a. FRB progenitors:
Model independent constraints from 121102
b. A coherent radio emission mechanism

Eli Waxman
Weizmann Institute of Science

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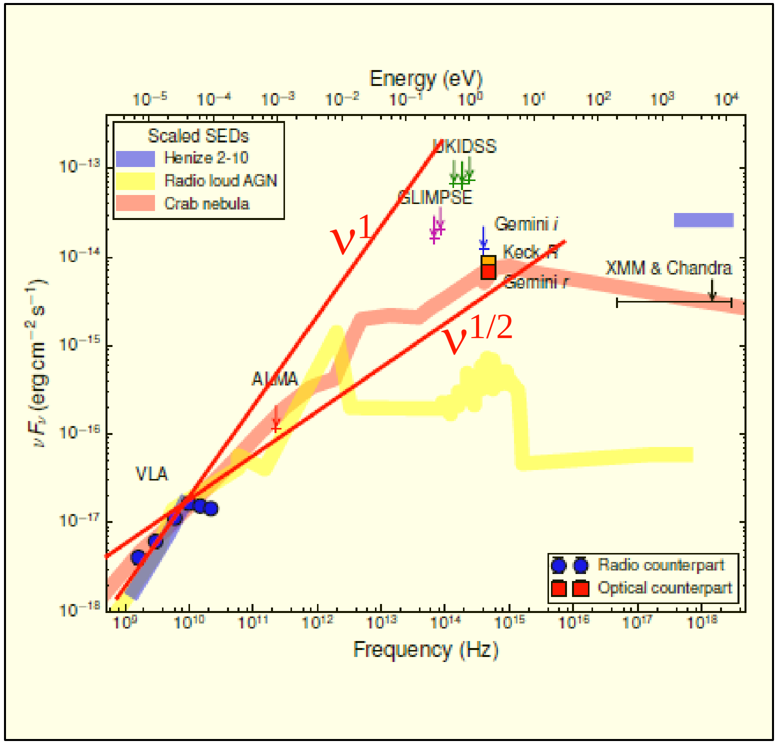
The persistent radio source associated with FRB121102: Key properties

Assumption: The FRB source is associated with the persistent source,
and resides within it.

1. d_L=970 Mpc, d_A= 680 Mpc.
2. t > 4 yr.
3. DM = 558$\pm$3 pc/cm^3,
   local DM< 200 pc/cm^3 .
4. Angular size consistent with

   scatter broadening, $\theta = 0.2 \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2}$ mas.
5. 10 to 30% variability on
   10 d time scale at 3 GHz.
6. νf_ν peak 2x10^{-17}erg/cm^{2}s (2x10^{39}erg/s)
   at 10 GHz.
7. $\nu f_\nu \sim \nu^1$ down to ~1 GHz



[Spitler et al. 16; Chatterjee et al. 17; Tendulkar et al. 17; Marcote et al. 17]

Persistent source size

1. Size consistent with scatter broadening
   → $\theta_s \ll 0.2$ mas, R ‹‹ 2×10^{18}cm.

2. ~30% variability at 3GHz on ~10d.
   - Intrinsic → R ‹ 10^{17}cm.
   - Refractive scintillation:

$$\theta_d = 0.2\left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{11/5}\left(\frac{SM_{-3.5}}{80}\right)^{3/5} \text{mas},$$

$$t_s = 20\ \frac{\theta}{0.2\ \mathrm{mas}}\left(\frac{\mathrm{v}}{50\ \mathrm{km/s}}\right)^{-1}\frac{d}{1\mathrm{kpc}}\ \text{day},$$

$$\left.\frac{\Delta f}{f}\right|_{\max} = 0.13\ \left(\frac{\theta_s}{0.1\ \mathrm{mas}}\right)^{-17/66}\left(\frac{SM_{-3.5}}{80}\right)^{-1/22}$$

$$\text{at } \nu|_{\max} = 3\ \left(\frac{\theta_s}{0.1\ \mathrm{mas}}\right)^{-5/11}\left(\frac{SM_{-3.5}}{80}\right)^{3/11} \text{GHz}$$ [e.g. Goodman 97].

→ Variability dominated by scintillation,
R ‹ 10^{18}cm.

Persistent source plasma properties

1. $R/t < 10^{10}$cm/s, no highly relativistic expansion.
2. No self-absorption

   → $\gamma_e > 10^{1.5} R_{17.5}^{-2}$, relativistic e$^-$ ($R = 10^{17.5} R_{17.5}\mathrm{cm}$).

→ Consider

a sphere R of relativistic radiating e$^-$, with density n_e and magnetic field B.

