THE ASTROPHYSICAL JOURNAL, 341:L59–L62, 1989 June 15

# PROBING THE FIRST HOURS IN THE LIFE OF SN 1987A

CLAES FRANSSON
Stockholm Observatory
AND
PETER LUNDQVIST
Lund Observatory

*Received 1988 December 7; accepted 1989 March 20*

## ABSTRACT

The observations of the narrow UV and optical emission lines of SN 1987A are modeled. The main properties of the observations are well reproduced by a shell ionized by the soft X-ray burst at the supernova shock breakout. These observations therefore provide constraints on the unobserved first hours of the supernova explosion. To explain the time evolution and fluxes of the lines, the peak radiation temperature of the supernova has to be between $4 \times 10^5$ K and $8 \times 10^5$ K, and the total number of ionizing photons above 100 eV $\sim 10^{56}$ ($\sim 2 \times 10^{46}$ ergs).

*Subject headings:* stars: circumstellar shells — stars: individual (SN 1987A) — stars: supernovae — ultraviolet: spectra

## I. INTRODUCTION

The first spectral observations of SN 1987A were made $\sim 35$ hr after the core collapse. The effective temperature was then $\sim 15{,}000$ K (Kirshner *et al.* 1987; Cassatella *et al.* 1987). Theoretical models of the outburst, however, predict that the peak effective temperature at the shock breakout, $\sim 2$ hr after core collapse, was (2–5) $\times 10^5$ K (Shigeyama, Nomoto, and Hashimoto 1988; Woosley 1988; Arnett 1988). Therefore, most of the cooling of the photosphere occurred before the discovery, and the much later spectral observations give few constraints on these early moments of the explosion. The discovery of narrow UV emission lines from circumstellar gas around SN 1987A several months after the explosion have, however, given us a late diagnostic of these epochs (Fransson *et al.* 1989, hereafter F89). In this *Letter* we model these observations quantitatively, and show that they indeed provide good constraints on the early evolution. Earlier discussions of the effects of an intense burst of far-UV radiation from SN 1987A (Fransson *et al.* 1987; Raga 1987; Dopita *et al.* 1987) have mainly discussed *possible* effects on the surrounding medium, but none have been able to put any constraints on the burst from actual observations. A preliminary version of our work can be found in Lundqvist and Fransson (1987) and Fransson (1988), and more detailed discussions of the model in Lundqvist and Fransson (1989) and of the dynamics of the shell in Chevalier (1988).

## II. MODELING THE UV EMISSION LINES

The UV observations and the main inferences from these are discussed in detail in F89 and Cassatella *et al.* (1989). In particular, N III] λ1750, N IV] λ1486, and N V λ1240 were seen as strong lines, and because of the different threshold energies of these ions (29.6 eV, 47.4 eV, and 77.5 eV, respectively) they serve as good diagnostics of the state of ionization in the gas. While both the N V and N III] lines, as well as C III] λ1909, increased their fluxes roughly linearly with time, the N IV] line, and also He II λ1640, had nearly constant fluxes. From C III] λλ1907–09 and N III] λλ1746–54, the electron density in the line-emitting region could be determined to be (2–3) $\times 10^4$ cm$^{-3}$. From optical observations of the [O III] λλ4959–5007/[O III] λ4363 ratio Wampler and Richichi (1989) determined a temperature of $\sim 5 \times 10^4$ K for the [O III] emitting gas, 300 days after the explosion. Furthermore, the [O III] emission was resolved with a radius of $\sim 1''$, or $7.8 \times 10^{17}$ cm ($\sim 300$ lt-days). This is in good agreement with the radius inferred from the time of the turnover in the UV fluxes, $t_{\max} \sim$ 400 days, which corresponds to a shell radius $R_s = ct_{\max}/2 \sim$ 200 lt-days $= 5 \times 10^{17}$ cm (Sonneborn *et al.* 1988).

It is unlikely that the radiation from the supernova shock wave or the radioactively induced X-ray emission contributes to the excitation of the gas (F89). Instead, the burst of energetic radiation accompanying the shock breakout was proposed as a likely source of energy (see also Lundqvist and Fransson 1987). Such a burst has been predicted on the basis of several hydrodynamical calculations of the explosion (e.g., Klein and Chevalier 1978; Falk 1978). The duration is of the order of hours, and most of the energy is coming out as EUV and soft X-ray emission.

