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Contribution of accretion to the soft X-rays from SN 1987A at the later phase

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Abstract. Based on the accretion model presented in our previous paper (Wu et al. 1998), which gives a satisfactory explanation for the evolution of the bolometric luminosity of SN 1987A in a later phase, we infer that the observed soft X-ray flux also originates from the accretion of the central neutron star. The result of the model calculations is in good agreement with the observed X-ray light curve of SN 1987A. Our calculations show the long-term behavior of the X-ray flux which increases with time until age $t \sim 4100d$, and thenceforth begins to decline slowly.

Key words: accretion, accretion disks – supernovae: individual: SN 1987A – stars: neutron – X-rays: star – radiation mechanisms: thermal

1. Introduction

In our previous work (Wu et al. 1998, Paper I hereafter), we successfully explained the observed evolution of the bolometric luminosity of SN 1987A in the later phase by use of the accretion of the assumed central neutron star. In Paper I, we have postulated a continuous gravitational infall of material within the expansion envelope, and presented the observational evidence. This is an extended accretion process, which is important for the evolution of the bolometric and X-ray luminosity at a later phase of SN1987A. It differs in certain important aspects from the previous accretion model by Chevalier (1989, 1991); for a detailed discussion see Sect. 2 of Paper I). The fit to the observations is extremely good, which indicates that the dominant energy source of radiation in the later phase is accretion, rather than radioactive decay. Besides, the good fit supports the assumption of the existence of a central neutron star.

From this model we draw an important inference: The radiation in the soft X-ray band will be detectable at a later phase of SN 1987A and increase with age during a long period. The reasoning is as follows: Most of the accretion energy is released in a narrow region very close to the surface of the neutron star, where the accreted gas must be hot plasma in thermal equilibrium and dense enough to be optically thick over a wide range of accretion rates. The radiation from the optically thick gas in thermal equilibrium has a blackbody spectrum. Therefore the accretion luminosity can be expressed as $_{acc.} \approx 4\pi r_\star^2 \sigma T_{bb}^4$ ($r_\star$ is the radius of the neutron star and T_{bb} is the blackbody temperature). The observed luminosity in the later phase is in the range of $10^{37} - 10^{38}\mathrm{erg/s}$ (Bouchet et al. 1996), hence the blackbody temperature T_{bb} can be estimated as about $10^7\mathrm{K}$ and accordingly the average energy of emitted photons is around 1keV, which is just in the soft X-ray waveband. Therefore, if the suggested accretion model given in Paper I is reasonable, we would inevitably conclude that there exists an X-ray point source —- the central neutron star. The observational verification of the existence of the X-ray point-like source would provide convincing support to our accretion model. However, it will be impossible to detect the point source for a very long time from direct observations. According to our knowledge of SN 1987A (e.g. 10HM and 10HMM models, Pinto & Woosley 1988a, 1988b), such a neutron star will be surrounded by an expanding envelope with a nearly uniform distribution of matter, and there is no obvious cavity at the center of the envelope. The optical depth τ_x for X-ray is much larger than 1, $\tau_x >> 1$ (McCray 1993). Therefore the X-ray flux from the central point source, when passing through the opaque envelope, will be absorbed and ionize the gas. In this case, it seems to be more plausible that, under the strong illumination of the soft X-ray radiation from the central neutron star, there will be a spherical region with highly ionized gas with temperature T_s as high as T_{bb} (see Sect. 2). Such a sphere with hot plasma will be a re-emission region of soft X-rays with a bremsstrahlung spectrum because the highly ionized hot plasma with much lower density must be optically thin to X-rays, and can still be treated approximately as a central point-like soft X-ray source due to its very small radius compared to that of the whole envelope. With the rarefaction of the expanding envelope, the X-ray absorbing optical depth τ_x will decrease gradually to make it more transparent to the central X-ray source. Therefore we expect that, despite the slow decrease of the total accretion luminosity, the soft X-ray flux will continuously increase with time as $\propto e^{-\tau_x} = e^{-\tau_1 t^{-2}}$. Here $\tau_x = \tau_1 t^{-2}$ is the absorption optical depth of the expanding envelope to the central point-like source, t is the age of SN 1987A in year, and τ_1 is the optical depth at $t = 1\mathrm{yr}$.

