A few issues in CSM interaction signals (and on mass loss estimates)

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Radio/X constraints on CSM around SNe Ia

Useful limit for SN 2011fe: $\dot{M}/v_w < \sim 10^{-8} M_\odot \text{yr}^{-1}/100 \text{km s}^{-1}$

Radio: Synchrotron
X-Ray: Inverse Compton (+ thermal)
What we see in radio and X

Radio: Synchrotron
X: Inverse Compton (low density)
Thermal (high density CSM)

Best studied cases: IIb/Ib/Ic
(lower density → less complication)
Shock ⇒ Relativistic particle acceleration

Shock wave
- B amplification
- Acceleration.

Equipartition
\[ E_B = \varepsilon_B \rho V^2 \sim B^2 \]
\[ E_e = \varepsilon_e \rho V^2 \]

\[ N_e(\gamma) \]
\[ \gamma \sim 1 \quad (T \sim \text{keV}) \]
\[ \gamma \gg 1 \]
Robustness of the mass loss estimate?

- Limits placed by signals from relativistic electrons.
- One assumes “macroscopic parameters”, $\varepsilon_e + \varepsilon_B$, under several assumptions.
  - (quasi-equipartition).
    - $U_e = \varepsilon_e \rho V^2$, $U_B = \varepsilon_B \rho V^2$.
  - A single power law.
    - Describes both e’s emitting radio synchrotron and X-ray IC.
- Not only for the mass-loss constraints, but interesting questions themselves (particle acceleration mechanism not yet clarified).
Non-thermal emission: SN vs. SNR

**Young SNe**
- Days to years
- Distance ~10 Mpc
- Time evolution: yes
- CR trapped (?)

**SNRs**
- >100 years
- ~ kpc
- No
- CR partly escaping

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**Graphical Representation**

- **Left Panel**
  - Days since explosion: 16, 20, 25, 35 days
  - Flux density (mJy)
  - VLA
  - Soderberg + 2012, Krauss + 2012
  - 10 GHz

- **Right Panel**
  - X-ray luminosity (10^40 erg s^-1)
  - SWIFT + Chandra
  - Soderberg + 2012
  - 10^39 erg s^-1
### Synchrotron Characteristics

\[ f_{\nu} \propto \nu^{\alpha} t^{\beta} \]

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\( p \): Rel-e distribution, \( n(E) \propto E^{-p} \)

\( m \): Shock evolution \( R \propto t^m \) ← CSM distribution

\( \delta \): opt-IR time evolution, \( L_{th} \propto t^\delta \) (observed)

\( \alpha, \beta \) (obs) \Rightarrow e's \ distribution \((p)\) + CSM distribution

Radio synchrotron from SNe (\(\sim \) GHz).

Generally, \(p \sim 3\).

It is very peculiar.
**Galactic SNRs in radio**

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**Prediction:** $p = 2$

$p \sim 3$ is peculiar

Mostly $\alpha = 0.5 - 0.7 \Rightarrow p = 2 - 2.4$
Synchrotron emitting e's energy

Synchrotron frequency

\[ E_B = \varepsilon_B \rho V^2 (\sim B^2) \]

SNR

\[ n \sim 1 \text{ cm}^{-3} \]
\[ V \sim 0.01c \]

⇒ \[ B \sim 100 \mu \text{G} \]
⇒ \[ 1 \sim 10 \text{ GeV} \]

SN (Ib/c)

\[ n \sim 10^6 \text{ cm}^{-3} \]
\[ V \sim 0.1c \]

⇒ \[ B \sim 1 \text{G} \]
⇒ \[ 10 \sim 100 \text{ MeV} \]

Energy of the emitting e's different.
Inverse Compton emitting e’s energy

\[ \sim 1 \text{ eV} \Rightarrow \sim 1 \text{ keV} \]

\[ e \text{’s energy: } \gamma \sim \sqrt{1000} \sim 30 \Rightarrow 20 \text{ MeV} \]

\[ < \text{ radio-synchrotron emitting e’s } \sim 100 \text{ MeV} \]
Injection problem(?)

Fermi mechanism requires:
Rel e’s mean path > Shock width

Rel e’s gyro radius
> thermal p’s gyro radius

$\gamma_e > \left( \frac{m_p}{m_e} \right) \left( \frac{V}{c} \right) \sim 200$ if $V \sim 0.1 \, c$
20 if $V \sim 0.01 \, c$

More serious in SNe Ia?

