FRB models:
(mostly) Robust constraints from observations

Eli Waxman
Weizmann Institute of Science
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What we would like to know

1. “Progenitors”
    a. The underlying source: NS, solar mass BH, super-massive BH (AGN)…
    b. The energy source: Rotation, B, accretion, planet crashes…
    c. The formation channel

2. Emission mechanism
    a. Dynamics: How is the emitting plasma formed?
    b. Microphysics: Relativistic charged “bunches”,
    Plasma instabilities (“masers”).

** Progress will be driven by observations, at different rates on different open questions (from 1a to, maybe, 2b).

Duration

- Δt <~ 1ms

  → A natural scale for compact objects

  NS, solar mass BH

  [See, however, J. Katz's talk]

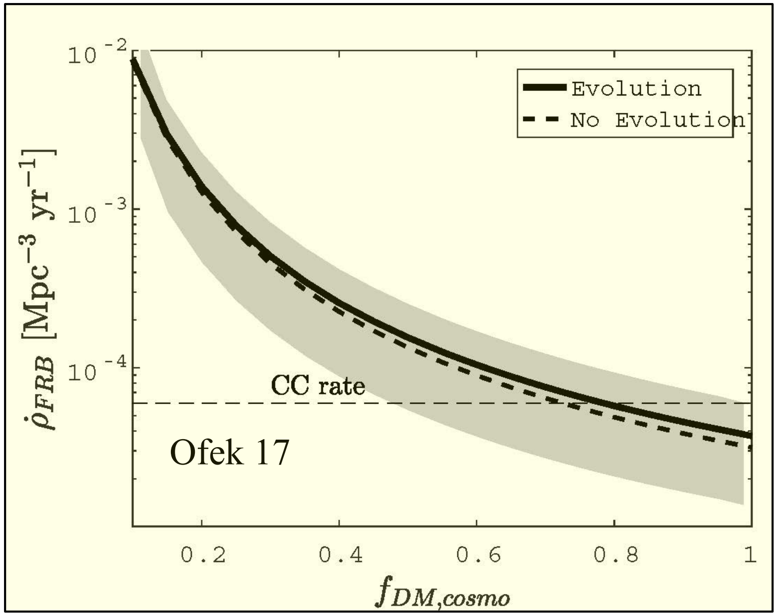
Rate

- Uncertainties: small event number, unknown z-evolution & LF.

- Nevertheless…
  ~3x10^6/yr @ 1 Jy ms, median DM~800 pc/cm^3
  Assuming IGM dominated DM, DM=250 d_{Gpc}, median d~3 Gpc

→ $R \approx \frac{0.5\times 3\times 10^6/\mathrm{yr}}{10^{11}\,\mathrm{Mpc}^3} = 2\times 10^{-5}/(\mathrm{Mpc}^3\mathrm{yr})$

Rate comparable to CC-SN rate,
~100 /yr to 100 Mpc.



- A significant improvement of the constraints may be obtained by understanding the joint ASKAP/Parkes(/CHIME) fluence/DM data.

Energy

- Characteristic radio energy

  $F=1$ Jy ms = 2×10^{-17} erg/cm^2,

  $E \sim 4\pi(3\text{Gpc})^2 F = 2 \times 10^{40}$ erg.

  (?Parkes/ASKAP: flat LF, Parkes ~ 10^{-16} erg/cm^2, E ~ 10^{41} erg).

- X-γ/rays

  2×10^{-17} erg/cm^2 = 10^{-7} MeV/m^2.

  LAT [~30 MeV], GBM [~1 MeV], BAT [~30 keV] sub-sec sensitivity

  ~ 10^{-8} erg/cm^2 = 100 MeV/m^2 = 10^{46} erg @ 100 Mpc (100/yr).

  → Non detection of ~10^2/yr implies $E_{X\gamma} < 10^{46}$ erg .

  Analysis was carried out for LAT [Yamasaki 16], GBM/BAT ?

  For the (1st) repeater: E[~1 keV] < $10^{45.5}$erg, E[~30keV] < $10^{47.5}$erg.

