MODEL CALCULATIONS AND SPECTROSCOPIC CONSTRAINS FOR SN1987A

P.Höflich
Max-Planck-Institut für Physik und Astrophysik, Institut für Astrophysik, Karl Schwarzschild Str. 1, 8046 Garching, FRG

Summary

We present synthetic spectra for atmospheres in order to interpret the observed spectra of the supernova 1987A during the first few months after the initial event. Spherical symmetry and density profiles are assumed which are given by the homologous expansion of the stellar structure of a B3 supergiant. For hydrogen, up to eight levels and, for helium, 16 levels are allowed to deviate from LTE. The radiation transport is calculated consistently with the rate equations both for the continua and for the lines. Radiative equilibrium is assumed. The observed spectra and colours in the optical wavelength range can be well reproduced by pure hydrogen models during the first few weeks. The behaviour of the UV flux is due to changes in the effective temperature and the photospheric radius. For later stages, the influence of elements other than hydrogen and helium must be taken into account in order to compare the calculated and observed spectra in the optical wavelength range. Reasonable agreement between calculations and observations can be obtained with the assumption of half solar abundances for all elements but for the s-process elements Sc,Ti and Ba which are overabundant. To explain the small changes in the spectra after about 3 weeks up to 4 months, we need a total hydrogen mass of about 8 to 10 $M_{\odot}$.

1. Introduction

Supernova 1987A in the LMC is the first type II supernova which has been observed simultaneously from the X-ray to the radio wavelength range beginning from the very early stages. In principle, these measurements allow very detailed checks of hydrodynamic models for supernova explosions and tests of stellar evolution calculations (Arnett, 1987; Woosley et al., 1987; Hillebrandt et al. 1987; Maeder, 1987; Truran, 1987). However SN1987A shows some pecularities with respect to observations of other type II supernovae: i) the very early occurrence of H lines and strong lines of heavier elements and the fast development of the flux spectrum at all wavelengths during the first few weeks, and ii) the relatively small changes in the spectra after about 4 weeks during several months after the explosion.

Detailed analyses of the observed spectra are helpful in order to answer questions concerning the hydrodynamic models, the mass of the envelope, the chemical composition as a function of radius and therefore the stellar evolution of the progenitor, etc. . A critical test for atmospheric calculations is the observed time dependences of the features.

To address these questions and to allow an interpretation of the observed spectra of SN1987A, we have modeled photospheres of type II supernovae by using a computer code for

https://doi.org/10.1017/S0252921100094045 Published online by Cambridge University Press

the construction of spherical extended non-LTE models (Höflich et al., 1986) which has been modified in order to allow for the treatment of high velocity fields (Höflich, 1987a, 1987b).

We assume stationarity and radiative equilibrium for the energy balance because the radiative timescales are short in respect to the hydrodynamic timescales soon after the initial increase in luminosity. Spherical symmetry is assumed. According to detailed numerical models (Falk and Arnett, 1977; Müller, personal communication, 1987; Nomoto, 1987; Nomoto et al., 1987) and also analytical solutions for strong shock waves in spherical expanding envelopes (Sedov, 1959) density profiles are taken which are given by the self-similar expansion of an initial structure, i.e.

$$\rho\ (\mathrm{r}) = \lambda^{-3}\ \rho(\mathrm{R}) \text{ and } \mathrm{r} = \lambda(\mathrm{t})\ \mathrm{R}\ ,$$

