THE REIONIZATION OF UNSHOCKED EJECTA IN SN1006

A. J. S. Hamilton and R. A. Fesen
Joint Institute for Laboratory Astrophysics
University of Colorado and National Bureau of Standards
and Center for Astrophysics and Space Astronomy,
University of Colorado, Boulder, Colorado 80309

ABSTRACT: The fortuitous positioning of the Schweizer and Middleditch OB subdwarf behind SN1006 has permitted the detection and subsequent confirmation by IUE of broad (±5000 km/s) Fe II absorption features which probably arise from unshocked iron ejecta in the center of SN1006. The mass of detected Fe II, ~0.012 $M_\odot$, is however only 1/25 of the ~0.3 $M_\odot$ of Fe within ±5000 km/s predicted by carbon deflagration models. IR and optical observations exclude any appreciable iron in grains or Fe I, but high ion stages, Fe III and up, could be present. Promising mechanisms for ionizing the unshocked iron in SN1006 include the radioactive decay of ^{44}Ti, and photoionization by UV and X-ray emission from the reverse shock. Although the photoionization model works, insofar as it permits as much as 0.2 $M_\odot$ of unshocked iron in the center of SN1006, agreement with the IUE data requires that the ejecta density profile be flatter, less centrally concentrated, than the W7 deflagration model of Nomoto, Thielemann, and Yokoi.

I. The Problem: Figure 1 shows the problem: Nomoto, Thielemann and Yokoi's (1984) W7 carbon deflagration model fits nicely to the IUE observations of Fe II absorption in SN1006 -- except that the predicted model density of Fe (all ion stages) is 25 times the observed density of Fe II.

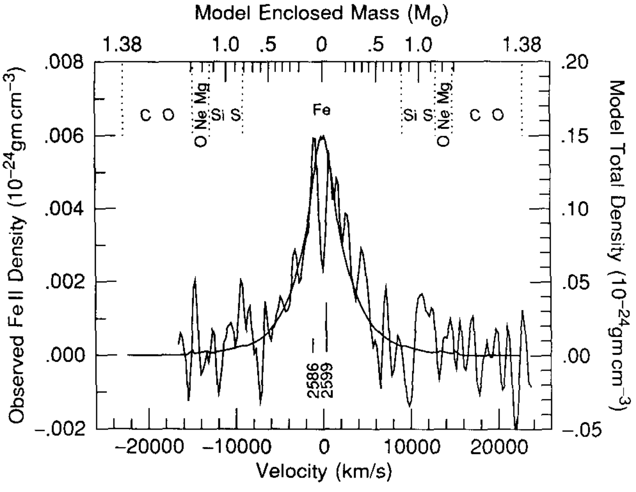

Figure 1. The Fe II λ2586, 2599 absorption line profile observed in SN1006 (Fesen et al. 1987), converted to density assuming no saturation, compared to Nomoto et al.'s (1984) W7 model evolved in free expansion to 980 years old.

https://doi.org/10.1017/S0252921100010212X Published online by Cambridge University Press

Could the Fe be hidden in Fe grains? No. Any appreciable depletion into grains in the Fe ejecta would make SN1006 a strong IRAS source, not observed. Fe I? No. No Fe I absorption is present in the Schweizer and Middleditch (1980) optical spectrum. Fe II? No. The relative equivalent widths of strong and weak Fe II absorption lines in the IUE data indicate that the Fe II lines are not saturated. Fe III, IV? Could be.

Mechanisms for ionizing unshocked ejecta:

(1) Radioactivity - the decay of ^{56}Ni leaves the plasma mainly neutral at 4 years old, but ^{44}Ti can have some effect later on -- see § II.
(2) Photoionization by ambient UV starlight - ionizes Fe I to Fe II in 100 years, but no higher.
(3) Cosmic rays - zilch.
(4) The ejecta has been reverse shocked after all - no - the reverse shock kills Fe II dead, contrary to the IUE data.
(5) Photoionization by UV and x-rays from reverse-shocked ejecta - the most probable answer.

II. The Radioactive Decay of ^{44}Ti The familiar $^{56}\mathrm{Ni} \xrightarrow{6d} {^{56}\mathrm{Co}} \xrightarrow{77d} {^{56}\mathrm{Fe}}$ decay scheme is no good for causing persistent ionization in SNRs: it dumps its energy too early, while the density is high, and recombination and cooling times are shorter than the age of the remnant.