- Optical

  10^{46} erg @ 3 Gpc = 21 mag [30s], 17 mag [1s]

  e.g.: ZTF ~ 21 mag [1min], $4\pi/10^3$, 0.1T → 100/yr.

Energy

- Characteristic radio energy ~2 x 10^{40} erg (10^{41} erg).
- X-γ-O limits

  Evidence for $E_{X\gamma} < 10^{46}$ erg

  (requires improved LF & z-dist, LAT/GBM/BAT).

  Possible optical limit- $E < 10^{46}$ erg.

  Improving the limit significantly (/10) will be challenging.

- Radio energy: No strong constraints on the energy source
- Total energy: unknown.

  However, 10^{46} $(\Delta\Omega/4\pi)$ erg is also not strongly discriminating

  (10^{46} erg ~ NS at 1s period).

Duration, Rate, Energy

- $\Delta t <\sim 1\text{ms}$ → likely NS, solar mass BH.
- Rate (1 Jy ms) comparable to CC-SN rate, ~100 /yr to 100 Mpc.
- Radio energy ~2 x 10^{40} erg (10^{41} erg),
  total probably < 10^{46} $(\Delta\Omega/4\pi)$ erg.

The persistent radio source associated with FRB121102: Robust source constraints

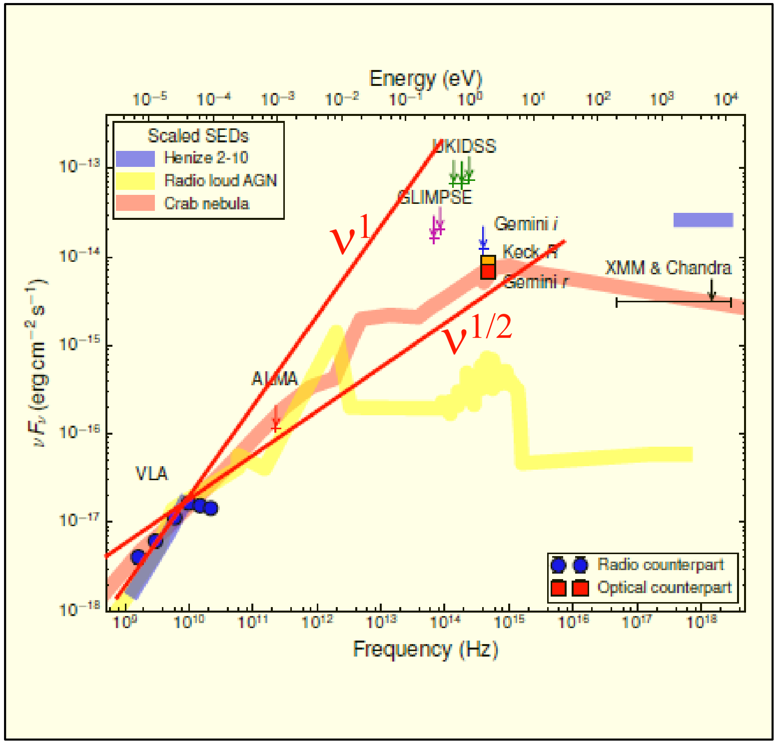
[Waxman 17]

The persistent radio source associated with FRB121102: Key properties

Assumptions:

- The persistent source was produced in a transient event (no continuous energy output),
- 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±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 << 2x10^{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