Models for the early soft X-ray burst of SN 1987A have been calculated by Shigeyama, Nomoto, and Hashimoto (1988), Woosley (1988), and by Arnett (1988). In the 11E1Y6 model by Shigeyama *et al.* the peak radiation temperature, in the following $T_{\text{peak}}$, is $\sim 4.3 \times 10^5$ K, while Woosley finds a peak temperature of $\sim 2 \times 10^5$ K, in his 10L and 10H models. The temperature decreases in $\sim 1.7$ hr to 50,000 K, and in $\sim 7$ hr to 25,000 K. Since the decay time of the burst is much less than the recombination time, the exact time evolution is not important for the ionization structure—only the *total* number of photons as a function of energy. We have integrated the spectra of Shigeyama *et al.*'s 11E1Y6 model and Woosley's 10L model over time, shown in Figure 1. Because these spectra are the superposition of blackbody spectra with a continuously falling temperature, there is a large excess of soft photons compared to a single-temperature blackbody spectrum. For the 11E1Y6 (10L) models we find that between 13.6 and 54 eV, $7.8 \times 10^{56}$ ($7.1 \times 10^{56}$) photons are produced, between 54 and 100 eV, $2.2 \times 10^{56}$ ($6.9 \times 10^{55}$) photons, and above 100 eV $1.3 \times 10^{56}$ ($8.9 \times 10^{54}$) photons. The difference above 54 eV is due to the considerably higher initial temperature in the

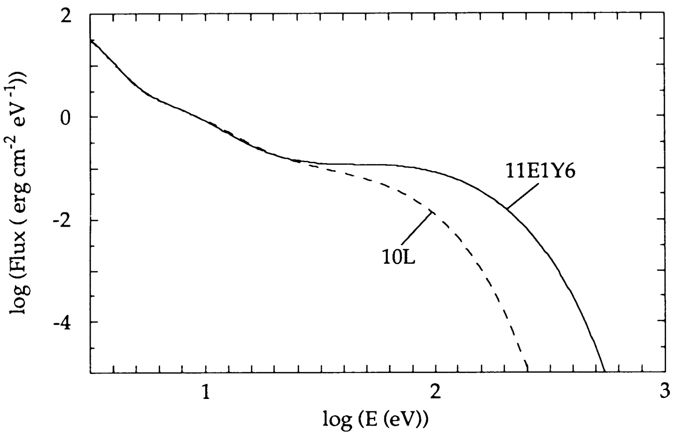

FIG. 1.—Time-integrated spectrum, $S_\nu$, above 3 eV for the Shigeyama *et al.* 11E1Y6 (*full line*) and Woosley 10L models (*dotted line*).

11E1Y6 model. Both these calculations assume that the spectrum has a blackbody form, which is far from clear (see § III).

The initial state of ionization depends for a given spectral shape on the parameter, $\Psi = S/4\pi R_s^2$, where $S$ is the time-integrated, total number of ionizing photons above energy $E_0 = 13.6$ eV. For the 11E1Y6 model $S = 1.1 \times 10^{57}$, and for the 10L model $S = 7.9 \times 10^{56}$. The maximum mass that can be ionized is $\sim 0.8\ (S/10^{57})\ M_\odot$. If $R_s$ is known, the spectral shape and $S$ provide the initial conditions for the subsequent evolution. To estimate the effect of the burst, we approximate the ionizing radiation with a spectrum of fixed form during an interval $\tau$. As an approximation to the integrated flux in Figure 1 we have used a free-free form $S_\nu \propto \exp\ (-h\nu/kT_{\rm ff})$. For the discussed models $T_{\rm ff}$ is $\sim$50%–75% of $T_{\rm peak}$.

In general, the ratio, $\Theta_i$, of the photoionization time scale, $t_i$, of the ion, $i$, and $\tau$, scales as $\Theta_i \propto \Psi^{-1}$. In the case of a free-free integrated spectrum, a cross section given by $\sigma(E) = \sigma_i(\chi_i/E)^3$, and for $kT_{\rm ff} \ll \chi_i$, we obtain

$$\Theta_i \equiv t_i/\tau = \Psi^{-1}\, \frac{E_1(E_0/kT_{\rm ff})}{\sigma_i} \left(\frac{kT_{\rm ff}}{\chi_i}\right)^4 e^{-\chi_i/kT_{\rm ff}}\,,$$

