Ultra High Energy Cosmic Rays from Mildly Relativistic Supernovae

Sayan Chakraborti

Tata Institute of Fundamental Research
Mumbai, India

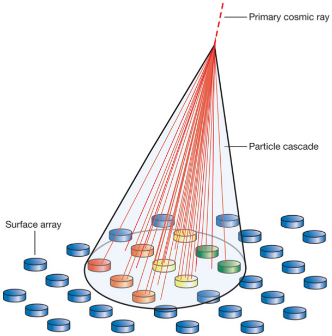
March 13, 2012

Outline

Chakraborti, Ray, Soderberg, Loeb, Chandra
2011 Nature Communications 2, 175

Ultra High Energy Cosmic Rays

- Pack a LOT of energy
- Cant be caught by satellites
- Detected by air-showers



Who ordered that?

- Interact with Lorentz boosted CMB photons
- Must come from within the GZK horizon
- Must have right combination of B-R
- Must have right rates and energetics
- Where are the sources?

Possible sources

- Galactic (but with very high galactic magnetic field)
- Cosmological (but with Lorentz Violation during propagation)
- Active Galactic Nuclei (AGNs)
- Gamma Ray Bursts (GRBs)
- Hypernovae
- ...

Why another solution?

- None of the existing astronomical sources are satisfactory
- Must investigate all potential sources before modifying physics
- New sources in hand

Mildly Relativistic Supernovae

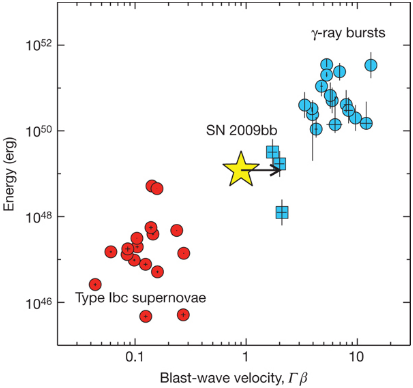


Figure: Comparison of SN 2009bb blastwave velocity and energy with those of type Ibc SNe and nearby GRBs. (Soderberg et al. Nature 2010)

SN 2009bb

- Found in radio follow up of > 100 type Ibc SNe
- Bright radio emission seen by VLA and GMRT
- Requires engine driven relativistic ejecta

Giant Metrewave Radio Telescope

GMRT map of host galaxy

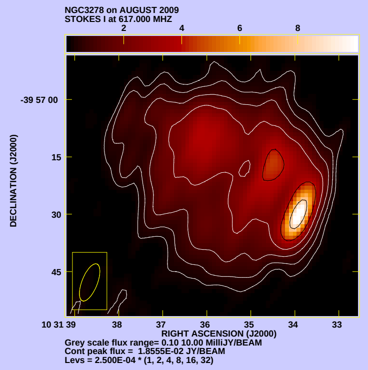
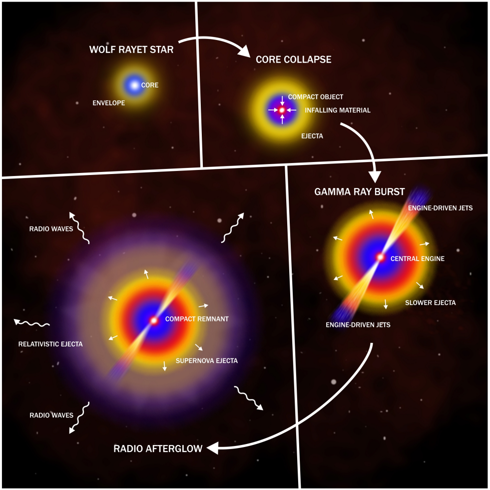
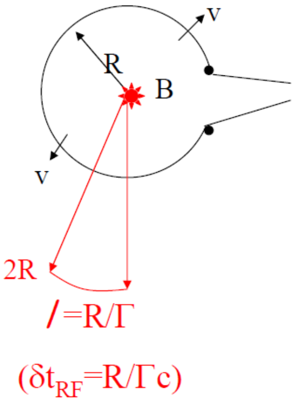


Figure: 617 MHz map of the host galaxy from the GMRT, showing the location of the supernova

Mildly Relativistic Supernovae



B-R Combination



From Waxman

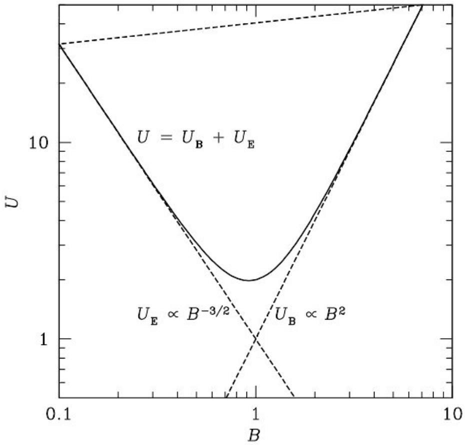
B-R Combination

$$V = \frac{1}{c}\dot{\Phi} \sim \frac{1}{c}\frac{BR^2}{R/v} = \beta BR$$

$$\varepsilon_p < \beta eBR/\Gamma$$

How to figure out B-R?