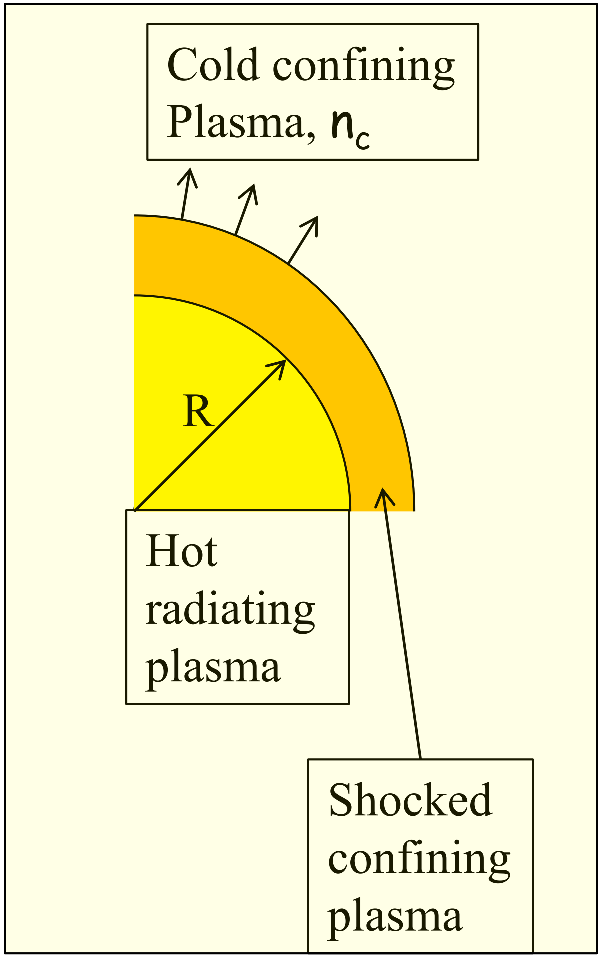
1. R/t < 10^{10}cm/s, no highly relativistic expansion.
→ Consider a sphere R of relativistic radiating e^-, with density n_e and magnetic field B.

2. Peak flux & freq. → 2 constraints on {R,γ_e,n_e,B}:
$B = 10^{-1.5}\gamma_{e,2.5}^{-2}\mathrm{G}$, $n_e = 0.1\gamma_{e,2.5}^{2}R_{17.5}^{-3}\mathrm{cm}^3$
$(\gamma_e = 10^{2.5}\gamma_{e,2.5})$.

3. ν<10 GHz spectrum → no significant cooling,
→ $\gamma_e > 250\,(t/10^9\mathrm{s})^{1/3}$.

4. No relativistic expansion → confining dense plasma, n_c.
- $v \approx \sqrt{\frac{P}{n_c m_p}} < R/t$ → a lower limit to n_c.
- Shocked shell contribution to DM, δDM, $vn_c t, vn_c\delta t \propto n_c^{1/2}$, → an upper limit to n_c.

- A solution exists- not trivial- for t<300 yr.



Cold confining Plasma, n_c

Hot radiating plasma

Shocked confining plasma

Persistent source plasma properties

1. A solution exists- not trivial- for

   $t < 300$ yr,

   10^{17}cm $< R < 10^{18}$ cm,

   $200 < \gamma_e < 10^3$, $B = 10^{-1.5}\gamma_{e,2.5}^{-2}\mathrm{G}$,

   $E_e \approx 10^{48.5}\gamma_{e,2.5}^{3}$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}, $M_c < 10^{-1.5}R_{17.5}^{4}M_{sun}$.

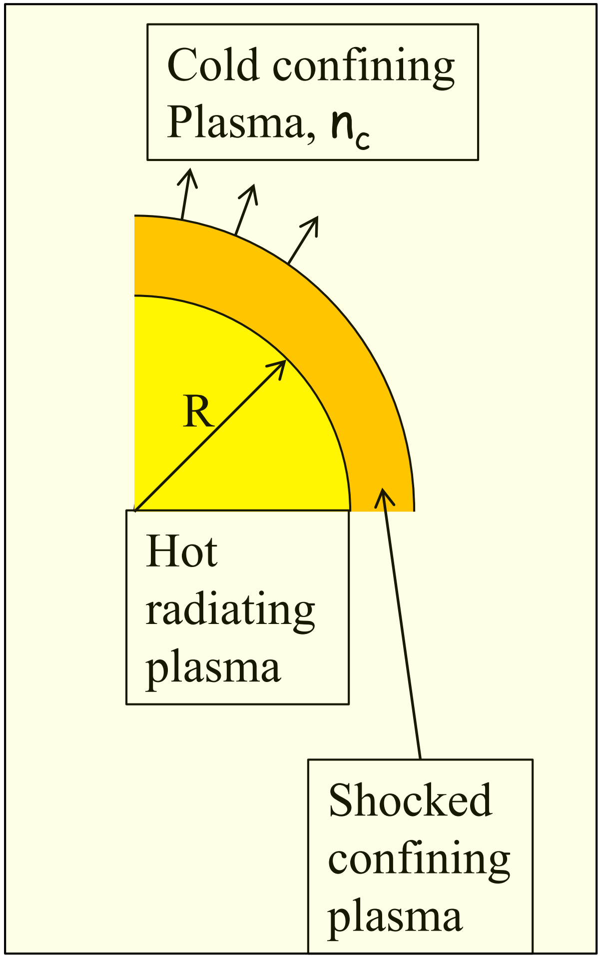
2. Nearly resolved. R may be determined @ 10GHz (directly if 10^{18}cm, by $\Delta f/f$ if 10^{17}cm).