3. The peak flux and freq. provide 2 constraints on $\{R, \gamma_e, n_e, B\}$,

$$B = 10^{-1.5} \gamma_{e,2.5}^{-2} \mathrm{G}, \; n_e = 0.1 \gamma_{e,2.5}^{2} R_{17.5}^{-3} \mathrm{cm}^3 \;\; (\gamma_e = 10^{2.5} \gamma_{e,2.5}).$$

4. The $\nu < 10$ GHz spectrum is consistent with no significant cooling, $t < t_{\mathrm{cool}}$

   → $\gamma_e > 250\,(t/10^9\mathrm{s})^{1/3}$.

The surrounding plasma

1. Expansion $v \approx \sqrt{\frac{U_e+U_B}{n_c m_p}} < R/t$

   → a lower limit to n_c.

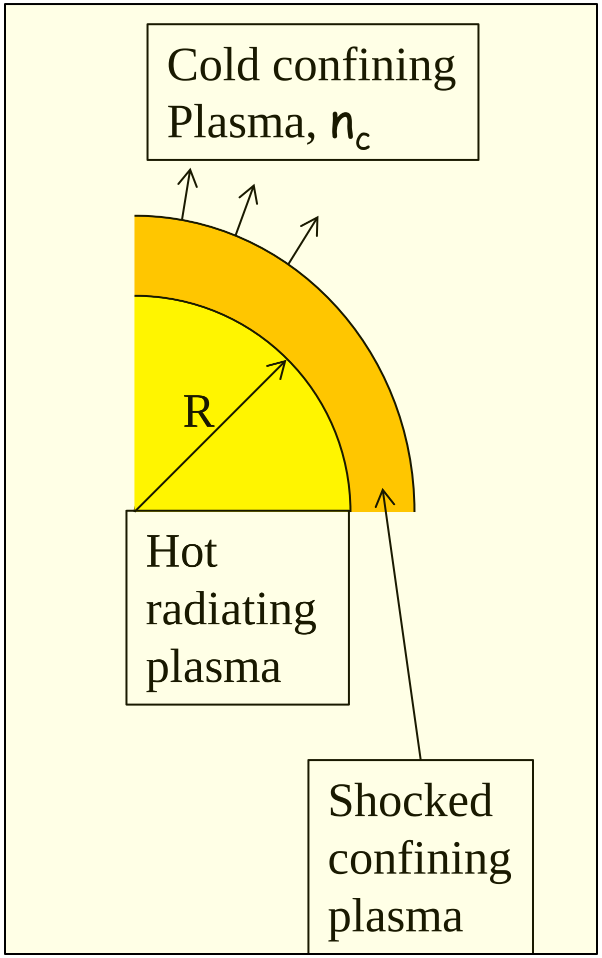
2. Shocked shell contribution to DM, δDM,

   $v n_c t, v n_c \delta t \propto n_c^{1/2}$,

   → an upper limit to n_c.

- A solution exists- not trivial- for

  $t < 2 \times 10^9 \mathrm{s} \min\left[R_{17.5}^{4/3}, R_{17.5}^{19/4}, 35R_{17.5}^{5}\right]$.


Cold confining Plasma, n_c

Hot radiating plasma

Shocked confining plasma

The persistent source properties

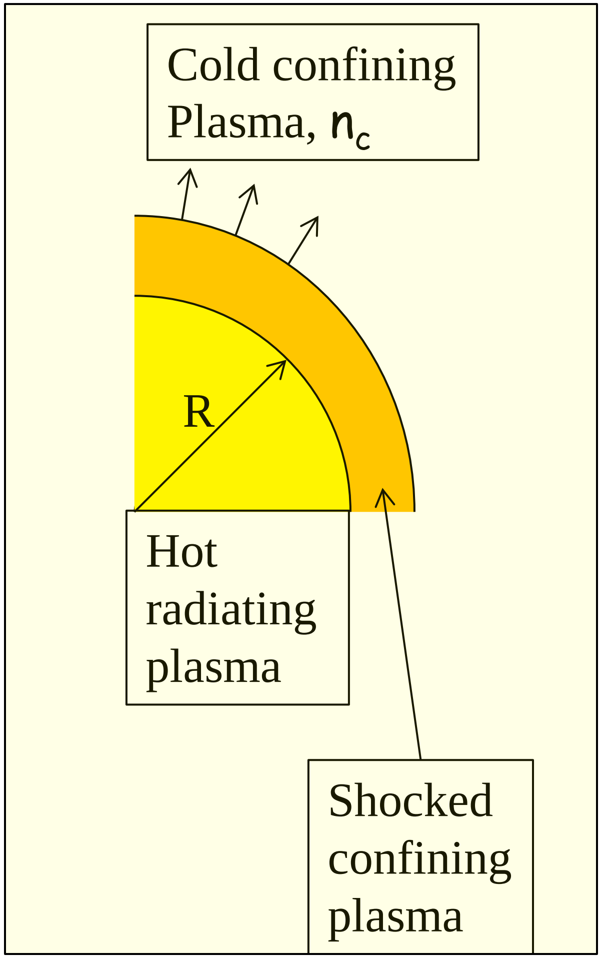
1. A solution exists- not trivial- for
   $t < 300$ yr,
   10^{17}cm $< R < 10^{18}$ cm,
   $200 < \gamma_e < 10^3$,
   $E_e \approx 10^{48.5}\gamma_{e,2.5}^{3}$erg, $\frac{E_B}{E_e} \approx 1\gamma_{e,2.5}^{-7}R_{17.5}^{3}$,
   $n_c < 10^{2.5}R_{17.5}$cm^{-3}, $M_c < 10^{-1.5}R_{17.5}^{4}M_{sun}$.