where r is the distance of a given mass element at time t and R its corresponding distance at time 0. The expanding matter of the envelope is mainly accelerated during the very first stages of the evolution. Consequently the expansion parameter λ is a linear function of time. The envelope is assumed to consist of hydrogen for models corresponding to the early stages. For later stages, helium and heavier elements are also included. For hydrogen, five to eight levels are allowed to deviate from the local thermodynamical equilibrium (LTE). All bound-bound and bound-free transitions have been included in the rate equations. In addition, two-quantum decay of the second energy level is taken into account. Helium is represented by a 16 level model atom (He I singlet: 1s, 2s, 2p, 3s, 3p, 3d, 4, 5; He I triplet: 2s, 2p, 3s, 3p, 3d, 4, 5; He II: 1). The bound-bound and bound-free opacities of the same transitions are also included in the radiation transport equation which is solved by the comoving frame method developed by Mihalas et al. (1975) for the first momentum of the intensity. To calculate the emitted flux in the observers frame and to archive energy balance, we use the integral method of Schmid-Burgk (1975) which has been modified in order to allow the treatment of high velocity fields. Thomson scattering, free-free opacities and the opacities due to the higher members of the Balmer series (up to the main quantum number of 30) are taken into account. These line opacities and the corresponding source functions are calculated under the assumption that populations of the upper levels are determined by LTE. This is a reasonable approximation because these populations are mainly dominated by collisional processes. In order to analyse later stages, line blanketing due to heavier elements is included for line formation calculations. Pure scattering and LTE is assumed for the level populations for all these lines. The ionisation balance of elements other than H and He is calculated under the assumption that photoionisation occurs from the ground states only. Here the radiation field is given by a H/He non-LTE model which is blanketed by lines of heavier elements (about 2000) in the UV. The ionisation balance of most of the ions is not very sensitive to this treatment as test calculations have shown in which the LTE approximation was used. Note that the assumption of LTE for the relative populations inside an ionisation state should be regarded as a first order approximation. This allows the identification of observed features, a representation of the blanketing due to the large number of weak lines and to give first estimates of the element abundances, if a lot of lines of a certain ion is taken into consideration. However the element abundances determined by this treatment may show major errors if only a few strong features are used (see below).

https://doi.org/10.1017/S0252921100094045 Published online by Cambridge University Press

2. Discussion of the models

Our models are described by the following free parameters: i) the initial density profile which is given by the stellar structure of a B3I star as calculated by A. Weiss (personal communication), ii) the expansion parameter λ, iii) the photospheric expansion velocity, iv) a statistical component of the velocity field, and v) the total luminosity. The total luminosity is determined by the observed flux in the visual wavelength range assuming the distance of SN1987A to be 46 kpc (Höflich, 1987a). Note that the velocity at the photosphere and the expansion parameter λ are free parameters for only one model at a certain time. For all other stages these two parameters are determined by the assumption of constant kinetic energy (see above).

The comparison of the synthetic and the observed spectra at a specific time allows us to deduce the photospheric radius R_{5000}, the corresponding effective temperature T_{eff}, the particle density N_o and the velocity field v at R_{5000}, the distance R_{HII} at which most of the hydrogen becomes neutral, and the mass fraction of the envelope M in solar units which has passed the photosphere. Please note that for extended geometries the photospheric radius is a definition. Here R_{5000} is the distance at which the optical depth for true absorption at 5000 Å equals 1 (from outside). This layer corresponds to the innermost layers from which photons can be observed because of the dominance of Thomson scattering τ_{sc} over bound-free opacities for all wavelengths but the far UV ($\tau_{sc}(R_{5000}) \geq 10$). In table 1 we give besides these quantities the value of n which approximately corresponds to a density profile $\propto r^{-n}$ at R_{5000}, and the dates corresponding to SN1987A.

During the first week, the photospheric radius is strongly increasing due to the fact that the expansion of the photosphere is mainly coupled to the expanding matter already a few hours after the initial event. Simultaneously, the effective temperature decreases rapidly. This explains the rapid drop in the observed UV flux as a consequence of the changes in T_{eff} and the increase of the IR-flux due to an increase in the photospheric radius. After about one to two weeks, the geometrical dilution of the material and the recombination of hydrogen outside a certain distance R_{HII} result in a much slower change in R_{5000} and, consequently, in smaller changes in time of the spectral energy distribution as long as the continuum is determined by electron scattering, i.e. the hydrogen envelope can be observed at the continuum forming region. The importance of an exact NLTE-treatment of H should be noted in respect to the electron density.

Firstly, pure hydrogen models are discussed in some detail. This allows an analysis of the optical spectra observed during the first few weeks. A comparison of the observed with the synthetic spectra show good agreement (figure 2). The early occurrence of broad absorption components can be understood as a result of the steeper density gradients and lower optical depths of electron scattering at the line forming region in comparison to normal type II supernovae, i.e. as a direct consequence of the fact that the progenitor star was a B3 supergiant. The increasing of the H_α emission is due to the growth of the line forming region and optical depth effects. The too low emission component of H_β on Feb. 24 may be a hint that the assumed density structure is somewhat too steep at this stage. Additional discrepancies, mainly in the spectrum corresponding to Mar.01, are a consequence of the omission of line blanketing due to elements other than hydrogen.

https://doi.org/10.1017/S0252921100094045 Published online by Cambridge University Press

Table 1: The distance R_{5000} at which the optical depth is 1 for true absorption at 5000 Å, the effective temperature T_{eff}, the particle density N_o, the velocity field v in km/sec and the n corresponding to a density profile $N(r) \propto r^{-n}$ at the distance R_{5000} are given for models with a density structure which is obtained by a homologous expansion of structure of a B3I star ($\dot{\lambda} \approx 10^{-3}$). All quantities are given in CGS. In addition the mass $\dot{M}$ in solar masses which has gone through the photosphere, the radius R_{HII} of the HII-region and the corresponding date are given for SN1987A. Please note that we assumed a statistical velocity of 2000, 1000 and 500 km/sec for model I-III, IV-V and VI.

