Magnetar Models of Fast Radio Bursts

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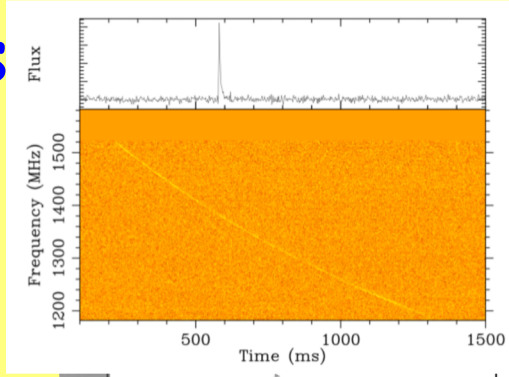
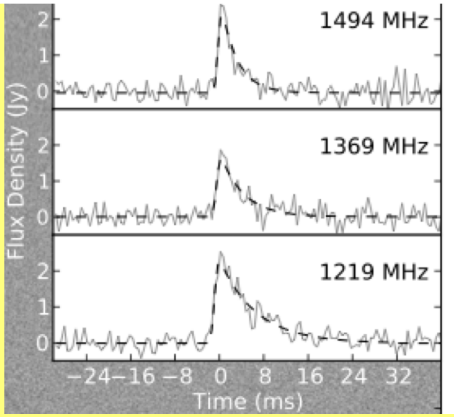
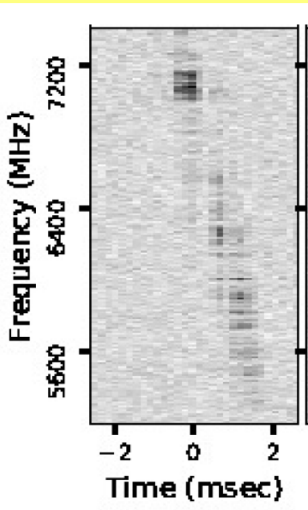
Fast Radio Bursts

- 2007 Lorimer (2001) burst/perytons
- ~GHz (only?) ~1ms? radio bursts
  - Dispersed and broadened; =>d<~2 Gpc?
  - $E_{FRB} \sim 10^{33} f_{beam}$ J? <<SNR, GRB
  - $\delta t >\sim 30\mu s$, spectrally complex
  - $T_B \sim 10^{30\text{-}40}$K?cf giant pulses
  - Can be highly linear (and circular) polarized
  - ~50 FRB; all sky frequency ~100 mHz?
- FRB 121102 - repeater
  - z~0.2 dwarf galaxy; steady source
  - Large, variable RM





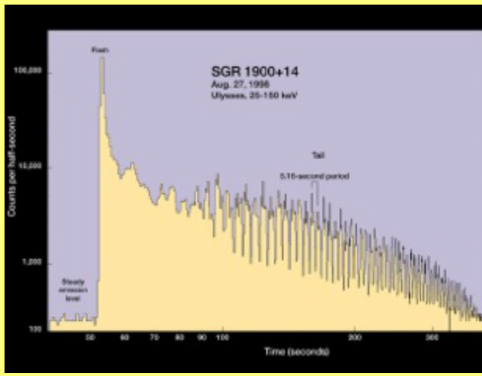


Many models: ET, DM, SGR/SN, AGN, PSR…
Should learn much, soon, CHIME, DSA, ASKAP…

Magnetars?

(Popov, Postnov…)

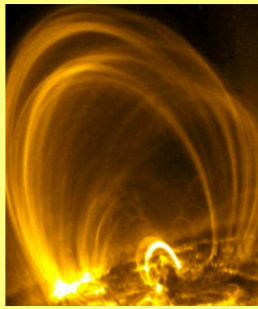
- B <~ 10^3 B_{Crab} ~100 GT; P~ 3-10 s *(Thompson, Duncan; Kouveliotou; Kaspi, Beloborodov…)*
  - SGR, AXP
  - MSM could be endpoint of stellar evolution
- Birthrate >~10^{-4} yr^{-1} $Galaxy^{-1}$
  - Repeat activity - 1-10 per magnetar
- Magnetic energy > 10^{40}J; elastic energy ~10^{39}J
  - Rotational energy ~ 10^{44} ->10^{37}J rapidly
- Magnetars flare as SGRs
  - $E_{X\gamma}$ ~$10^{37\text{-}39}$ J ~$10^{4\text{-}6}$ E_{FRB}
  - Radio sometimes observed



Relativistic, spinning SF+SC nuclear matter with B~30 B_{crit}
The boring and conservative explanation!

