Supernova Resonance-scattering Profiles in the Presence of External Illumination

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ABSTRACT. We discuss a simple model for the formation of a supernova spectral line by resonance scattering in the presence of external illumination of the line-forming region. The simple model provides a clear understanding of the most conspicuous toplighting effect: a rescaling or, as we prefer, a “muting” of the line profile relative to the continuum. This effect would be present in more realistic models, but would be harder to isolate. An analytic expression for a muting factor for a P Cygni line is derived that depends on the ratio E of the toplighting specific intensity to the specific intensity from the supernova photosphere. If $E < 1$, the line profile is reduced in scale or “muted.” If $E = 1$, the line profile vanishes altogether. If $E > 1$, the line profile flips vertically: then having an absorption component near the observer-frame line-center wavelength and a blueshifted emission component.

1. INTRODUCTION

In a simple but useful model of spectral line formation during the photospheric phases of a supernova, a line forms by resonance scattering in a homologously expanding atmosphere above a sharp photosphere. An unblended line has a P Cygni profile with an emission feature near the observer-frame line-center wavelength and a blueshifted absorption. Synthetic spectra calculated on the basis of this simple model have been found to fit the observed spectra of most supernovae reasonably well and to be useful for establishing constraints on the composition structure of the ejected matter. For a detailed discussion of the model, see Jeffery & Branch (1990), who also provided an atlas of line profiles and compared synthetic spectra to numerous observed spectra of the Type II SN 1987A. Recent studies based on the simple model, using the SYNOW supernova synthetic-spectrum code, include Millard et al. (1999) on the Type Ic SN 1994I and Hatano et al. (1999) on the Type Ia SN 1994D.

In the bright Type IIn SN 1998S we have encountered an event for which the above simple model fails. The supernova SN 1998S has been observed extensively with the Hubble Space Telescope (HST) as a target of opportunity by the Supernova INtensive Study (SINS) group (Garnavich et al. 2000; Lentz et al. 2000; and Blaylock et al. 2000, all in preparation), as well as from the ground (Leonard et al. 1999). The observed spectra, especially at short wavelengths and early epochs, contain numerous narrow ($\lesssim 500$ km s$^{-1}$) absorption and emission features that formed in circumstellar matter. The optical and ultraviolet spectra also contain broad ($\sim 5000$–$10,000$ km s$^{-1}$) features that formed in the supernova ejecta. All of the broad features show little contrast with the continuum, especially at early times. It is not plausible that the radial dependence of the optical depths of all of the supernova lines should be such that the line profiles come out to be shallow, and in synthetic spectrum calculations with the SYNOW code in its simplest form we cannot account for the relative strengths of the spectral features of SN 1998S. The presence of the circumstellar features suggests that the broad supernova features were being affected by light from the region of circumstellar interaction: i.e., the line formation region was illuminated not only from below by light from the photosphere but also from above by light from the circumstellar interaction. We refer to this external illumination of the supernova line-forming region as “toplighting.”

In this paper we present a simple model of resonance-scattering line formation in the presence of toplighting. This simple model provides a clear understanding of the most conspicuous toplighting effect: a rescaling or, as we prefer to call it, a “muting” of the line profiles relative to the continuum. This effect would be present in more realistic models, but would be harder to isolate.

Section 2 presents the model. The emergent specific intensities are derived in § 3. The line profile and a muting factor are derived in § 4. In § 5, we offer a picturesque description of radiative transfer in the model atmosphere. A final discussion appears in § 6.
2. THE MODEL

Suppose that supernova line formation takes place by isotropic resonance scattering in a spherically symmetric atmosphere that has a sharp photosphere with radius \( R_{\text{ph}} \) as an inner boundary and a circumstellar-interaction region (CSIR) as an outer boundary. Assume that the CSIR is a shell of zero physical width and optical depth, and let its radius be \( R_{\text{cs}} \) (see Fig. 1): \( R_{\text{cs}} \geq R_{\text{ph}} \) in all cases, of course. For simplicity, assume that the photosphere emits an outward angle-independent specific intensity \( I_{\text{ph}} \), that the CSIR emits isotropically with specific intensity \( I_{\text{cs}} \), and that \( I_{\text{ph}} \) and \( I_{\text{cs}} \) are constant over the wavelength interval of interest. When \( I_{\text{cs}} \) is set to zero, we have what we will call the standard case. Nonzero \( I_{\text{cs}} \) gives the toplighting case.

