Electron Injection in a Young SN & Evolution Towards SNR

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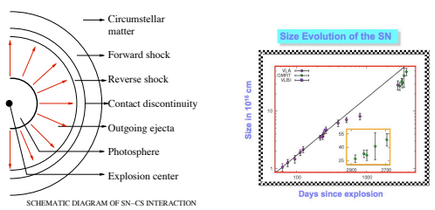
ABSTRACT

The blast wave shock in SN 1993J has very high Mach numbers – sonic and Alfvenic Mach numbers are in excess of 100, ideal for ion plasma instabilities which generate plasma waves that energize electrons upon interaction. Plasma in the shock-circumstellar interface is strongly magnetized, with the energy density of magnetic field exceeding that of the relativistic particles by a factor of $10,000$. This small "equipartition" factor for a young type IIb SN is in contrast to that of older Supernova remnants, where this factor is near unity. Evolution of the radio spectrum of young supernovae can determine the change of the shock compression ratio as the SN ages, and through comparison with models of particle acceleration coupled with hydrodynamics, indicate the injection factor: the fraction of the total electrons that end up in the superthermal tail.

2 Blast-wave Shock in SN 1993J

2.1 Shock, sonic and Alfven speeds

The interaction of a supernova explosion (SN) with the Circumstellar Medium (CSM) has the following schematic picture:

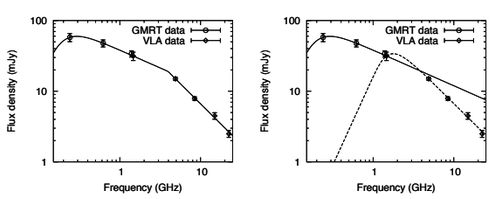


Synchrotron self absorption spectral fits to GMRT low frequency data of days 3000-3730 indicate velocities of the outer part of the supernova (shock velocity) to be $v_s \sim 11000$ km s^{-1} (Chandra etal 2004).
Ion sound speed in the upstream (unshocked circumstellar) gas $c_s = (\gamma k T_e/m_p)^{1/2}$, (where $\gamma = 5/3$, m_p proton mass) on day d = 3800 about $c_s = 90$ km s^{-1} with the *electron* temperature T_e of the circumstellar medium flash ionized by UV & X-ray emission soon after shock breakout maintained at $1-5\times10^5$ K (Chevalier & Fransson 2001 (CF)). The preshock magnetic field is uncertain. Biermann & Casinelli (1993) estimate the field in the wind of the progenitor OB or Wolf Rayet stars 3 G at reference radius 10^{14} cm. On day 3800, at $R = 5\times10^{17}$ cm the upstream magnetic field is at least 1 mG. The upstream ion density at this position (scaled from that of CF at $R = 1\times10^{16}$ cm) is 400 cm^{-3}. Thus Alfven velocity $v_A = 110$ kms^{-1} and sonic and Alfvenic Mach numbers upstream are $M_s \geq M_A \sim 100$.

2.2 Magnetic field orientation

The angle between shock normal and mean magnetic field $\Theta_{\mathbf{nB}} \geq \pi/4$ in a quasi-perpendicular shock. A SN shock propagating into a magnetized progenitor wind quickly becomes perpendicular to the ambient magnetic field since the field lines are wound up into a spiral (Achterberg & Ball 1994). Spacecraft observations of energetic particles streaming ahead of the Earth's bow shock and that of Uranus indicate that quasi-perpendicular geometry energizes electrons while quasi-parallel regions of the shock surface energize ions (Malkov & Drury 2001 & references).

2.3 Synchrotron Break in SN 1993J



Combined GMRT & VLA spectrum (day 3200). Synchrotron break is at 4 GHz. Spectral index α (before break) $= 0.51 \pm 0.01$. $\Delta\alpha = 0.62 \pm 0.04$. Right panel: Synchrotron self absorption (SSA) model fit only with GMRT data (solid line) and only with VLA data (dashed line). Synchrotron Energy losses and synchrotron break frequencies are:

$$\left(\frac{dE}{dt}\right) = -1.58\times10^{-3}\,B^2E^2 \text{ and } \nu_{\rm break} = \left(\frac{\rm t}{1.4\times10^{12}\rm s}\right)\left(\frac{\rm B}{\rm Gauss}\right)^{-3}$$

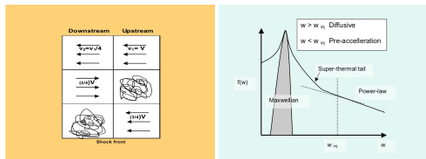
Break frequency together with age gives $B \sim 200$ mG. Adding adiabatic loss and Fermi acceleration gain, cumulative electron lifetime gives synchrotron break frequency as (Chandra et al., 2004)

$$\nu_{break} = \frac{2\times10^{24}}{B_0^3}\left[\frac{R^2}{20\kappa_\perp}t^{-1/2} - 2t^{1/2}\right]^2 \text{ Hz with } \mathrm{B} = \mathrm{B}_0/\mathrm{t}$$

This gives the magnetic field as **330 mG** when $\kappa_\perp = 3\times10^{24}$ cm^{2}s^{-1} similar to SN 1987A. This suggests that the SN plasma is dominated by magnetic energy density $\geq$ 10,000 times the relativistic energy density.

