FRB emission mechanisms

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Preliminaries - coherent emission
Coherent emission - preliminaries

- Intensity: amplitude\(^2\)

- Coherent emission:
  - Antenna mechanism (externally enforced, each particle emits independently of others - simple emission, but who is the music conductor?)
  - Plasma maser (intrinsically achieved, particles “decide” to emit together - difficult physics, no need for the conductor)
Antenna

- **Antenna** (curvature emission by bunches): each particle emits on its own. Particles do not “talk” to each other, they obey the “ultimate ruler”, so that their waves add-up coherently. (E.g. deaf musicians watching a conductor.) Works well in the lab: experimentalist (like an orchestra conductor) makes special conditions, eg. the E-field driver

- Let’s never again talk about coherent curvature emission by bunches. Yes, there are wigglers (FELs; Goldreich-Keeley inst.). But: generally, plasma process in astrophysics are in kinetic regime (random phase), while in laboratory in reactive regime (finely tuned, all in phase)

- Mild velocity dispersion suppresses bunching (Benford, Asseo)
Plasma maser

- Plasma has normal modes
- A particle can **resonantly** emit and absorb normal mode (need \( v > v_{ph} \) - Cherenkov!)
- Emission and absorption rates is proportional to the number of waves present \( n_k \) - induced process
- A new **wave is emitted in phase** with the shaker-wave
- More particles can emit than absorb - population inversion
- Can be **continuous** unstable distribution
- No overall ruler/conductor
- Many (too many...?) plasma masers
Plasma astrophysics primer: Plasma Maser.

- **Plasma maser**: non-equilibrium distribution $f(p)$ (in momentum space, not physical space) results in coherent emission of plasma normal modes. **Population inversion**: there is more particles willing to emit a wave than willing to absorb it.

$$\Gamma \propto \left( \frac{s \omega_B}{\gamma \beta} \frac{\partial}{\partial p_{\perp}} + k_{\parallel} \frac{\partial}{\partial p_{\parallel}} \right) f(p_{\parallel}, p_{\perp})$$

need $> 0$ for growth

$s > 0$

$\epsilon = (n + 1/2) \hbar \omega_B$

Landau levels

$m_{eff, \parallel} \sim \gamma^3 m_e$

$f(p_{\perp}) \propto \delta(p_{\perp})/p_{\perp}$

$\partial_{p_{\perp}} f < 0$

$s = \Delta n < 0$

$m_{eff, \perp} \sim \gamma m_e$

$s = \Delta n > 0$
Random phase (kinetic) instabilities

- Unstable distribution

- Particles emit waves. Instability driven by +derivative -> =0

Plasma turbulence, with random phases, no coherent structures in real space, no “bunches”
A music theory of radio emission:

- Build a guitar:
  - Guess (justify, calculate) the distribution functions \( f(p) \)
  - Find dispersion relation for normal modes \( \omega(k) \)

- Find a musician to play:
  - Find resonant condition - are there any resonant particles to excite the normal modes?
    \[
    \omega(k) - k_\parallel v_\parallel = s\omega_B / \gamma \rightarrow v_{res}
    \]

- Can he play well?
  - Find growth rate \( \Gamma \propto \left( \frac{s\omega_B}{\gamma\beta_\perp} \frac{\partial}{\partial p_\perp} + k_\parallel \frac{\partial}{\partial p_\parallel} \right) f(p_\parallel, p_\perp) \)

- Can he play loud?
  - Find saturation level (quasilinear?)

- But there no conductor to keep the rhythm - self-organization
Narrow spectral features expected

- Resonances: narrow spectral features
  - Can be erased by large-scale inhomogeneities in density/B-field
  - How to escape?
  - How to distinguish from propagation? - nu-scaling (?)
Narrow features in pulsar spectra

Hankins + 2003
Back to FRBs
Radio typically has very little energy

- Energy collected by all radio telescopes over half a century ~ energy of a falling snowflake.
- Walking at 1 m/sec, stop on reaction time of 100ms, convert into radio - 100 Jy FRB seen at the Moon. **Cannot compare with available mechanical energy.**
- **But:** Repeater: ~ $10^{40}$ erg/sec in radio - huge!
- Crab pulsar in radio - $10^{-6}$ of $L_{sd}$, $10^{32}$ erg/s
  - can reach 1% during Giant Pulse
  - this is a high frequency EM part of the EM power, not mechanical
- System can be in force balance (so, no pressure jumps, no shocks), yet unstable to produce radio emission, eg. due to kinetic anisotropy - can converted into radio large fraction of free energy, no “waste” on baryons, bulk motion etc
Road fork # I - msec duration. Relativistic bulk motion or intrinsic?