In brief, according to our accreting model, the emergence of the soft X-ray flux from the central point-like source (the

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high ionization spherical region) at a later stage of SN 1987A is inevitable. Such an ionization region is formed by the radiation from the central accreting neutron star. In a certain period, the X-ray luminosity will increase with age in a definite manner.

Our theoretical predictions are consistent with the present observations. In this paper, we attempt to use the same accretion model given in Paper I, and combine it with the 10HMM model (Pinto & Woosley 1988b), to calculate the X-ray light curve in the later stage of SN 1987A, and compare it with the observations (Hasinger et al. 1996). Undoubtedly, a successful fitting would display the advantage of our accretion model: two observational facts which seem to be independent to each other (the decrease of the bolometric luminosity and the marked increase of the soft X-ray flux with time), can be explained satisfactorily by the use of the same accretion model. This is the main feature that distinguishes our model from other shock heating models for X-rays (Chevalier 1982, Beuermann et al. 1994, Gorenstein et al. 1994, Suzuki et al. 1993, Masai & Nomoto 1994, Luo et al. 1994, Chevalier & Dwarkadas 1995).

In Sect. 2, we determine the plasma temperature T_s of the high ionization sphere and the time evolution $T_s(t)$ by use of the calculated accretion light curve $L_{acc.}(t)$ given in Paper I. T_s is an important parameter for the calculation of the bremsstrahlung luminosity L_s of the central plasma sphere. Next we calculate the X-ray optical depth $\tau_\nu(t)$. Finally, combining the calculated $T_s(t)$ and $\tau_\nu(t)$, we obtained the basic formula for the evolution curve of the emergent X-ray luminosity $L_X(t)$ in the ROSAT observational band (0.5-2)keV. In Sect. 3, we present the model calculations for the X-ray light curve and compare it with the observations. Finally, in Setc .4, we give some conclusions and discussion.

2. Model calculation

2.1. *Formation of ionization sphere, temperature T_s and luminosity L_s*

As mentioned above, because the optical depth of X-ray absorption of the cold envelope $\tau_x >> 1$ for a very long time. The blackbody radiation from the central neutron star will cause a spherical ionization region around the neutron star to be formed. The sphere is filled with fully ionized hot plasma and will be a region of the secondary emission of soft X-rays with a bremsstrahlung spectrum because the fully ionized hot plasma is optically thin for X-rays and the dominant mechanism is the bremsstrahlung radiation. For a steady ionization region, from considerations of energy conservation, we infer that the emergent bremsstrahlung luminosity from the ionization sphere L_s should equal the original blackbody luminosity L_{acc}, $L_s = L_{acc.}$. Obviously, the expected spectrum of the emergent X-ray flux, when passing through the optically thick envelope, must be a modified bremsstrahlung spectrum due to the absorption effect of the envelope. This is consistent with present observations (Hasinger et al. 1996). We notice that, during a relatively long time, the ionization sphere (the re-emission region) is very much smaller than the envelope, and can still be regarded approximately as a point-like source. For this purpose, we roughly estimate the order of the radius R_s of the sphere as follows: if we are only interested in the upper limit of R_s, all the heavy elements, including the helium new born in the explosive nucleosynthesis, can be neglected in the ionization-recombination equilibrium consideration. The ionization sphere can be regarded as a pure HII region. Then the upper limit of R_s can be estimated from the simplified ionization-recombination equilibrium equation for hydrogen:

$$\frac{4\pi}{3}R_s^3\alpha_H N^2 = S \tag{1}$$

where α_H is the recombination rate coefficient of hydrogen, $N = N_+ = N_- = N_e$ is the number density of hydrogen ions in the sphere. S is the emission rate of the photoionization photons from the central X-ray point source (number of ionization photons per second), which can be estimated as $S \approx \frac{L_{acc.}}{h\bar{\nu}}$ (photon number/sec), where $h\bar{\nu}$ is the average energy of the photoionization photons. The calculated accretion luminosity curve $L_{acc.}(t)$ of SN 1987A is given in Paper I, from which $h\bar{\nu}$ can also be deduced. According to the 10HMM model (Pinto et al. 1988b), we get the hydrogen number density N as a function of time. We obtain tha upper limit of R_s from Eq. (1), and find that R_s is much smaller than the radius R of the envelope, $R_s << R$ in a very long period. If the contributions of heavy elements and of helium are all taken into account, the estimated value of R_s is even smaller. So the ionization sphere can still be approximately regarded as a point-like X-ray source, which is very convenient in the calculation of the emergent X-ray luminosity as shown in the following derivations (Sect. 2.2).

The plasma temperature T_s of the spherical ionization region can be obtained as follows: for an incident photon from the central accreting neutron star, passing through the ionization sphere, the average energy loss of the photon in each collision with the thermal electron can be expressed as (Rybicki & Lightman 1979):

$$\frac{\overline{\Delta\varepsilon}}{\overline{\varepsilon}} = \frac{4kT_s - \overline{\varepsilon}}{m_0c^2} \tag{2}$$

Before escaping from the sphere, the photon will reach the "saturated scattering" (the comptonization process stops). Eventually we have $\overline{\Delta\varepsilon} = 0$, and the average energy of the photon will be $\overline{\varepsilon_f} = 4kT_s$. On the other hand, the average energy of the original photon from the accreting neutron star can be derived from the Planck formula for the blackbody radiation as $\overline{\varepsilon_i} = h\bar{\nu} \approx 3.83kT_{bb}$. According to the conservation of the number of photons in the scattering process and the conservation of energy for the steady ionization sphere, the average energy of photon passing through the sphere is invariant, $\overline{\varepsilon_f} = \overline{\varepsilon_i}$, therefore we get

$$T_s \approx 0.96T_{bb} \approx T_{bb} \tag{3}$$

Eq. (3) shows that the plasma temperature T_s of the ionization region is nearly the same as the original blackbody temperature T_{bb} of the accreting neutron star. In Sect. 1 we have pointed out that $kT_{bb} \approx 1$keV, thus $kT_s \approx 1$keV. Therefore the high energy

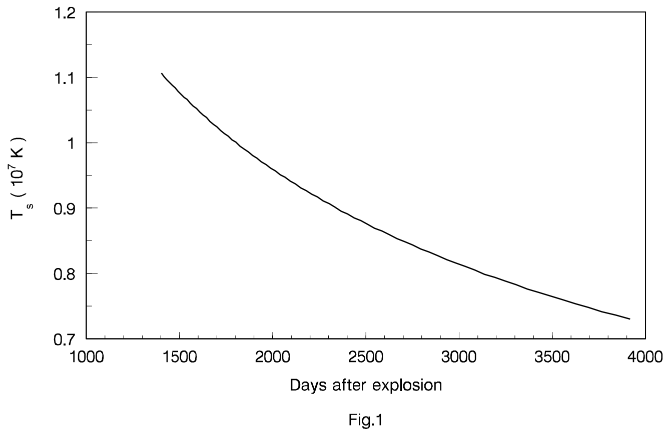

Fig. 1. Time evolution of the temperature $T_s(t)$ of the full ionized sphere

section of the bremsstrahlung spectrum reaches the soft X-ray waveband.

The plasma temperature T_s can be obtained by use of the formula $L_{acc.} \approx 4\pi r_*^2 \sigma T_{bb}^4$ and the calculated accretion light curve $L_{acc}(t)$ given in Paper I. The calculated $T_s(t)$ evolution curve is shown in Fig. 1. T_s is an important parameter in the calculation of the bremsstrahlung luminosity.