[Waxman 17]

3. RM & circular polarization?
   - RM $=1.5\times10^5$ rad/m^2 → $n_{sc}l_{sc}B_{sc}=0.2$ pc G/cc.
   - RM decrease (30% @ 1.5yr), DM unchanged,

     → $DM_{sc} < 10$ pc/cc → $B_{sc} > 0.02$ G.
   - $P_{circ} = RM*\lambda^2*(\omega_B/\omega) = 0.3\,(B_{sc}/1G)(5GHz/\nu)^3 < 1\%$

     → $B_{sc} < 0.03$ G → $B_{sc} \sim 0.03$ G, $n_{sc}l_{sc} \sim 10$ pc /cc.



** RM screen may be provided by shocked n_c:
$B_{ep} \sim 0.03$ G, $n_cR \sim 10$ pc/cc.
Predicts $P_{circ} \sim 1$ at 1 GHz. [Gruzinov 18]

The persistent source: Progenitor hints

- $\varepsilon_e \sim m_p c^2$, $\frac{E_B}{E_e} \sim 1$ suggests:
  Ejection of a mildly relativistic $10^{-5} M_{sun}$ shell,
  that collided with a pre-ejected $M_c \sim 10^{-1.5} M_{sun}$ shell/"wind".
  Possibly: NS formed by accretion induced collapse.

- The plasma properties are similar to those obtained by Beloborodov 17, Margalit 18. The main differences:
  No free parameters and assumptions on age & E_B/E_e,
  which are derived from a Unique over-constrained solution.

- Challenges for meeting the constraints in "Magnetar" models.
  a. No massive ejecta observed.
     1 M_{sun} @ 10^{18}cm produces 30 pc/cc: the bulk of the ejecta must be driven to large radii, but confining the radiating plasma at 10^{17}cm.
  b. $N_e \sim 10^{52}$ implies a pair flux (in F_{GJ} units) of $\mu_\pm \sim 10^{12}$.
     Many orders of magnitude above the Crab, $\mu_\pm \sim 10^4$.
     Hence, Magnetar models preceding FRB121102 predicted strong emission peaking at Optical-X rays rather than radio [eg Murase et al. 16].

Producing FRBs

Coherent emission mechanisms

- E_{FRB}~ 10^{39}erg ~ 10^{-10} $E_{persistent}$; <L_{FRB}> ~ 10^{-5} $L_{persistent}$
  → Stringent constraints on the sources are unlikely,
  Identification of a unique mechanism is unlikely (see Pulsar history).

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

- Two types of configurations.
  a. "Masers": Unstable non-thermal plasma particle distribution, leading to electro-magnetic instabilities.
  b. "Curvature radiation" from e^- bunches [e.g. Kumar et al 17].

The "gyro-freq." maser

- Reflected electrons form a highly anisotropic momentum distribution, which is unstable.
- Coherent EM waves are produced at the electron gyro-frequency [Sazonov 73; Gallant et al. 92, Lyubarski 14; Ghisellini 17].