We assume that the atmosphere is in homologous expansion. In homologous expansion the radius of a matter element \( r \) is given by

\[
r = vt ,
\]

where \( v \) is the constant radial velocity of the matter element and \( t \) is the time since explosion which is assumed sufficiently large that initial radii are negligible.

Line formation is treated by the (nonrelativistic) Sobolev method (e.g., Rybicki & Hummer 1978; Jeffery & Branch 1990; Jeffery & Vaughan 2000) in which the line profile in the emergent flux spectrum depends on the radial behavior of the Sobolev line optical depth \( \tau \) and the line source function \( S \) (which is a pure resonance scattering source function following our earlier assumption). We consider only isolated (unblended) line formation and do not include any continuous opacity in the atmosphere.

We note for homologous expansion that the resonance surfaces for observer-directed beams are planes perpendicular to the line of sight. (A resonance surface is the locus of points on which beams are Doppler shifted into resonance with a line in an atmosphere with a continuously varying velocity field.) If we take \( z \) to be the line-of-sight coordinate with the positive direction toward the observer, the resonance plane for a wavelength shift \( \Delta \lambda \) from the line-center wavelength \( \lambda_0 \) is at

\[
z = -\frac{\Delta \lambda}{\lambda_0} ct ,
\]

where \( z/t \) is the plane’s velocity in the \( z \)-direction. Blueshifts give positive \( z \)-planes and redshifts, negative \( z \)-planes.

3. THE EMERGENT SPECIFIC INTENSITIES

For resonance scattering the source function of a line is just equal to the mean intensity. In our model the line source function is

\[
S(r) = WI_{\text{ph}} + (1 - W)I_{\text{cs}} ,
\]

where \( W \) is the usual geometrical dilution factor,

\[
W = \frac{1}{2} \left[ 1 - \sqrt{1 - \left( \frac{R_{\text{ph}}}{r} \right)^2} \right]
\]

(see, e.g., Mihalas 1978, p. 120).

The first term in equation (3) accounts for radiation from the photosphere and the second, for radiation from the CSIR.

Consider a line-of-sight specific intensity beam that does not intersect the photosphere (i.e., one that has impact parameter \( p > R_{\text{ph}} \) in the standard \( p, z \) coordinate system) and that has a wavelength in the observer’s frame that differs from the line-center wavelength by \( \Delta \lambda \). In a toplighting case such a beam originates from the CSIR as shown in Figure 1. From the Sobolev method, the emergent specific intensity of such a beam can be seen to be

\[
I_{\Delta \lambda}(p > R_{\text{ph}}) = I_{\text{cs}} e^{-\tau} + [W I_{\text{ph}} + (1 - W)I_{\text{cs}}] 
\times (1 - e^{-\tau}) + I_{\text{cs}} ,
\]

where, of course, \( W \) and \( \tau \) must be evaluated at the Sobolev resonance point for the \( \Delta \lambda \) value under consideration. Similarly, the emergent specific intensity of a line-of-sight beam...
that originates from the photosphere (i.e., has \(p \leq R_{\text{ph}}\)) can be seen to be
\[
I_{\lambda \lambda}(p \leq R_{\text{ph}}) = I_{\text{ph}} e^{-\tau} + [W I_{\text{ph}} + (1 - W) I_{\text{cs}}] \\
\times (1 - e^{-\tau}) + I_{\text{cs}}. 
\] (6)

Equations (5) and (6) can be rearranged into the convenient expressions
\[
I_{\lambda \lambda}(p > R_{\text{ph}}) = (I_{\text{ph}} - I_{\text{cs}}) W(1 - e^{-\tau}) + 2 I_{\text{cs}},
\] (7)
\[
I_{\lambda \lambda}(p \leq R_{\text{ph}}) = (I_{\text{ph}} - I_{\text{cs}}) e^{-\tau} + (I_{\text{ph}} - I_{\text{cs}}) \\
\times W(1 - e^{-\tau}) + 2 I_{\text{cs}}. 
\] (8)

