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Contribution of accretion to the bolometric luminosity of SN 1987A

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Abstract. The investigations of the bolometric light curve of SN1987A are briefly reviewed. We suggest that the accretion luminosity produced by an assumed neutron star in the center of SN1987A is important for the evolution of the bolometric light curve at a later stage. We emphasize the marked difference of our model with previous accretion models, where the backfall of material mainly occurs within the first few seconds after the explosion and the details of accretion are dependent on the explosion mechanism which is very uncertain. In this paper, we are concerned with the continuous gravitational infall of material within the expansion envelope. Our suggestion is directly inspired by the observation of the line profile and is weakly dependent on the explosion model. Taking as typical values of the neutron star mass $M = 1.4M_{\odot}$ and radius $R = 10^6 cm$, the model calculation fits the observed light curve well. This a posteriori supports the assumption of central neutron star.

Key words: accretion, accretion disks – stars: neutron – supernovae: individual: SN 1987A

1. Introduction

Since the explosion of SN1987A, observations from radio to γ-ray wavelengths have been carried out (Chevalier 1992), and have given the bolometric light curve (the thermal emission from far infrared bands to the UV) (Suntzeff & Bouchet 1990, Bouchet et al., 1991a, Bouchet et al. 1991b, Suntzeff et al. 1991, Whitelock 1991 and Suntzeff et al. 1992). Many models have been constructed to analyze the evolution of the light curve at a later stage, but none of them can give a satisfactory explanation, particularly for the observed bump around day 1050 (Bouchet et al. 1996).

We review these explanations and suggest that the model of accretion on the assumed neutron star in the center of the supernova can give a satisfactory explanation both for the bump and for the flattening of the light curve after day~ 900. The existence of the neutron star is a key question. Although the observation of the neutrino burst (Bionta et al. 1987, Hirata et al. 1987) confirms the existence of the neutron star, there is still no direct evidence. Many discussions on whether or not the neutron star exists have been presented (Woosley 1988, Kumagai et al. 1989, Chevalier 1992, McCray 1993, Hillebrandt 1991) but no definite answer has been given yet. In this paper, the good fitting of the accretion model to the observed bolometric light curve could be indirect evidence of the existence of the neutron star.

In Sect. 2, we review previous research and present our model. We emphasize the substantial difference between other accretion models and ours. In Sect. 3, we focus on the calculation of the accretion on the neutron star. Finally, we give our result and discussion in Sect. 4.

2. Previous models and the new considerations

During a short time after the explosion of SN1987A, the released energy was accumulated in a small, optically thick ($\tau \gg 1$) central region, where photons were trapped and could not escape. The pressure in the hot radiation bubble created by neutrino heating (Arnnet 1996) became so large that it pushed the envelope to expand quickly. Such an expanding envelope can be simply regarded as a black body with luminosity $L = 4\pi R_p^2 \sigma T_{eff.}^4$ due to $\tau \gg 1$ where $T_{eff.}$ is the effective temperature and R_p is the radius of the photosphere. During the first days after the explosion, $T_{eff.}$ decreased drastically from $\sim 10^6 K$ to $\sim 5500K$, and then stayed there for some time (Hamuy et al. 1988). R_p, on the other hand, increased during the first three months because of the envelope expansion. After reaching a maximum value, the photosphere shrank quickly due to the decrease of the optical depth τ as a result of the decreasing gas density in the expanding envelope. At last, the photosphere vanished at $t \sim 120d$. From then on, the time scale of photon escape from the envelope was much smaller than the age t of the supernova, and the decay of the radioactive elements became the dominating energy source for the bolometric luminosity of SN1987A.(Catchpole et al. 1988, Hamuy et al. 1988). Detailed models for the energy deposition by γ-rays from the radioactive decay were developed by Kumagai et al. (1989) and Woosley et al. (1988,1989).In their models, the bolometric luminosity is the sum of all the individual contributions from various modes of radioactive decay. The theory fits the observation well before day 800. However, thenceforward, the decline of the observed luminosity is markedly slower than the expectation of the mod-