From the given values of R_s and T_s, we obtain the spectral luminosity of the thermal bremsstrahlung radiation from the ionization sphere as follows:

$$\begin{aligned} L_s(\nu, T_s) &= (\frac{4\pi}{3} R_s^3) j_{ff}(\nu, T_s) \\ &= (\frac{4\pi}{3} R_s^3) \times \\ &\times \ (6.8 \times 10^{-38} S T_s^{-\frac{1}{2}} \overline{g}_{ff}(\nu, T_s) e^{-\frac{h\nu}{kT_s}}) \end{aligned} \quad (4)$$

where $S = \sum_z N_e N_z Z^2$ (Rybicki & Lightman 1979). Eq. (4) shows that the spectrum of the bremsstrahlung radiation has the form $L_s(\nu, T_s) \propto \overline{g}_{ff}(\nu, T_s) e^{-\frac{h\nu}{kT_s}}$. We have pointed out that, from a consideration of energy conservation, the total bremsstrahlung luminosity L_s from the sphere equals the accretion luminosity L_{acc} of the central neutron star, i.e.

$$L_s \equiv \int_0^\infty L_s(\nu, T_s) d\nu = L_{acc.}(t) \quad (5)$$

So we can rewrite Eq. (4) in the following form:

$$L_s(\nu, T_s) = \frac{L_{acc.}(t) \overline{g}_{ff}(\nu, T_s) e^{-\frac{h\nu}{kT_s}}}{\int_0^\infty \overline{g}_{ff}(\nu, T_s) e^{-\frac{h\nu}{kT_s}} d\nu} \quad (6)$$

Hereafter we will use Eq. (6) to replace Eq. (4). The advantage of Eq. (6) is obvious, the uncertain R_s value no longer occurs and the new quantity $L_{acc.}(t)$ is already given in Paper I. Compared to Eq. (4), Eq. (6) is much simpler in the practical calculation.

2.2. The optical depth of the photoelectric absorption τ_ν of the envelope

$L_s(\nu, T_s)$ given in Eq. (6) is not the final emergent luminosity when the radiation passes through and escapes from the envelope, because radiative transfer has not been taken into consideration. Therefore it is necessary to calculate the absorption thickness τ_ν of the envelope to the central point source. For this purpose, we need a knowledge of the chemical composition of the gas and the abundance ratios, the spatial distribution of the gas, the size of the envelope, etc. At first glance, it seems easy to complete this calculation by use of the 10HMM model. But we emphasize that the abundance of various elements given in 10HMM model can not be used for this purpose, because most of the heavy elements in SN 1987A are produced in the explosive nucleosynthesis. From the observations it is inferred that these newborn heavy species are distributed throughout the envelope in a lumpy fashion (stirred, not homogenized). The lumpy distribution permits more soft X-rays to emerge. So far we have little knowledge about the clumpiness of the heavy elements (absorber). Despite the persistent debate about this question (e.g. Li et al. 1993, Müller et al. 1991), some authors believe that the filling factor of the clumps that consist of heavy elements is much less than 1 (Kumagai et al. 1989, Li & McCray 1993, Spyromilio & Pinto 1991), $f_v << 1$. If this estimate of the f_v-value is correct, a large fraction of the X-ray flux from the central source will miss absorption by the clumps of the heavy elements and easily penetrate the envelope. Thus the influence of the absorption clumps on the emergent X-ray luminosity can be simply attributed to the geometrical "covering effect". Therefore in the following calculation of the optical thickness, only the absorption of the primitive light elements H and He is taken into consideration. The newly formed helium in the explosive nucleosynthesis is also distributed in a lumpy fashion, and can therefore also be disregarded in the calculations of the absorption depth. According to the 14E1 model, the primitive abundance ratio of H and He of the expanding envelope is about 10 to 1 (Hashimoto et al. 1989). Therefore, the optical thickness of the envelope to the central X-ray source can be written as