Use Rybicki and Lightman



How to figure out B-R?

Chevalier's Prescription for SSA

$$R \simeq 4.0 \times 10^{14} \alpha^{-1/19} \left(\frac{f}{0.5}\right)^{-1/19} \left(\frac{F_{op}}{\mathrm{mJy}}\right)^{9/19} \left(\frac{D}{\mathrm{Mpc}}\right)^{18/19} \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-1} \mathrm{cm}, \quad (1)$$

$$B \simeq 1.1 \alpha^{-4/19} \left(\frac{f}{0.5}\right)^{-4/19} \left(\frac{F_{op}}{\mathrm{mJy}}\right)^{-2/19} \left(\frac{D}{\mathrm{Mpc}}\right)^{-4/19} \left(\frac{\nu}{5\ \mathrm{GHz}}\right) \mathrm{G}. \quad (2)$$

SN 2009bb: Spectrum

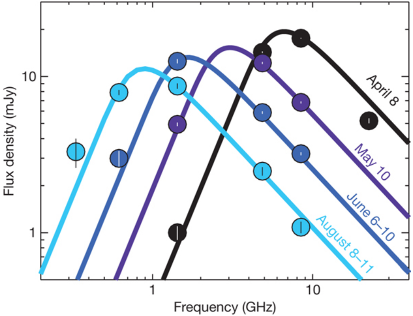


Figure: Radio spectrum (F_ν) of SN 2009bb, obtained from coordinated observations using the VLA and GMRT. The spectrum at high frequencies is given by optically thin synchrotron, while it is suppressed at low frequencies by SSA. (Soderberg et al. Nature 2010)

SN 2009bb: B-R Evolution

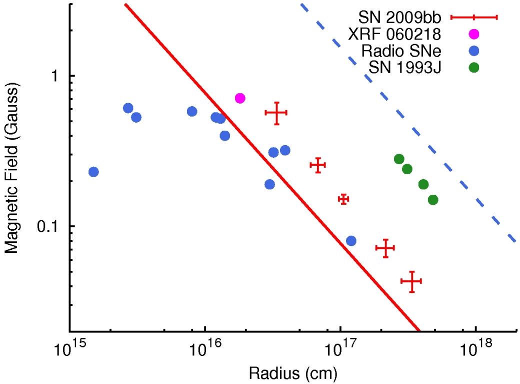


Figure: Hillas Diagram: SN 2009bb may accelerate Fe to 166 EeV

Energy Injection Rate

- $\Gamma_{inj} = (0.7 - 20) \times 10^{44}$ erg Mpc^{-3} yr^{-1}
- At the rate of SN 2009bb like objects, each of them has to put in around $E_{SN} = (0.3 - 9) \times 10^{51}$ ergs
- Much more than the $E_{eq} \approx 10^{49}$ ergs required to naively explain the radio emission in SN 2009bb
- Re-examine energy budget

SN 2009bb: Energy Budget

Collisional slowdown

$$\frac{d\gamma}{\gamma^2 - 1} = -\frac{dm}{M} \tag{3}$$

$$dE = c^2(\gamma - 1)dm \tag{4}$$

$$\text{and} \quad \rho \propto r^{-2} \tag{5}$$

$$\frac{m(R_2)}{m(R_1) + M_0} = -(\gamma_1 - 1)^{1/2}(\gamma_1 + 1)^{1/2} \int_{\gamma_1}^{\gamma_2} (\gamma' - 1)^{-3/2}(\gamma' + 1)^{-3/2} d\gamma' \tag{6}$$

Radius Evolution in Observer's Time: R(t)

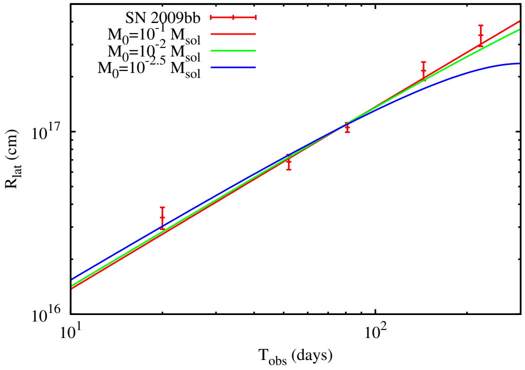


Figure: $R_{lat}(t_{obs})$ evolution in the observer's frame, determined from SSA

Blastwave Energetics

Mass-Energy estimates

$$M_0 \simeq 1.4 \times 10^{-3} M_\odot \quad (7)$$

$$E_{Baryons} \gtrsim 3.3 \times 10^{51} \mathrm{ergs} \quad (8)$$

Coupled with (uncertain) rates for these objects, gives the correct energy for the energy injection rate required in UHECRs.

Are there enough of them?