The radioactive decay $^{44}\mathrm{Ti} \xrightarrow{47yr} {^{44}\mathrm{Sc}} \xrightarrow{4h} {^{44}\mathrm{Ca}}$, with a 47 year half-life, is more effective. The principal decay scheme, with a branching ratio of 0.932 for positron emission, is:

(1) $^{44}\mathrm{Ti} \xrightarrow{47yr} {^{44}\mathrm{Sc}^+} + \nu$ (orbital electron capture)
(2) $^{44}\mathrm{Sc} \xrightarrow{4h} {^{44}\mathrm{Ca}^*} + e^+ + \nu$ (positron emission, mean energy .767 MeV)
(3) $^{44}\mathrm{Ca}^* \rightarrow {^{44}\mathrm{Ca}} + \gamma$ (excited Ca emits 1.159 MeV gamma-ray).

The neutrinos and gamma-rays escape, but the positrons Coulomb scatter off electrons in the plasma before annihilating. The heated electrons then collisionally excite and ionize the plasma. Since at 47 years old the recombination time exceeds the age of the remnant, any ionization which occurs as the result of the decay of ^{44}Ti persists to the present time.

It is believed that the explosive nucleosynthesis of radioactive ^{44}Ti is the dominant source of ^{44}Ca in the galaxy. If ^{44}Ti is synthesized in the cosmic ratio of $^{44}\mathrm{Ca}/^{56}\mathrm{Fe} = 1.41 \times 10^{-3}$, then ^{44}Ti decays produce $1.41 \times 10^{-3} \times 0.767$ MeV $\times$ 0.932 = 1.01 keV per Fe ion, sufficient in principle to ionize Fe several times.

Detailed calculations including adiabatic and collisional cooling losses show that the amount of Fe ionization is a sensitive function of ejecta density and ^{44}Ti abundance, with appreciable ionization occurring only for at least a cosmic fraction of ^{44}Ti.

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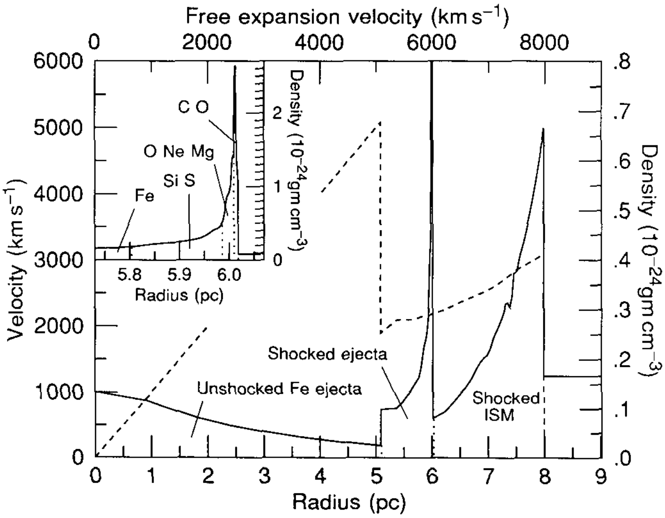

Figure 2. Velocity (dashed line) and density (solid line) structure in Nomoto et al.'s W7 model, evolved by spherically symmetric hydrodynamic simulation into a uniform ambient medium, to the point where the reverse shock has penetrated as far as the 5000 km/s free expansion radius, as appropriate for SN1006 at the present time, according to the IUE Fe II line widths. At the present 980 year age of SN1006, the inferred ambient interstellar density is 0.07 H atoms cm^{-3}, the swept up interstellar mass is 5.3 $M_\odot$, the distance is 1.8 kpc, and the blast wave velocity is 4100 km/s, corresponding to an expansion rate $r \propto t^{0.52}$.

Problems: In current carbon deflagration models,

(a) ^{44}Ti is synthesized in only 1/10 the cosmic ratio of ^{44}Ca/^{56}Fe;

(b) ^{44}Ti is synthesized in a shell outside the iron, not mixed in it.

III. Reverse Shock Photoionization Model:

(1) Use Nomoto, Thielemann and Yokoi (1984) W7 model as starting point for spherically symmetric hydrodynamic simulation.

(2) Evolve W7 model into uniform ambient medium until the reverse shock has reached the 5000 km/s free expansion radius, as indicated by IUE, and illustrated in Fig. 2.

(3) Adopt a two-layer approximation to ejecta composition, 0.8 $M_\odot$ of Fe on the inside, 0.6 $M_\odot$ of Si on the outside.

(4) Compute time-dependent photoionizing UV and x-ray emission from the reverse shock in the "instantaneous" approximation, where material entering the reverse shock is collisionally excited and ionized to a high ionization state immediately it is shocked.