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els, implying that there should be another energy source which became important at $t > 800d$. Suntzeff et al. (1992) and Dwek et al. (1992) suggested that the problem could be resolved by increasing the abundance of ^{57}Co with a longer decay time. They assumed an isotopic ratio of ^{57}Co/^{56}Co as large as five times the solar value (0.024) and produced a satisfactory result. However, it is in conflict with X-ray observations (Kurfess et al. 1992, Varani et al. 1990) which give an upper limit for the ratio of ^{57}Co/^{56}Co of less than 1.5 times the solar abundance. Based on the work of Kumagai et al. (1989) and Woosley et al. (1988), Zheng et al. (1993) considered the contributions of all radioactive elements. In their work, the mass of ^{56}Co, ^{57}Co, ^{44}Ti and ^{22}Na is set to be 0.075M$_\odot$, 0.0043M$_\odot$, $1.2 \times 10^{-4} M_\odot$ and $2.0 \times 10^{-6} M_\odot$ respectively. The total bolometric luminosity will be $L_{bol.} = L_{^{56}Co} + L_{^{57}Co} + L_{^{44}Ti} + L_{^{22}Na}$. But they still fail to account for the discrepancy between theory and observations. Another possibility was suggested by Clayton et al. (1992), Fransson & Kozma (1993) and Fransson et al. (1996). They point out that, after $t \sim 800d$, the great decrease of electron and ion densities due to expansion increases the time scales of recombination and cooling, which become finally much larger than the time scales of the modes of radioactive decay ($\tau_{56} \simeq 111.3d$ and $\tau_{57} = 391d$) and the age of the supernova. So the condition $max[t_{rec.}, t_{cool}] << min[\tau_{decay}, t_{age}]$ will no longer be valid and the approximation of the steady state (the emitted recombination luminosity equals to the instantaneous radioactive energy input) is no longer correct. The large time scale $t_{rec.}$ implies the slowing down of the recombination process. Therefore the ionization degree χ_e will remain nearly constant (Fransson & Kozma called it a "frozen effect in ionization structure"). Therefore $n_e(t) \approx n_i(t) \propto t^{-3}$ for the homologous expansion, and the bolometric luminosity (mainly due to the recombination and thermal Bremsstrahlung) $L_{bol.} \propto EM = \int n_e n_i dV \propto t^{-3}$ because the emitting volume $V \propto t^3$. Although this can be helpful to explain the flattening of the bolometric light curve at $t > 800d$, the theoretical result $L_{bol.} \propto t^{-3}$ is still steeper than the observed slope of the curve $L_{bol.}^{obs.} \sim t$. Hence, an extra energy source apart from the heating of the radioactive decay is still needed. Bouchet et al. (1996) suggested that this energy could be provided from a compact object at the center of the supernova, e.g. a neutron star surrounded by an accretion disk depositing matter either continuously or at varying intervals onto the collapsed object. However in their consideration, the accretion is only an exotic assumption. People could be in doubt about the origin of the accreted material: where is it from? How and when did the accretion disk form? etc. The answer might be very model-dependent. Besides, the observed bump in the bolometric light curve around day 1050 remains an open problem. We noticed the discrepancy between the two data sets given by ESO (Bouchet et al. 1996) and CTIO (Suntzeff et al. 1992) observation teams. The inflection (or "bump") of the bolometric light curve at about day 1050 is not apparent in CTIO data. However, we believe the bump is real rather than an observational artifact because the observed bump occurs at the days when the level of luminosity is about $10^{38} erg/sec.$, which is just around the Eddington luminosity of a typical neutron star. We do not think this is only an accidental coincidence caused by observational error.

