Observing the Effects of Cosmic Ray Acceleration in Young Supernovae

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Supernovae - a recap

Explosive death of stars

Energy $\sim 10^{51}$ erg $\Rightarrow$ Strong fast shocks

About 250 Supernovae discovered per year

Various types of SNe $\Rightarrow$ diverse progenitors

Not Galactic!

Not Supernova Remnants but...

Young Supernovae $\Rightarrow$ 1 day to 1 year
Radio SNe: Fireballs of Synchrotron

Optical
\( \sim 6000 \text{ K} \)

Radio
\( \sim 10^9 \text{ K} \)

Xrays
\( \sim 10^7 \text{ K} \)

Chevalier82
Chevalier98
Weiler+01

NOT TO SCALE
Proton-Proton Collisions

\[ p + p \rightarrow p + p + \pi^\pm + \pi^0 \]

\[ \pi^0 \rightarrow \gamma + \gamma \]

\[ \pi^\pm \rightarrow \mu^\pm + \nu_\mu \]

\[ \mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu + \nu_e \]
Proton-Proton Collisions

\[ t_{pp} = \frac{1}{n\sigma_{pp}c} \approx 35 \text{ Myr} \; n^{-1} \]

\[ \tau_{pp} \approx 5 \frac{A_w}{M_{\odot}/\text{yr}} \frac{R}{10^{16}\text{cm}} \left( \frac{V_{sh}}{5000 \text{ km/s}} \right)^{-1} \]

\[ \gamma_{e,2} \approx \frac{1}{4} \frac{m_{\pi}}{m_e} \approx 70 \]
Recipe and Ingredients

- **Dynamics**: Free expansion, wind medium
- **Particle injection**: power law, Exp cut-off
- **Cooling**: Adiabatic, Synchrotron, InvCompton
- **Radiation**: Synchrotron, free-free absorption
- **pp-collision**: most detailed cross section from Kelner et al. (2006)
Collision Cross Sections

\[ \sigma_{\text{inel}} = \left( 34.3 \pm 1 \right) \left[ 1 - \left( \frac{E_{\text{th}}}{E_p} \right)^4 \right]^2 \]

\[ E^2 \frac{dN}{dE}, \text{TeV cm}^{-2} \text{s}^{-1} \]

\[ \alpha = 2, \beta = 1 \]

\[ E_0 = 1000 \text{ TeV} \]

\[ E, \text{TeV} \]
Evolution of Particle Distribution

Radius = $10^{13} - 10^{17}$ cm

$\log_{10}(N(\gamma) \times \gamma^2)$
Evolution of Particle Distribution

Radius = $10^{13} - 10^{17}$ cm

Protons

$\log_{10}(N(\gamma) \times \gamma^2)$ vs. $\log_{10}(\gamma)$
Radio Synchrotron Lightcurves

\[ \nu = 10 \text{ GHz} \]

VLA

Primary $e^-$
Secondary $e^-$
Total

Log$_{10}(L_v)$ (erg/s/Hz) vs. Log$_{10}$(Time) (day)
Radio Synchrotron Lightcurves

\( \nu = 100 \text{ GHz} \)

\begin{align*}
\text{Primary } e^- & \quad \text{Red line} \\
\text{Secondary } e^- & \quad \text{Blue line} \\
\text{Total} & \quad \text{Black line}
\end{align*}
Radio Synchrotron Lightcurves

\[ \text{ALMA} \]
\[ \nu = 1000 \text{ GHz} \]

\[ \log_{10}(L) \text{ (erg/s/Hz)} \]

\[ \log_{10} \text{(Time)} \text{ (day)} \]
Synchrotron: Primary & Secondary e−

![Graph showing luminosity vs. time for primary and secondary electrons, with luminosity in erg/s/Hz and time in days.]

- primary e−
- secondary e−
- Total
- SNe IIa

Luminosity (erg/s/Hz)

Time (day)

$K_{ep} = 0.01$

$K_{ep} = 0.001$
Take-home Message

ALMA is in a unique position to observe the synchrotron emission due to the secondary e-
Thank You!
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VLA picture courtesy of Drew Medlin (dmedlin@aoc.nrao.edu)

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- Dynamics: Free expansion, wind medium
- Particle injection: power law, Exp cut-off
- Cooling: Adiabatic, Syn, InvCompton
- Radiation: Synchrotron, free-free absorption
- pp-collision cross section: Kelner et al. (2006)
Why is it important to see proton acceleration?

- Identify sources of Cosmic rays
- Several aspects of particle acceleration process
- Identify sources of neutrinos

Proton synchrotron is usually smothered by electron synchrotron
SNe as Cosmic Ray accelerators

- Large energy output: $E \sim 10^{51}$ erg
- Strong shocks
- Efficient particle accelerators
- Dense environment: observed mass-loss rates
- Interaction powered SNe: Type IIn and Super-Luminous SNe

![Graph showing luminosity (Billion Suns) vs. days since explosion](image)
SNe as Cosmic Ray accelerators