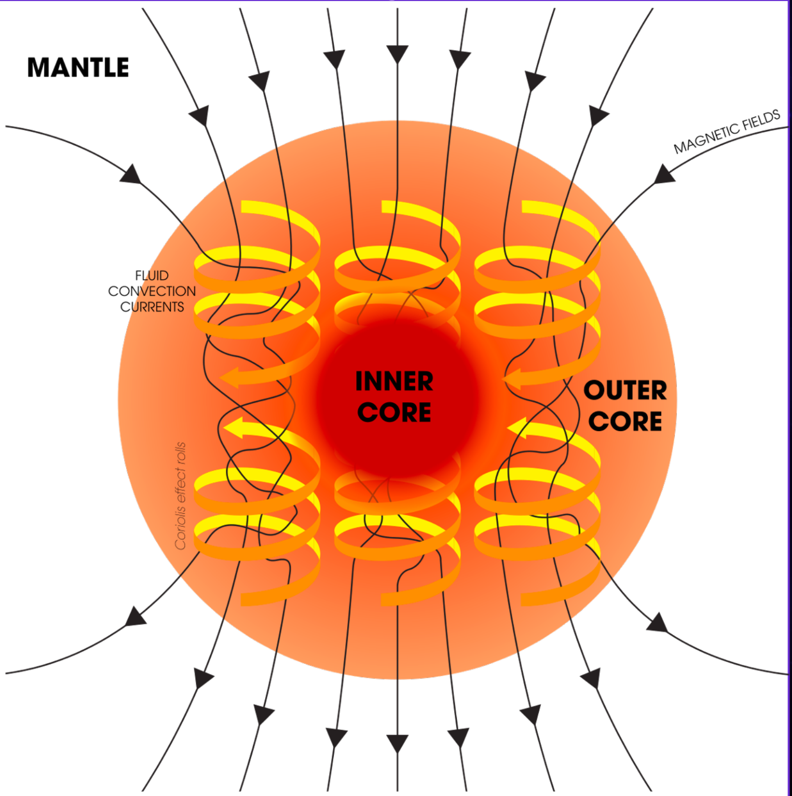
Conservation of L and ϕ

- Large massive star forms a rapidly spinning neutron star due to conservation of angular momentum
- Since the surface area has been reduced, conservation of B flux demands increased B strength
- Therefore, a pre collapse star with a large magnetic field will become a magnetar after core collapse
- A star that collapses from a radius ~10^6 km to ~10 km will drop its surface area by a factor of 10^10, so a B of 100 G becomes 10^12 G.
- Further B growth from the increased dynamo at the new rotation speed.

$$\vec{L} = m\vec{v} \times \vec{r}$$

$$\Phi \equiv \int \vec{B} \cdot \hat{n}\, da$$

The Dynamo



https://en.wikipedia.org/wiki/Dynamo_theory

Discovery and Observation

- Very very rare, even among neutron stars
    - Only about 30 have ever been discovered
- First was discovered in 1979
    - Astronomers discovered a star flashing in low gamma rays
    - Later produced a flash of gamma rays that produced 100 solar luminosities in 0.2 seconds
- A small fraction (only 5 known examples) also exhibit pulsar-like jets

Persistent Emission

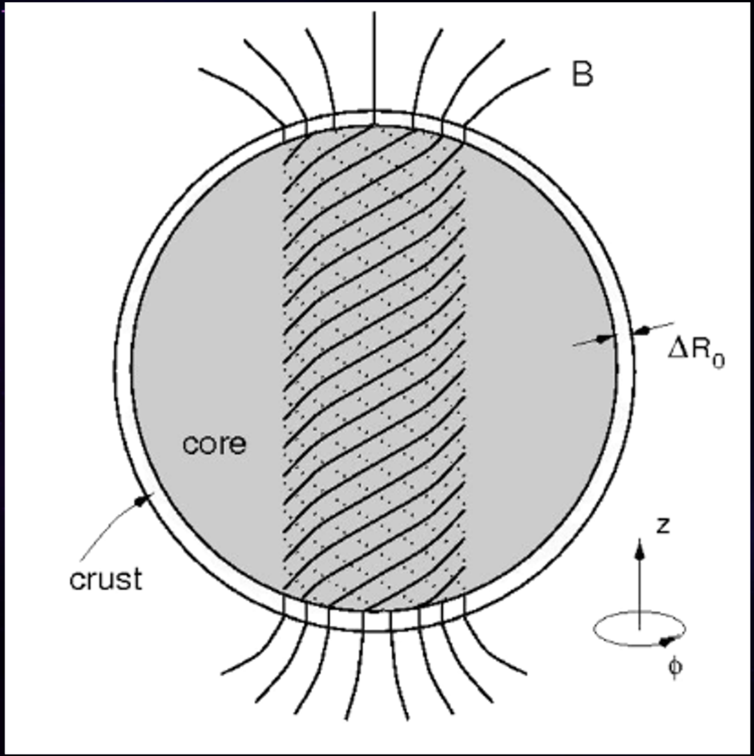
- The 1st discovered magnetar in 1979 was later found to have a persistent x-ray emission
- Found in the x-ray, and has noticeable variance
  - Gradual changes in flux and wavelength