Shock velocity

\[ V_c = 8 \times 10^9 E_{51}^{0.43} \left( \frac{M_{SN}}{M_\odot} \right)^{-0.32} A_*^{-0.12} t_d^{-0.12} \text{cms}^{-1} \]

A*=(\text{Mdot}/v_w)/(10^{-5}M_\odot\text{yr}^{-1}/1000\text{kms}^{-1})
A*~1 for a WR (SNe Ib/c) \Rightarrow V \sim 0.1c.
A* \sim 0.01 for a SD (SNe Ia) \Rightarrow V \sim 0.3c.

\[ \gamma_e > \left( \frac{m_p}{m_e} \right) (V/c) \sim 200 \text{ if } V \sim 0.1 \text{ c} \]
\[ 600 \text{ if } V \sim 0.3 \text{ c} \]
\[ >> \gamma_{\text{syn}} (\sim 100), \gamma_{\text{IC}} (\sim 30) \]

Anyway, studying SNe IIb/Ib/Ic (“low” density) is the only way to calibrate the assumptions we use for Ia’s.
Young SNe ⇒ Probe for e’s acceleration

Requires non-Fermi Mechanism (Injection?)

Young SNe

SNRs

Fermi Mechanism

What is the energy scale here?

\[ N_e(\gamma) \]

\[ \text{keV} \sim \text{MeV} \]

\[ \sim 100 \text{ MeV} \]

\[ \sim 10 \text{ GeV} \]

Rel e’s energy
If there is a change in the spectral slope, could be detectable with ALMA.

X-ray

Calc. example

thermal

Compton

Synchrotron

$p \sim 2 @ > 100 \text{ MeV}$

$p \sim 2 @ > 500 \text{ MeV}$

$p \sim 3$ throughout

SN IIb 2011dh... radio mass loss estimate

$\varepsilon_e = 6 \times 10^{-3}$, $\varepsilon_B = 5 \times 10^{-2}$, $A^* = 4$

$\varepsilon_e = 1 \times 10^{-2}$, $\varepsilon_B = 1 \times 10^{-3}$, $A^* = 30$

Adiabatic Cooling (IC)
Constraints on Shock Microphysics (+CSM)

Mass loss

Low velocity model
(similar to Soderberg+12)

Dynamics from optical emission constraints
(velocity higher, but still consistent with VLBI)

\[ \sim 2 < A^* \sim 30 \]

\[ \varepsilon_e < 0.01 \] (!!)

\[ \varepsilon_B \) can be anything
(unless A* fixed)
Importance of inverse Compton

• Sometimes people do the following to explain X-rays from SNe IIb/Ib/Ic.
  e.g., Soderberg+2012, Krauss+2012, Horesh+2012

• Radio interpretation assuming “adiabatic”.

• Introducing large $\varepsilon_e (>0.1)$ (to get many relativistic electrons).

Equi-partition

$E_B = \varepsilon_B \rho V^2 \sim B^2$

$E_e = \varepsilon_e \rho V^2$
Inverse Compton in Radio is important

$\varepsilon_e = 0.006$

$\varepsilon_e = 0.26$

No/little evidence of IC cooling in most of SNe IIb/Ib/c.

$\Rightarrow \varepsilon_e$ is generally below 1%.
Radio + X from SN IIb 2011dh

- $A^* \sim 30$
  - $X$ is thermal.
- $A^* \sim 4$
  - $X$ is Compton.
- Radio emitting $e$’s $\Rightarrow$ equivalent to $\varepsilon_e < 0.01$
  - CSM upper-limit in Ia’s increases by $\sim 10$ (if the same with 2011dh).
SNe Iax: Radio and X-ray so far constraining?

- Low V $\Rightarrow$ faint.
- Observations need to go down by another factor of 10 to be constraining.

![Graph showing luminosity vs. time for different models.](image)
Summary

• Relativistic electrons responsible to SN radio and X are at the low energy.
  – It is probably below the lower-limit where the “standard” acceleration works.

• A need to constrain the e’s properties at this energy scale.
  – SNe IIb/Ib/Ic in multi-λ is a (only?) way.
  – SN 2011dh useful information (e.g., IC in radio constrains the radio-syn e’s pretty well).
  – But the difference to Ia’s should always be kept in mind.