If \(I_{\text{cs}} = 0\), these expressions reduce to the standard- or nontoplghting-case Sobolev expressions for emergent specific intensity. If the resonance point is not in the line-forming region (i.e., it occurs at \(r < R_{\text{ph}}\) or \(r > R_{\text{cs}}\), or it is in the occulted region from which no beam can reach the observer), then \(\tau\) is just set to zero in the expressions which then reduce to the continuum expressions
\[
I_{\lambda \lambda}(p > R_{\text{ph}}) = 2 I_{\text{cs}},
\] (9)
\[
I_{\lambda \lambda}(p \leq R_{\text{ph}}) = I_{\text{ph}} + I_{\text{cs}}. 
\] (10)

The emission component of a P Cygni line is largely due to \(I_{\lambda \lambda}(p > R_{\text{ph}})\) beams and the absorption component, to \(I_{\lambda \lambda}(p \leq R_{\text{ph}})\) beams. To see how going from the standard to the toplighting case affects the components, it is best to consider equations (7) and (8). From equation (7), we see that toplighting tends to reduce the line emission by changing \(I_{\text{ph}}\) to \(I_{\text{ph}} - I_{\text{cs}}\). From equation (8), we see that toplighting tends to fill in the absorption trough (caused by the \(e^{-\tau}\) factor of the \(I_{\text{ph}} e^{-\tau}\) term) by adding a positive term to the source function. Both emission component and absorption trough are reduced relative to the continuum by the addition of continuum terms: \(2 I_{\text{cs}}\) in the first case and \(I_{\text{cs}}\) in the second. Thus we can see (at least for \(I_{\text{ph}} > I_{\text{cs}}\)) that adding toplighting to an atmosphere is likely to reduce the relative size of line components (i.e., to mute them). When \(I_{\text{ph}} = I_{\text{cs}}\), the line components should vanish altogether as comparing equations (7) and (8) and equations (9) and (10) shows. In § 4, we give a definite analytical analysis of the effect of toplighting on line profile formation and confirm the muting effect.

### 4. The Line Profile and the Muting Factor

The flux profile seen by a distant observer is obtained from
\[
F_{\lambda \lambda} = 2\pi \int_{0}^{R_{\text{cs}}} dp \, p I_{\lambda \lambda}(p),
\] (11)
where the integration is over impact parameter. (Actually, the quantity in eq. [11] divided by the square of the distance to the observer is the flux measured by the observer. But for brevity here and below we just call this quantity flux.) We can obtain semianalytic expressions for the flux in the standard and toplighting cases by breaking the integration for the flux into components. These semianalytic expressions then allow a fully analytic formula for a muting factor which describes the muting effect of toplighting.

By inspection of equations (7)–(11) with \(I_{\text{cs}} = 0\), we obtain the standard-case results for flux in the continuum and in the line. The continuum flux is
\[
F(\text{con}) = I_{\text{ph}} F_0,
\] (12)
where
\[
F_0 = \pi R_{\text{ph}}^2.
\] (13)
The line flux is
\[
F_{\lambda \lambda} = I_{\text{ph}}(F_1 + F_2),
\] (14)
where
\[
F_1 = 2\pi \int_{0}^{R_{\text{ph}}} dp \, p e^{-\tau},
\] (15)
\[
F_2 = 2\pi \int_{0}^{(R_{\text{ph}} - 2z)^{1/2}} dp \, p W(1 - e^{-\tau}).
\] (16)

Note that the \(F_1\) and \(F_2\) factors are dependent on \(z\) and therefore on wavelength. Also recall that \(\tau = 0\) for a resonance point outside of the atmosphere or in the occulted region. The contrast factor (i.e., relative difference of line flux from continuum flux) for the standard case is
\[
\frac{F_{\lambda \lambda} - F(\text{con})}{F(\text{con})} = \frac{F_1 + F_2 - F_0}{F_0}.
\] (17)

Again from equations (7)–(11), but with nonzero \(I_{\text{cs}}\), we obtain by inspection the toplighting-case results for flux in
the continuum and line. The continuum flux is

\[ F^{\text{top}}(\text{con}) = I_{ph} F_0 + I_{cs}(2G_0 - F_0) \]
\[ = (I_{ph} - I_{cs})F_0 + 2I_{cs} G_0 , \quad (18) \]

where

\[ G_0 = \pi R_{cs}^2 . \quad (19) \]