In this paper, we also concentrate our attention on the accretion luminosity from the assumed central neutron star. But we emphasize the marked difference between the present model and previous accretion models. In fact, there have been some discussions and calculations of the fallback of matter toward the assumed newborn neutron star (Colgate 1988, Michel 1988, Pinto et al. 1988, Schinder et al. 1987, Chevalier 1989,1992). But in their discussions, the fallback of material mainly occurs within the first few seconds after explosion, e.g. by the decrease of radiation pressure in the central hot bubble due to the neutrino losses, or by the reverse shock wave driven back to the center due to the collision of the mantle gas with the envelope, etc. The details of fallback are strongly dependent on the explosion mechanism, which is very uncertain. Besides, we notice that the calculated accretion luminosity (Chevalier 1989) is too low to explain the observed bolometric light curve of SN1987A at a later stage. In contrast to their discussions, in this paper we are interested in the continuous gravitation infall of material within the expansion envelope. This is a long-time accretion process, which is really important for the evolution of bolometric luminosity, particularly at a later stage of SN1987A. However, such an accretion possibility has been ignored for a long time. We emphasize that our suggestion is directly inspired by the observation of the profiles of emission lines, which is independent on the detailed explosion models. It is well known that, for a simple spherical symmetric model of the expansion envelope, the calculation shows that: (1) if the line emission is confined to a thin spherical shell, the line profile will be rectangular with full width equal to twice the radial expansion velocity of the shell; (2) if there is no line emission within some central region with radial expansion velocity $v < v_1$, the line profile will be flat-topped for $\mid \Delta\lambda \mid \leq \frac{v_1}{c} \lambda_0$ (3). if the line-emission is uniform throughout a sphere with velocity gradient from $v_{min} \approx 0$ to v_{max}, the line profile will be a parabola (McCray 1991). The fact that the observed line profiles during the nebular phase of SN1987A are normal in shape, and not noticeably flat-topped, enables us to infer that the line-emitting elements, including hydrogen, are mixed throughout the supernova envelope (at least in a macroscopic "lumpy" sense, Pinto & Woosley 1988a), and there is no obvious cavity at the center of envelope. In other words, the observed profiles show that the range of the radial velocity is really from $v_{min} \approx 0$ to $v_{max} \approx 2500 km/sec$ in the central region of the freely expanding envelope which produces most of line emission. The existence of very low radial velocity $v \gtrsim 0$ is just an important evidence of the inevitability of gravitation infall of material located in the envelope because the acceleration driven by the radiation pressure already ceases in the nebular phase, and the effect of gravitation of the newborn central compact star on the material with $0 \lesssim v \leq v_{esc.}$ can not be ignored anymore. In other words, the "free expansion" of envelope is only a rough approximation which can not be used to describe the gas elements with very low velocities $v \gtrsim 0$ if v is less than the escape velocity, $v < v_{esc.}$.

In brief, in our model, the possibility of accretion and the origin of the accreted matter are directly confirmed by the observation of line profiles, rather than an external assumption.

Another advantage is that the origin of both the peculiar bump around 1050 day and the flattening of observed bolometric light curve after $t > 800d$ becomes understandable according to our infall mechanism. The accretion luminosity determined by the accretion rate $\dot{M}_{acc.}(t)$ depends on the mass of the infalling gas. Denoting the infall rate of mass as $\dot{M}_{inf.}(t) \equiv \frac{dM_{inf.}}{dt}$, the accretion rate $\dot{M}_{acc.}(t)$ in principle is near to $\dot{M}_{inf.}(t)$, $\dot{M}_{acc.}(t) = \dot{M}_{inf.}(t)$. $\dot{M}_{inf.}(t)$ can be deduced if the velocity field and the space distribution of the density of the ejected matter in the envelope is known. However, as we will see below, in the early stage, during a rather long period ($t_{*1} < t < t_{*2}$) after the explosion, the calculated infall rate $\dot{M}_{inf.}(t) \equiv \frac{dM_{inf.}}{dt}$ is markedly larger than the critical accretion of the neutron star — the Eddington limit $\dot{M}_{Edd.}$, i.e, $\dot{M}_{inf.}(t) > \dot{M}_{Edd.}$. In this case, the realistic accretion luminosity $L_{acc.}(t)$ will be restricted at the level of Eddington luminosity $L_{Edd.}$, $L_{acc.}(t) = L_{Edd.}$ ($\dot{M}_{acc.}(t) = \dot{M}_{Edd}$). The excess infalling matter with low velocities $v \approx 0$ will be prevented from the accreting due to the balance between the radiation pressure and the gravitation, and stayed in the vicinity of the central neutron star. The total excess mass of the deposited matter $\Delta M = \int_{t_{*1}}^{t_{*2}} [\dot{M}_{inf.}(t) - \dot{M}_{Edd.}] dt$, where t_{*1}, t_{*2} are the critical times at which the calculated infall just equals the critical accretion rate $\dot{M}_{Edd.}$, $\dot{M}_{inf.}(t_{*1}) = \dot{M}_{inf.}(t_{*2}) = \dot{M}_{Edd.}$. After the age t_{*2}, $t > t_{*2}$, calculation shows $\dot{M}_{inf.}(t) < \dot{M}_{Edd.}$. But the equality $\dot{M}_{acc.}(t) = \dot{M}_{Edd.}$ will prolong to $t = t_{*2} + \Delta t$ because the deposited excess material ΔM begins to be accreted at t_{*2}. So the relation $L_{acc.}(t) = L_{Edd.}$ can be retained for a period Δt after $t > t_{*2}$. Therefore we expect that there will be an “Eddington platform” in the accretion light curve after $t > t_{*2}$ which can be used to explain the peculiar bump around day 1050 in the observed light curve.