- Some difficulties.

i. "gyro maser" emission at perpendicular e+- shocks observed in 1D calculations, but suppressed in 2D [Sironi & Spitkovsky 09].

ii. In the "magnetar" scenario [Beloborodov 17],

$$\nu = 3\, r_{13}^{-1}\left(L_{f,47}L_{w,39}\right)^{1/4}\mathrm{GHz},$$

$$E = 10^{40} r_{13}\epsilon_{-1}\sigma_w^{-1}\Gamma_w^{-2}\left(L_{f,47}L_{w,39}\right)^{1/4}\mathrm{erg},$$

$$\tau = 3\Gamma_4^{-2}\mu s.$$

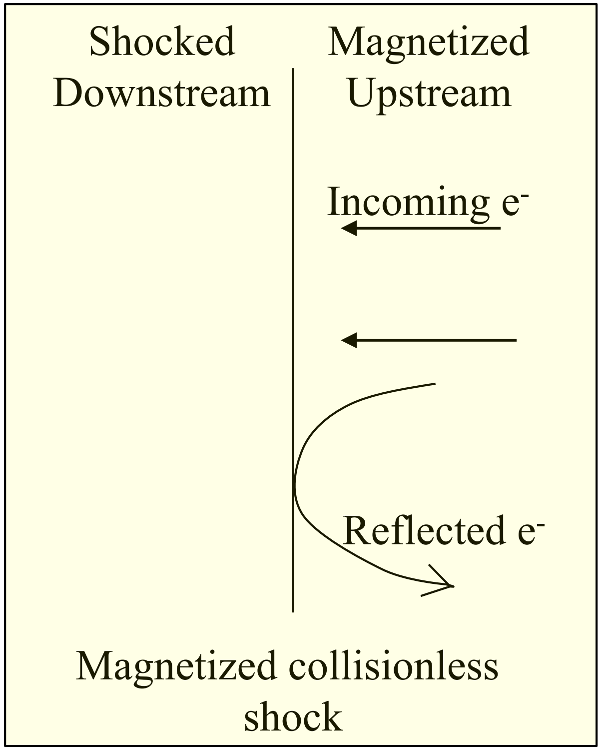
7 parameters vs. 3 observed,

Strong emission at lower radio freq. ($E \sim 1/\nu$).

iii. 10^{47}erg at optical/X/γ:

$$h\nu_{\mathrm{synch.}} = \gamma_e^3 h\nu_{\mathrm{gyro}}$$

$$= 1\mathrm{eV}, 1\mathrm{keV}, 1\mathrm{MeV} \text{ for } \gamma_e = 10^{2,3,4}$$



Shocked Downstream

Magnetized Upstream

Incoming e^-

Reflected e^-

Magnetized collisionless shock

Non magnetized collisionless shock maser

- Scattering at the shock leads to isotropic but 'non-thermal' momentum distribution. If $\frac{dn_e}{d\gamma_e}$ rises faster than γ_e^2, a maser instability may form [McCray 66; Zheleznyakov 67; Sazonov 70; Sagiv & Waxman 02].