- Time scale $t_{ob} \sim \text{msec} = \frac{\Delta r}{c} \frac{1}{2\Gamma_{bulk}^2}$, luminosity $L \propto \delta^4$
- Is $\Gamma_{bulk} \sim 1$ or $\Gamma_{bulk} \sim 10^4$?
  
  $\Gamma_{bulk} \sim 1$

(Due to large-scale motion; Large Gamma invoked shocks - need enough material to shock against)

- Crab on steroids
- Solar-like radio with magnetar flares

\[ \Gamma_{bulk} \sim 10^4 \]

\[ \sim 10^{15}-10^{17} \text{ cm} \]

Lots of power – needs large volume to shock

Cyclotron maser at a shock (Lyubarsky, Beloborodov)

Ring distribution

Gallant +, 1992
\[ \Gamma_{bulk} \sim 1 \leftarrow \text{NS magnetospheres} \]

- Instantaneous luminosity for the Repeater:
  \[ L_{iso} = 4\pi D^2 (\nu F_{\nu}) \sim 10^{41} \text{ergs}^{-1} \]
- duration (assume intrinsic) -> size
- Equipartition B-field:
  \[ B_{eq} = \sqrt{8\pi} \frac{\sqrt{\nu F_{\nu} D}}{c^{3/2} \tau} = 3 \times 10^8 \tau_{-3}^{-1} \text{ G} \]

(Large gamma within magnetosphere: similar B-field to collimate a beam)

- **NS magnetospheres!** (Clean, relativistic)
  - Stellar-mass BHs (?) - accretion-supplied B-field is dirty.
  - WD magnetosphere(?)
Also: the non-linearity parameter “a”

- EM non-linearity parameter
  \[ a = \frac{eE}{m_e c \omega} \approx 10^5 \gg 1 \]

- If no B: \( \gamma \sim a \) huge radiative losses (eg. induced Compton)

- Actually, ExB drift, so
  \[ a = \frac{eE}{m_e c \omega_B} \leq 1 \]

(so, emission from magnetosphere is not self-contradictory)
Road fork # II - giant pulses vs magnetar flares

- We are not yet in a position to construct **microscopic** models of radio emission
- we are left only to discuss the **macroscopic** limitations

- Model I: Giant pulses, Crab on steroids, rotationally powered – theoretical limitations

- Model II (hypothetical): magnetar flares, magnetically powered – observational limitations
Macroscopic Model I: Rotationally powered super-Giant Pulses

- very young SNRs, 10-100 years
  - free-free absorption in new SN shell $\tau_{ff} \sim 1 \text{ @ } 300 \text{ MHz}$ (no LOFAR)
  - DM through the shell
    \[ DM \approx 100 s \left( \frac{t}{\text{yrs}} \right)^{-2} \]
- Crab’s GPs reach $\sim 1\%$ efficiency of $L_{sd}$
- If $\nu F_{\nu} \propto L_{sd}$ need $\sim 10^4$ higher peak power from 100 Mpc
  - Few msec period, with Crab-like B-field - reasonable to expect
  - Spin-down times $\sim 10$-100 yrs
  - Rates within 100 Mpc are OK.
- Injection rate $f_{inj} \propto \dot{E}^{-1}$ (observed $f \propto \dot{E}^{-3/2}$ - consistent with observed distribution of fast pulsar)
  - Very flat distribution of distances to a given brightness (type of Malmquist bias)
It was a good model, but not from \( \sim 1 \) Gpc

- Radio power \( L_{iso} \) cannot be larger than the spin-down (must be magnetospheric, hard to store much more energy in the magnetosphere)
  \[
  \nu F_\nu = \eta \frac{L_{sd}}{4\pi D^2}
  \]
  The most powerful Crab’s GP have \( \eta = 10^{-2} \)

- Need high B - short P (at least few msec)
  \[
  \tau_{SD} = \frac{\pi I_{NS}}{2D^2 \nu F_\nu P_{min}^2} \approx 600 \eta \text{ yrs}
  \]
  For Crab: 6 yrs if all in GPs
  FRB 160102 could be even worth

- Constant DM: \( t > 100 \) yrs
- \( \eta \sim 1 + 1 \) msec spin at birth + 100 yrs < age < 600 yrs - NO.

