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Is SN 1987A Entering a New Phase of Evolution?

R. A. Stathakis[1], R. D. Cannon[1] and J. Spyromilio[2]

[1] Anglo-Australian Observatory, PO Box 296,
Epping, NSW 2121, Australia
rl@aaoepp.aao.gov.au
[2] European Southern Observatory, Karl-Schwarzchild-Strasse 2,
D-8046 Garching bei München, Germany

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Abstract: Optical spectra of the ejecta of SN 1987A taken at the AAT now cover seven years of evolution. In recent years, SN 1987A has been in a phase known as freeze-out. The timescales for recombination have exceeded those of energy deposition, and the ionisation structure has become fixed. During this phase, cooling is slow and the optical spectrum has been extremely stable. Our latest spectrum, however, shows significant change. [FeI] and [FeII] emission from iron-rich clumps has dominated the optical emission from the supernova over the last four years. All the [FeII] features have disappeared in our latest spectrum from December 1993 and model fits of [FeI] features indicate that these clumps have cooled to the critical temperature of 1000 K. They may be entering a phase of rapid cooling known as the infrared catastrophe. In addition, emission at high velocities has strengthened, in line with the predictions of freeze-out. SN 1987A may be entering a new, and previously unobserved, phase in supernova evolution.

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1. Structure of the Envelope

The spectrum of SN 1987A has been monitored for seven years at the AAT, resulting in a high-quality and comprehensive database. The supernova envelope is rapidly and homologously expanding (i.e. $V_r \propto r$), so emission lines are Doppler–broadened and nearly optically thin. Consequently we can use line profile analysis to determine the spatial distribution of emission in the ejecta (although the position of the emission source we obtain is uncertain in a ring perpendicular to the line of sight). For convenience, positions are usually given in velocity units to avoid time dependence.

Modelling of observed line profiles from the first two years has shown that the structure of the supernova is complex, containing smooth and clumped material. A working model has emerged, which is discussed in Stathakis et al. (1991), Spyromilio & Graham (1992), Hanuschik et al. (1993) and Spyromilio, Stathakis & Meurer (1993). Uncertainty remains in the relative contributions of smooth and clumped ejecta, but while clump numbers and sizes can vary, the models agree on the basic ejecta structure.

The bulk of the envelope is arranged in chemically distinct shells resulting from the different nuclear burning cores: H, He, O–Si and Fe–Ni. Although the outer extent of the H shell is at $V_r \sim 35\,000$ km s^{-1}, for $t > 400$ days optical emission has come only from the inner region of the envelope, $250 < V_r < 3100$ km s^{-1}. At $t \sim 500$ days (in May 1988) the O–Si shell cooled sufficiently for dust to form. The dust is distributed uniformly within this shell with an optical depth of $\tau \sim 3{\cdot}5$.

Oxygen and its associated elements magnesium and carbon are located in small clumps which are restricted to incomplete thin shells on either side of the boundary between the He and O–Si shells. They were created when the expanding shock wave hit the boundaries of the shells, creating a Rayleigh–Taylor instability. There are large clumps of hydrogen, calcium and iron scattered through the ejecta. The favoured explanation is that these clumps were formed when the interior Ni bubble became unstable and burst asymmetrically, throwing radioactive material into the outer ejecta, pulling hydrogen into the O–Si shell, and forming mixed, hot clumps. The result was an excess of γ-ray production on the far side of the supernova envelope. (However, modelling to date of the Ni bubble has failed to explain the observed degree of asymmetry.) When dust formed, the clumps at larger radii suffered smaller extinction and became the dominant emission source.

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2. Evolutionary Phases

(2a) The Infrared Catastrophe

Axelrod (1980) pointed out that once a supernova envelope cooled to below 1000 K, cooling would become increasingly efficient via the fine-structure lines, especially the 63 μm [OI] transition. Runaway cooling would occur until the ejecta was at $\sim$500 K, and optical emission would become negligible. He called this phase the infrared catastrophe. At the time, no supernova had been observed over a sufficiently long period to test the theory.

The nearby supernova 1987A was an ideal test case. While the supernova has not disappeared into the mid-infrared as predicted, it seems likely that the infrared catastrophe did occur, but for only part of the ejecta. The formation of dust requires low temperatures, so the sudden appearance of dust through the O–Si shell in mid-1988 indicated that sudden cooling had taken place. Yet model fits of the [FeII] spectrum of SN 1987A on day 734 (Spyromilio & Graham 1992) give the temperature of the emitting iron as 4000 K. This apparent discrepancy can be resolved if the unclumped iron (95% of the total mass) underwent the infrared catastrophe, but the clumped iron did not, due to its higher density. Consequently, the iron spectrum observed since day 500 is emitted by the hydrogen–iron clumps.

(2b) Freeze-out

From about day 1000, SN 1987A entered a period of slow change. The timescales for recombination had become longer than those for energy deposition, and the ionisation structure became fixed. This phase, known as freeze-out, has been described by Fransson & Kozma (1993). The implications for the optical spectrum are that the input energy is higher than expected for a simple core-heated model, emission from the outer envelope begins to dominate over emission from the core, and cooling becomes dominated by adiabatic processes, so the temperature of the ejecta falls as t^{-2}. This phase could explain the observed flattening of late-time supernova light curves.