2.4 Electron acceleration: quasi-perpendicular shocks

First order Fermi acceleration (Diffusive Shock Acceleration) results from particles repeatedly crossing the shock, and being scattered off by turbulence generated coherent structures in upstream and downstream flows. Particles at the background temperature downstream in perpendicular shocks cannot move freely along the shock normal in a strong magnetic field, until they are "pre-accelerated" so that their Larmor radius becomes large compared to the mean free path for scattering off the coherent structures. The electrons that are able to cross the shock undergo betatron acceleration owing to the compression of the magnetic field in the shock (since $p_\perp^2/2B$ remains adiabatically invariant; $p_\perp$ being the perpendicular component of momentum - see Levinson (1996)).



The particle momentum distribution becomes nearly isotropic in the local frame moving with the bulk fluid velocity U(x) due to scattering off the hydromagnetic waves that propagate at $v_A \ll U$. The pitch angle averaged distribution $f(x,p,t)$ (see e.g. Malkov and Drury, 2001) in the test particle approximation is given by a (time-*independent*) solution in the upstream (with flow speed u_1): $f = f_0(p)\exp(-\mathrm{u_1 x}/\kappa)$ with

$$f_0 = \eta_{inj} p^{-q}$$

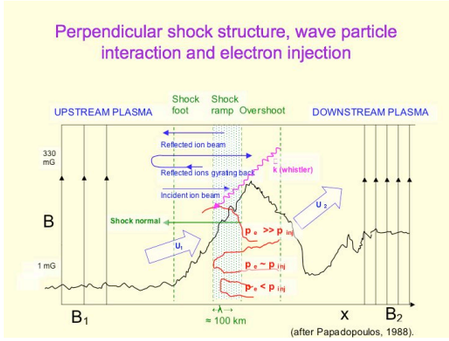
and power law index $q = 3\sigma/(\sigma-1)$, σ being the shock compression ratio and η_{inj} is the normalization constant determining the rate at which the high energy population is supplied from the thermal pool of particles.

2.5 Cross-field diffusion and plasma waves

Particles in superluminal shocks, that have been once swept downstream can only recross into upstream region by cross-field diffusion with coefficient $\kappa_\perp$. For electron injection the condition of cyclotron resonance $\omega - k_{||}v_{||\alpha} = \pm\omega_{c\alpha}$ (ω_c's are cyclotron resonance frequencies for $\alpha = e, i$ electrons and ions) is difficult to satisfy, since waves generated by thermally leaking protons with $k \sim \omega_{ci}/u_1$ are too long to resonantly interact with electrons. Levinson (1996) invoked electron self generated waves in perpendicular shocks. An initially isotropic distribution of electrons transmitted through the shock develops anisotropy. This generates the whistler waves (for $p \leq p_A = m_p v_A$) which have the requisite short wavelengths that cause pitch angle scattering and maintain an anisotropy where wave growth is balanced by energy-loss processes. This requires strong shocks or Mach numbers in excess of 100. The flow in SN 1993J (see above estimates of sonic and Alfvenic Mach numbers) satisfy this.

3 Wave particle interaction & plasma instabilities in electron pre-acceleration

The reflected ion beam at the quasi-perpendicular shock gyrates in the foot of the shock and generates lower hybrid waves. They propagate nearly perpendicular to the magnetic field with frequency $\omega \sim \omega_{LH} \sim \sqrt{\omega_{ce}\omega_{ci}}$. They interact with electrons of arbitrary energy via Cerenkov resonance and accelerate them from thermal electrons to $v \approx c$. For sufficiently fast shocks $V_{shock} \geq 0.02c = 6000$ kms^{-1} the waves can grow.

