Infrared Spectroscopy of SN 1987A

By JASON SPYROMILIO

Anglo-Australian Observatory, P. O. Box 296, Epping NSW 2121, Australia

Infrared spectra of SN 1987A have been obtained at the Anglo-Australian Telescope since the explosion of this supernova. I present highlights from this program which include the analysis of the molecular emission, the determination of the mass of ^{57}Co in the ejecta and the analysis of the emission due to dust in the ejecta. I also show the spectrum of the supernova in the infrared 5 years after explosion.

1. Introduction

Prior to the explosion of supernova 1987A only a few supernovae had been studied spectroscopically in the infrared (see Frogel *et al.* 1987; Graham *et al.* 1986). Although recently a number of very powerful common-user infrared spectrographs have become available to the community most of the observations of supernova 1987A were made using the previous generation of instrumentation. The near-infrared data discussed here were obtained at the Anglo-Australian Telescope using the FIGS and IRIS spectrographs through a collaboration of the author with Peter Meikle (Imperial College London) and David Allen (Anglo-Australian Observatory). Mid-infrared data were also obtained at the AAT using the UCLIR spectrograph by David Aitken (Australian Defence Forces Academy), Pat Roche (University of Oxford) and Craig Smith (ADFA).

Other groups have also been involved in infrared studies of supernova 1987A. The other major southern observatories (CTIO & ESO) have also presented infrared spectra of SN 1987A although these will not be discussed here. In addition the Kuiper Airborne observatory has obtained extremely valuable data in the atmospheric windows not accessible from the ground (see Wooden in these proceedings).

2. Molecular Emission

The most tightly bound molecule is carbon monoxide with a dissociation energy of 11 eV. Emission by CO had been observed in novae (Ferland *et al.* 1979). It was therefore not a major surprise that emission by CO was observed in the infrared spectra of supernova 1987A. Both the fundamental (at 4.6 μm) and the first overtone at 2.3 μm were detected. What was however a surprise was the detection of CO as early as 110 days after explosion. The analysis of Spyromilio *et al.* (1988) showed the CO expanding with a smaller velocity that was observed even for the iron group elements (see Fig. 1). The temperature of the CO was found to be around 2000 – 3000 K while the atomic species in the ejecta at the same time indicated temperatures above 4000 K. This is consistent with the high partition function that molecular species have making them extremely efficient coolants. The expansion velocity of the CO was around 2000 km/s. Manufacturing the CO in the ejecta in the hostile environment present 110 days after explosion could only be achieved if the CO was shielded from the UV recombination radiation. This was the first evidence for density inhomogeneities in the ejecta.

Emission by SiO was also seen in the spectra of SN 1987A (Meikle *et al.* 1989; Roche *et al.* 1992). The parameters derived from the fundamental band at 8.2 μm are in general agreement with those derived for the CO. Miller *et al.* (1992) have shown that features

https://doi.org/10.1017/S025292110000806X Published online by Cambridge University Press

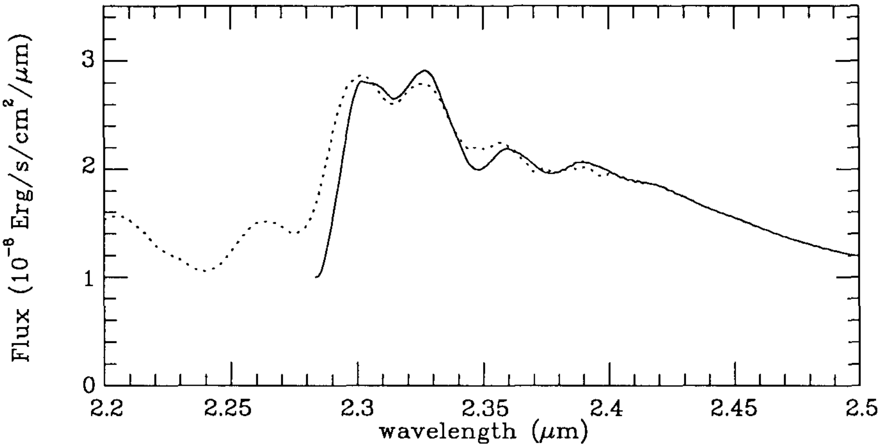

FIGURE 1. Carbon monoxide in supernova 1987A 255 days after explosion. (Spyromilio *et al.* 1988)

in the L window previously unidentified are consistent with emission by $H_3{}^+$ although this identification is sensitive to the location of the continuum in that window.

