Magnetars

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What are magnetars?

- Magnetically powered neutron stars
- Neutron stars with magnetic fields larger than $B_{\text{QED}} = \frac{m^2 c^3}{(e\hbar)} \approx 4.4 \times 10^{13}\text{G}$
- I will use both definitions and also focus on effects that become important as $B$ approaches $B_{\text{QED}}$. 
How do they differ?

- No pulsed radio emission - the pulsar mechanism may not work in supercritical fields (Baring & Harding ‘00) or could be geometry (long-periods $\Rightarrow$ small beam).
- X-ray and $\gamma$-ray emission in excess of spin-down energy.
- Strong bursts of soft-gamma rays - biggest explosions that repeat
How does the physics differ?

- Magnetic stresses exceed yield stress of the crust (Thompson & Duncan ‘96)
- Atoms strongly distorted; may condense at $P=0$.
- Radiative corrections of QED may be important.
The physics is messy.
Outline

• Thermal emission
  – What comprises the atmosphere?

• Non-thermal emission
  – Optical/IR - Gamma-Rays

• Bursts
  – What are they?
Magnetar Atmospheres

- Atmosphere - thin layer (few centimeters) on the surface of a neutron star in which the spectrum forms.
- Iron, hydrogen or something else?
- What role does the strong field play?
A Condensed Atmosphere

- The “thermal” component of the radiation from magnetars is remarkably close to a blackbody.
- Radiation of all energies reaches high optical depth at the same temperature.
- Calculate dielectric properties of surface

Adelsberg, Lai, Potekhin ‘04
The Condensed Spectrum

- After determining the reflectivity, use Kirchoff’s Law.
- The spectrum lacks narrow features but isn’t a BB either.
- Freezing point:
  - Fe, $10^6$ K at $\sim 10^{13}$ G
  - H, $10^6$ K $> 10^{14}$ G

- Adelsberg, Lai, Potekhin ‘04
Why hydrogen or iron?

• The conventional wisdom was that the surfaces of neutron stars consist of iron.
  – NSE $\Rightarrow$ Fe $\Rightarrow$ lots of X-ray lines!!!
• When no lines were found, the new conventional wisdom was that the surfaces of neutron stars would consist hydrogen. Fall-back or ISM accretion, plus settling.
  – H-atmospheres help reconcile estimates of neutron star radii: no strange quark stars yet.
  – Don’t expect many lines from hydrogen.
Conventional wisdom: neither conventional nor wise.

- Chang, Arras and Bildsten have calculated the process of diffusive nuclear burning of hydrogen on the surfaces of neutron stars.
- Key ideas:
  - Carbon easily captures protons at the temperatures of hot envelopes: diffusion limited.
  - In cooler neutron stars, nuclear limited.
  - Strong magnetic fields reduce the Fermi energy.
- Magnetar hydrogen atmosphere is consumed in days. Thick He envelopes don’t last either.
Optical Birefringence

- The observed optical polarization provides a unique diagnostic of the plasma near the neutron star.
- We assume that the radiation is thermal and comes from the entire surface.
- The signature weakens for more strongly magnetized NSs.

- Shannon & Heyl ‘04
X-ray Birefringence (1)

- The thermal radiation from neutron stars is highly polarized.
- Vacuum polarization of the magnetosphere ensures that the observed polarization will be large.

Heyl, Shaviv & Lloyd ‘04
X-ray Birefringence (2)

- Deep in the atmosphere the modes are plasma dominated.
- Outside the modes are vacuum dominated.

Ho & Lai ‘03
X-ray Birefringence (3)

- Ho & Lai '04
Non-thermal Emission (1)

- X-rays, gamma-rays and optical.
- Özel points out that no thermal mechanism powered by energy through the crust can account for the optical emission and be consistent with the X-ray emission.

- Özel ‘04; Hulleman et al. ‘00

\[
\nu F_\nu \text{ (erg s}^{-1} \text{ cm}^{-2})
\]

\[
\nu \text{ (Hz)}
\]

4U 0142+61
Non-thermal Emission (2)

- INTEGRAL and RXTE found persistent non-thermal hard x-rays from two magnetars: Kuiper et al. ‘04, Molkov et al. ‘04, Mereghetti et al. ‘04
Non-thermal Emission Models

• Özel ‘04 proposes that that a pair-plasma at the Goldreich-Julian density at $r \sim 50R$ suffices to explain the optical emission if the typical energy of the electrons $\gamma \propto B^{-1/4}$, yielding $\nu F_\nu \propto \nu^2$. The emission is rotation powered.

• Thompson and Beloborodov ‘04 propose:
  – Bremsstrahlung in a thin surface layer heated by magnetospheric currents to $kT \sim 100\text{keV}$. $\nu F_\nu \propto \nu^1$
  – If the electron temperature were $\sim 1\text{ MeV}$, this could explain the flux as well. $\nu F_\nu \propto \nu^3$
  – Runaway positrons in the current emit synchrotron radiation; passively cooling spectrum $\nu F_\nu \propto \nu^{1/2}$ up to $\sim 1\text{ MeV}$.
Non-thermal Emission (3)

- A simple model can account for the non-thermal emission from optical to GeV.
- The spectrum predicted by T&B is too steep in the optical at high-energy without adding a synchrotron component.
Understanding the bursts

• Standard model (Thompson & Duncan ‘96); magnetic reconnection of an evolving supercritical field; imagine the sun with a solid crust.
  – Magnetic helicity flows through the crust sporadically driving strong currents through the magnetosphere (Alfvenic cascade)
• Alternative picture - reconnection also generates fast waves that shock.
Fast-Mode Pair Cascade (1)

• Equal energy is dumped in equal intervals of $B$.

- Heyl & Hernquist ‘04
Fast-Mode Pair Cascade (2)

- Enough pairs may be produced near the star to make a fireball.

Heyl & Hernquist ‘04
Fast-Mode Pair Cascade (3)

- Non-thermal emission:
Non-thermal emission:
- Initial pairs are at rest in the frame of the wave.
- Early generations of synchrotron photons pair produce until

\[ E_\gamma \sim 2.5 \times 10^{-3} \frac{B_{\text{QED}}}{B} mc^2 \]

\[ \frac{dE}{dE_\gamma} \propto E_\gamma^{-2} \]
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- The innermost pairs cool the most quickly \( \frac{dE}{dE_{\gamma}} \propto E_{\gamma}^{-1/2} \)
- Cold pairs emit at the cyclotron frequency
  \[ \frac{dE}{dE_{\gamma}} \propto E_{\gamma}^{1} \]
A Model for Magnetars

• The surface of a magnetar emits various MHD waves into the magnetosphere.
  – Alfven waves power the traditional Thompson & Duncan burst.
  – Fast waves form shocks due to QED. Sometimes the wave is large enough to produce a fireball; otherwise it generates non-thermal emission from the optical to $\gamma$-ray.
Shannon & Heyl ‘04