Optical and Infrared Observations of Radioactive Elements in Supernovae.

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Abstract

At late phases the powering of supernova light curves is often provided by the decay of radioactive elements synthesized in the explosions. This is unambiguously revealed when the light curve decline follows the half life time of the decaying elements, and the bolometric luminosity then directly provides the mass of ejected radioactive material. I will focus on the best observed element, $^{56}\text{Ni}$, and demonstrate that different supernovae eject different amounts of this element. SN 1994W ejected very small amounts of nickel, possibly caused by black hole formation. SN 1998bw may instead have ejected more $^{56}\text{Ni}$ than any other supernova to date. I will also discuss our ISO non-detection of [Fe II] 26 $\mu$m in SN 1987A, which can be used to estimate an upper limit on the mass of ejected radioactive $^{44}\text{Ti}$.

1 Introduction

Optical and infrared observations of core-collapse supernovae provide crucial clues about the formation of radioactive nuclei. Although we read in astronomy text books that the elements in the universe are constantly created and expelled in supernova explosions, the hard, observational, evidence for this story may not be as compelling as we would like (e.g., Kirshner 1996). Determining the ejected masses of radioactive material from the energy budget in late light curves is one of the most direct pieces of evidence that explosive nucleosynthesis is indeed taking place in supernovae. I will present two supernovae that ejected substantially different amounts of $^{56}\text{Ni}$ than did the 'canonical' SN 1987A. I will also report on our non-detections of SN 1987A with the Infrared Space Observatory, and how these observations were used to obtain an upper limit on the amount of ejected radioactive $^{44}\text{Ti}$. 
2 Nickel masses in core-collapse supernovae

If the optical depth in the ejecta is high enough to trap the energetic gamma-rays from the decaying radioactive elements, the late supernova light curve decline will reflect the half life time of the element decay rate. The most important radioactive isotopes for supernova powering are $^{56}$Ni, $^{57}$Ni, and $^{44}$Ti, dominating at successively later phases. Only for SN 1987A have all three decays been observed to power the light curve. Observations of other SNe usually cover only the $^{56}$Ni phase, as revealed in the bolometric light curve by a fading of 0.98 magnitudes every 100 days. With a handle on the gamma-deposition, we need to determine the bolometric luminosity to deduce the mass of ejected nickel. This has been determined for a dozen supernovae. Table 1 shows an incomplete sample, obtained with varying degrees of sophistication. Patat et al. (1994) presented 8 Type IIP SNe with late time absolute V-magnitudes. Here, I have assumed the same bolometric correction as for SN 1987A, i.e., a linear scaling with $0.071 M_\odot$ of $^{56}$Ni. This gives a mean value for these 8 SNe of $0.075 M_\odot$ of $^{56}$Ni with a standard deviation of only $0.03 M_\odot$. In fact, the number 0.07 occurs rather frequently in Table 1. Though there exist no theoretical justification for this number, only the Australian group around Brian Schmidt seemed to find supernovae with varying yields of nickel.

3 The low amount of $^{56}$Ni in SN 1994W

But not all supernovae eject the same amount of $^{56}$Ni. SN 1994W ejected significantly less nickel than the canonical 0.07 $M_\odot$ (Sollerman, Cumming & Lundqvist 1998, hereafter SCL98). This discovery was later followed by another low-nickel supernova, SN 1997D (Turatto et al. 1998). This is important for understanding the galactic iron-enrichment, but may also tell us something about the explosion mechanism itself, and possibly even about the nature of the compact remnant formed in the supernova explosion.

We know that fall-back is an important process taking place after a successful shock has been launched in the supernova explosion. The innermost material falling back onto the newly formed neutron star will largely be made up of $^{56}$Ni. It is also clear that a substantial amount of fall-back may trigger a collapse of the neutron star into a black hole. The quantitative features of this scenario may be difficult to calculate, but the main consequences are clear. A supernova for which fall-back is efficient enough to form a black hole will have a diminished amount of radioactive material ejected. An underluminous light curve tail from a Type IIP supernova may therefore be the signature of a supernova that formed a black hole (Woosley & Timmes 1996). SN 1994W, discovered on 1994 July 29 in NGC 4041 may indeed be such a case. At the
plateau stage this supernova was very luminous, but then showed an unprece-
dented drop in the light curve (see Fig. 1 in SCL98). In 12 days the supernova
faded by 3.5 magnitudes, and then continued to fade rapidly on the light curve
tail.