3. Mixing of the Iron Group Elements

Evidence that the radioactive species were mixed out to the fast moving regions of the ejecta came from the study of the infrared line profiles. The transitions emitting in the infrared are ideally suited to study supernovae. They are well separated in wavelength space and therefore even with the high velocities exhibited by supernovae line blending is not a problem. Moreover the temperature and ionization structure in the ejecta of supernovae is such that the low lying transitions of neutral or singly ionized ions are amongst the dominant coolants. These transitions emit strongly in the near infrared. By studying the line profiles of the iron group elements in SN 1987A (see Fig. 2) Spyromilio, Meikle & Allen (1990) showed that the iron group elements were non-uniformly distributed within the ejecta and that some iron was moving at velocities as high as 3000 km/s. Moreover the line profiles were redshifted relative to the nominal velocity of the supernova (as determined by the narrow circumstellar lines). A similar redshift was observed in the γ-ray lines (Tueller 1990) and could be providing evidence for an asymmetric explosion.

4. ^{57}Co

The evolution of the transitions of cobalt in the infrared spectra of SN 1987A was used to show that radioactive ^{57}Co was present in the ejecta. Varani *et al.* (1991) used the ratio of the 1.533 [Fe II], and 1.547μm [Co II] lines which is very insensitive to density and temperature to determine the abundance of ^{57}Co (see Fig. 3). Danziger *et al.* (1991) and Roche *et al.* (1993) used the rate of decay of the mid IR (10.52 μm) line to also determine the ^{57}Co abundance. This isotope of cobalt has a much longer lifetime than ^{56}Co and at late times dominates the heating of the ejecta. The determination of its abundance is important for the energetics of the light curve of the supernova. Moreover the determination of the abundance is an important constraint of the nucleosynthesis occurring in supernovae with implications for the enrichment of the interstellar medium. Observations with the GRO satellite have detected ^{57}Co γ-rays (Kurfess *et al.* 1992) in agreement with our results.

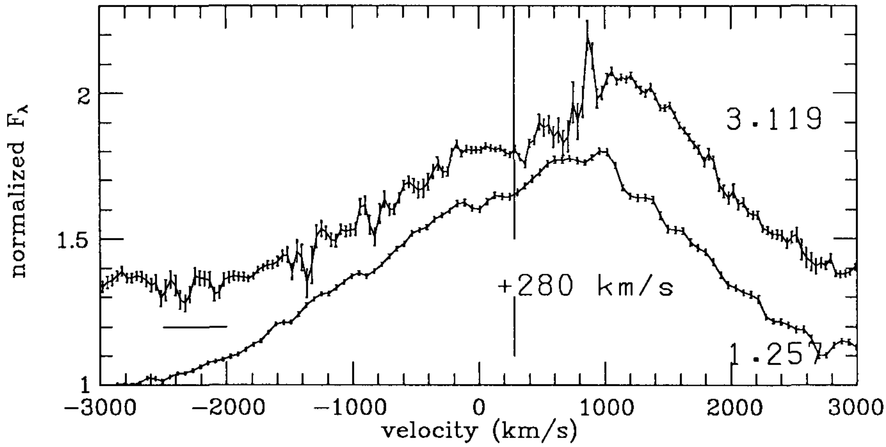

FIGURE 2. SN 1987A IR line profiles of the iron group elements (Spyromilio, Meikle & Allen 1990)

