TYPE II SUPERNOVA PHOTOSPHERES AND THE DISTANCE TO SUPERNOVA 1987A

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I. Introduction and Summary

Among the many historic opportunities provided by the recent supernova in the LMC is that to improve our understanding of the physical conditions in the neighborhood of supernova photospheres, even though 1987A was initially characterized by radial and time scales smaller (by a factor 5-10) than "standard" more luminous SNII. Two consequences of this understanding, which we shall focus on in this contribution, are (a) an estimate of the (frequency-dependent) location and thickness of the photosphere and (b) the only direct determination of the distance of the supernova (via the generalized Baade method). We find that the photosphere is sharp enough to allow the use of plane-parallel geometry in the calculation of the emergent continuum spectral flux, if we confine our attention to those epochs (temperature T ~ 5000-6000 K) at which hydrogen is recombining at the photosphere. We also find that the distance to this supernova is 43 ± 4 kpc. The reliability of this determination should improve when accurate spectrophotometric data for dates other than March 1 become available to us.

II. Model Photospheres

We have extended our previous calculations of radiative transfer within low-density photospheres (Hershkowitz, Linder, and Wagoner 1986; Hershkowitz and Wagoner 1987) to conditions appropriate to SN 1987a. Our only major assumption is that the photosphere is spherically symmetric and relatively sharp (steep gradient of optical depth). Although we will see that recombination does sharpen the photosphere (as expected), the possible presence of a second bright image associated with the supernova (Nisenson, Papaliolios, Karovska, and Noyes 1987; Meikle, Matcher, and Morgan 1987) might force us to eventually abandon spherical symmetry.

In addition to this geometrical assumption, our models employ the following approximations, most of which have been validated by previous calculations:

a) The velocity gradient is not strong enough to induce either an explicit time dependence of the physical conditions affecting an emerging photon or a significant violation of radiative detailed balance in the hydrogen lines. This last result, coupled with the fact that collisional excitations are negligible at these densities ($n_H \sim 10^{10} - 10^{12}$ cm^{-3}), means that the (non-LTE) level populations of hydrogen are governed solely by a balance between photoionization and direct

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recombination. This induces a cancellation which reduces the effective bound-free absorptive opacity of hydrogen.

b) The Eddington factor $f_\nu = K_\nu/J_\nu$ and the outer boundary condition on H_ν/J_ν are taken to be that of a scattering-dominated (plane-parallel) atmosphere (Mihalas 1978). The absorptive opacity is usually less than the scattering opacity, especially in the more luminous (lower density) Type II supernovae.

c) The effective continuum scattering opacity $\chi_\nu(\mathrm{sc})$ is dominated by electron scattering and by the combined effect of very many velocity-gradient broadened spectral lines [$\chi_\nu(\mathrm{bb})$]. We have used the results of Karp, Lasher, Chan, and Salpeter (1977) [incorporating 260,000 lines] to estimate this contribution to the opacity. We have fitted their full grid of frequency-binned results (kindly provided by Alan Karp) to smooth functions of mass density ρ, matter temperature T, and inverse velocity gradient $t-t_o \cong r/v$ (where t_o is the time when the mass element began freely coasting after the passage of the shock). Although this contribution of lines cannot be rigorously described by either a true opacity or emissivity, and Karp et al. (1977) assumed that the level populations were governed by LTE, we believe that the approximate equality of J_ν and B_ν at the photosphere and the above-mentioned dominance of radiative excitations allow one to use their results as a first approximation to a scattering opacity. Since their calculation employed a standard Pop. I abundance (heavy element mass fraction Z = 0.02, two to four times greater than that in the LMC) and their line list may be incomplete, as another first approximation we have rescaled their line opacity by a factor $Z_*/0.02$.

d) The continuum absorptive opacity κ_ν is dominated by hydrogen (H and H^-) bound-free and free-free processes. The constraint of statistical equilibrium allows us [using the result mentioned in (a) above] to eliminate the explicit appearance of the departure coefficients of the hydrogen level populations in the transfer equations, which results in increased numerical accuracy and stability (Hershkowitz, Linder, and Wagoner 1986).

