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SN 1998bw: The Case for a Relativistic Shock

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Abstract. SN 1998bw shot to fame by claims of association with GRB 980425. Independent of its presumed association with a GRB, this SN is unusual in its radio properties. A simple interpretation of the unusually bright radio emission leads us to the conclusion that there are two shocks in this SN: a slow moving shock containing most of the ejecta and a relativistic shock ($\Gamma = 2$) which is responsible for the radio emission. This is the first evidence for the existence of relativistic shocks in supernovae. It is quite plausible that this shock may produce high energy emission (at early times and by inverse Compton scattering). As with other supernovae, we expect radio emission at much later times powered primarily by the slow moving ejecta. This expectation has motivated us to continue monitoring this unusual SN.

1. Introduction

Accounts of the discovery of optical and radio emission from the supernova SN 1998bw has been given elsewhere (Galama et al. 1998, Kulkarni et al. 1998). The primary link between SN 1998bw and GRB 980425 is the coincidence of the two events in space and time (Galama et al. 1998). Unfortunately, the coincidence window (16-arcmin error circle, ± 1 day) is not sufficiently small to make a firm claim of the association.

BeppoSAX NFI observations show that there are two sources, a secularly fading source coincident (within the NFI error radius of 1.5 arcmin) with SN 1998bw and a source which is not coincident with the SN and which appeared to fade by the end of the first NFI observation (initiated 10 h after the burst and total duration of 40 h). The latter source has not been detected in subsequent NFI observations (see GCN 151 for summary; also contribution by E. Pian in these proceedings). A simple interpretation is that the transient source is the x-ray afterglow of GRB 980425. Another possibility is that the transient source is unrelated to GRB 980425. Upcoming ASCA observations may clarify this confusing situation.

What has been lost in all the exciting developments is that SN 1998bw is *an unusual supernovae, regardless of its association to GRB 980425*. Indeed, it's claimed and controversial association tends to overshadow the unusual nature of this SN. We now exclusively focus on the radio properties of this SN. The radio observations were conducted with the Australia Telescope Compact Array (ATCA)[1] as a part of our GRB effort.

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2. Radio Observations

In Figure 1 we present the up-to-date radio light curve of SN 1998bw. The radio luminosity of SN 1998bw is unusually high but what really sets it apart from other radio SN is the emergence of copious radio emission at early times. Supernovae expand and thus their size increases with time. Thus the parameter which best distinguishes SN 1998bw from other radio SN is the specific intensity (i.e. the ratio of flux to the solid angle of the source). It is conventional in radio astronomy to express specific intensity in units of brightness temperature and the conversion is done using the Rayleigh-Jeans formula.

We assume that the radio emission originates from the same region as the optical emission in which case the expansion speed is 60,000 km s^{-1} The predicted angular expansion is then $\sim 1\mu$arcsec per day. Such a source would be compact enough, particularly in the first two weeks, to suffer from strong scattering due to density inhomogeities in the Galactic interstellar medium. In contrast to GRB 970508 (Frail et al. 1997), only a smooth rise to a maximum was seen for the radio emission from SN 1998bw. This strongly suggests that the expansion of the radio photopshere greatly exceeds that of the opti-

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cal. Kulkarni et al. (1998) inferred $v_{exp} > 0.3c$ from the absence of refractive scintillation at 20 and 13 cm.

As noted in Kulkarni et al. (1998) the peak brightness temperature of SN 1998bw is 10^{13} K. This is two orders of magnitude higher than that inferred for previously studied radio SN (Chevalier 1998). The inferred brightness temperature is also in excess of the well known inverse Compton limit $T_{\rm icc} \sim 5 \times 10^{11}$ K for a source radiating via the incoherent synchrotron mechanism (Kellermann & Pauliny-Toth 1968, Readhead 1994).