$$L_{\rm ph}^{\rm min} \simeq 4\pi R^2 \sigma T_0^4 \simeq 3 \times 10^{35} \left(\frac{B}{4 \times 10^{15}\,{\rm G}} \right)^{4/3} \;{\rm erg\,s^{-1}}$$

- Find lower limit of B = 10^{14} G, and upper limit of B = 7 * 10^{15} G at the surface of Soft Gamma Repeaters.

Persistent Emission

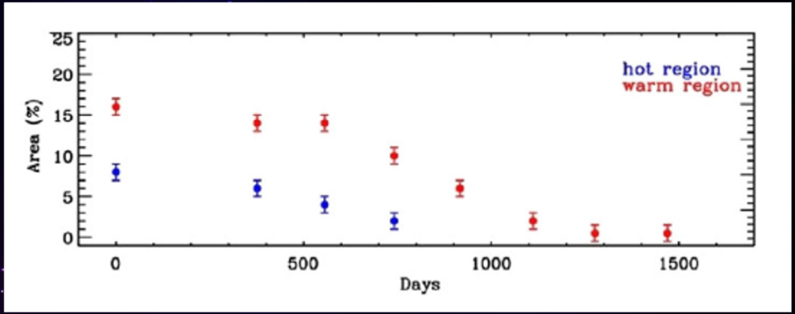
- Any stable magnetar needs both a poloidal and toroidal B field component
  - $E_p/E \lesssim 0.8$
- Charges move along closed field lines, confined to the star
  - Toroidal B field shears crust of star along equipotentials
  - This then twists the external field
- The creation and decay of magnetospheric twists can explain long term evolution
- System is unstable when field lines are too twisted



Magnetic Field with toroidal component

Transient Magnetars

- Class of magnetars with extreme variability
  - 10-1000 times x-ray flux over hours
  - Outbursts last ~1 yrs
  - Discovered in 2002
- Small hot areas close to poles responsible for increased flux
  - Small regions cannot explain all observed flux from transient magnetars
  - 0.3 - 0.9 keV (3.48 - 10.44 *10^6 K) hotter than surface average
  - Surface average temp of 0.1 - 0.2 keV



Area coverage of hot and warm regions

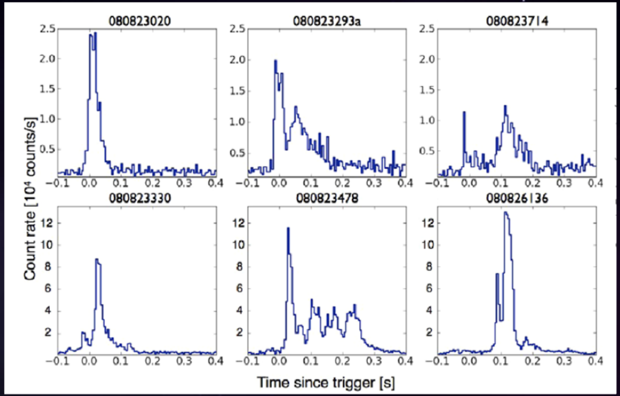
Transient Magnetars

- Proposed heating mechanisms of energy flowing from deep in the crust or currents flowing in twisted magnetosphere hitting the star.
  - Found that injecting energy deep into the crust is released in neutrinos rather than photons
  - But energy injected at crust is limited to ~10^{43} ergs
  - Decay in twist after crust displacement deposits charges onto surface, heating up displaced region
- Outbursts are associated with a subsequent transient radio emission with a delayed decay.
  - Flat radio spectrums