Our set of model photospheres, as defined by the above conditions, can be essentially characterized by three free parameters (in addition to $t-t_o$), in much the same way as stellar photospheres. These are an effective temperature T_e, a scale height ΔR, and the effective abundance Z_*, defined by the relations

$$\int_0^\infty F_\nu d\nu = \sigma_R T_e^4 \, , \qquad \int_r^\infty n_H dr = n_H(r)\Delta R \, , \qquad \chi_\nu(\mathrm{bb}) \propto Z_* \, . \tag{1}$$

Here F_ν is the spectral flux and n_H is the total hydrogen number density. Although we have strictly assumed an exponential density profile $\rho(r)$, if the photosphere is sharp only the local value of $\Delta R(r)$, as defined by equation (1), is important.

In Figure 1 is shown one of the key relations which characterize the physical conditions near the photosphere for a model which we will see produces a reasonably

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good fit to the observed spectrum near the beginning of the recombination phase of SN 1987a (March 1). Plotted is the total optical depth

$$\tau_\nu = \int_r^\infty \chi_\nu dr = \int_r^\infty [\chi_\nu(sc) + \kappa_\nu]dr \qquad (2)$$

at frequencies in the infrared, visible, and near ultraviolet. Note that the n_H axis is a linear measure of radial distance. We choose to define the extent of the photosphere in the following way. Let the outer extent be the point where the flux F_ν reaches within 3% of its emergent value. Let the inner extent be the point where the mean intensity J_ν reaches within 3% of the Planck function $B_\nu(T)$.

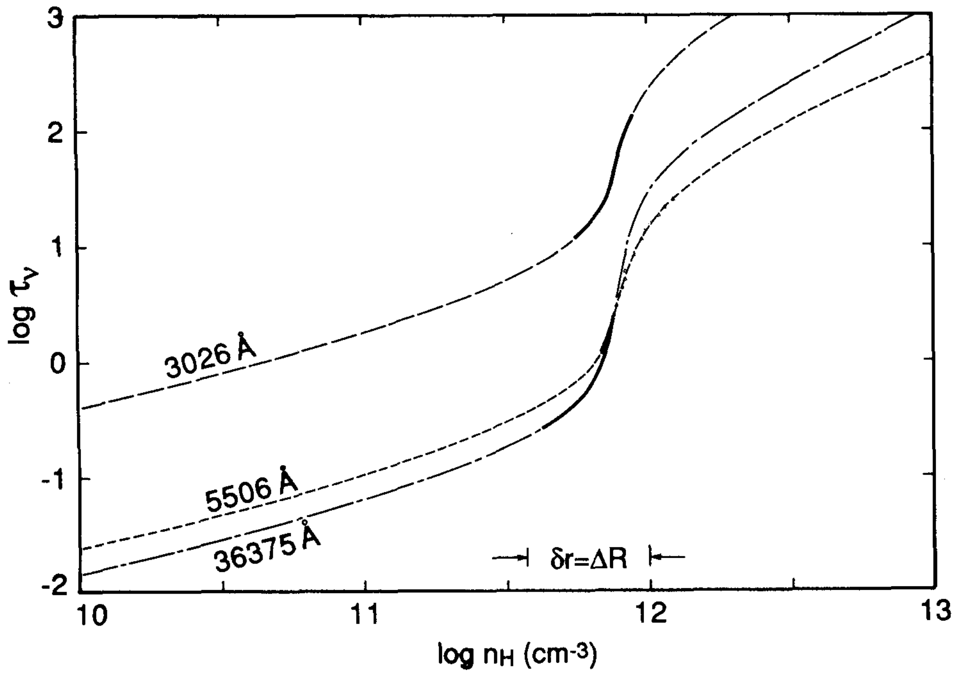

Figure 1. The total optical depth at three wavelengths is plotted versus the total hydrogen number density. The extent of the photosphere is indicated by the solid portion of the curves. A radial distance equal to the scale height is also shown. The model parameters are T_e = 5750 K, $\Delta R = 4 \times 10^{13}$ cm, $Z_* = 0.010$.