where $E_1(x)$ is the first exponential integral and $\chi_i$, the ionization potential. This equation describes the dependence on $\Psi$, $T_{\rm ff}$, and $\chi_i$ fairly well. In Table 1 we give numerically evaluated values of $\Theta_i$ for hydrogen, helium, and nitrogen, for different values of $T_{\rm ff}$, assuming $S = 10^{57}$ photons and $R_s = 5 \times 10^{17}$ cm, i.e., $\Psi = 3.18 \times 10^{20}$ cm$^{-2}$. Values for other parameters can be obtained using $\Theta_i \propto \Psi^{-1}$. For $\tau \gg t_i$, i.e., $\Theta_i \ll 1$, the ion will be completely ionized; thus the most populated stages occur for ions with $\Theta_i \sim 1$. Table 1 therefore gives a good estimate of the initial state of ionization for a given spectrum and value of $\Psi$. Because the dependence on $T_{\rm ff}$ dominates, the observation of lines from N V therefore implies that $T_{\rm peak}$ must have been at least $\sim 2 \times 10^5$ K.

After the initial ionization the gas will recombine on a time scale $t_{\rm rec} = (\alpha_r\, n_e)^{-1}$, where $\alpha_r$ is the recombination coefficient. For the nitrogen stages of interest these are 472 $(T_e/10^5\ {\rm K})^{0.8}(n_e/10^4\ {\rm cm}^{-3})^{-1}$ days for N VI to N V, 28 $(n_e/10^4\ {\rm cm}^{-3})^{-1}$ days for N V to N IV, 26 $(n_e/10^4\ {\rm cm}^{-3})^{-1}$ days for N IV to N III, and 35 $(n_e/10^4\ {\rm cm}^{-3})^{-1}$ days for N III to N II. The latter three time scales are for $10^5$ K, but vary by less than a factor of $\sim 2$ from $5 \times 10^4$ K to $2 \times 10^5$ K. The decrease in recombination time from the He-like stages, like N VI, to the lower stages is important. If $T_{\rm peak}$ is less than $\sim$(1–2) $\times 10^5$ K, most of the nitrogen atoms will be in N IV and N V initially. Therefore, at densities higher than $\sim 10^3$ cm$^{-3}$, recombination of N V occurs rapidly to N III–IV, and the N V emission drops quickly after the burst. In the opposite case when $T_{\rm peak}$ is higher than $\sim$(2–3) $\times 10^5$ K, most of the nitrogen is in N VI, and there will be a slow, but steady "leakage" to the lower stages, and emission from these ions is present for a long time. Above $\sim$50,000 K recombination of N III is stopped by collisional ionization of N II.

The *received* luminosity, $L$, from the shell at time $t$ is $L = (c/2R_s) \int_{t_{\rm min}}^{t} L_e(t_e)\, dt_e$. Here $L_e(t_e)$ is the luminosity emitted by the shell at time $t_e$, and $t_{\rm min} = \max\ (0, t - 2R_s/c)$. If the emissivity drops rapidly with time, the volume contributing to the observed emission is constant, and thus also the luminosity. On the other hand, if the recombination or cooling time is long compared to $R_s/c$, the emitting volume increases with time, and $L = (ct/2R_s)L_e$. After $t = 2R_s/c$, the whole shell becomes visible to us, and $L$ remains constant until $\sim t_{\rm rec}$.

The nearly linear rise of the N V line shows that the emissivity is not restricted only to the initial phase. If most nitrogen *initially* was in N V, it would all recombine in only $\sim$10–30 days. If most of the nitrogen instead was in N VI initially, and then slowly recombined into N V and lower stages, this would give a linear rise. Thus, the increasing N V flux up to $\sim$400 days shows that *nitrogen must have been ionized up to* N VI *initially.* Returning to Table 1, $T_{\rm peak}$ has to be at least $\sim$(2–3) $\times 10^5$ K.