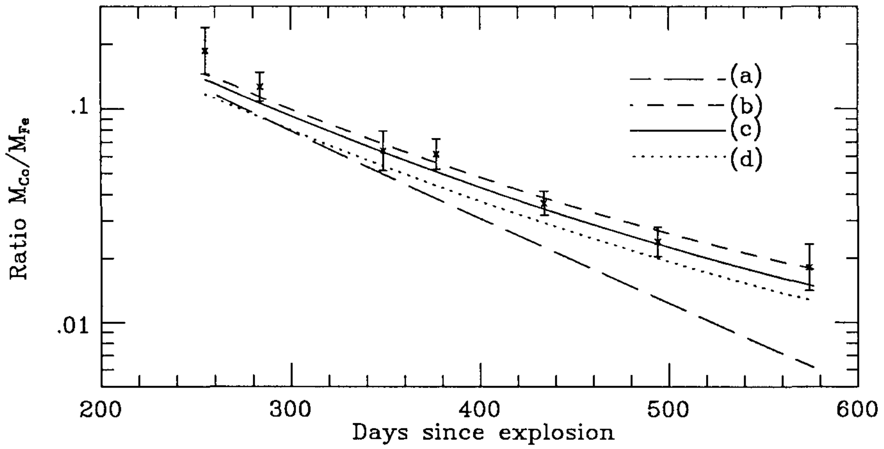

FIGURE 3. evolution of the Fe/Co mass ratio in SN 1987A as derived from near IR observations. Model (a) ^{56}Ni alone; (b)–(d) models described in Varani *et al.* (1990)

5. Dust

Soon after the explosion of supernova 1987A Dwek (1988) suggested that dust would form within the ejecta and totally obscure the supernova at an age of a few hundred days. Dust did indeed form in the ejecta after 500 days but did not totally obscure the ejecta. Like the rest of the ejecta the dust seems to have formed in clumps as well as a diffuse component. Although this effect was discovered from a study of optical transitions (Lucy *et al.* 1991) the bulk of the dust emission appeared, as would be expected, in the mid-infrared (Roche *et al.* 1993; Wooden these proceedings).

The infrared line profiles also moved to the blue as dust obscured the red side of the ejecta. However this shift was of similar extent as the that observed in the optical which is inconsistent with the details of the Lucy *et al.* (1991) model (see Spyromilio *et al.* 1990) but not the spirit of that model. A flat extinction curve can be achieved using more optically thick dust located in clumps. From the mid-infrared data it has been possible to exclude silicates and graphite as the dominant components of the dust since their characteristic spectral features are absent (Wooden these proceedings). The

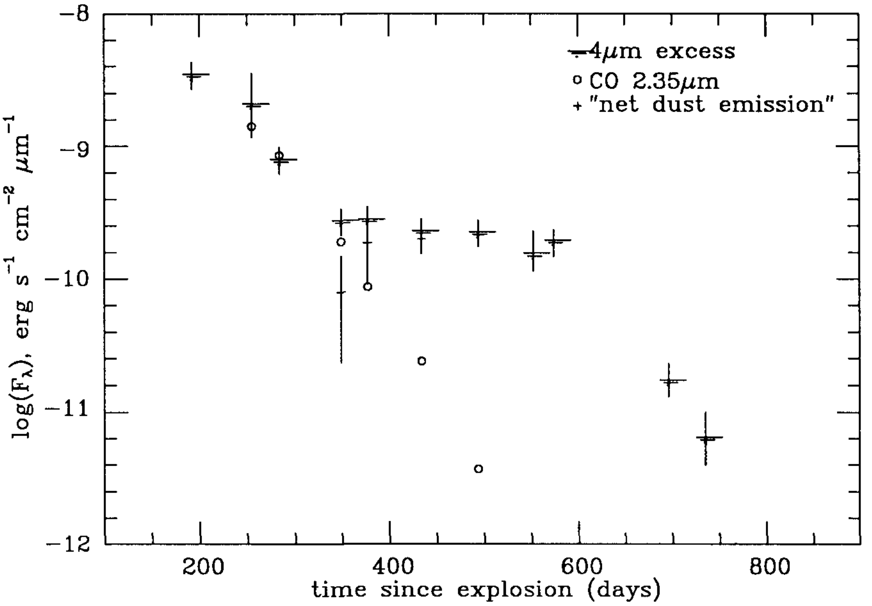

FIGURE 4. The 4μm excess from the AAT data showing no evidence for significant dust contribution prior to day 250. (Meikle *et al.* 1993)

infrared spectra of SN 1987A from the AAT have allowed us to accurately determine that the onset of dust formation occurred 350 days after explosion (Meikle *et al.* 1993; Roche *et al.* 1993).