- Hosted by gas rich spirals (remember HIPASS correlation?)
- 21 cm fluxes of NGC3278 indicates $\sim 1.9 \times 10^9 M_\odot$ of HI.
- SNe Ibc occur at a rate of $\sim 1.7 \times 10^4$ Gpc^{-3} yr^{-1}
- SN 2009bb like events 0.7% $\sim 1.2 \times 10^{-7}$ Mpc^{-3} yr^{-1}
- XRF 060218 like $\sim 2.3 \times 10^{-7}$ Mpc^{-3} yr^{-1}
- > 60 arrival directions need to be explained
- How do we spot these objects?

Are there enough of them?

- ~ 4 objects within 200 Mpc per year
- Cosmic rays of different energies have different travel delays due to deflections by magnetic fields
- $\langle \tau_{delay} \rangle \approx 10^5$ yrs
- May receive particles from any of 4×10^5 possible sources at any time.

X-Ray transients

Assuming that, the accelerated electrons have the same initial power-law index for their energy spectrum as the protons, and that they lose all their energy radiatively (Waxman & Loeb 2009).

Rate of X-Ray transients

$$\dot{n}\Delta t \backsimeq 3 \times 10^{-7} \left(\frac{\epsilon}{0.002}\right) \left(\frac{\Gamma_{inj}}{10^{44}\ \mathrm{erg\ Mpc^{-3}yr^{-1}}}\right) \left(\frac{\nu L_\nu}{10^{40}\mathrm{erg\ s^{-1}}}\right)^{-1} \mathrm{Mpc}^{-3} \tag{9}$$

SN 2009bb had an X-ray luminosity of $L_X = 4.4 \pm 0.9 \times 10^{39}$ erg s^{-1}. This luminosity and the rate of the relativistic SNe, together can account for the UHECR flux, if they remain active accelerators for Δt of order ~ 1 year.

Radio transients

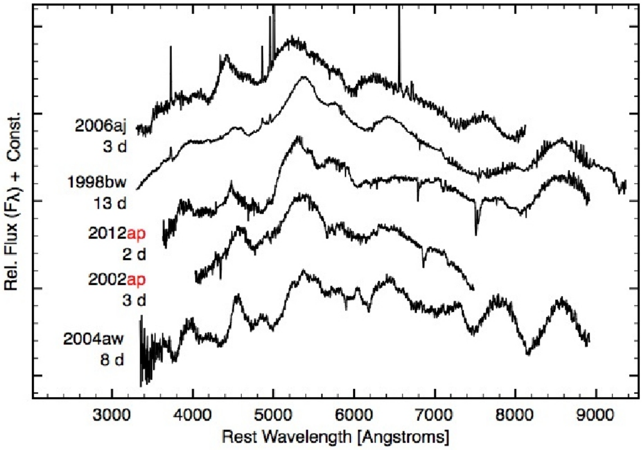
Assuming that the electrons and magnetic fields together have a fraction ϵ of the energy of the relativistic protons (which is assumed to be divided equally into ~ 10 logarithmic bins, assuming $p \approx 2$ for the protons), we compute the minimum required rate of such transients with peak radio luminosity L_{op}, which remain mildly relativistic at least until the SSA peak frequency drops to ν, as

Rate of X-Ray transients

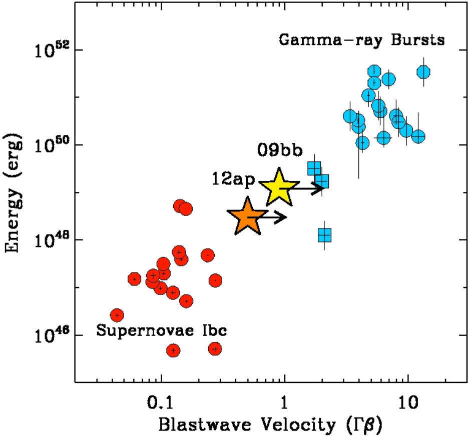
$$\dot{n} \simeq 3 \times 10^{-7} \left(\frac{\Gamma_{inj}}{10^{44}\ \mathrm{erg\ Mpc^{-3} yr^{-1}}}\right) \left(\frac{\epsilon}{0.002}\right) \left(\frac{L_{op}}{10^{29}\ \mathrm{ergs/sec/Hz}}\right)^{-23/19} \times \left(\frac{\nu}{0.5\ \mathrm{GHz}}\right) \left(\frac{2}{\eta^{11}(1+\eta^{-17})}\right) \mathrm{Mpc^{-3} yr^{-1}} \quad (10)$$

Radio analogue of Waxman & Loeb's equation for X-Ray transients.

SN 2012ap: A new broad-lined Sn Ib/c



SN 2012ap: Relativistic Ejecta



Thanks

- My collaborators Alak, Alicia, Avi and Poonam
- VLA (run by NRAO) and GMRT (run by TIFR) for observations
- All of you for coming to the talk

Questions?

If you have a question later, email me at sayan@tifr.res.in