Radio Pulses from Shock Breakout in Type Ia Supernovae

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ABSTRACT

The shock from Type Ia supernova produces a relativistic fireball as it breaks out from the surface of a white dwarf. Synchrotron cooling of the fireball electrons on the WD magnetic field produces a pulse lasting tens of milliseconds at radio frequencies of 10GHz-THz. We show that the expected radio flux is detectable out to cosmological distances of hundreds of Mpc, and may account for peculiar radio transients that were reported by Lorimer et al. (2007, 1013) and Keanes et al. (2012). Detection of the predicted radio pulses in future events would allow to pinpoint the time of the explosion, calibrate the SN Ia rate in the local Universe, and identify a coincident electromagnetic signal to the gravitational wave signal expected in double-degenerate progenitors.

1. Expected Signal

The shock breakout from the WD surface in Type Ia supernovae, produces a fireball of photons, electrons, positrons and protons. We adopt the physical parameters of the fireball based on the latest detailed model by Nakar & Sari (2012). Initially, the pair density is high and the fireball is optically thick, but at breakout the pair density drops below the background electron density and the photon to electron ratio is of order $\sim 10^3$. At that time the rest-frame temperature of the fireball is $\sim$ 50keV and the plasma moves out with a final Lorentz factor of $\gamma \sim 10$. The typical photon energy as seen by an external observer is $\sim$MeV.

The total number of MeV photons in the fireball is $\sim 10^{47}E_{41}$, where $E_{41} \equiv (E/10^{41}$ ergs) is their total energy. Nakar & Sari estimate E_{41} in the range of 0.1–10 for SN Ia. Given the expected photon to electron, this implies a total number of fireball electrons, $N_e \sim 10^{44}E_{41}$. Since the fireball moves through the pre-existing dipole magnetic field B of the progenitor WD, its electrons radiate a synchrotron luminosity,

$$L \sim N_e P_{\rm syn} \sim 10^{39}\gamma_1^2 B_4^2 E_{41} \text{ erg s}^{-1}, \tag{1}$$

where $\gamma_1 \equiv (\gamma/10)$, $B_4 = (B/10^4\text{G})$, and the synchrotron power emitted per electron is $P_{\rm syn} = \frac{4}{3}\gamma^2(B^2/8\pi)\sigma_T c$ (Rybicki & Lightman 1979). Most of the emission would be at a frequency

$$\nu_{\rm syn} \sim 10^3\gamma_1^2 B_4 \text{ GHz}. \tag{2}$$

The magnetic field is modified by the disruption of the WD at much later times since the WD envelope, in which the field is anchored, moves at a non-relativistic speed of only $\sim 10^4$ km s^{-1} = $0.03c$

At a distance d (assumed to be much smaller than the Hubble distance $\sim (c/H_0) = 4$Gpc) the observed flux per unit frequency would be,

$$f_\nu = \frac{L}{4\pi d^2 \nu_{\rm syn}} \sim 0.1 B_4 E_{41} d_2^{-2} \text{ mJy}. \tag{3}$$

where $d_2 \equiv (d/100 \text{ Mpc})$. The duration of the radio pulse is expected to be tens of milliseconds, the time it takes the fireball to traverse the strong field region of the WD progenitor of radius $R_{\rm wd} \sim 10^9$ cm. If the fireball plasma is slowed down by debris gas around the WD over a time $\tau_{\rm dec} \ll R_{\rm wd}/c$, then the duration of the radio pulse will be shortened to $\tau_{\rm dec}$.

We can calculate the expected luminosity distribution of pulses based on the probability distribution of magnetic field strength B in WDs. Perhaps the bright radio pulses detected by Lorimer et al. (2007, 2013) and Keanes et al. (2012) originated from a WD with an unusually strong magnetic field $B_4 \sim 10^4$.

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