From these results, we construct Table 1, which provides a quantitative measure of the location and thickness of the photospheric region. Of special interest are the last two rows, giving the radial extent of the photosphere as a fraction of the scale height ΔR and the radius of the photosphere on March 1 (as determined in the next section to be $R_p = 4.3 \times 10^{14}$ cm).

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Table 1. Thickness of Photosphere

$\lambda(\mathring{A})$	3026	5506	36375
τ_ν(min)	11.6	1.34	0.27
τ_ν(max)	126	2.30	2.56
log n_H(min)	11.74	11.84	11.63
log n_H(max)	11.95	11.88	11.88
$\Delta r/\Delta R$	0.48	0.09	0.58
$\Delta r/\Delta R_p$	0.045	0.008	0.054

It should be pointed out that the true extent of the photosphere is given by the greatest outer radius (at the longest wavelength) and the smallest inner radius (at the shortest wavelength), giving $(\Delta r)_{max} = 0.069\ R_p$. We note, however, that the thickness of the photosphere is much less at the visible wavelengths, where most of the flux exists. In any case, these results indicate that the plane-parallel approximation is a reasonable one under these conditions of recombination. This sharpening of the photosphere is due in large part to the precipitous reduction of the electron density with temperature. The results of Höflich, Wehrse, and Shaviv (1986), which indicated that some effects of spherical extension could be important, were based on models with effective temperatures well above those of recombination.

III. Determination of Distance

The Baade method (Baade 1926; Branch and Patchett 1973; Kirshner and Kwan 1974), as generalized to objects of arbitrary redshift emitting an arbitrary continuum spectrum (Wagoner 1980, 1987) provides a powerful, relatively reliable way to directly determine the distance to any expanding (or collapsing) spherically symmetric source with a well defined photosphere. As indicated in the last section, if we restrict our attention to times t well after the time t_o when any particular shell of matter was last accelerated, the radius of the photosphere is given by

$$R_p = v_p(t-t_o) \qquad [\gg R(t_o)] \quad , \tag{3}$$

where $v_p(t)$ is the velocity of the matter at the photosphere at that particular time. The (radial) angular size θ of the photosphere is given by

$$\theta^2 = (1+z)^3\ e^{\tau_I}\ f_\nu/F_{\nu'} \quad , \tag{4}$$

where z is the source redshift, $\tau_I(\nu)$ the optical depth due to intervening matter, and f_ν the observed flux. The frequency ν' is that measured in the center-of-mass (c.m.) frame of the supernova, taken to be the same as that of the parent galaxy. The (proper motion) distance is then $D = R_p/\theta$.

The only complete (UV→IR) absolute spectrophotometry that we have thus far been able to obtain was acquired on March 1, 1987 (Kirshner et al., 1987; Bouchet et al. 1987; Danziger et al. 1987). Below we shall use that data to determine the angular size of the photosphere at that time. But first we shall determine the photospheric radius.

It is easily seen that there must be a discontinuity in slope of the P-Cygni line profiles at a frequency corresponding to the velocity of the matter at the photosphere, if the photosphere is sharp. However, as Branch (1980) has shown, this discontinuity is most easily observed if the line Sobolev optical depth $\tau_{ij} \lesssim 5$, in which case the break appears at the frequency of maximum absorption. Using the results of Blanco et al. (1987) and Phillips (1987) [assuming that the LMC velocity had been removed], we do indeed find that the weakest lines (FeII λ5018, FeII λ5169, Bγ λ21656) do give the same velocity, $v_p = (8.5 \pm 0.4) \times 10^3$ km s^{-1} for March 1.1-1.4 (UT). As expected, the velocities obtained from the frequencies of maximum absorption of the stronger lines are greater than this.