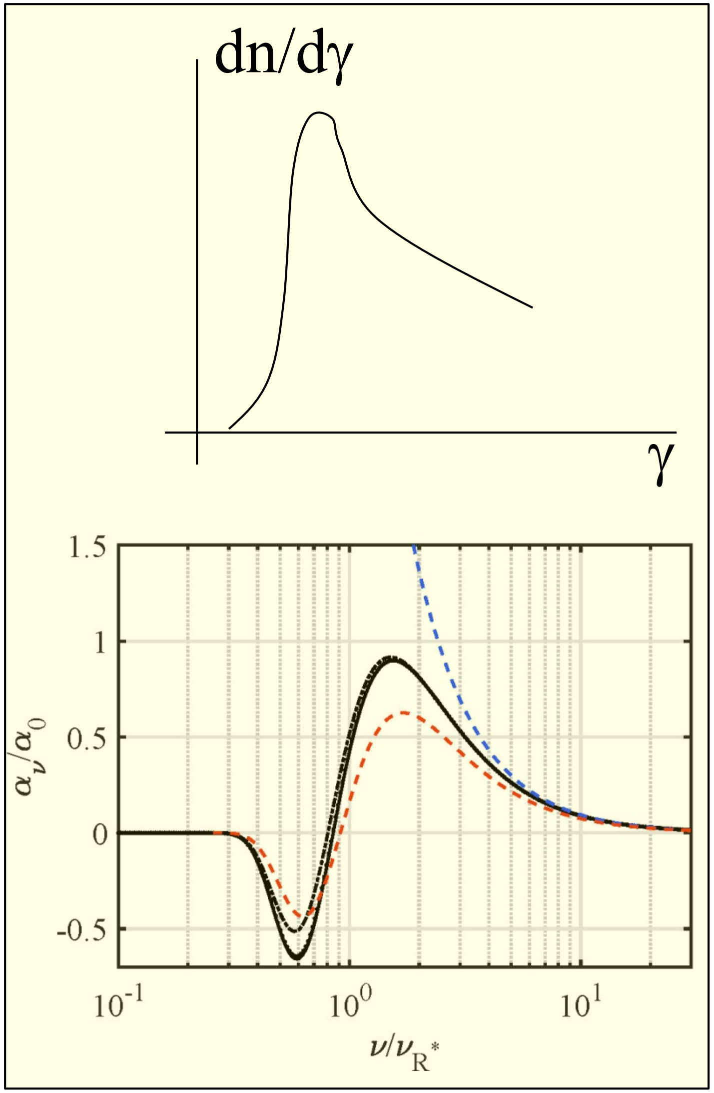
- Instability possible for both $\gamma_e^2 \gg \nu_p/\nu_B$ and $\gamma_e^2 \ll \frac{\nu_p}{\nu_B} \approx \sqrt{\frac{\epsilon_e}{\epsilon_B}}$ [Sagiv & Waxman 02].

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

$$\alpha_\nu = \alpha_0 F\left(\frac{\nu}{\nu_{R^*}}\right),$$

$$\alpha_0 = \frac{\pi}{2\sqrt{3}} \frac{\nu_B}{c} \sqrt{\frac{\nu_B}{\nu_p}} \, , \nu_{R^*} = \nu_p \sqrt{\frac{\nu_p}{\nu_B}}$$

[Waxman 17].



Some technical comments

- The maser instability should be derivable directly from a solution of the plasma dispersion relation.
- The Einstein coefficient method provides a "short cut" that is valid for

$$\nu_p^2 \nu_B/\nu^3 \ll \frac{c\alpha_\nu}{\nu} \ll |1-n| \ .$$

- These conditions are satisfied at ν_{R^*} as

$$\nu_p^2 \nu_B/\nu^3 \approx \left(\nu_B/\nu_p\right)^{5/2} \ll \frac{c\alpha_\nu}{\nu} \approx \left(\nu_B/\nu_p\right)^2 \ll |1-n| \approx \left(\nu_B/\nu_p\right) \quad .$$

- A direct solution of the plasma dispersion relation confirms the qualitative results (with some interesting deviations).
- Numerical simulations show that ~1% of the energy may be converted to the maser emission [Gruzinov & Waxman in prep].