$$\begin{aligned} \tau_\nu &= N_H \sigma_H(\nu) R + N_{He} \sigma_{He}(\nu) R \\ &\approx N_H R(\sigma_H(\nu) + 0.1 \sigma_{He}(\nu)) \end{aligned} \quad (7)$$

where $R = V_{max} t$ is the radius of the cold envelope, and the maxim expanding velocity $V_{max} \approx 2500 \mathrm{km/sec}$ in the 10HMM model. For the homologous free expansion, $N_H(t_y) = N_{H1} t_y^{-3}$ is the number density of hydrogen at age t_y (t_y is the age in years). N_{H1} is the hydrogen density at age $t_y = 1$, which is given by the 10HMM model (Pinto et al. 1988b). $\sigma_H(\nu)$ and $\sigma_{He}(\nu)$ represent the photoelectric absorption cross section of hydrogen and helium respectively (Robert & Steven 1979). Denoting the column density of hydrogen of the envelope at age t_y as $N(t_y) \equiv N_H R \equiv N_1 t_y^{-2}$, where N_1 is the column density at $t_y = 1\mathrm{yr}$. Then the optical thickness τ_ν can be rewritten as

$$\tau_\nu = N_1 t_y^{-2} (\sigma_H(\nu) + 0.1 \sigma_{He}(\nu)) \quad (8)$$

2.3. The emergent luminosity $L_X(t)$

Combining Eq. (6) and Eq. (8), we obtain the emergent spectral luminosity from the envelope as

$$L_\nu^{out} = L_s(\nu, T_s)e^{-\tau_\nu} = \frac{L_{acc.}(t)\overline{g}_{ff}(\nu, T_s)e^{-\frac{h\nu}{kT_s}}}{\int_0^\infty \overline{g}_{ff}(\nu, T_s)e^{-\frac{h\nu}{kT_s}}d\nu} e^{-N_1 t_y^{-2}(\sigma_H + 0.1\sigma_{He})} \quad (9)$$

The observation band of ROSAT is $(0.5-2)\mathrm{keV}$ (Hasinger et al. 1996). In order to compare it with observations, Eq. (9) should be integrated in the energy range of $(0.5-2)\mathrm{keV}$. Then we get:

$$L_{0.5-2\mathrm{keV}}^{out} = \frac{L_{acc.}(t)}{\int_0^\infty \overline{g}_{ff}(\varepsilon, T_s)e^{-\frac{\varepsilon}{kT_s}}d\varepsilon} \times \int_{0.5keV}^{2keV} \overline{g}_{ff}(\varepsilon, T_s)e^{-\frac{\varepsilon}{kT_s}} e^{-N_1 t_y^{-2}(\sigma_H + 0.1\sigma_{He})} d\varepsilon \quad (10)$$

where $\varepsilon = h\nu$.

However, we emphasize that Eq. (10) still does not represent the real emergent X-ray luminosity because so far the absorption of heavy elements in clumps has not been taken into consideration. Since the photoelectric absorption cross sections of heavy elements are very much larger than that of hydrogen, the incident X-rays from the central sphere to the surface of the clumps are totally absorbed. Therefore the absorption of the clumps can be simply described as a geometrical "covering effect". Denoting the covering factor as f_c which is an adjustable parameter in our model (f_c is defined as the ratio of the total cross section area of all the clumps to the surface area of the spherical envelope). Therefore the transparency is $(1 - f_c)$ and the real emergent luminosity in band $(0.5 - 2)\mathrm{keV}$ is given as:

$$L_X(t) = L_{0.5-2\mathrm{keV}}^{out} = \frac{L_{acc.}(t)(1 - f_c)}{\int_0^\infty \overline{g}_{ff}(\varepsilon, T_s)e^{-\frac{\varepsilon}{kT_s}}d\varepsilon} \times \int_{0.5keV}^{2keV} \overline{g}_{ff}(\varepsilon, T_s)e^{-\frac{\varepsilon}{kT_s}} e^{-N_1 t_y^{-2}(\sigma_H + 0.1\sigma_{He})} d\varepsilon \quad (11)$$

The absorption of heavy elements is simply represented by a geometrical factor $(1 - f_c)$, which also implies that we neglect the absorption of the traces of heavy elements which diffuse from clumps into the envelope.