Allowing for uncertainties in the shock breakout time (relative to the neutrino burst on Feb. 23.316) and the spread of observation times, we obtain $t-t_o = 5.8 \pm 0.3$ days. From equation (3), these values then give

$$R_p = (4.26 \pm 0.3) \times 10^{14} \text{ cm} \qquad \text{(March 1.1-1.4)} \quad . \tag{5}$$

In order to obtain the angular radius from equation (4), we must first transform our emergent fluxes F_ν, calculated in the frame moving with the matter, to the c.m. frame of the supernova. [The galactic redshift correction $(1 + z)^3$ is negligible because the velocity of the LMC is 280 km s^{-1}.] Approximating the angular distribution of the emergent intensity by that of a pure scattering atmosphere, we obtain for this Doppler correction

$$\Delta \log F_\nu \cong 0.434\beta[1.732 - 0.711(d\log F_\nu/d\log \nu)] \quad , \tag{6}$$

with $\beta = v_p/c = 0.028$ for this epoch.

Next we must consider the correction for intervening absorption, τ_I. To do this, we assume that the total amount is given by $A_\nu = E_{B-V}\ \psi(\nu)$ magnitudes, with $\psi(\nu)$ the same function for our galaxy and the LMC. The existing evidence (Clayton and Martin 1985) indicates that this is not a bad approximation at the wavelengths $\lambda > 2600$ Å where appreciable flux exists during the recombination era. If we consider any two frequencies ν_* and $\nu >> \nu_*$, then the function

$$\tilde{F}(\nu,\nu_*) - \tilde{f}(\nu,\nu_*) = 0.4\ E_{B-V} \quad , \tag{7}$$

where $\tilde{Q}(\nu,\nu_*) \equiv [\log Q(\nu) - \log Q(\nu_*)]/[\psi(\nu) - \psi(\nu_*)]$, should be independent of frequency (as well as distance) for any particular source. Therefore, plotting $\tilde{F}$ - $\tilde{f}$ versus ν with fixed ν_* for various models (T_e, ΔR, Z_*) allows one to identify the best model atmosphere as that one which produces the smallest frequency dependence. The magnitude of the resulting (approximate) constant then provides the amount of absorption. We choose $\lambda_* = 5.01\ \mu m$, the longest wavelength at which data are available, since of course the intervening absorption is smallest there [$\psi(\lambda_*) = 0.07$].

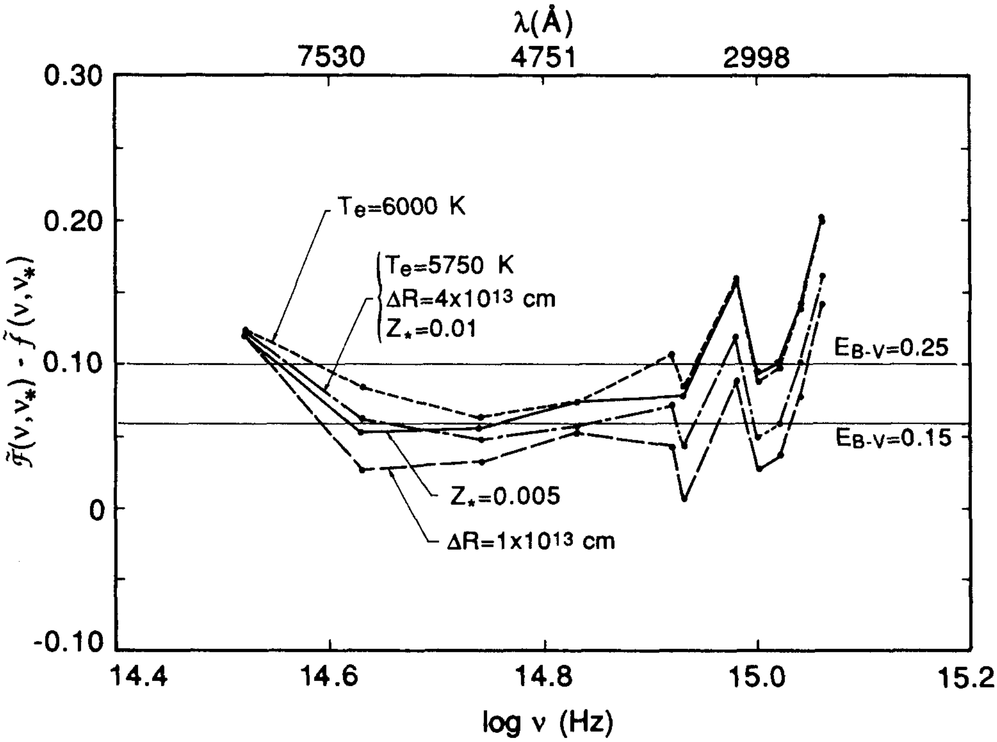

Figure 2. The absorption corrected combination of emitted and observed relative fluxes [eq. (7)] versus frequency. Lines corresponding to two choices of color excess are also shown. Results from our "fiducial model", as well as models in which only the parameter indicated has been varied, are shown.