The absolute R-band magnitudes of SN 1994W are significantly fainter than
those of the well observed SN 1987A. This tells us that SN 1994W ejected less
radioactive nickel than the canonical $0.07 \, M_\odot$. The exact amount of nickel
somewhat depends on the interpretation of the fast decline rate on the light
curve tail, as detailed in SCL98. However, regardless of the interpretation, the
mass of ejected $^{56}$Ni was very low, $< 0.015 \, M_\odot$. In fact, the observations are
consistent with a scenario where all nickel fell back onto the neutron star, per-
haps causing it to implode to a black hole, and where the late emission is due
to explosion energy diffusing out of the denser core/mantle region (Woosley
& Weaver 1986).

Clearly this is not an unambiguous proof of black hole formation. However, if
a massive star would form a black hole due to extensive fall back, the observ-
atio nal consequence should be a light curve that looks pretty much like that
observed for SN 1994W. These discoveries have triggered some interesting the-
oretical investigations. Zampieri et al. (1998) have discussed the prospects of
directly observing the black hole accretion luminosity emerging at late phases
for supernovae with low input of radioactive heating. Keeping an observational
eye on also the faint supernovae may thus be rewarding.

4 SN 1998bw - The most nickel rich supernova to date

SN 1998bw was probably associated with the Gamma-ray burst GRB 980425.
Early modeling implied a very energetic explosion ejecting some $0.5 - 0.7 \, M_\odot$
of $^{56}$Ni, an order of magnitude more than for SN 1987A (Iwamoto et al. 1998;
Woosley, Eastman & Schmidt 1999). However, Höflich et al. (1999) noted that
if SN 1998bw were an asymmetric explosion the early light curve may give an
erroneous estimate of the nickel-mass. We obtained late time observations to
model the supernova at phases when the ejecta are optically thin, and the
effects of asymmetry should be minimal (Sollerman et al. 2000).

Using the massive CO-star models of Iwamoto et al. (1998) and Woosley
et al. (1999), we modeled the late time emission in detail. To successfully
reproduce the peaked line profiles in the spectra we had to macroscopically
mix the original structure and increase the inner densities. Having a handle
on the distribution of material in the supernova, we could then accurately
calculate the gamma-deposition and thus determine the nickel-mass required
to power the late light curve. We obtained $0.5 \, M_\odot$ in one model, and $0.9 \, M_\odot$ in
the other. Independent of the exact number, simple arguments show that SN 1998bw ejected at least 0.3 M\textsubscript{\odot} of \textsuperscript{56}Ni, significantly more than the 0.07 M\textsubscript{\odot} of SN 1987A. Together with SN 1994W, it is thus clear that core-collapse supernovae can eject very different amounts of nickel.

Due to the high velocities the ejecta of SN 1998bw became almost completely transparent to the gamma-rays at later phases, and the energy input should eventually be dominated by the kinetic energy from the positrons emitted in the radioactive decays. Then the nickel-mass is directly given by the bolometric luminosity. A preliminary bolometric light curve is reported in Patat et al. (2001) and modeled by Nakamura et al. (2001). We are currently trying to improve on this.

This is because the background of SN 1998bw is very complex and even PSF-subtraction is likely to overestimate the luminosity of the SN at late phases. Figure 1 shows three subsequent HST/STIS images of the region with a scale of merely 1.5'' × 1.5''. It is clear that several objects will fall into any ground based PSF. These images also show that one of the objects is still fading, confirming the SN identification made by Fynbo et al. (2000). To assess the problem of background subtraction in greater detail we have obtained late VLT template images to subtract from our earlier images, a technique utilized in the High-z supernova context (Fig. 2).

Moreover, including our late VLT-IR photometry and the HST photometry we can construct a better late time light curve to address the importance of positron deposition at this very late stage. A preliminary attempt is shown in figure 3.

5 The amount of \textsuperscript{44}Ti in SN 1987A

The emission of SN 1987A at very late times (\gtrsim 1500 days) is powered by the decay of \textsuperscript{44}Ti. This nucleus is also produced in the very center of the supernova, and thus probes the early phases of the explosion.