3. Fitting with observations

Because the clumps are in synchronized expansion with the whole envelope due to the requirement of pressure balance, the adjustable parameter f_c, the covering factor, would be a time-independent constant in the free expansion. The accretion light curve $L_{acc.}(t)$, hence the evolution of temperature $T_s(t)$ has been given in Paper I. From Eq. (11) we see that another quantity which affects the time-behavior of the X-ray emergent luminosity $L_X(t)$ in band $(0.5 - 2)\mathrm{keV}$ is the column density of hydrogen N_1 at $t = 1$. N_1 is also given by the 10HMM model. The average value is estimated at about $10^{25}/\mathrm{cm}^2$. In this paper, we take N_1 as a parameter finely adjusted in a narrow range around $10^{25}/\mathrm{cm}^2$. We adjust the values of N_1 and f_c in the range of $0.5 \times 10^{25}/\mathrm{cm}^2 < N_1 < 1.5 \times 10^{25}/\mathrm{cm}^2$ and $0.1 < f_c < 0.4$, respectively. The fitting to the ROSAT observation data, which is obtained with values $N_1 = 8.0 \times 10^{24}/\mathrm{cm}^2$ and $f_c = 0.2$, is shown in Fig. 2. The solid points and the open points correspond to luminosities which are obtained from the count rates obtained by PSPC and HRI respectively, according to the conversion relationship given by Hasinger et al. (1996). The total accretion light curve $L_{acc.}(t)$ given in our previous paper is also present in Fig. 2 for comparison with the X-ray light curve.

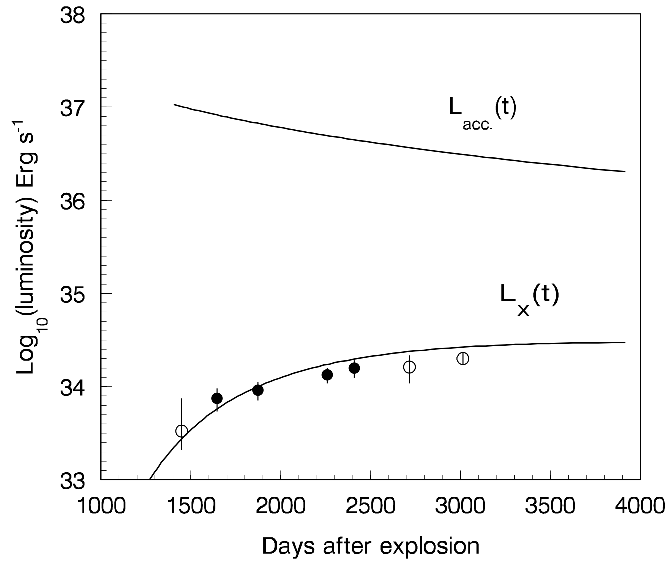

Fig. 2. The fitting of the theoretical 0.5-2keV X-ray light curve $L_X(t)$ (here taking $N_1 = 8.0 \times 10^{24}/\mathrm{cm}^2$ and $f_c = 0.2$) with the observation (the filled circles and the open circles represent the X-ray luminosity which is converted from observed counts given by Hasinger et al. (1996) according their converting relationship). The accretion light curve $L_{acc.}(t)$ (Wu et al. 1998) is also presented.

Therefore, although both the bolometric and the X-ray radiation originate from the same accretion mechanism, their time-evolution behavior is totally different. Here we would like to mention that the shape of calculated X-ray light curve in Fig. 2 is f_c-independent, only decided by the parameter N_1.