2. Nearly resolved. R may be determined @ 10GHz (directly if 10^{18}cm, by $\Delta f/f$ if 10^{17}cm).

3. $\varepsilon_e \sim m_p c^2$, $\frac{E_B}{E_e} \sim 1$ suggests:
   Ejection of a mildly relativistic $10^{-5}M_{sun}$ shell, that collided (collisionless shock) with pre-ejected $M_c \sim 10^{-1.5}M_{sun}$ shell/"wind".

4. Challenging for "Magnetar wind" models.
   a. No massive ejecta,
   b. $N_e \sim 10^{52}$ implies $\mu_{\pm} \sim 10^{12}$.

[see however Beloborodov 17]



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Coherent emission mechanism

FRBs- most likely produced by unstable plasma configuration leading to coherent emission [Katz, Lyutikov…] .

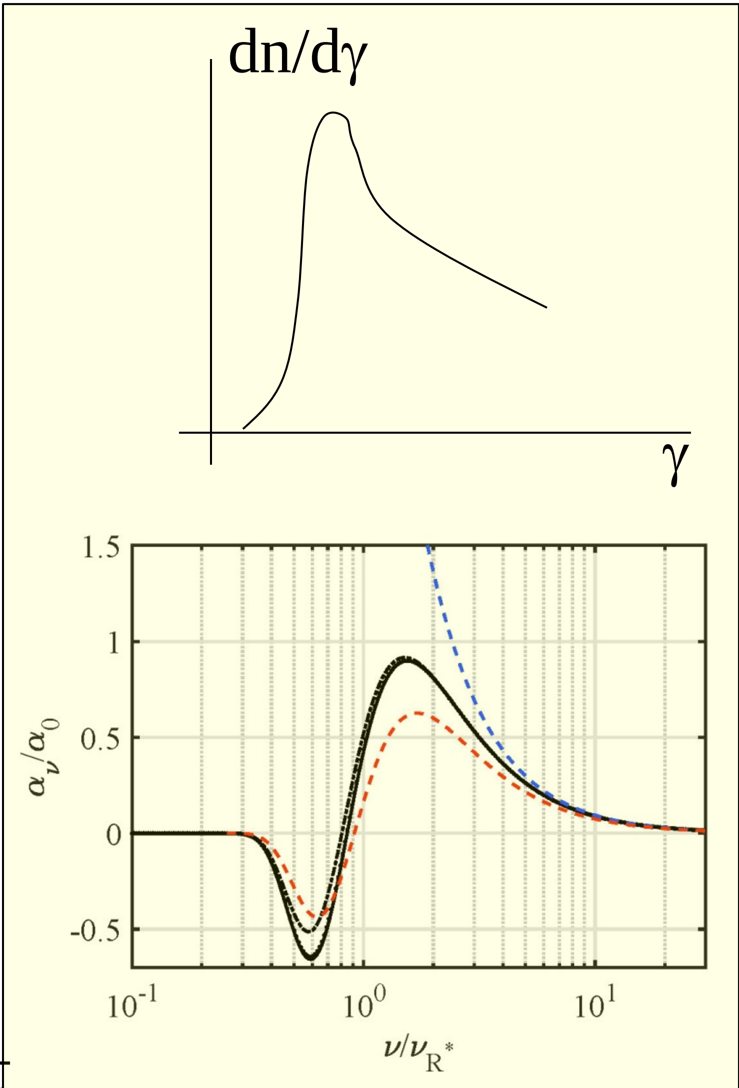
1. $E_{FRB} \sim 10^{39}$erg ~ 10^{-10} $E_{persistent}$; $\langle L_{FRB} \rangle \sim 10^{-5}$ $L_{persistent}$

   → Stringent constraints on the sources are unlikely,
   Identification of a unique instability is unlikely.