We now discuss a calculation where all important heating and cooling processes have been included. Since the recombination time scale is long compared to the decay time of the ionizing flux, the ionization and temperature have to be calculated time dependently. We include all relevant processes, such as photoionization, radiative and dielectronic recombination, collisional ionization, and line cooling by collisional excitation

TABLE 1

PHOTOIONIZATION TIME SCALE PARAMETERS $\Theta_i$ FOR A BURST WITH TEMPERATURE $T_{\rm ff}$ AND A FORM $S_\nu \propto \exp\ (-h\nu/kT_{\rm ff})$

| $T_{\rm ff}$ ($10^5$ K) | H I | He I | He II | N II | N III | N IV | N V | N VI |
|---|---|---|---|---|---|---|---|---|
| 0.8.......... | 9.41 − 4 | 5.79 − 3 | 3.21 + 0 | 1.14 − 2 | 7.72 − 1 | 1.60 + 2 | 4.39 + 3 | ... |
| 1.0.......... | 1.02 − 3 | 4.20 − 3 | 9.91 − 1 | 7.35 − 3 | 2.93 − 1 | 2.46 + 1 | 3.73 + 2 | ... |
| 2.0.......... | 1.33 − 3 | 2.35 − 3 | 9.79 − 2 | 3.26 − 3 | 4.41 − 2 | 5.82 − 1 | 2.65 + 0 | ... |
| 4.0.......... | 1.75 − 3 | 1.94 − 3 | 3.30 − 2 | 2.40 − 3 | 1.85 − 2 | 9.18 − 2 | 2.22 − 1 | 1.02 + 6 |
| 6.0.......... | 2.06 − 3 | 1.91 − 3 | 2.40 − 2 | 2.28 − 3 | 1.45 − 2 | 5.08 − 2 | 9.77 − 2 | 5.27 + 3 |
| 8.0.......... | 2.30 − 3 | 1.95 − 3 | 2.09 − 2 | 2.29 − 3 | 1.31 − 2 | 3.84 − 2 | 6.53 − 2 | 3.72 + 2 |
| 10.0.......... | 2.50 − 3 | 2.00 − 3 | 1.95 − 2 | 2.32 − 3 | 1.25 − 2 | 3.28 − 2 | 5.16 − 2 | 7.51 + 1 |
| 20.0.......... | 3.19 − 3 | 2.26 − 3 | 1.82 − 2 | 2.58 − 3 | 1.22 − 2 | 2.53 − 2 | 3.35 − 2 | 2.97 + 0 |

NOTE.—A total of $10^{57}$ ionizing photons and a distance to the shell of $R_S = 5 \times 10^{17}$ cm are assumed.

as multilevel atoms. For further details we refer to Lundqvist and Fransson (1989). We use $n_e = 2.6 \times 10^4$ cm$^{-3}$ and $R_s = 5 \times 10^{17}$ cm, in agreement with the observations. The mass of the shell is 0.03 $M_\odot$, giving a shell thickness of $3.8 \times 10^{14}$ cm. The abundance ratios of the elements included are H:He:C:N:O:Ne:S equal to $1{:}0.1{:}3.9 \times 10^{-5}{:}1.9 \times 10^{-4}{:}9.7 \times 10^{-5}{:}2.3 \times 10^{-5}{:}4.3 \times 10^{-6}$, corresponding to a total CNO metallicity of 0.3 times solar and N/C = 5 and N/O = 2. The nitrogen enhancement is motivated by the results in F89. Except for the shell radius and to some extent the density, both determined from observations, our conclusions are not sensitive to these parameters. To study the sensitivity of the observed emission to the soft X-ray burst we have for the ionizing flux in one model used the spectrum of the 10L model, and in another model the harder 11E1Y6 burst.

Figure 2*a* shows for the 11E1Y6 spectrum the temperature and ionization in the middle of the shell as a function of time, together with the integrated (= observed) line fluxes. Because of the small mass, the shell is nearly optically thin, and the ionization roughly constant within the shell. The temperature is initially $0.9 \times 10^5$ K close to the inner edge of the shell, $1.35 \times 10^5$ K in the middle and increases to $1.7 \times 10^5$ K at the outer edge. Hydrogen and helium are fully ionized, while C, N, and O are in their helium like stages, C v, N vi, and O vii, in agreement with Table 1 ($T_{\rm peak} \sim 4.3 \times 10^5$ K). For $T_e = 10^5$ K and $n_e = 2.6 \times 10^4$ cm$^{-3}$, the recombination time is 182 days for N vi to N v, comparable to the evolutionary time scale. A population of N v therefore slowly builds up, which then rapidly recombines to N iv and N iii. The gas temperature, however, is high enough for collisional ionization to prevent the gas from recombining further. The cooling also occurs on the same time scale and proceeds rather smoothly. At $\sim 300$ days the temperature is $\sim 5.5 \times 10^4$ K, and at $\sim 500$ days $\sim 2.8 \times 10^4$ K.