The line flux is

\[ F^{\text{top}}_{\lambda} = (I_{ph} - I_{cs})(F_1 + F_2) + 2I_{cs} G_0 . \quad (20) \]

The 2\(I_{cs} G_0\) terms in equations (18) and (20) just account for the toplighting specific intensity beams aimed toward the observer from both the near and far hemisphere of the CSIR. These beams of course can interact with the line and the photosphere, and this interaction is accounted for in the other terms. Note that \(G_0 \geq F_0\) and \(G_0 \geq F_1\), where the equalities hold only in the degenerate case where \(R_{cs} = R_{ph}\). Also note that \(G_0 \geq F_2\), where the equality holds only in the degenerate case where both coefficients are zero: i.e., \(R_{cs} = R_{ph} = 0\). From these inequalities, it is clear that \(F^{\text{top}}(\text{con})\) and \(F^{\text{top}}_{\lambda}\) can never be less than zero: a physically obvious result, of course.

The contrast factor in the toplighting case is

\[ \frac{F^{\text{top}}_{\lambda} - F^{\text{top}}(\text{con})}{F^{\text{top}}(\text{con})} = \frac{(I_{ph} - I_{cs})(F_1 + F_2 - F_0)}{(I_{ph} - I_{cs})F_0 + 2I_{cs} G_0} \]
\[ = \frac{(1 - E)(F_1 + F_2 - F_0)}{(1 - E)F_0 + 2EG_0} , \quad (21) \]

where

\[ E = \frac{I_{cs}}{I_{ph}} . \quad (22) \]

We define the muting factor \(m\) to be the ratio of the toplighting-case contrast factor to the standard-case one:

\[ m = \frac{1 - E}{1 - E + 2E(R_{cs}/R_{ph})^2} . \quad (23) \]

Since all \(F_1\) and \(F_2\) factors have canceled out, \(m\) is fully analytic and wavelength independent. The muting factor \(m\) is a monotonically decreasing function of \(E\) with a physical maximum of 1 at \(E = 0\) and with only one stationary point, a minimum at \(E = \infty\). The muting factor in fact goes to zero at \(E = 1\) and becomes negative for \(E > 1\). Thus for \(E = 1\) the P Cygni profile of a line vanishes and for \(E > 1\) the line flips: there is an absorption feature at the line-center wavelength and a blueshifted emission feature. (Note that this flipped P Cygni profile is not the same as the “inverse” P Cygni profile that would be produced by a contracting rather than an expanding line-forming region.) A picturesque way of understanding a flipped P Cygni line is given in § 5.

The minimum value of \(m\) at \(E = \infty\) is given by

\[ m(E = \infty) = \frac{1}{1 + 2(R_{cs}/R_{ph})^2} . \quad (24) \]

Note that \(m(E = \infty) \geq -1\) with the equality holding only for \(R_{cs}/R_{ph} = 1\), which is the lower limit on \(R_{cs}/R_{ph}\). Thus

\[ |m| \leq 1 . \quad (25) \]

Since the absolute value of \(m\) is always less than or equal to 1, toplighting always mutes a line profile: hence our choice of “muting” for the name of the toplighting effect on line profiles.

We can consider a couple simple examples of muting by toplighting. First, consider \(E = \frac{1}{2}\) and \(R_{cs}/R_{ph} = 2\). Note that geometrically thin supernova atmospheres have not been identified, and thus \(R_{cs}/R_{ph} \geq 2\) may be typical in real supernovae. With the given input values, \(m = \frac{1}{3}\) and the contrast factor of the line with respect to the continuum is reduced by this factor in going from a standard case to a toplighting case. The contrast factor of an absorption trough of a standard-case P Cygni line has absolute lower limit of \(-1\) (i.e., zero flux). Thus, even if this lower limit case were realized for a standard-case P Cygni line, the toplighting counterpart absorption would have absorption trough depth of only \(\frac{1}{3}\) of the continuum level.