Synchrotron maser: Dynamics

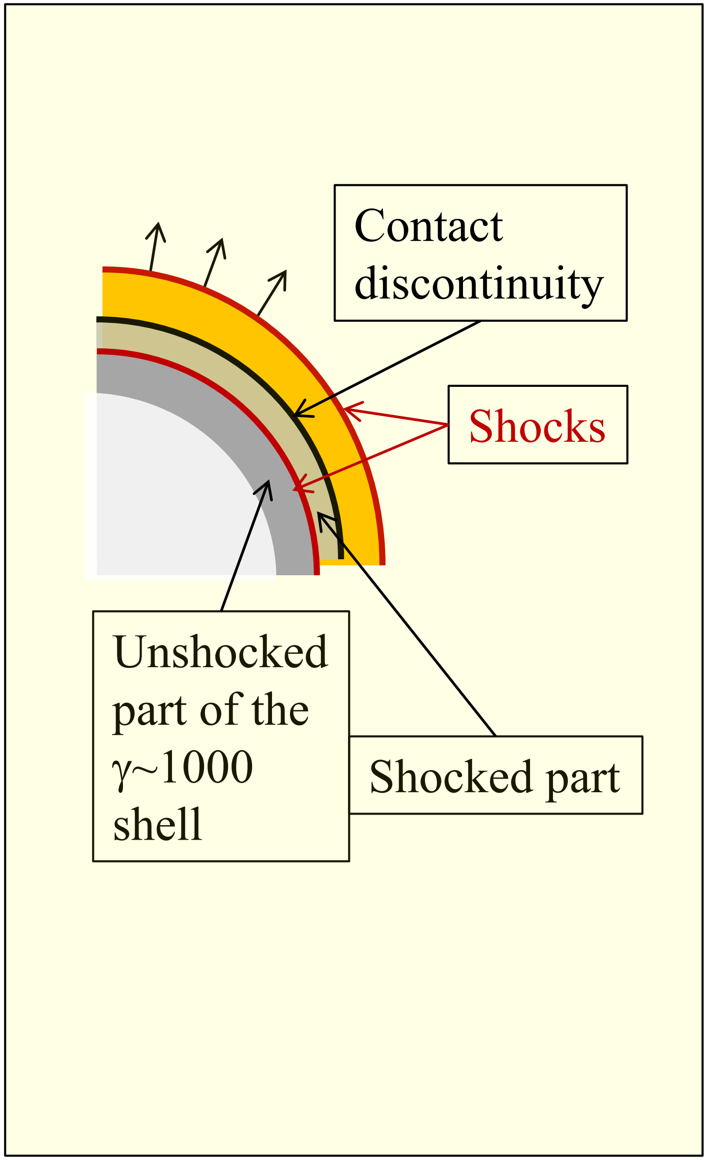
- A highly relativistic shell, with energy E_s and $$\gamma_s = 10^3 \left(\frac{E_s/10^{41}\text{erg}}{n/0.1\text{cm}^{-3}}\right)^{1/8} (\Delta t/0.1\text{ms})^{-3/8},$$ is heated by the reverse shock to $T_s \sim m_p c^2$ at $r \sim \gamma_s^2 c\Delta t$ (for source radius < $c\Delta t$).
- In the shocked shell $$\gamma_s \nu_{R^*} = 0.2 \left(\frac{E_s/10^{41}\text{erg}}{\Delta t/0.1\text{ms}} \frac{n/0.1\text{cm}^{-3}}{\epsilon_B/0.01}\right)^{1/4} \text{GHz}$$ $$\alpha_0 \Delta r = 200 \left(\frac{E_s}{10^{41}\text{erg}} \frac{n}{0.1\text{cm}^{-3}} \frac{\Delta t}{0.1\text{ms}}\right)^{1/4} \left(\frac{\epsilon_B}{0.01}\right)^{3/4}$$

→ 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. $\{n, \varepsilon_B\}$ not free parameters.

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



Contact discontinuity

Shocks

Unshocked part of the γ~1000 shell

Shocked part

Summary

- Δt <~ 1ms → likely compact- NS, solar mass BH.
- Rate (1 Jy ms) comparable to CC-SN rate, ~100 /yr to 100 Mpc.
  All probably repeating (0.1 Jy ms rate).
- Radio energy ~2 x 10^{40} erg (10^{41} erg), total probably < 10^{46} ($\Delta\Omega/4\pi$) erg.

** Rate & E constraints may be improved by
ASKAP/Parkes/Chime LF & z-dist. and Opt(-X-γ) observations.

** Progenitors will most likely be identified by localization.

- (1st) Persistent source:
  t<300 yr, E=$10^{49.5}$erg in $10^{-5}M_{Sun}$ surrounded by < $10^{-1.5}M_{sun}$ at ~10^{17}cm.
  Hints to a NS formed with relatively low M & E ejecta, AIC.

- FRB mechanism- most likely plasma instability ("maser"), identification of a unique instability is unlikely (see Pulsar history).
  - Gyro-maser: E~1/ν problem, predicts E~ 10^{46}erg in optical/X/γ.
  - Non-magnetized maser: efficient conversion of kinetic energy to coherent radio emission, weak ~10MeV emission.