No.	R_{5000}	T_{eff}	N_o	v	n	R_{HII}	Date	$\dot{M}$
I	1.28E14	12400 K	3.8E12	20000.	13.	-	Feb25	7.E-3
II	2.4E14	9150 K	1.3E12	16500.	10.	3.9E14	Feb26	1.2E-2
III	4.9E14	6500 K	4.8E11	12000.	7.2	7.8E14	Mar02	2.E-1
IV	9.1E14	5100 K	3.6E11	8000.	5.6	1.15E15	Mar09	8.E-1
V[1]	1.05E15	4800 K	3.3E11	6000.	5.2	1.25E15	Mar16	1.3
VI[2]	1.15E15	5000 K	4.0E11	4500.	3.8	1.32E15	Apr02	3.8

[1] H and He model

[2] H, He, C, N, O, Na, Mg, Si, S, Sc, Ca, Ti, V, Cr, Mn, Fe, CO, Ni, Sr and Ba model

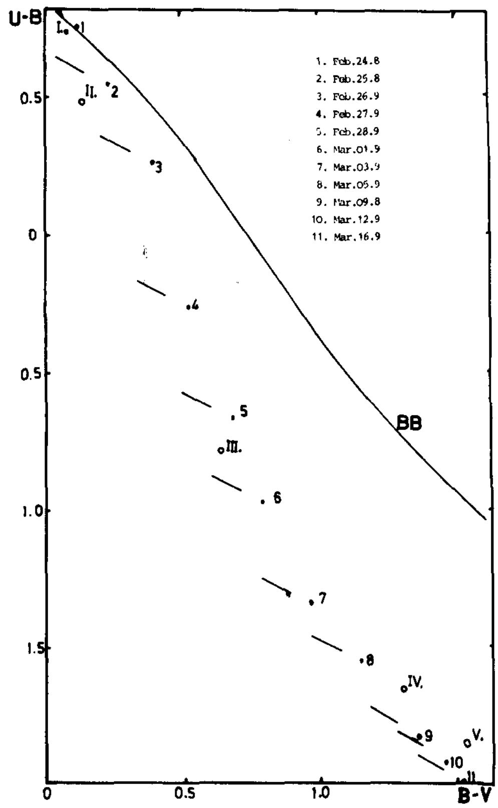

Figure 1: The colour index E_{U-B} as a function of E_{B-V} in the filter system of Johnson (1966). The indices as derived from a Planck function (BB; thin line), those as observed by Menzies et al. (1987) without (dots with numbers) and including interstellar reddening correction (A_{B-V} = 0.08...0.18 mag ,Wampler et al., 1987; bars), and those as calculated (open circles) by the models I-VI (see table 1) are given.

