Magnetars, Electromagnetic Pulses and Fast Radio Bursts

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Fast Radio Bursts

- 2007 Lorimer (2001) burst/perytons
- ~GHz (only?) ~1ms? radio bursts
  - Dispersed and broadened; $d<\sim 2$ Gpc?
  - $E_{\text{FRB}} \sim 10^{33} f_{\text{beam}} J? \ll \text{SNR, GRB}$
  - $\delta t \gg 30\mu s$, spectrally complex
  - $T_B \sim 10^{30-40} K? \text{cf giant pulses}$
  - Can be highly linear (and circular) polarized
  - ~50 FRB; all sky frequency ~100 mHz?

- FRB 121102 - repeater
  - $z \sim 0.2$ dwarf galaxy; steady source
  - Large, variable RM

Many models: ET, DM, SGR/SN, AGN, PSR… Should learn much, soon, CHIME, DSA, ASKAP…
Magnetars?

- $B < \sim 10^3 B_{\text{Crab}} \sim 100 \text{ GT}; P \sim 3-10 \text{ s}$
  
  - SGR, AXP
  - MSM could be endpoint of stellar evolution

- Birthrate $\sim 10^{-4} \text{ yr}^{-1} \text{ Galaxy}^{-1}$
  
  - Repeat activity - 1-10 per magnetar

- Magnetic energy $> 10^{40} \text{ J};$ elastic energy $\sim 10^{39} \text{ J}$
  
  - Rotational energy $\sim 10^{45} \text{ J} $ but soon lost; $P \sim 5 \text{ s}$

- Magnetars flare
  
  - $E_x \sim 10^{37-39} \text{ J};$ magnetic? rotation
  - Radio sometimes but

Relativistic, spinning SF+SC nuclear matter with $B \sim 30 B_{\text{crit}}$

The boring and conservative explanation!
Why Magnetars?

- Known source!
- Birthrate \( \sim 10 \) mHz; FRB \( \sim 0.1-100 \) mHz
- Repeat activity
- Magnetic energy \( > 10^{40} J \)
- Elastic energy \( \sim 10^{39} J \)
- Magnetars glitch, wander and flare
  - Rotational energy could be much larger
- Active when young \( < \sim 100 \) yr?
- Pulsars produce coherent radio waves
Quakes and Flares

- **Pulsar glitches** – $\Delta P/P \sim 10^{-6-8}$, $\Delta E \sim 10^{30-32} J$
  - Vortex line unpinning?
  - Magnetars are slow rotators; $\rho_{\text{GJ}}$ unimportant

- **Neutron astrology**
  - $\mu \sim 0.02$ K in lattice, maximized below neutron N drip?
  - $\rho \sim 4 \times 10^{14}$ kg m$^{-3}$, $\mu \sim 10^{28}$ Nm$^{-2}$, $B \sim 100$ GT
  - Most of crust moves horizontally, incompressibly
  - $L \sim 300$ m, $E_{\text{magnetoelectric}} < 10^{34} \varepsilon_1^2$ J; $V_{\text{shear}} \sim 0.01$-1 c, $t \sim 3$-100 $\mu$s
  - Good transmission unlike pulsars

- **Magnetic flares**
  - (Beloborodov)
  - Most of surface covered with closed field lines
  - Complex, multipolar, potential field has “coronal holes”
  - Invoked for SGR etc
Force-Free Electrodynamics

• Sufficient plasma for currents; insufficient for inertia
  \[ j = \frac{(\mathbf{B} \cdot \nabla \times \mathbf{B} - \mathbf{E} \cdot \nabla \times \mathbf{E}) \mathbf{B} + \nabla \cdot \mathbf{E} \mathbf{E} \times \mathbf{B}}{B^2} \]

• Characteristics for linear waves
  - Fast mode: \( \omega = k \), unimportant
  - Intermediate mode: \( \omega = k || \), \( V_g = c \) along \( \mathbf{B} \); favored?

• Amplitude growth: \( \delta B / B \sim B^{-1/2} \) on open field lines
  - Nonlinearity-> steepening when \( r > ct \sim 100 \text{ km} \)
    • Bullwhip, tsunami…
  - Compute using Smooth Particle ElectroDynamics?

Pulse of toroidal field propagates into magnetosphere along open field lines?
Pair Production

- $T_{\text{ns}} \sim 10\text{MK};$ Compton processes near star
  - $E \sim 10\text{ EV/m}$
  - E.B?

- $R \sim 10 - 10^3 \, R_{\text{ns}}$
  - Curvature $\gamma$-rays
  - $\gamma$-B pair production
  - Avalanche

- Eventually pair production ceases
  - Mode convert to EM wave
ElectroMagnetic Pulse

- **Linear e-mode launched at** $R_{ns}$
  - $(\delta B/\phi/B) \sim 0.05$; $\lambda \sim 300$ m; $U \sim 10^{33}$ J;
  - pair production by inverse Compton, synchrotron processes

- **Wavefront become nonlinear at** $R_{nl} \sim 10 R_{ns}$
  - $(\delta B/\phi/B) \sim B^{-1/2}$

- **Wave detaches from field, propagates spherically, may steepen**
  - Energy $\sim B_{\phi}^2 R^2 \Delta \sim$ const; Flux: $B_{\phi} R \Delta \sim B\text{dipole} R^2 \sim R^{-1}$;
  - $\Rightarrow B_{\phi} \sim$ const, $\Delta \sim R^{-2}$;

- **Pair production too slow when** $R \sim 1000 R_{ns}$??
  - $\Delta \sim 0.1$ m $\Rightarrow$ GHz frequencies
  - Linearly polarized
  - Intergalactic propagation disperses and scatters wave.
  - Alternatively an “Anomalous Cyclotron” maser may operate.

**Waves are launched and may steepen $\Rightarrow \sim$GHz emission?**
Propagation Effects

- High brightness radio emission subject to:
  - Induced Compton Scattering
  - Stimulated Raman Scattering
  - Same as pulsars

- Interstellar and Intergalactic Scintillation
  - Powerful probe of plasma turbulence spectra
    - Many correlations predicted

- Gravitational Lensing
  - Await macrolensing delay in months for $\sim 10^{-3}$ FRBs
  - Microlensing by stars

FRBs even more interesting as probes than as sources?
Summary

- FRB are <ms radio pulses every minute
- Good for Ap, Cos, plasmas, QED?
- Magnetars ($\rho_{\text{nuc}}$, $10^{15}$G, 0.1$c^2$)-HED Heaven!
- Quake/flare create EMP
- Force free electrodynamics with pairs
- e-mode along B - nonlinear, steepen $\rightarrow$ EM
- Polarized pulses dispersed and broadened
- Should repeat without observable $\gamma$-rays
- Good near-term observational prospects
- Pulsarshine?