Because initially nitrogen is in N vi, the received N v flux displays a nearly linear rise with time. N iii] $\lambda 1750$ also has a nearly linear increase of the flux, resulting from the slow recombination, while the emissivity of N iv] $\lambda 1486$ is more concentrated to the early stages, giving a fairly constant flux. The nearly constant flux of He ii $\lambda 1640$ shows that most of the emission is coming from the early phase. This is because collisional excitation is important for temperatures higher than $\sim 9 \times 10^4$ K, in addition to recombination. Consequently, the light curve of this line is sensitive to the high-energy tail of the ionizing burst.

In the second model (Fig. 2*b*) we have taken the softer burst of the Woosley 10L model. Otherwise the model is the same as that discussed earlier. Compared to Figure 2*a*, the most apparent difference is in the conditions in the shell immediately after the burst. The peak temperature is in the middle of the shell only $8.5 \times 10^4$ K, compared to $1.35 \times 10^5$ K in the 11E1Y6 model. Also the initial ionization is lower. Instead of ionizing up to the He-like stages, most ions are in the Li-like stages (N v, O v–vi, etc.). Consequently, the N v abundance decays by a factor of $\sim 5$ in only 40 days. The light curves of both the N v and N iv] lines therefore become flat. Also recombination from N iii to N ii occurs more rapidly, since the lower temperature makes collisional ionization inefficient earlier, making the final decay of the N iii] line more rapid. The low initial temperature makes collisional excitation unimportant for He ii $\lambda 1640$. The observed flux of this line is therefore nearly linear.