As pointed out by Readhead (1994), high brightness temperatures also result in exceedingly large estimates of minimum energy. The total energy of a synchrotron source is

$$U/U_{eq} \;=\; 1/2\;\eta^{11}(1\;+\;\eta^{-17}),$$

where $\eta = \theta/\theta_{eq}$ and θ_{eq} is referred to as the equipartition angular radius and U_{eq} is the equipartition energy which is also (approximately) the minimum energy. The strong dependence of U on η consequently means that a high price must be paid in U for sources smaller than, or larger than θ_{eq}. As noted by Kulkarni et al. (1998), if the angular size used is consistent with v_{exp}=60,000 km s^{-1} then $\theta = 7 \times \theta_{eq}$, and therefore the source energy would be dominated by relativistic electrons $U_e = 10^{54}$ erg - much larger than the total energy release in a typical supernova. Therefore, the only reasonable hypothesis is to assume $\theta \simeq \theta_{eq}$, leading to v_{exp}=1.2c-1.9c, $U_{eq} \simeq 5 \times 10^{48}$ erg, and $M_{ej} \simeq 10^{-5}$ M$\odot$.

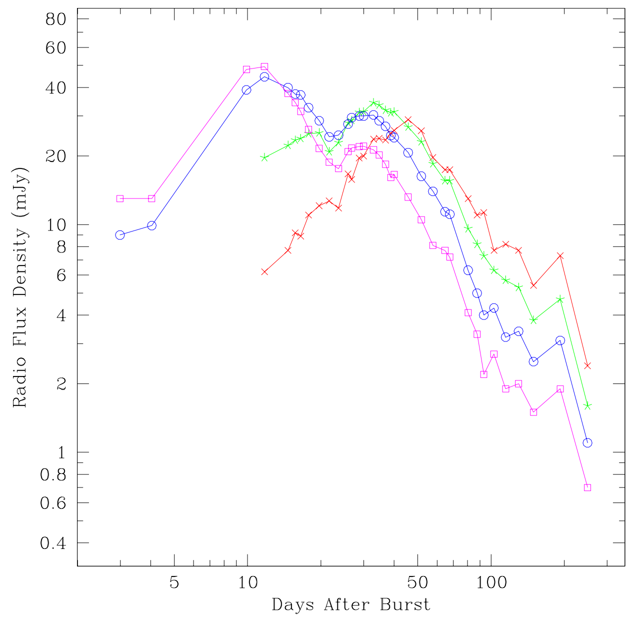

Fig. 1. The radio light curve of SN 1998bw at four wavelengths (20cm=cross, 13cm=star, 6cm=circle and 3cm=square). The last measurements were made on 1998 December 30, nearly 250 days after the gamma-ray burst. On this day the 1-σ uncertainty in these flux measurements is 0.5 mJy for 20 and 13-cm, and 0.3 mJy for 6 and 3-cm.

3. An Alternative Model

Recently, Waxman & Loeb (1998) have produced an alternative *sub-relativistic* model to explain the radio curve shown in Figure 1. In their model, the radio emission arises in the post-shocked gas (shock speed of 60,000 km s^{-1}). They assume rapid equilibration between the electrons and protons and a modest compressed magnetic field. In this model, the energy in the magnetic field is many orders of magnitude smaller than that in the energetic particles. The curious result is that Waxman & Loeb (1999) are able to reproduce the observed spectrum (save for a high frequency point) and an energy estimate comparable to that of Kulkarni et al. This is curious because it is a general result that the total energy is minimized only when there is equipartition between the electrons and magnetic field strength.

The Waxman & Loeb analysis is based on the assumption of mono-energetic electrons. Sari, Kulkarni & Phinney (1999) have carried out a detailed analysis using a thermal energy spectrum and find that for a non-equipartition plasma (as envisaged by Waxman & Loeb) the total energy is much higher than 10^{49} erg. Thus it appears that the simplification used by Waxman & Loeb does grossly underestimate the total energy. Thus we conclude that either the energy of the radio emitting plasma is 10^{52} erg or that there exists a relativistic shock in this SN.

4. The Future: Evidence For A Slow Shock?

We have argued above that the radio emission in the first ~100 days had its origin in a mildly relativistic shock which carries only a small amount of mass (10^{-5} M$\odot$) and energy (10^{49} erg). The bulk of the ejecta mass and energy of the SN is presumably traced by the optical photosphere. Thus, it is reasonable to expect some late-time radio emission from this slower-moving shock as it interacts with any circumstellar material. We continue to make multi-wavelength measurements toward SN 1998bw at the ATCA with this in mind. Our results to date shown in Figure 1 suggests that the power-law-like decay has persisted for at least 250 days.

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