In Figure 2 we plot the left-hand side of equation (7) at frequencies ν where the best values of the observed continuum flux are available and the denominator is large enough to be accurate. Results for our "fiducial model" (Fig. 1) and three others are shown. From these results and those for many other values of the parameters we can draw the following conclusions.

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a) The lack of an observed Pashen jump ($\lambda' = 8203$ Å) puts an upper limit on the photospheric density, corresponding to $\Delta R \gtrsim 2 \times 10^{13}$ cm. It was also found that excess UV flux was produced unless $\Delta R \lesssim 6 \times 10^{13}$ cm.

b) The UV flux was most sensitive to the parameter Z_*, since it controlled the dominant opacity at those wavelengths. It has been found that values in the range $Z_* \cong 0.01 - 0.02$ were required to reduce the UV flux sufficiently.

c) The shape of the spectrum in the visible region was most sensitive to the effective temperature. Values in the range $5600 \lesssim T_e \lesssim 5900$ K gave reasonable fits.

d) Those computed spectra which best matched the observed continuum at the wavelengths indicated (they all matched well in the infrared) were consistent with the expected amount of absorption indicated by the limiting values of E_{B-V} shown on Fig. 2.

In addition to these estimates of the allowed ranges of our parameters, we have computed the sensitivity of the flux at our normalization wavelength ($\lambda_o = 3.16$ µm) to changes in these parameters. We obtain $\partial \log F_{\nu_o} / \partial \log X = -0.03$ ($X = \Delta R$), $+0.05$ ($X = Z_*$), and $+1.7$ ($X = T_e$). Using all these results, we arrive at a value

$$\log F_{\nu_o}, (\mathrm{erg\ cm^{-2}\ s^{-1}\ Hz^{-1}}) = -4.61 \pm 0.03 \quad (\lambda_o = 3.16\ \mu\mathrm{m}) \tag{8}$$

for the Doppler-corrected emitted flux. (The Doppler correction at this wavelength is $\Delta \log F_\nu \cong +0.01$.) The spectrum of our fiducial model, absorbed by the amount indicated, is compared to the observed spectrum and a blackbody in Figure 3.

At our normalization wavelength, the absorption corresponding to $E_{B-V} = 0.18$ (Sonneborn et al. 1987) gives us a flux correction $\Delta \log f_\nu = 0.013$. We adopt a de-absorbed observed flux $\log f_{\nu_o}$ (erg cm^{-2} s^{-1} Hz^{-1}) = -21.60 ± 0.03 at $\lambda_o = 3.16$ µm, using the data plotted by Bouchet et al. (1987). We note that the calibration of their spectrophotometry is claimed to agree with their broad band infrared photometry to better than 10%. Their K photometry in turn appears to agree with that of the South African group (Menzies et al. 1987) to within 4% at this time.

This observed flux gives an angular radius

$$\log \theta = -8.495 \pm 0.02 \tag{9}$$

from equations (4) and (8). Combining this result with equation (5) then leads to the distance