Summarizing, the most important effect of the higher peak

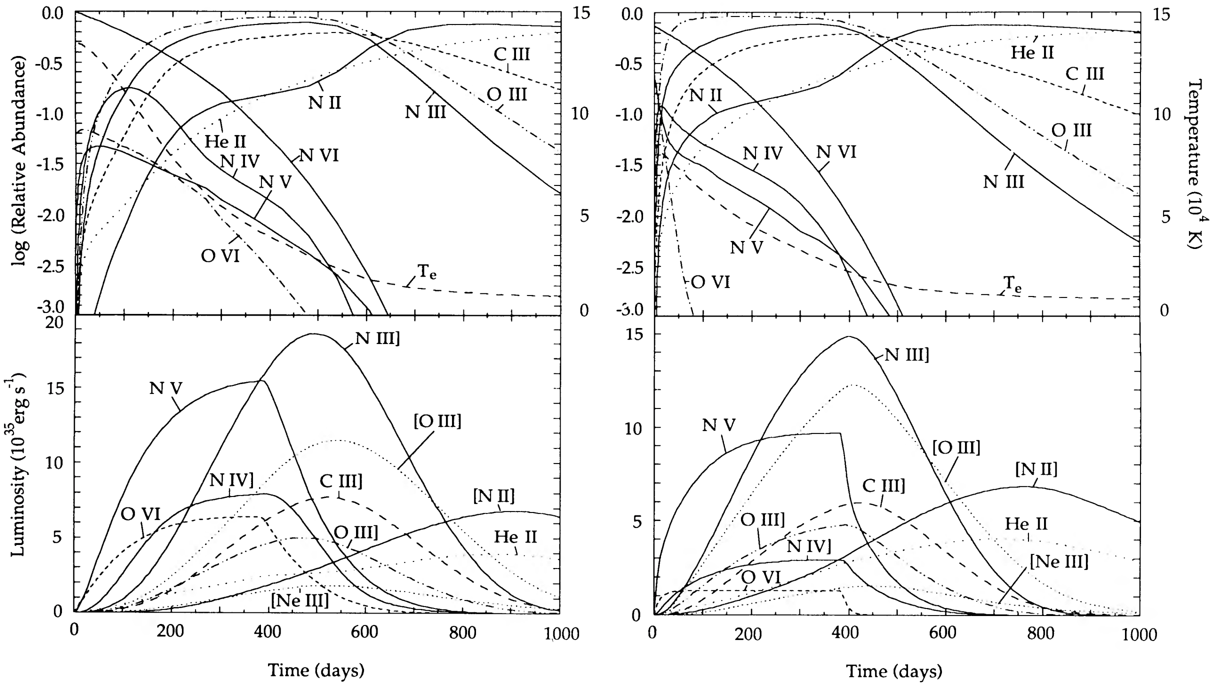

FIG. 2*a*

FIG. 2*b*

FIG. 2.—(*a*) Evolution of a shell of electron density $2.6 \times 10^4$ cm$^{-3}$, mass 0.03 $M_\odot$, and radius $5 \times 10^{17}$ cm, ionized by the soft X-ray burst. The ionizing spectrum is taken from the Shigeyama *et al.* 11E1Y6 model. The upper panel shows the temperature and relative abundances in the middle of the shell as a function of time. The lower shows the *received* (= observed) line luminosities, integrated over the observable parts of the shell. The lines shown are O vi $\lambda 1034$, N v $\lambda 1240$, N iv] $\lambda 1486$, He ii $\lambda 1640$, O iii] $\lambda 1664$, N iii] $\lambda 1750$, C iii] $\lambda 1909$, [Ne iii] $\lambda\lambda 3869$–3968, [O iii] $\lambda\lambda 6300$–64, and [N ii] $\lambda\lambda 6548$–83. (*b*) Same as Fig. 2*a*, but with the ionizing spectrum from the Woosley 10L burst.

of both permitted and forbidden lines. H I and He II are treated temperature of the 11E1Y6 model is the higher gas temperature and degree of ionization, compared to the 10L model. The models demonstrate the necessity to ionize up to N VI, or higher, for the observed N V luminosity to increase linearly with time. As a lower limit we find that $T_{\rm peak}$ has to be $\sim 4 \times 10^5$ K. In principle, the N V emission could come from gas of lower density. To give the observed N V flux for a total number of ionizing photons of $\sim 10^{57}$, the density of this component, however, has to be higher than a few times $10^3$ cm$^{-3}$. Even at this density the N V recombination is rapid compared to the evolutionary time scale. Such a low density is also unlikely, from the modeling of the evolution of the other lines (Lundqvist and Fransson 1989), and the observational determination from the C III and N III lines (Cassatella *et al.* 1989), which give a density of $(2\text{–}4) \times 10^4$ cm$^{-3}$. A further constraint comes from the N III] $\lambda$1750/N IV] $\lambda$1486 ratio, which for constant density decreases with increasing radiation temperature. In the range $(1\text{–}4) \times 10^4$ cm$^{-3}$, we have found that an observed ratio of (1.5–4) requires a $T_{\rm peak}$ between $(4\text{–}8) \times 10^5$ K. Similarily, in order not to give too strong an N V line relative to the N III and N IV lines, $T_{\rm peak}$ has to be less than $8 \times 10^5$ K. Any contribution from a low-density component will only decrease this limit. Also the constant flux of He II $\lambda$1640 indicates an initial gas temperature of more than $\sim 10^5$ K, implying a $T_{\rm peak}$ higher than $\sim 3 \times 10^5$ K. In fact, an even higher temperature than in the 11E1Y6 model, or a high-energy tail, might be necessary. Finally, we use the fact that the gas temperature, as determined from the [O III] lines, at 300 days was $\sim 5 \times 10^4$ K (Wampler and Richichi 1989). The 11E1Y6 model fulfils this requirement well (Fig. 2*a*), while the 10L model appears to have a spectrum which is too soft. *Therefore, all these constraints result in a required peak radiation temperature between* $4 \times 10^5$ *K and* $8 \times 10^5$ *K.* As is also apparent from Figures 2*a* and 2*b*, the observation of the O VI $\lambda$1034 line could be a good temperature indicator. Absorption of this emission by hot interstellar gas may, however, decrease the flux. An interesting independent constraint on the integrated UV flux above $\sim$1200 Å may come from observations of the interstellar dust echo in the UV (Chevalier and Emmering 1988). This is characterized by a narrow width outside the optical rings.

## III. DISCUSSION

From the observed UV and optical emission lines of SN 1987A we have found that the peak *radiation* temperature from the supernova at the time of the shock breakout must have been in the range $(4\text{–}8) \times 10^5$ K. A more precise statement is that the number of photons above $\sim$100 eV has to be at least $\sim 10^{56}$ ($\sim 2 \times 10^{46}$ ergs). This, therefore, provides the main observational constraint on the very early evolution of SN 1987A.