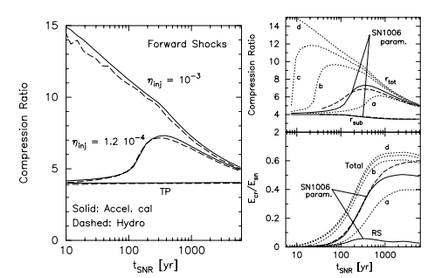


Ions have three populations at the shock foot: 1) the incoming upstream (undisturbed) flow, 2) reflected ions flowing in the opposite direction and 3) reflected ions gyrating back into the downstream region. At high Alfvenic Mach numbers M_A of the shock:

$$2\left(\frac{M_A}{\beta}\right)\left(\frac{m}{m_p}\right) > 1$$

where β is the local ratio of kinetic to magnetic pressure (found to be typically $0.1-0.15$) and m and m_p are electron and ion masses, the counter-streaming ion beams are Buneman unstable and the instability feeds into the electron acceleration process on rapid timescales of electron plasma (inverse) frequency (Schmitz et al 2002; Dieckmann et al 2000). Shimada & Hoshino (2000) show with a fully kinetic code that at high Mach numbers the electron phase space holes start appearing in the foot of the shock and the downstream electron distribution shows a high energy tail. The scaling of the width of the phase space islands (that is the height of the separatrix that bound the islands of stability) that trap the high energy tail for electron pre-acceleration will be studied.

4 Injection in SNRs: How do they connect with Supernovae ?



Self-generation of magnetic turbulence by counter streaming energetic particles leads to a stronger scattering of the particles themselves, and more acceleration. Ellison et al (2004) used a method of nonlinear diffusive shock acceleration together with a hydrodynamic simulation of SNR evolution which is of interest to young supernovae too (see below). Their **figure 5 and 11** reproduced here, shows how the compression ratio evolves as the SN ages, for fixed injection rates η_{inj}. Since the compression ratio directly impacts on radio-band spectral index $\alpha = 3/[2(\sigma-1)]$, a monitoring of SNe with a range of ages would show, the evolution of the shock characteristics. (Note that the pre-break spectral index α in SN 1993J implies: present compression ratio $\sigma = 4$). In particular, the compression ratio has a bell-shaped curve with age if the injection factor is $\leq$ a critical value η_{inj}. Thus a spectral evolution of a young SN like 1993J may lead to an estimate of the injection factor. They show that the fraction of E_{SN} going into relativistic particles E_{CR} evolves with age depending on the injection factor (for parameters similar to SN 1006). For SN 1993J, the similar ratio of energy density in relativistic particles to that in the magnetic field has been determined by fitting the Synchrotron Self Absorption model in the radio frequency bands (see section above). As this (equipartition) factor is close to unity for older SNRs such as the Crab, this also undergoes an evolution with age. We estimate the injection factor $\eta_{inj} \sim 2\times10^{-4}$ for SN 1993J by comparing with the results of Ellison et al (2004).

4.1 Electron thermalization and injection

Petruk & Bandiera (2006) have computed the normalization (similar to η_{inj}) of the electron injection distribution by using the probability of an electron to recross the shock from downstream to upstream (following Jones & Ellison 1988). The injection efficiency is found to be a decreasing function of a single argument: $M^2\chi_s$ where $\chi_s = T_{es}/T_s$, T_{es}, T_s being the post-shock electron temperature and the mean shock temperature. Ghavamian et al (2007) find from an analysis of optical spectra from non-radiative (adiabatic) SNRs that for high Mach number shocks, the equilibration ratio $\chi_s \propto M^{-2}$ as in the case if the electron heating in the precursor were mediated by ion lower-hybrid modes. Thus for high Mach numbers, the parameter $M^2\chi_s$ that controls the electron injection efficiency would be independent of the Mach number of the shock. The evolutionary models of the compression factor σ or the E_{CR}/E_{SN} computed by Ellison et al (2004) with constant injection efficiency η_{inj} are thus applicable in evaluating how the equipartition factor (between relativistic electrons and magnetic field energy) evolves with time.

5 Conclusions

- Synchrotron cooling break in GMRT+VLA spectrum of SN 1993J. Plasma is dominated by magnetic energy density over relativistic energy density by a factor of 10,000.
- The equipartition factor evolves from a very low value (as above) for young SNe to a factor close to unity for SNRs like the Crab SN which is close to a thousand years of age.
- Blast wave shock in SN 1993J has high sonic and Alfvenic Mach numbers to sustain plasma instabilities and wave-particle interaction mediated electron injection proposed in the literature.
- Spectral evolution of a young SN to a SNR phase, can determine the evolution of the compression factor and the injection factor η_{inj} (Ellison). Since the evolution of the spectrum and equipartition factor (of relativistic particles vs magnetic field energy) depend upon η_{inj}, the extent of the observed evolution between SN 1993J and older SNRs suggests that the injection factor is a few times 10^{-4}.

6 Acknowledgments

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