Next consider \(E = \infty\) and \(R_{cs}/R_{ph} = 2\). Here \(m = -\frac{1}{2}\). Since \(m\) is negative, the toplighting has produced a flipped P Cygni profile. The standard-case P Cygni absorption trough would be turned into a toplighting-case emission peak with an upper limit on the contrast factor of \(\frac{1}{2}\).

Figure 2 shows examples of P Cygni files with \(E\) values that effectively span much of the \(E\) parameter range.

Since there is no upper limit on the contrast factor of a standard-case P Cygni emission peak, prima facie it seems that a negative muting factor with large absolute value could lead to negative observed flux in a corresponding toplighting-case absorption component. This does not happen of course. As we showed above, the observed flux in the toplighting case is never mathematically negative. For another point of view, consider the following argument. The standard-case P Cygni line emission peak is largest for an opaque line (i.e., one with \(\tau = \infty\) everywhere in the...
atmosphere) and large $R_{cs}/R_{ph}$. For such a line, the emission peak contrast factor can only increase with increasing $R_{cs}/R_{ph}$ as $\sim \ln (R_{cs}/R_{ph})$ ($R_{cs}$ considered here just as an outer boundary radius) (e.g., Jeffery & Branch 1990, p. 189), but the absolute value of the muting factor for large $R_{cs}/R_{ph}$ decreases for increasing $R_{cs}/R_{ph}$ like $(R_{cs}/R_{ph})^{-2}$. Thus the muting factor always scales to prevent negative observed flux from arising mathematically.

The ratio of the monochromatic luminosities of the CSIR and the photosphere (taken independently of each other) is

$$\Gamma = \frac{L_{cs}}{L_{ph}} = \frac{4\pi(2\pi R_{cs}^2 I_{cs})}{4\pi(2\pi R_{ph}^2 I_{ph})} = 2E \left( \frac{R_{cs}}{R_{ph}} \right)^2,$$  \hspace{1cm}  (26)

where the factor of 2 accounts for the fact that both hemispheres of the CSIR region contribute to flux in any given direction. The ratio $\Gamma$, in fact, appears in the denominator of the muting factor formula, equation (23). If we use equation (26) to eliminate $E$ from equation (23), we obtain

$$m = \frac{2(R_{cs}/R_{ph})^2 - \Gamma}{2(R_{cs}/R_{ph})^2 - \Gamma + 2(R_{cs}/R_{ph})^2 \Gamma}.$$  \hspace{1cm}  (27)

Now $m$ as a function of $\Gamma$ monotonically decreases with $\Gamma$ from $m = 1$ at $\Gamma = 0$ to a minimum $m = -1/[1 + 2(R_{cs}/R_{ph})^2]$ at $\Gamma = \infty$ (the only stationary point). It is clear that $\Gamma$ will have to be large in some sense in order to obtain strong muting. For the sake of definiteness say $m \leq \frac{1}{2}$ is "strong" muting. Then

$$\Gamma \geq \Gamma \left( m = \frac{1}{2} \right) = \frac{2(R_{cs}/R_{ph})^2}{2(R_{cs}/R_{ph})^2 + 1}.$$  \hspace{1cm}  (28)

is required for strong muting. Since $R_{cs}/R_{ph} \geq 1$ is required physically, a necessary, but not sufficient, condition for strong muting is $\Gamma \geq \frac{1}{2}$. If, as suggested above, $R_{cs}/R_{ph} \geq 2$ for supernovae, then a necessary, but not sufficient, condition for strong muting in supernovae is $\Gamma \gtrsim \frac{8}{9}$. Consequently, only those supernovae whose monochromatic luminosities are strongly enhanced by circumstellar interaction will have line profiles that are strongly muted by toplighting.

### 5. Picturesque Description

To complement the mathematical description of the radiative transfer in the standard and toplighting cases of our simple model, we present here a picturesque description.