Several groups have made calculations of the early emission from SN 1987A. Of the two models discussed, the 10L model by Woosley (1988) had too soft a burst spectrum to explain the UV observations, while the 11E1Y6 model by Shigeyama, Nomoto, and Hashimoto (1988) did better in this respect. The too soft early flux in the 10L, or other similar models, does, however, not necessarily rule out these in other respects. All published models of the light curve of SN 1987A treat the radiation from the photosphere as an *LTE blackbody*. It is, known, however, from several earlier calculations that substantial deviations from LTE occur (Klein and Chevalier 1978; Falk 1978; Imshennik and Utrobin 1977). Since electron scattering dominates absorption, and the absorptive opacity decreases as $\kappa_a \propto \nu^{-3}$, the thermalization depth increases with frequency as $(3\kappa_e \kappa_a)^{-1/2} \propto \nu^{3/2}$. Thus, the spectrum becomes increasingly hard at higher energies. Klein and Chevalier and Falk find that including electron scattering, the radiation temperature increases by a factor of 2–3, compared to a blackbody. Therefore, the radiation temperatures given by the LTE models of SN 1987A may be underestimated by a factor of this order, and, e.g., the 10L model may come into the allowed range. Preliminary calculations indicate that an increase in this direction indeed occurs (Wheeler and Harkness 1989). In order to really test these hydrodynamic models, more accurate calculations of the flux have to be done, including the effects of electron scattering, as well as line transfer. In this *Letter* we have demonstrated that the observations and analysis of the UV emission lines give a unique constraint on these models at epochs not normally accessible to direct observations.

We are grateful to Claes-Ingvar Björnsson, Roger Chevalier, Mike Shull, Joe Wampler, and Craig Wheeler for many discussions.

## REFERENCES

Arnett, W. D. 1988, in *Supernova 1987A in the Large Magellanic Cloud, Proc. of the Fourth George Mason Astrophysics Workshop*, ed. M. Kafatos and A. G. Michalitsianos (Cambridge: Cambridge University Press), p. 301.
Cassatella, A., Fransson, C., Gilmozzi, R., Kirshner, R. P., Panagia, N., Sonneborn, G., and Wamsteker, W. 1989, in preparation.
Cassatella, A., Fransson, C., van Santvoort, J., Gry, C., Talavera, A., Wamsteker, W., and Panagia, N. 1987, *Astr. Ap.*, **177**, L29.
Chevalier, R. A. 1988, *Nature*, **332**, 514.
Chevalier, R. A., and Emmering, R. T. 1988, *Ap. J.* (*Letters*), **331**, L105.
Dopita, M., Meatheringham, S. J., Nulsen, P., and Wood, P. R. 1987, *Ap. J.* (*Letters*), **322**, L85.
Falk, S. W. 1978, *Ap. J.* (*Letters*), **225**, L133.
Fransson, C. 1988, *Proc. Astr. Soc. Australia*, **7**, 520.
Fransson, C., Cassatella, A., Gilmozzi, R., Kirshner, R. P., Panagia, N., Sonneborn, G., and Wamsteker, W. 1989, *Ap. J.*, **336**, 429 (F89).
Fransson, C., Grewing, M., Cassatella, A., Panagia, N., and Wamsteker, W. 1987, *Astr. Ap.*, **177**, L33.
Imshennik, V. S., and Utrobin, V. P. 1977, *Soviet Astr. Letters*, **3**, 34.
Kirshner, R. P., Sonneborn, G., Crenshaw, D. M., and Nassiopoulos, G. E. 1987, *Ap. J.*, **320**, 602.
Klein, R. I., and Chevalier, R. A. 1978, *Ap. J.* (*Letters*), **223**, L109.
Lundqvist, P., and Fransson, C. 1987, in *Proc. ESO Workshop on the SN 1987A*, ed. I. J. Danziger (Munich: ESO), p. 495.
———. 1989, in preparation.
Raga, A. C. 1987, *A.J.*, **94**, 1578.
Shigeyama, T., Nomoto, K., and Hashimoto, M. 1988, *Astr. Ap.*, **196**, 141.
Sonneborn, G., *et al.* 1988, *IAU Circ.*, No. 4685.
Wampler, E. J., and Richichi, A. 1989, *Astr. Ap.*, in press.
Wheeler, J. C., and Harkness, R. P. 1989, private communication.
Woosley, S. E. 1988, *Ap. J.*, **330**, 218.

CLAES FRANSSON: Stockholm Observatory, S-133 00 Saltsjöbaden, Sweden

PETER LUNDQVIST: Lund Observatory, Box 43, S-221 00 Lund, Sweden