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; ρ_{GJ} unimportant
- **Neutron astrology** *(eg Blaes et al 1989, Levin & Lyutikov 2012)*
  - $\mu \sim 0.02$ K in lattice, maximized below neutron N drip?
  - $\rho \sim 4 \times 10^{14}$ kg m^{-3} , $\mu \sim 10^{28}$ Nm^{-2}, B ~ 100 GT
  - Most of crust moves horizontally, incompressibly
  - L ~ 300m, $E_{magnetoelastic} < 10^{34}\ \varepsilon_{-1}^{2}$ J; $V_{shear} \sim .01\text{-}1$ c, t ~ 3-100μs
  - 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;
- Ignore charged particles
- Ignore background rotation, current, GR; can include
- Ignore inertia; modest multiplicity

$$\rho \mathbf{E} + \mathbf{j} \times \mathbf{B} = 0$$

$$\mathbf{j} = [(\mathbf{B}\cdot\mathrm{curl}\,\mathbf{B} - \mathbf{E}\cdot\mathrm{curl}\,\mathbf{E})\mathbf{B} + \mathrm{div}\,\mathbf{E}\,\mathbf{E}\times\mathbf{B}]/B^2$$

- Characteristics for linear waves
  - Fast (EM) mode: w=k, unimportant
  - Intermediate mode: $w=k_{||}$; $V_g=c$ along B
    - $\delta B \sim k \times B$; $\delta j \sim B$; $\delta E \sim \delta B \times B$
  - Solutions for spherical WKB waves

- Amplitude growth: $dB_\phi/B \sim B^{-1/2}$ on open field lines

Nonlinearity-> steepening when r > ct ~ 100 km ~ 10 R_{ns}

- Bullwhip, tsunami…

Pulse of toroidal field/current propagates along open toroidal flux tube

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
  - Wave may steepen; if so
    - Energy $\sim B_\phi^2 R^2 \Delta \sim$ const; Flux: $B_\phi R \Delta \sim B_{dipole} R^2 \sim R^{-1}$
    - $\Rightarrow B_\phi \sim$ const, $\Delta \sim R^{-2}$
  - Slower steepening likely; radiation reaction, inertia reconnection?
- **Pair production too slow at $R \sim R_{em} \sim 100\ R_{nl} \sim 1000\ R_{ns}$?**
  - Current -> displacement current; EM Pulse
  - $\Delta \sim 0.03$ m; broad band; polarized; Fourier spectrum up to ~10GHz
  - Intergalactic propagation disperses and scatters the pulse
  - Extreme view; if pulse does not steepen to cm, can invoke AC maser

7 v 2018

Weird/(wired?) reconnection?

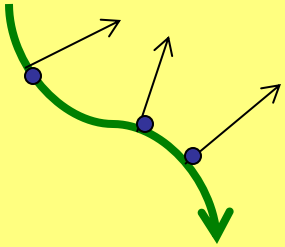
Slaved Particle ElEctroDYnamics

- Relativistic force-free electrodynamics.

$$dx/dt = v = (ExB)/B^2$$

$$dv/dt=f(v,B)$$

$$dB/dt=f'(v,B)$$



- Solve for particle motions
- Reconstruct field
- Modify when plasma is charge-starved
  - Balance E.B with local pair production

Work in Progress!

Pair Production

- $R \sim R_{ns}$
  - $T_{ns} \sim 10MK$; Compton processes near star
  - $E \sim EV\ m^{-1}$, $I \sim EA$!
  - Pairs in Landau ground states
  - Small E.B accelerates particles
- $R >\sim R_{nl} \sim 10\ R_{ns}$
  - Curvature γ-rays
  - γ-B pair production
  - Avalanche
- $R >\sim 100\ R_{nl} \sim 1000\ R_{ns}$
  - Pair production inadequate?
  - Mode convert to EM wave

Good problem for Relativistic PIC codes

Propagation Effects

- **High brightness radio emission subject to:**
  - **Induced Compton Scattering**
  - **Stimulated Raman Scattering**
  - **Geometric optics caustics in magnetosphere,**
- **Interstellar and Intergalactic Scintillation**
  - **Powerful probe of plasma turbulence spectra**
    - Many correlations predicted
    - Caustics formed by IGM
- **Gravitational Lensing**
  - **Await macrolensing delay in months for ~10^{-3} FRBs**
  - **Microlensing by stars**

FRBs even more interesting as probes than as sources?

Quakes or Flares?

- **Quake**
  - Permanent displacement of crust
  - Open flux tube rotates
  - $B_\phi \sim e^{-z2/2}$
  - $j_p \sim -z\, e^{-z2/2}$
- **Flare**
  - Relieve stress in closed field
  - Open field returns to original state
  - $B_\phi \sim z\, e^{-z2/2}$
  - $j_p \sim (1-z^2)e^{-z2/2}$
  - Reconnection geometry?

Quake-like disturbances may be more durable

Summary

- FRB are <ms radio pulses every minute
- Quake/flare create EMP
- Force free electrodynamics with pairs
- e-mode along B - nonlinear,steepen - EMP
- Polarized pulses dispersed and broadened
- Should repeat without observable γ-rays
- Good near-term observational prospects
- HED Experiments?
- Pulsarshine?