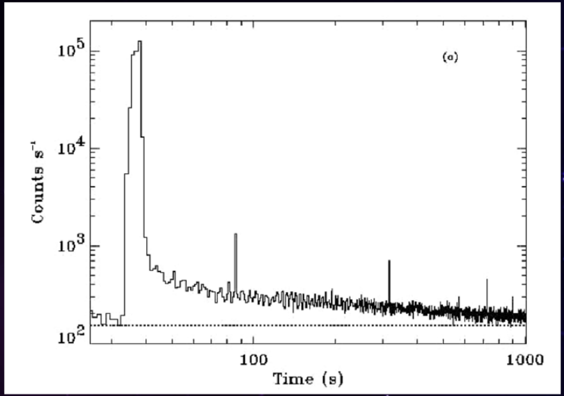
Magnetar Bursts

- Bursts
  - Sudden emission of energy in x-/gamma rays in short time spans
- 1. Short Bursts
  - Most common
  - Duration ~0.1-1s; Energies 10^{41} erg
- 2. Intermediate Bursts
  - Duration ~1-40s; Energies 10^{41}-10^{43} erg
- 3. Giant Flares
  - Rare (only 3 ever observed!)
  - Energy output: ~10^{44}-10^{47}erg
  - Long duration

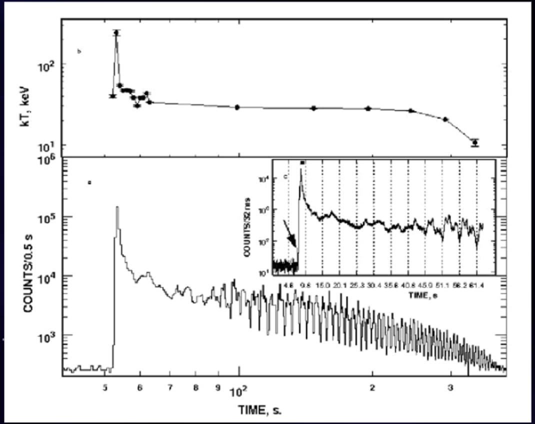
Magnetar Bursts



Short bursts from SGR 0501+4516



Intermediate burst from SGR 1900+14

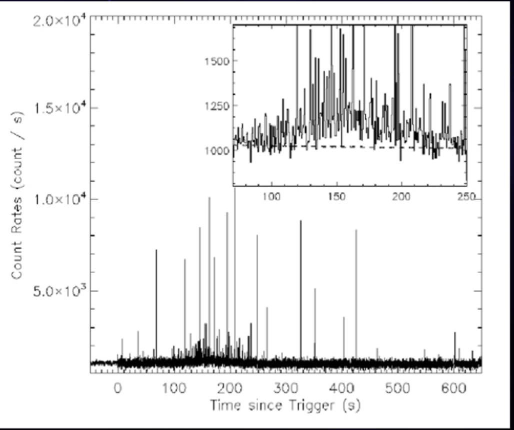


Giant Flare from SGR 1900+14

Citation: Images from Figure 21 in
R Turolla *et al* 2015 *Rep. Prog. Phys.* **78** 116901

Magnetar Bursts

- Very variable
  - Long periods of quiescence
  - Dramatic burst storms
  - Some have clear peaks, others not
    - depends on telescope
  - No clear correlation between frequency of bursts and magnetic field strength of source
- Burst storms
  - Unusually high short burst activity
    - 10s to 100s of bursts in a few hours



Burst Storm from 1E 1547.0-5408

Citation: Images from Figure 21 in
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Summary

- What a magnetar is
    - Birth
    - How it works
    - How it was discovered
- Types of magnetars
    - Persistent
    - Transient
    - Bursts

Citations

- R Turolla *et al* 2015 *Rep. Prog. Phys.* **78** 116901 https://iopscience.iop.org/article/10.1088/0034-4885/78/11/116901/pdf
- https://www.cv.nrao.edu/~sransom/web/Ch6.html
- https://en.wikipedia.org/wiki/Magnetar