First consider the standard case. We use $R_{cs}$ just as an outer boundary of the atmosphere in this case. If no line is present, the photons emitted by the photosphere just escape to infinity and the flux in any direction is just $I_{ph} F_{0}$: this is the continuum emission. Adding a resonance-scattering line to the atmosphere has the overall effect of reducing the wavelength-integrated emission of the supernova in the wavelength interval that the line can affect. This interval is $(\lambda_0 + \Delta \lambda_{\text{max}}, \lambda_0 + \Delta \lambda_{\text{min}})$, where

$$\Delta \lambda_{\text{min}} = -\lambda_0 \frac{R_{cs}}{ct}, \quad \Delta \lambda_{\text{max}} = \lambda_0 \frac{\sqrt{R_{cs}^2 - R_{ph}^2}}{ct}.$$  \hspace{1cm}  (29)

The reason for the loss in wavelength-integrated emission is that the line, scattering isotropically, will scatter some photons back to the photosphere where in our simple model they are simply absorbed. In a more realistic model, the photons absorbed by the photosphere are a feedback that helps determine the photospheric state. The particular observer-directed photons which are absorbed are those scattered toward the observer in the occulted region: they simply hit the photosphere as they head toward the observer.

Because of the homologous expansion, photons continuously redshift in the comoving frame of the atmosphere. Thus, photons emitted by the photosphere at or redward of $\lambda_0$ escape the atmosphere without scattering. (Note formally they can scatter at $\lambda_0$ at the point of emission on the photosphere, but this effect is assumed accounted for in specifying $I_{ph}$, the constant photospheric specific intensity.) Thus the line scatters photons that before scattering were blueward of $\lambda_0$ in observer-frame wavelength. The line scattering does not change a photon’s comoving-frame wavelength (not at all in our simple model and not significantly in reality), but by changing its propagation direction relative to the matter flow it does change its observer-frame wavelength. Consider photons scattered toward a distant observer. If the scattering occurs from matter moving away from, mainly perpendicular to, or toward the observer, then

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the scattered photons in the observer frame have wavelengths redward of \( \lambda_0 \), near \( \lambda_0 \), or blueward of \( \lambda_0 \), respectively.

From the preceding remarks, it is clear that the observer receives all the photons emitted by the photosphere into the line of sight at and redward of \( \lambda_0 \) plus the unscattered photons from blueward of \( \lambda_0 \). In addition there are photons scattered into the line of sight by the line from the whole wavelength interval \((\lambda_0 + \Delta\lambda_{\text{min}}, \lambda + \Delta\lambda_{\text{max}})\). The scattering component is strongest near \( \lambda_0 \), while the resonance planes for scattering are largest and they come closest to (and even touch) the photosphere where the source function and usually the scattering opacity are largest. (Because of the nature of homologous expansion, all the photons scattered toward the observer from a plane perpendicular to the line of sight have the same observer-frame wavelength: see § 2.) These planes are near \( z = 0 \). The scattering component grows progressively weaker as one moves away from near \( \lambda_0 \): i.e., as the resonance planes get farther from \( z = 0 \). This scattering behavior results in the P Cygni profile emission feature with its peak near \( \lambda_0 \).

The scattering of photons out of the line of sight from blueward of \( \lambda_0 \) causes a flux deficiency relative to the continuum: this is the P Cygni profile blueshifted absorption. As we argued above, the wavelength-integrated emission in the wavelength interval \((\lambda_0 + \Delta\lambda_{\text{min}}, \lambda + \Delta\lambda_{\text{max}})\) is less than in the line's absence. Consequently, the P Cygni absorption feature will be larger than the P Cygni emission feature. (This ratio of feature size is not necessarily obtained if the line is not a pure resonance scattering line.)

Now consider the toplighting case. First, imagine that there is no photosphere or line; there is just the radiating, optically transparent, spherical shell CSIR. The flux in any direction is \( 2I_{cs}G_0 \) at all wavelengths. Now add a line to the atmosphere enclosed by the CSIR. The line has, in fact, no effect on the flux emission. The comoving-frame radiation field at the line-center wavelength at any point inside the atmosphere is isotropic. The line scattering is isotropic. In the comoving frame, an isotropic field isotropically scattered is unchanged. Since the comoving-frame radiation field is unchanged, the observer-frame radiation field is also unchanged.

Now remove the line, but add a nonemitting (but, of course, opaque) photosphere. The flux in all directions at all wavelengths is now \( I_{cs}(2G_0 - F_0) \). The photosphere just acts as a net absorber. But if one now adds a line, the line will scatter some photons directed toward the photosphere into directions leading to escape.