3. Suggested instabilities, e.g.
   a. Highly anisotropic e^- distribution
      [Sazonov 73; Lyubarski 14; Ghisellini 17]
      (Note: "gyro-freq maser" emission at collisionless, magnetized, perpendicular e+- shocks observed in 1D calculations is suppressed in 2D [Sironi & Spitkovsky 09]).
   b. "Curvature radiation" from e- bunches [e.g. Kumar et al 17].

4. A different mechanism:
   Synchrotron "maser" emission in an isotropic non-thermal e^- distribution.

Synchrotron maser: Negative reabsorption



1. $$\alpha_\nu = -\frac{1}{4\pi m_e \nu^2}\int d\gamma_e \gamma_e^2 P_\nu(\gamma_e)\frac{d}{d\gamma_e}\left(\gamma_e^{-2}\frac{dn_e}{d\gamma_e}\right)$$
   $$= \frac{1}{4\pi m_e \nu^2}\int d\gamma_e \gamma_e^{-2}\frac{dn_e}{d\gamma_e}\frac{d}{d\gamma_e}(\gamma_e^2 P_\nu)$$

   Necessary:

   'non-thermal' $\frac{dn_e}{d\gamma_e}$ rising faster than γ_e^2,

   $\gamma_e^2 P_\nu(\gamma_e)$ decreasing with γ_e.

2. The 2nd condition may be satisfied in the presence of a plasma.

   [McCray 66; Zheleznyakov 67; Sazonov 70; Sagiv & Waxman 02]

   $$\frac{\omega c}{k} = n,\ c \longrightarrow \frac{c}{n},\ \frac{1}{\gamma^2} \longrightarrow \frac{1}{\gamma^2} + 1 - n^2 = \frac{1}{\gamma^2} + \frac{\nu_p^2}{\nu^2}$$

   Instability possible for both $\gamma_e^2 \gg \nu_p/\nu_B$

   and $\gamma_e^2 \ll \frac{\nu_p}{\nu_B} \approx \sqrt{\frac{\epsilon_e}{\epsilon_B}}$ [Sagiv & Waxman 02].

   For a narrow e$^-$ distribution and $\gamma_e^2 \gg \nu_p/\nu_B$,

   $$\alpha_\nu = \alpha_0 F\left(\frac{\nu}{\nu_{R^*}}\right),\quad \alpha_0 = \frac{\pi}{2\sqrt{3}}\frac{\nu_B}{c}\sqrt{\frac{\nu_B}{\nu_p}},\ \nu_{R^*} = \nu_p\sqrt{\frac{\nu_p}{\nu_B}}$$

   [Waxman 17].

Some comments

1. The maser instability should be derivable directly from a solution of the plasma dispersion relation.

2. The Einstein coefficient method provides a "short cut" that is valid for
$$\nu_p^2\nu_B/\nu^3 \ll \frac{c\alpha_\nu}{\nu} \ll |1-n| \, .$$

3. These conditions are satisfied at ν_{R^*} as
$$\nu_p^2\nu_B/\nu^3 \approx \left(\nu_B/\nu_p\right)^{5/2} \ll \frac{c\alpha_\nu}{\nu} \approx \left(\nu_B/\nu_p\right)^2 \ll |1-n| \approx \left(\nu_B/\nu_p\right) \quad .$$

4. A direct solution of the plasma dispersion relation would be useful, especially to verify that the maser instability is the fastest.

Synchrotron maser: Dynamics

1. A highly relativistic shell, with energy E_s and

$$\gamma_s = 10^3\left(\frac{E_s/10^{41}\mathrm{erg}}{n/0.1\mathrm{cm}^{-3}}\right)^{1/8}(\Delta t/0.1\mathrm{ms})^{-3/8},$$

is heated by the reverse shock to $T_s \sim m_p c^2$ at $r \sim \gamma_s^2 c\Delta t$ (for source radius < $c\Delta t$).