At these very late phases most of the supernova light emerges outside the bands observable from ground. Only a few percent of the emission emerges in the UVOIR and constructing a bolometric light curve from such observations is utterly difficult. The most sensitive way to determine the powering at this stage should instead be in the far-IR. The emission line of [Fe II] 26 \textmu m appears to be the ideal probe and accounts for almost half of the supernova emission at these phases. This line was observable by the Infrared Space Observatory (ISO) which was therefore pointed toward SN 1987A. However, no emission from the supernova was detected (Lundqvist, Sollerman, Kozma et al. 1999).
From the upper limit on this emission, together with detailed modeling of the supernova, we achieved an upper limit on the amount of titanium powering the late emission. Including a number of possible uncertainties (atomic data, distance, mixing etc.) resulted in an upper limit of $^{44}\text{Ti}$ of $<1.5 \times 10^{-4} \, \text{M}_\odot$ from the non-detection at day 3999.

However, Borkowski et al. (1997) indicated that another set of ISO data reached a ten times lower limit, severely challenging estimates from explosion models. We analyzed these data when they became available from the ISO data archive. Again, no emission from the supernova was observed, but the obtained upper limit on the flux was indeed lower. With an updated code for the modeling, we arrived at an upper limit of $\sim 8 \times 10^{-5} \, \text{M}_\odot$ from the non-detection at day 3425 (Lundqvist, Kozma, Sollerman & Fransson 2001).

In the new investigation we furthermore analyzed several systematic effects that could affect the far-IR lines. We found that a certain type of positron-escape from the iron-rich gas to the macroscopically mixed Si-gas rich regions could decrease the flux in the 26 $\mu$m line by some 30% without significantly altering the optical bands that are indeed well reproduced by the model. Including this effect we conclude that no more than $\sim 1.1 \times 10^{-4} \, \text{M}_\odot$ of $^{44}\text{Ti}$ was ejected from SN 1987A.

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Table 1
Some nickel yields from core-collapse supernovae

| Supernova | M($^{56}$Ni) | Source                        |
|-----------|-------------|-------------------------------|
| SN 1969L  | 0.083 M☉    | Patat et al. (1994)           |
| SN 1979C  | 0.060       | Patat et al. (1994)           |
| SN 1980K  | 0.036       | Patat et al. (1994)           |
| SN 1983K  | 0.10        | Patat et al. (1994)           |
| SN 1985P  | 0.039       | Patat et al. (1994)           |
| SN 1986I  | 0.13        | Patat et al. (1994)           |
| SN 1988A  | 0.069       | Patat et al. (1994)           |
| SN 1987A  | 0.071       | Suntzeff & Bouchet (1990)     |
| SN 1990E  | 0.073       | Schmidt et al. (1993)         |
| SN 1992am | 0.30        | Schmidt et al. (1994)         |
| SN 1991G  | 0.024       | Blanton et al. (1995)         |
| SN 1994I  | 0.07        | Young et al. (1995)           |
| SN 1992H  | ~ 0.075     | Clocchiatti et al. (1996)     |
| SN 1993J  | 0.08        | Houck & Fransson (1996)       |
Fig. 1. HST/STIS CLEAR images of SN 1998bw and its environment. The images are obtained in June 2000 (upper left), November 2000 (upper right), and in August 2001 (lower left). The scale is merely $1.5'' \times 1.5''$. Lower right shows a subtraction between the first and the final frame. The supernova is clearly identified. (Courtesy of the Supernova INtensive Study-team featuring S. Holland.)
Fig. 2. The template subtraction method. Upper left shows the supernova and its galaxy in September 1999, 503 days past explosion. Upper right is the template image. The subtraction is shown in the lower left. Note that only the supernova is seen, as well as some residuals from saturated stars. Lower right shows a blowup of the supernova region, before and after subtraction.

Fig. 3. Preliminary bolometric light curve from the template subtraction method. Late time observations from VLT (triangles, $L_{BVRI}$) and HST (squares, $L_{CL}$). **Added:** The final version of this light curve is published in Sollerman et al. 2002 (A&A, 386, 944), where a possible interpretation of the very late light curve in terms of powering of more long-lived isotopes is given.