3. New Results

(3a) Recent Observations

Since 1990, the spectrum of SN 1987A has been dominated by a nebular spectrum emitted by the circumstellar shell of the progenitor star. However, faint broad features from the ejecta are still observable, although considerable care is needed to remove contamination from the neighbouring stars. Observations taken between days 1325 and 1885 show virtually no change in the optical spectrum, apart from a possible strengthening of the wings of strong features, as predicted by the freeze-out model. The spectrum taken on 1993 December 18 (day 2487), however, shows marked changes (Figure 1). Note that [MgI] and NaI are essentially constant.

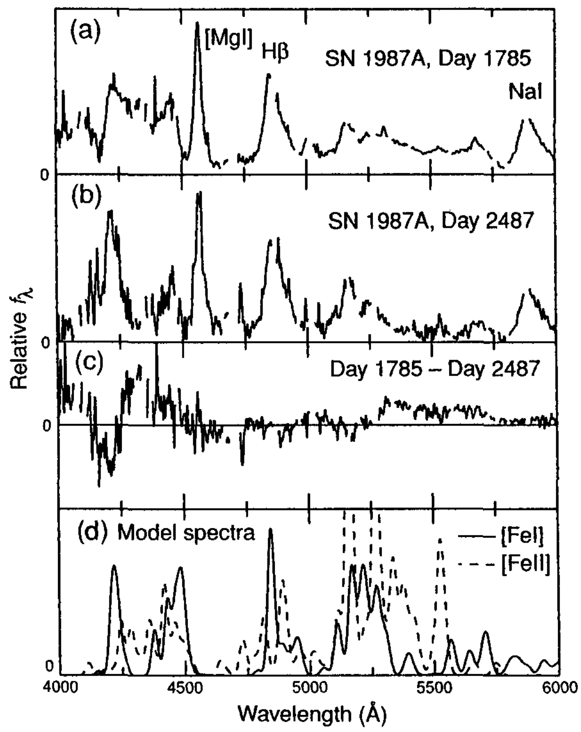

Figure 1—SN 1987A observed on day 1785 (a) and day 2487 (b), smoothed, rebinned, and normalised to match at 6100 Å. Regions affected by strong CSM lines have been removed from the spectra for clarity. Panel (c) shows the difference of the two spectra (day 2487–day 1785) after normalisation. Panel (d) compares example model spectra of [FeI] at 1000 K, $N_e = 10^5$ cm^{-3} (solid) and [FeII] at 3000 K, $N_e = 10^5$ cm^{-3} (dashed). Despite some discrepancies, due to limitations of the models, there is qualitative agreement between the changes seen in the spectrum and the difference of the two models ([FeII]–[FeI]).

(2b) Spectral Models

Spyromilio & Graham (1992) have developed non-LTE models for the transitions between the lower levels (up to 3·3 eV) of [FeI] and [FeII]. Figure 1 shows best fits of [FeII] to the spectrum from day 1785 and [FeI] to the observation on day 2487. Despite the limitations of the models, it is clear that the changes seen are due to the disappearance of [FeII] features, and the strengthening of some [FeI] lines. Both model fits have $N_e = 10^5$ cm^{-3}, and indicate a minimum decrease in temperature from 2000 to 1000 K. This decrease agrees with the predicted cooling rate for adiabatic cooling. [FeII] emission falls rapidly below 2000 K, explaining the change in ionisation state.

Surprisingly, [FeI] and [FeII] do not appear to give consistent solutions on day 1785. [FeI] ratios match the 1000 K model well, but the presence of [FeII] requires a minimum temperature of 2000 K. Although this is possibly an indication of problems with the model, an alternative explanation is that the iron spectrum on that date results from a range of temperatures. As explained above, the spectrum comes from independent clumps, so it would not be impossible for some clumps to cool more rapidly than others.

4. Conclusion

While the freeze-out model seems to work well for recent observations, there is a strong possibility that other, more rapid processes may be taking over. Once material cools to 1000 K, it reaches the regime of the infrared catastrophe. We may be seeing the hydrogen–iron clumps just as they start runaway cooling. If so, our next spectrum of the supernova may have no iron emission, and little, if any, hydrogen emission. The remaining sources of emission will be the oxygen clumps and outer regions of the envelope which are being heated by the delayed recombination. If, on the other hand, the clumps do not undergo infrared catastrophe, but continue to cool slowly, this will be an interesting challenge to the theory of infrared catastrophe.

Note added in proof: A new spectrum, obtained on 1994 December 27 and 28, did not show any dramatic changes compared with the earlier spectra.

Axelrod, T. 1980, PhD Dissertation, UCRL-52994 (University of California)
Fransson, C., & Kozma, C. 1993, ApJ, 408, L25
Hanuschik, R. W., Spyromilio, J., Stathakis, R., Kimeswenger, S., Gochermann, J., Seidensticker, K. J., & Meurer, G. 1993, MNRAS, 261, 909
Spyromilio, J., & Graham, J. R. 1992, MNRAS, 255, 671
Spyromilio, J., Stathakis, R., & Meurer, G. 1993, MNRAS, 263, 530
Stathakis, R. A., Dopita, M. A., Cannon, R. D., & Sadler, E. 1991, in Supernovae, ed. S. Woosley (New York: Springer), 95