2. In the shocked shell

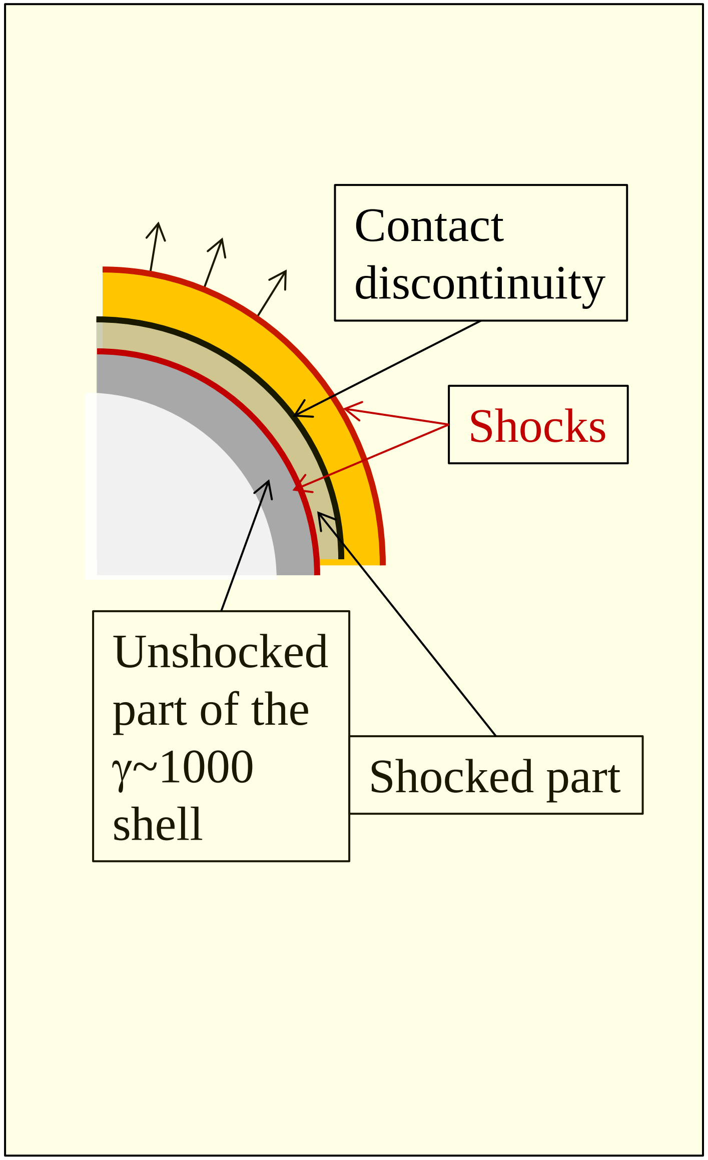
$$\gamma_s \nu_{R^*} = 0.2\left(\frac{E_s/10^{41}\mathrm{erg}}{\Delta t/0.1\mathrm{ms}}\frac{n/0.1\mathrm{cm}^{-3}}{\epsilon_B/0.01}\right)^{1/4}\mathrm{GHz}$$

$$\alpha_0\Delta r = 200\left(\frac{E_s}{10^{41}\mathrm{erg}}\frac{n}{0.1\mathrm{cm}^{-3}}\frac{\Delta t}{0.1\mathrm{ms}}\right)^{1/4}\left(\frac{\epsilon_B}{0.01}\right)^{3/4}$$

→ For E_s & Δt typical for FRBs:

a. $E \sim E_s$ will be emitted over Δt at ~1 GHz, provided $\frac{dn_e}{d\gamma_e}$ is steeper than γ_e^2 below the peak.

b. A burst of ~10 MeV γ's with $E < E_{FRB}$ is predicted from the forward shock.



Summary

- Persistent source properties.
  - $t<300$ yr, 10^{17}cm $<R<10^{18}$cm, $E=10^{49.5}$erg, $E_B/E_e\sim1$, $\varepsilon_e\sim1$GeV.
    Plausibly: $10^{-5}M_{Sun}$ ejected at a mildly relativistic speed.
  - $M_{surround} < 10^{-1.5}\,(R/10^{17.5}\mathrm{cm})^4\,M_{sun}$.
  - Likely: "weak stellar explosion", NS formed with relatively low M & E ejecta.

- FRB mechanism.
  - Synchrotron maser due to non-thermal e^- distribution:
    efficient conversion of kinetic energy to coherent radio emission.
  - The ejection of a highly relativistic shell,
    $E_s\sim10^{41}$erg and $\gamma_s\sim10^3$ corresponding to $\Delta t\sim0.1$ms characteristic of FRBs,
    produces conditions appropriate for strong GHz synchrotron maser emission.
  - FRBs predicted to be accompanied by bursts of ~10 MeV γ's with $E<E_{FRB}$.
  - FRBs may be beamed within $\theta_s\sim1/\gamma_s\sim10^{-3}$.
    The total energy emitted by FRB events over the source lifetime is $<10^{44}\theta_s^2$erg.