Repeating FRB at 1 Gpc + constant large DM excludes rotationally powered emission
Macroscopic Model II: magnetar flares (type-iii)

- Solar type-III radio emission in magnetars (Lyutikov 2006)
- **Initial** stage of a “reconnection flare” - jets of particles, hence coherent emission - like Crab flares (Lyutikov et al. 2016)
- Best case - observe radio burst associated with magnetar burst and flares.
- Constraining limits from SGR 1806-20 flare
  - SGR flare was $10^{47}$ erg/s -> radio efficiency of Repeater$10^{-6}$ - OK?
  - But would give a GJy from 10 kpc - not seen in Parkes side-lobes (Tendulkar + 2016)
  - No radio from PSR J1119-6127 X-ray (radio efficiency < $10^{-8}$)
Collapse of an ABC system of magnetic islands

Two stages:
- Fast acceleration, not much B-field dissipated (X-point collapse)
- Slower acceleration, dissipation (island merger)

Lyutikov+ 2017
Best hope: other wavebands

- **Radio**: $> 10^{40}$ erg/s
- **Optical**: $> 10^{45}$ erg/s
- **X-rays**: $> 10^{50}$ erg/s, GRB-like rates - not correct
- All sky X-rays monitors can see magnetar-type flare to ~ 40 Mpc, but targeted observation (e.g. of the Repeating FRB) can detect weaker
- Afterglows: jetted magnetar post-burst outflows (Keane 2016, Lyutikov 2006)?

![Diagram of jetted magnetar post-burst outflows](Lyutikov2006)
Counter-part strategy: optical

- Optical energetics >> radio (If !)
- Peak flux ~ 9m (but only for few msec - fast read-outs!)
- m~ 15 image in 60 sec PTF, ASAS-SN, EVRYSCOPE (LSST!) - PTF might have seen, as star-like points in single exposure.
- Optical would look at FRB every ~ 10 hours (10 sq. degrees field of view)
- Fast readout is good
- **Radio and optical - stare at the same patch**
- For The Repeater, the optical power is in the $10^{45}$ erg/sec
- Multi-frequency radio (triggered LOFAR obs.)

Lyutikov & Lorimer 2016
Conclusion

- Amazingly, radio power (+ constant DM and non-changing properties of The Repeater) puts energetic limits on the type of emission (rotationally vs magnetically powered; does not yet constrain particular instability that drives radio emission). Neither looks too promising for now.

- Perhaps there is some slack left in either:
  - Highly non-stationary processes in pulsar outer magnetospheres
  - Explosive reconnection events in magnetar magnetospheres - can they generate unstable distributions and radio bursts?
My favorite pulsar radio emission mechanism
What excites gyration: anomalous cyclotron resonance

- A particle can emit a cyclotron photon with no initial gyration
  \[ \omega - k \parallel v \parallel = -\frac{\omega_B}{\gamma} \]
- Particle goes **up** in Landau levels and emits a photon - radio
- Spontaneous **down** cyclotron boosted in UV-X-rays
- IC - VHE gamma rays

From ~100 MHz to ~2 TeV - 20 orders in energy

Lyutikov 2012, also in prep.
Relativistic reconnection, kinetic beaming - Sterl’s talk

- There is a paradigm shift in high energy astrophysics - acceleration in reconnection events (no shocks) - Crab nebula flares.
- Reconnection mini-jets
- Kinetic beaming, but, like in pulsars – what is the coherence mechanism?

\[ \Gamma_{eff} \sim 2\Gamma \gamma_j \]

Clausen-Brown & Lyutikov 2012

Lyutikov 2006
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Gallant +, 1992
Radio emission from NSs

- There are three types of coherent emission from NS: type-I, type-II, type-III
  - Type I: log-normal dist., Crab precursor, polar caps, rotationally-driven
  - Type II: GPs, power-law, Crab MP&IP, border between open/closed field lines, rotationally-driven
  - Type III: magnetars, on close field lines, crustal shear-driven (reconnection, \text{Solar})

Serylak+ 2009
Glitches?

- There are no bright EM signals with glitches
- Magnetospheric changes are tiny, $10^{-6}$
- Time scales - crustal shear ~ 100 msec (for ~ msec time scale the energy must be stored in the magnetosphere).

- Juste pour rire/just for laughs, let’s make a glitch FRB model
  - Imagine you are walking at 1 m/sec. And then, “suddenly” a glitch: on human reaction time of 100 msec, you change your speed by $10^{-6}$ to (1 m - micrometer)/sec. And then you convert all that energy into radio waves at 1 GHz.
  - Boom! - Mega-Jy signal 3 km away!
  - This is obviously ridiculous, but astrophysically, scaling “this with that”, it makes sense, right?
  - Not for radio (could be OK for high energy)
  - (Mechanical to radio vs EM to radio)
What excites gyration: anomalous cyclotron resonance

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  \[ \omega - k || v || = \gamma \frac{\omega_B}{\gamma} \]
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Observational constraints on FRB emission mechanisms

• $> 10^4$ per day (not prompt GRBs)

• repetitive (not catastrophic events like NS-NS mergers)

• isotropic (extra-Galactic); $D \sim 1$ Gpc - (cosmological)

• coherent emission, $T_b \approx 10^{34}$ K

• DM is constant to $\sim \%$ over few years

• Polarization is messy

• Very unfortunately, there is no clear evidence for two different populations
Crab

Aligned from radio to VHE gamma - common origin