$$D = 43.3 \pm 4\ \mathrm{kpc} \quad . \tag{10}$$

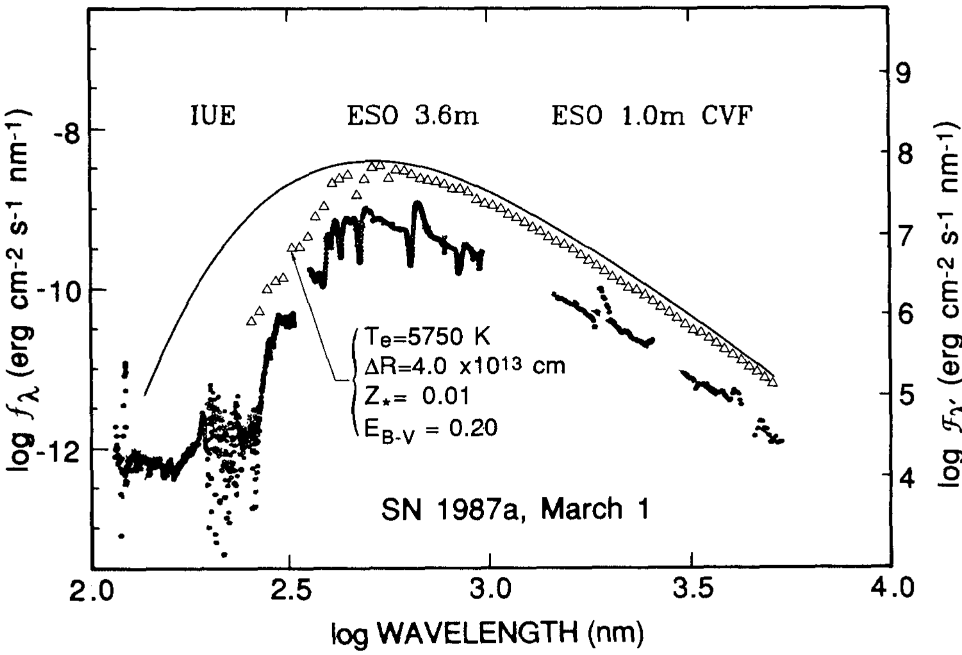

Figure 3. A composite spectrum of SN 1987a observed on March 1 (Danziger et al. 1987) is compared with one of our best-fitting (absorbed) computed spectra, corresponding to the parameters indicated. Both the theoretical spectrum (triangles) and that of an (unabsorbed) blackbody at the same effective temperature have been displaced by the same amount for clarity (see separate scales). No theoretical points are shown at wavelengths shorter than that at which the other stars dominate the flux.

Using essentially the same method, but assuming blackbody emission (in disagreement with our calculated spectra), Branch (1987) obtained a distance of 55 ± 5 kpc. This is another example of effects such as flux dilution and distortion produced by a scattering dominated photosphere (Wagoner 1981).

The distance to the LMC has been determined by various classical methods. Extensive JHK photometry of Cepheids has yielded a very recent value of 51.8 ± 1.2 kpc (Welch et al. 1987), in agreement with that obtained from optical photometry (Caldwell and Coulson 1986). However, the largest value of the distance, 58.1 ± 1.9 kpc (Visvanathan 1985), was obtained from 1.05 μm photometry of Cepheids. The use of RR Lyrae variables has given 48.3 ± 2.2 kpc (Walker 1985), while photometry of B stars has yielded 45.7 ± 4.2 kpc (Shabbrook and Visvanathan 1987). The lowest value of the distance, 43.7 ± 4.0 kpc (Schommer, Olszewski, and Aaronson 1984), was obtained from main-sequence fitting of two globular clusters; although Chiosi and Pigatto (1986) have obtained a larger distance by including convective overshooting. It should be noted that all these results refer to the mean distance of the LMC, and

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are subject to effects of the uncertain deficiency in heavy elements.

Our direct determination of the distance to the supernova, unlike these determinations of the distance to the LMC, involves no distance ladder calibrations or selection effects. In addition, the assumptions involved in this method are independently tested by a) the match between the frequency dependence of the computed and observed spectra, b) the requirement that the ratio of the two time dependent quantities (R_p and θ) that determine the distance remains constant, and c) the predicted break in the (weaker) line profiles. It is especially important that we acquire accurate data for other dates so that we can invoke test (b). We believe that the distance to any Type II supernova is most reliably determined during that period of time when the photosphere lies within the hydrogen recombination shell, because this gives a long time base with which to more accurately determine R_p as well as a sharper photosphere to more accurately determine θ.

IV. Acknowledgments

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