(5) Calculate collisional excitation and ionization of shocked gas in the high-temperature Bethe approximation.

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(6) Include processes of collisional excitation, autoionization, fluorescence, multiple ionization. Approximately 70 photoionizing "lines" of Fe II to Fe XVI, and 40 "lines" of Si II to Si XII, each "line" standing for a complex of several individual lines. Use oscillator strength sum rules to check that no important source of photoionizing emission has been missed.
(7) Include ambient photoionizing starlight.
(8) Follow detailed self-consistent time-dependent radiative transfer and photoionization of expanding unshocked Fe and Si ejecta.
(9) Ionization state of material entering the reverse shock determined self-consistently.

Figures 3 and 4 show the results of the phiotoionization calculations just described.

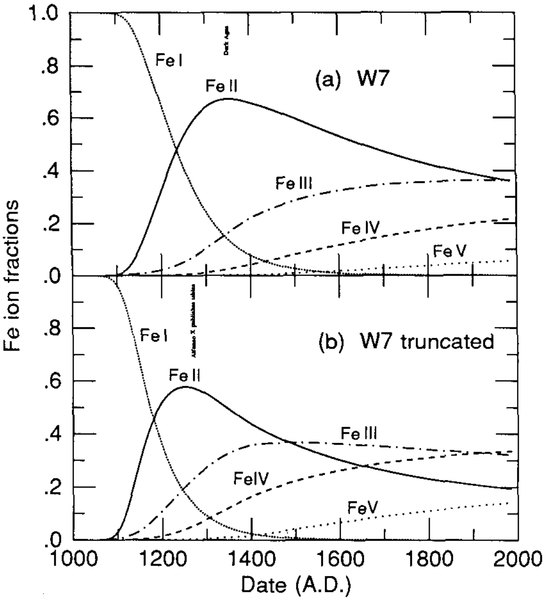

Figure 3. The evolution of Fe ion fractions at the center of SN1006, photoionized by ambient starlight and UV and x-ray emission from the reverse shock in (a) Nomoto et al.'s W7 model (top panel), and (b) Nomoto et al.'s W7 model with a truncated central ejecta density (bottom panel). Ionization is faster in the truncated model because the optical depth is smaller.

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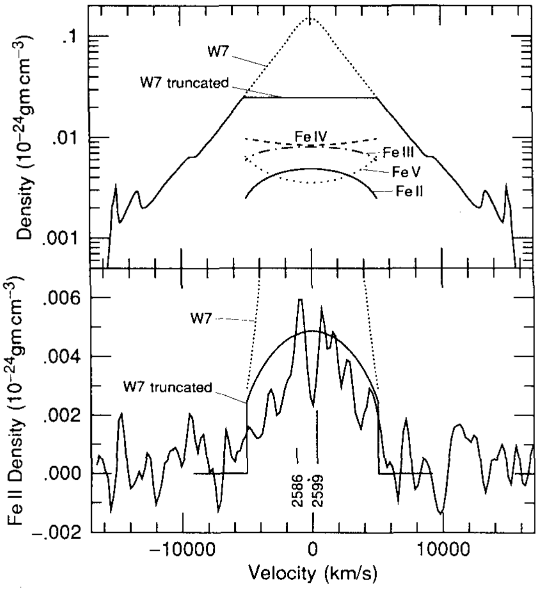

Figure 4. Fe II density (lower panel) computed in the truncated W7 model, compared to the IUE observations of the Fe II λ2600 line. The unmodified W7 model predicts too much Fe II (dotted line). The upper panel shows the total and Fe ionic densities predicted by the truncated W7 model, along with the total density in the unmodified W7 model. The truncated model contains 0.20 $M_\odot$ of Fe within $\pm$5000 km/s, as opposed to the 0.36 $M_\odot$ of Fe in the plain W7 model.

IV. Conclusions: The radioactive decay of ^{44}Ti should have an appreciable effect in ionizing the layer of ejecta where the ^{44}Ti is. However, it probably has a negligible effect on inner layers of iron ejecta.

UV and x-ray emission from the reverse shock is able to cause appreciable photoionization of unshocked iron ejecta. However, agreement with the observed IUE Fe II absorption line profiles requires the ejecta density profile to be flatter, less centrally concentrated, than the W7 model of Nomoto, Thielemann and Yokoi (1984).

Acknowledgments: We are grateful to Ken Nomoto for providing the W7 model evolved into the free expansion phase.

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https://doi.org/10.1017/S025292110010212X Published online by Cambridge University Press