6. The Infrared Catastrophe

The radioactive decay of ^{56}Co which powers the late-time supernova produces γ-rays and positrons around the MeV range. The γ-rays Compton scatter and produce fast electrons which in turn ionize, excite and heat the gas as they slow down. The division of the energy from the radioactive decay into heating, ionizations and excitations does depend on the composition and the electron fraction of the ejecta but for the purposes of this discussion it can be safely assumed that most of the energy (>80%) goes into heating the thermal electron gas. The ejecta cool through collisionally excited transitions of low ionization species. Excluding molecular species and hydrogen the dominant coolants in the supernova have been forbidden lines of neutral and singly ionized iron, neutral oxygen, singly ionized calcium, neutral carbon and neutral silicon. Apart from calcium and silicon all other species have strong fine structure ground state transitions. These transitions have extremely low excitation temperatures and for most purposes are temperature independent. As the ejecta cool the efficiency of the ionic coolants approaches a plateau where the higher excitation energy levels can no longer be populated but the ground state lines remain saturated. The heating due to the radioactivity declines due to the decrease of the available energy and the increased transparency of the ejecta. The heating and cooling rates around 1000 K can no longer be balanced and the ejecta cool rapidly. The result would be that only the mid and far infrared transitions would emit. This effect postulated by Axelrod (1980) is called the 'infrared catastrophe' and has never been directly observed.

Spyromilio & Graham (1992) by modeling (see Fig 5) the combined near-infrared and optical spectrum have shown that the mass of emitting iron plummeted around the epoch

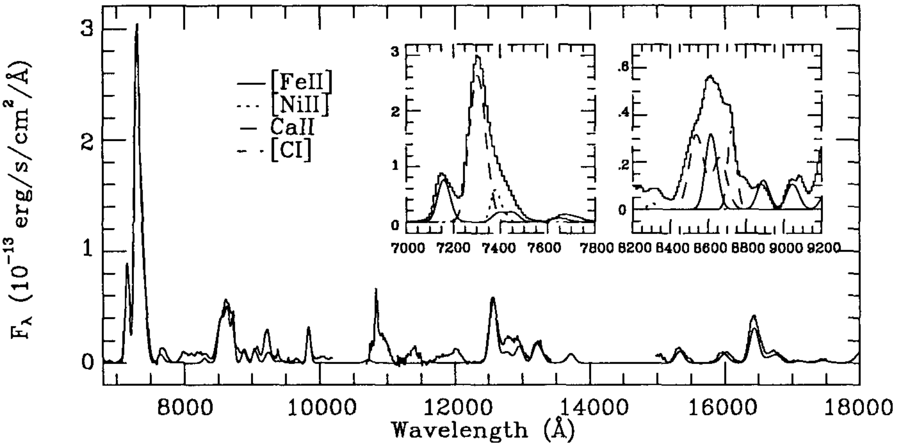

FIGURE 5. Spectra of SN 1987A with model fitting the forbidden emission by FeII (Spyromilio & Graham 1992)

of dust formation. One of the scenarios they proposed to explain this was that the ejecta had cooled catastrophically leaving some material hot which continued to emit. This scenario has been given support by the KAO observations (Dwek *et al.* 1992) and by the recent analysis of the entire iron spectrum by Li *et al.* (1993).

7. The Asymmetric Wind

Around 60 days after explosion, the UV spectrum of SN 1987A began to exhibit narrow lines of highly ionized nitrogen and other species. This emission has been analyzed in great detail by Lundqvist & Fransson (1991) and has been shown to arise from circumstellar gas. The near infrared spectrum around 400 days after explosion exhibited strong narrow emission by the He I 1.083 μm transition. By using the spectral imaging technique Allen, Meikle and Spyromilio (1989) were able to determine the spatial distribution of the helium emission and to show that not only was the emission asymmetric but also that the progenitor had anomalously high helium abundance in the wind preceding the explosion.

8. The spectrum 5 years after explosion

SN 1987A is the only supernova for which continuous high signal to noise data have been obtained for as many as 5 years after explosion in the infrared. Using the new generation of infrared spectrographs based on 2-D IR arrays we have been able to extend the coverage to such an unprecedented epoch. The spectrum has not varied dramatically after the third year and is dominated by the circumstellar emission by He I 1.083 μm. Hydrogen Paschen β and γ are observed as is the He I singlet equivalent of the 1.083 line at 2.058 μm. The emission by the ejecta is of particular interest. Although strong emission is seen in the 1.64 μm blend the weakness of the 1.257 [Fe II] line indicates that the 1.64 μm feature is now again dominated by [Si I] emission. Meikle *et al.* (1993) have shown that the [Si I] contribution to that feature had steadily decreased after day 500 predominantly due the drop of the electron density below the critical value for the excitation of this transition. Its reappearance as the dominant emitter suggests a non-thermal heating mechanism.