4. Conclusions and discussion

(1) We have presented a good fit to the observed bolometric light curve in the later phase as well as the observed small bump around day 1050 by use of the accretion model of the central neutron star in Paper I. In this paper, we suggest that the dominant energy source of the observed X-ray flux at a later phase is still the accretion of the central neutron star. Therefore, our model succeeds in explaining two observational phenomena which seem to be independent to each other by the same accretion mechanism.

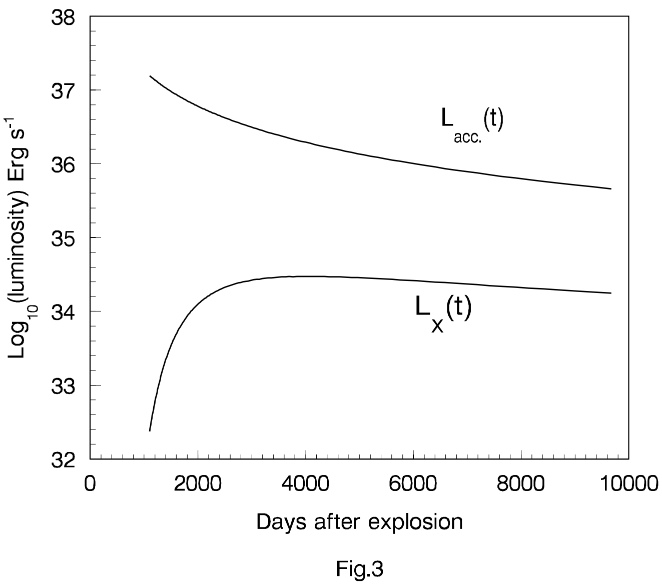

Fig. 3. Time evolution of the theoretical 0.5-2keV X-ray light curve $L_X(t)$ (taking $n_1 = 8.0 \times 10^{24}/\mathrm{cm}^2$ and $f_c = 0.2$).

(2) In this paper, we use the same accretion model as in Paper I, with one additional assumption: the compact clumpyness of the newly formed heavy elements and helium, both the filling factor f_v and the covering factor f_c are small. So the absorption by heavy elements of the X-rays from the central point-like source can be simply treated as a geometrical "covering effect". The successful fit with the observations in this paper seems to be favourable to this assumption.

(3) Concering the origin of the X-ray emission, so far most of authors prefer the shock heating mechanism (Chevalier 1982, Beuermann et al. 1994, Gorenstein et al. 1994, Suzuki et al. 1993, Masai & Nomoto 1994, Luo et al. 1994, Chevalier & Dwarkadas 1995, Nomoto & Suzuki 1997). In their opinion, the observed X-ray flux is the thermal radiation produced by the shock interactions when the fast expanding envelope sweeps up the remnant material of the blue supergiant wind inside the ring of SN 1987A. Masai & Nomoto presented a model calculation (1994) and predicted that the fast ejecta will finally hit the ring nebula in AD 2003 to give rise to a drastic increase of X-ray luminosity. We believe their arguments and recognize the existence of the shock heating mechanism. But the good quantitative fitting with the observed increase of X-ray flux by use of our accretion model would imply that the dominant component of the X-ray flux might originate from the accretion, rather than from shock heating.

(4) Based on our accretion model, we can predict some other observational properties of the X-ray at the later phase. Firstly, from the calculated X-ray light curve based on our accretion model we see (Fig. 3) that, after increasing for a long time till age $t \approx 4100d$ (AD 1998), the increase of the emergent X-ray flux will cease, then begin to decline slowly. This is a prediction of our model, which only depends on the value of N_1. The decrease behavior of the X-ray luminosity will be come more and more similar to the total accretion luminosity.

Secondly, if our model is reasonable, the emergent spectrum would be a modified bremsstrahlung spectrum due to absorption by the envelope. The evolution of the bremsstrahlung spectrum would be determined by the calculated temperature evolution $T_s(t)$ as shown in Fig. 1 and $\tau_\nu(t)$. Finally, the calculated $T_s(t)$ curve predicts a definite evolution of the hardness ratio which will monotonically decrease with age t. We expect the observational confirmation in future.

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