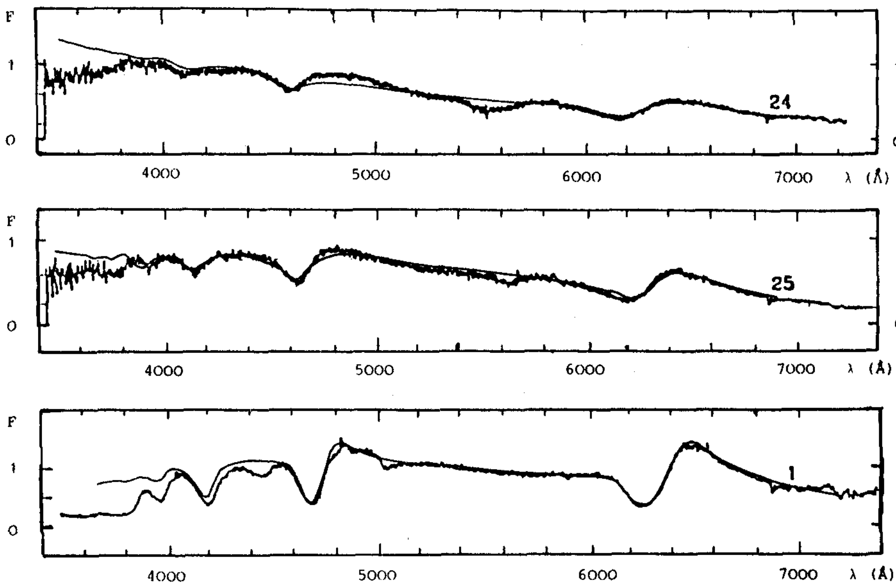

Figure 2: Spectra as observed by Menzies et al. (1987) at February 24.9, February 25.9 and March 1.8 in comparison with the synthetic spectra as calculated by the corresponding models I to III (see table 1). We assume an interstellar reddening A_{B-V} of 0.08 mag.

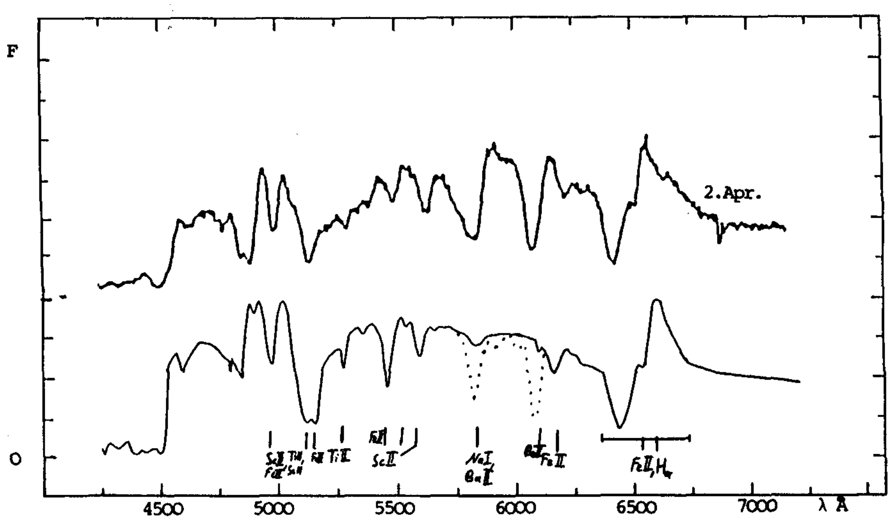

Figure 3: Spectrum as observed by Menzies et al. (1987) at Apr. 2. in comparison with the reddened synthetic spectrum (thin line) as calculated by model VI (see table 1) assuming half solar abundances for all elements but Sc, Ti, V,Cr,Sr and Ba (2.5*solar). The flux as calculated by the same model but enlarged Ba abundance (50*solar) is shown between 5600 and 6200 Å (dotted line). In addition identifications of some strong features are given.

https://doi.org/10.1017/S0252921100094045 Published online by Cambridge University Press

The comparison between the calculated and the observed colour index E_{U-B} as a function of E_{B-V} shows good agreement (figure 1). The early departure from the slope expected from a black body fit, which is a good approximation for normal type II supernovae, is mainly due to H-line blanketing. Discrepancies between the observed and the calculated colour relation after about 2 weeks are due to the neglect of line blanketing by elements other than hydrogen (and helium) for these models. Therefore, a quantitative analysis of the observed spectra using pure hydrogen (and helium) atmospheres is restricted to about the first few weeks.

In order to analyse later stages and to get first estimates for the chemical abundances we have carried out line formation calculations by using some simple approximations with respect to the treatment of the heavier elements (see above). A comparison between the synthetic spectrum and the spectrum observed on Apr.02 in the optical wavelength range is shown in figure 3. In addition, some strong features are marked by ions which give the main contribution to the opacity. Note, however, that the calculated spectral slope is mainly determined by blanketing due to weak lines (about 1000), especially those of ScII, TiII and FeII. We use half solar abundances for all elements but the s-process elements Sc,Ti,V,Cr,Sr and Ba (2.5$_*$solar) to get the best fit. Features due to the s-process elements Sc, Ti and Ba can be identified. A reduction of the abundances with respect to the sun is needed in order to reduce line blanketing effects mainly due to iron at the longer wavelengths, and an overabundance of Sc and Ti is needed to fit some of the observed features and to explain the spectral slope below 5300 Å. In principle, the observed spectrum can be well reproduced with the exception of two strong features at about 5800 and 6080 Å which can be attributed to a blend of NaI and BaII and to a single BaII line, respectively. In order to get quantitative agreement, Na and Ba have to be choosen overabundant by a factor of about 10-15 and 50, respectively, in relation to the sun. However these estimates are based on a LTE-analysis of only few strong features and should be regarded as very uncertain. In fact test calculations show that the overabundances of Na and Ba may be reduced to a factor of 5-8 and 10-20 by NLTE-effects.