https://doi.org/10.1017/S025292110000806X Published online by Cambridge University Press

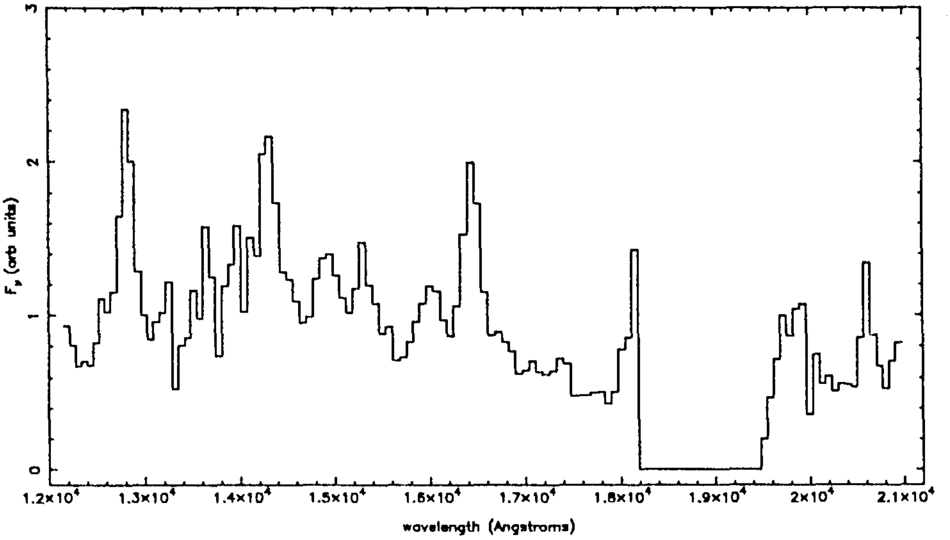

FIGURE 6. SN 1987A 21/2/1992 AAT & IRIS

Acknowledgements

The work presented here is the result of a long collaboration with Peter Meikle, David Allen and Gian Varani. The data could not have been obtained without the excellent support afforded us by the staff at the AAT.

REFERENCES

Allen D. A., Meikle, W. P. S., & Spyromilio, J. 1989, Nature, 342, 403

Axelrod, T. S. 1980, PhD dissertation, University of California

Danziger, I. J., Lucy, L. B., Bouchet P., & Gouiffes C. 1991, in Woosley S.E., ed., Supernovae, Springer-Verlag, New York, p.69

Dwek, E. 1988, ApJ, 329, 814

Dwek, E., *et al.* 1992, ApJ, 389, L21

Ferland, G. J., *et al.* 1979, ApJ, 227, 489

Frogel J. A., *et al.* 1987, ApJ, 315, L129

Graham, J. R., *et al.* 1986, MNRAS, 218, 93

Kurfess, J. D. 1992, ApJ, 399, L137

Li H., McCray R., & Sunyaev R.A. 1993, ApJ, 419, 824

Lucy L. B., Danziger I. J., Gouiffes C., & Bouchet P. 1991, in Woosley S.E., ed., Supernovae, Springer-Verlag, New York, p.82

Lundqvist P., & Fransson, C. 1991, ApJ, 380, 575

Meikle W. P. S., Allen D. A., Spyromilio J., & Varani G.-F. 1989, MNRAS, 238, 193

Meikle W.P.S., Spyromilio J., Allen D. A., Cumming R. J.,& Varani G.-F. 1993, MNRAS, 261, 535

Miller S., Tennyson J., Lepp S., Dalgarno A. 1992, Nature, 355, 420

Roche P. F., Aitken D. K., & Smith C. H. 1992, MNRAS, 252, 39p

Roche P. F., Aitken D. K., & Smith C. H. 1993, MNRAS, 261, 522

Spyromilio J., Meikle W. P. S., Allen D. A., & Learner R. C. M. 1988, Nature, 334, 327.

Spyromilio J., Meikle W. P. S., & Allen D.A. 1990, MNRAS, 242, 669

Spyromilio J., & Graham J. R. 1992, MNRAS, 255, 671

Tueller J. *et al.* 1990, ApJ, 351, L41

Varani G.-F., Meikle W. P. S., Spyromilio J., & Allen D. A. 1990, MNRAS, 245, 570

Wooden D.H., 1993, these proceedings.