The result is that the wavelength-integrated flux in the wavelength interval \((\lambda_0 + \Delta\lambda_{\text{min}}, \lambda + \Delta\lambda_{\text{max}})\) is increased by the addition of the line.

Again one has to consider how the line scattering shifts the observer-frame wavelength. The nonemitting photosphere causes there to be a “cone of emptiness” in the radiation field converging at any point in the atmosphere. This reduces the line source function at every point in the atmosphere from the no-photosphere case. Thus, observer-directed beams in the limb region of the atmosphere that interact with the line must be reduced from the no-photosphere case. The closer the resonance point for a beam is to the \( z = 0 \) location, the greater the effect of the “cone of emptiness,” and the weaker the emergent beam will be. Beams that do not interact with the line will be unchanged from the no-photosphere case. The upshot is that centered on \( \lambda_0 \) there will be flux deficit relative to the continuum: an absorption feature around the line-center wavelength.

On the other hand, beams from the photodisk region (i.e., the nonlimb part of the atmosphere on the near side of the photosphere) are enhanced by the line scattering. Without the line, the photodisk specific intensity is just \( I_{cs} \) from the near hemisphere of the CSIR; the beams from the far hemisphere of the CSIR are occulted by the photosphere. But with the line there is scattering into the line of sight in the photodisk region. Consequently, there is an enhancement in flux over the continuum: i.e., a flux emission feature. Since the photodisk region is moving toward the observer this flux emission feature is blueshifted from \( \lambda_0 \).

One thus finds that toplighting with a nonemitting photosphere gives rise to a flipped P Cygni line with a blueshifted emission and an absorption centered near the line-center wavelength. From the argument about wavelength-integrated flux above, we see that the blueshifted emission must be larger than the absorption trough centered near line-center wavelength.

In a general toplighting case the photosphere emits, and so there is a competition between P Cygni and flipped P Cygni line formation. Clearly in most supernovae the competition is won by P Cygni line formation. For flipped P Cygni line formation to win, \( E = I_{cs}/I_{ph} \) must be greater than 1 (see § 4).

6. DISCUSSION

The treatment of toplighting in supernova resonance-scattering line formation has been presented here in its simplest form for its heuristic value. For example, we have not discussed how the toplighting might change the radial dependence of the line optical depth \( \tau(r) \), and we have not considered the possibility that the CSIR reflects supernova light back into the line forming region. The toplighting version of the SYNOW code that we (Blaylock et al. 2000, in preparation) are using to analyze the spectra of SN 1998S allows for an angular dependence of the radiation from an optically thin circumstellar shell and for a wavelength dependence of the photospheric and CSIR specific intensities. Including toplighting allows us to obtain improved fits to the observed spectra of SN 1998S and shows that
some of the P Cygni line profiles in the early-time SN 1998S may be flipped. (It is not easy to be sure of the flipped profiles because of the numerous superimposed circumstellar features.) Lentz et al. (2000, in preparation) find that allowing for toplighting in detailed non-LTE calculations also leads to improved fits.

Among core-collapse events, SN 1998S has been uniquely well observed at ultraviolet wavelengths, but physically it is not an exceptional case. Line profiles in other circumstellar-interacting core-collapse events presumably also are affected by toplighting. But as we showed in § 4, only those supernovae whose monochromatic luminosities are strongly enhanced by circumstellar interaction will have line profiles that are strongly muted by toplighting.

Examples of supernovae with relatively strong circumstellar interaction (as known from relatively strong radio emission) are SN 1979C, SN 1980K, and SN 1993J. All these supernovae showed rather featureless UV spectra in the ~1800–2900 Å region in comparison to supernovae known not to have had strong circumstellar interaction (Jeffery et al. 1994). Perhaps a UV-peaked toplighting continuum was muting the UV spectra of SN 1979C, SN 1980K, and SN 1993J.

Spectropolarimetry and nebular-phase line profiles indicate that SN 1998S and its circumstellar shell were not spherically symmetric (Leonard et al. 1999) as has been assumed here, and core-collapse events in general appear to be asymmetric (Wang, Wheeler, & Chocchiatti 1996). Eventually, asymmetric toplighting will have to be taken into account in spectrum calculations.

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