Note that the early occurrence of strong absorption features in the optical wavelength range is due to a low density in the outer region and therefore may be a hint for a low mass loss of the progenitor in the near past. The spectra observed later than Apr.02 up to about 4 months after the initial event show only small changes. This behaviour is to be expected from the models as long as the continuum is dominated by Thomson scattering, i.e. as long as the continuum region is formed in hydrogen rich layers. Therefore, the total mass of the hydrogen shell can be estimated to be 8-10 $M_\odot$. Note in addition that hydrogen features are visible for some more months because parts of the H lines are formed at much larger radii than R_{5000}.

3. Results

The observations can be understood by models with a density profile which is given by the holomogous expansion of a B3I star.

For the early stages pure hydrogen models can be used. The flux variations with time of the continua in the ultraviolet, the optical and the infared wavelength range are due to an early rapid decrease in the effective temperature and an increase in the photospheric radius. The smaller changes in the following are a result of the slow increase of the photospheric radius mainly due to a geometrical dilution effect and due to the recombination of hydrogen outside a certain radius. The early occurrence of the absorption features due to hydrogen and the rapid development of the spectrum in contrast to type II supernovae other than SN1987A can be understood as due to the steep density gradient and is therefore a direct consequence of the spectral type of the progenitor. The increase in the emission component of the hydrogen lines is due to the growth of the line forming region. For later stages, the line absorption due to heavier elements must be taken into account. The spectra can be understood by models with half solar abundances for all elements but the s-process elements (Sc, Ti and Ba) and Na which are overabundant. From the relatively small changes in the observed spectrum during several months after a few weeks, a mass of 8 to 10 $M_\odot$ can be infered for the H-rich envelope.

However we have also to stress the limits of the models. Because of the LTE-treatment of the heavier elements the given abundances should be regarded as a first estimate. Especially NLTE-treatment is needed in a more accurate determination of Na and Ba abundances. These models are restricted to stages at which the continua are dominated by electron scattering, i.e. to the first few months after the initial event.

References

Arnett, W.D. *Astrophys.J.* **319** 136 (1987)

Falk,S.W.; Arnett, W.D. *Astrophys.J.Suppl.* **33** 515 (1977)

Hillebrandt,W.; Höflich,P.; Truran,J.W.; Weiss,A. *Nature* **327** 597 (1987)

Höflich,P. *Proceedings of the 4th workshop on Nuclear Astrophysics* Ringberg (1987a)

Höflich,P. *Proceedings of the ESO-workshop on SN1987A* Munich (1987b)

Höflich,P.; Wehrse,R.; Shaviv,G. *Astron. Astrophys.* **163** 105 (1986)

Johnson,H.L. *Ann.Rev.Astron.Astrophys.* **4** 197 (1966)

Maeder, A. *Proceedings of the ESO-workshop on SN1987a* (1987)

Menzies,J.W. et al. *Spectroscopic and photometric observations of SN1987A. The first 50 days* preprint (1987)

Mihalas,D.; Kunasz,R.B; Hummer,D.G. *Astrophys.J.* **202** 465 (1975)

Nomoto, K. personal communication (1987)

Nomoto, K.; Shigeyama,T.; Hashimoto,M. *Proceedings of the ESO-workshop on SN1987A* Munich (1987)

Schmid-Burgk,J. *Astron.Astrophys.* **40** 149 (1975)

Sedov,L.I. *Similarity and Dimensional Methods in Mechanics* , Academic Press, New York, p. 260 (1959)

Truran, J.W. *Proceedings of the ESO-workshop on SN1987A* Munich (1987)

Wampler, E.J.; Truran, J.W.; Lucy, L.B.; Höflich, P.; and Hillebrandt, W. *Astron. Astrophys.* **182** L51 (1987)

Woosley,S.E.; Pinto, P.A.; Martin,P.G.; Weaver,T.A. *Astrophys.J.* **318** 664 (1987)