In Sect. 3, we will estimate the infall rate of mass under the approximation of ballistic or free falling motion, in spite of the effect of radiation pressure on the accretion. This is a good approximation for the calculation of accretion luminosity because the influence of radiation pressure created by accretion itself is remarkable mainly in the early time when the infall rate $\dot{M}_{inf.}(t) > \dot{M}_{Edd.}$. But we have mentioned that, during that period, the effect of radiation pressure is nothing but the deposition or accumulation of accreted matter in the vicinity of the neutron star. This means that we can treat the gravitation infall and the effect of radiation pressure separately or independently, which could be the simplest way for the treatment of radiation pressure.

3. Calculation of the accretion luminosity of the central neutron star

We begin with the calculation of $\dot{M}_{inf.}(t)$. Firstly we must know when the infall motion of the material in envelope begins. This is a difficult problem. We can not infer this time from observations. We denote the initial time of infall motion as t_0 and take it as an adjustable parameter in our model calculation. However, it is possible to restrict the t_0-value in a believable and relatively narrow range. It is known that the acceleration within the envelope ceases within hours or at most days after the explosion, then the free expansion begins (McCray 1996). We believe that the remarkable gravitational infall of material within the envelope must begin around the moment when the accelerated outflow of gas in envelope ceases. Therefore the t_0-value has to be taken in the range of hours or days.

As mentioned above, at time t_0, the envelope is in the free expansion phase and the velocity field has a very simple form. The material is distributed approximately uniform throughout the major part of the envelope within $v_{max} \leq 2500 km/sec.$,with no apparent cavity at the center of the envelope, (but it is believed that there exists a small hot radiation bubble created by neutrino heating, Colgate 1988, Arnett 1996). There is a radial gradient of velocity $v = v(r)$. The expanding velocity increases outward from $v_{min} = 0$ in the innermost shell of envelope to $v_{max} \approx 2500 km/sec.$ at the outermost shell. The infalling material which we are interested in is located just at the inner portion of the envelope where $v < v_{esc.}$. For a given elementary matter with velocity v_0 at time t_0, the distance r_0 from the assumed central neutron star is roughly given as $r_0 = v_0 t_0$ under the approximation of free expansion (McCray 1993). However, as mentioned above, such an approximation is not good to describe the gas elements located in inner shells where the velocities are very low and less than the local escape velocity, $v_0 < v_{esc.}(t_0)$. A more realistic and reasonable relation is $r_0 > v_0 t_0$ in this region. In order to avoid the complicate argument and derivation (in fact, this is nearly impossible because the physics is very uncertain before $t < t_0$), we simply use an empirical expression to describe the $r_0 \sim v_0$ relation, i.e.

$$r_0 = b(v_0) v_0 t_0 \quad (1)$$

where $b(v_0)$ is a correction coefficient describing the deviation from free expansion. Obviously it is required that $b(v_0) >> 1$ for $v_0 \to 0$ and $b(v_0) \to 1$ if $v_0 \to \infty$. Quantitatively speaking, the asymptotic behavior of $b(v_0)$ depends on the value of the escape velocity $v_{esc.}(t_0)$ at t_0. $b(v_0) >> 1$ for $v_0 << v_{esc.}(t_0)$ and $b(v_0) \simeq 1$ for $v_0 >> v_{esc.}(t_0)$. The following empirical expression for $b(v_0)$ seems to be suitable to this requirement, i.e.

$$b(v_0) = \frac{\pi}{2 arctg(v_0 / v_{esc.}(t_0))} \quad (2)$$

(Obviously, other forms of function $b(v_0)$ with the same asymptotic behavior are also available. But the calculation shows that no remarkable changes occur in the resultant calculated curves Figs. 3–5, when different expressions of $b(v_0)$ are adopted, as we desired.)

The value of $v_{esc.}(t_0)$ can be obtained from the equation

$$\frac{1}{2} v_0^2 - \frac{G M_*}{r_0} = E(t_0, v_0, r_0) = 0 \quad (3)$$

M_* is the mass of the neutron star, combining Eq. (3) with Eq. (1) and Eq. (2), we have

$$\frac{1}{2}v_{esc.}^2 - \frac{GM_*}{b(v_{esc.})v_{esc.}t_0} = 0 \quad (4)$$

Therefore

$$v_{esc.}(t_0) \simeq (\frac{GM_*}{t_0})^{1/3} \quad (5)$$

which is weakly dependent on t_0 ($v_{esc.} \propto t_0^{-1/3}$). All gas elements with velocities within $0 \leq v_0(t_0) \leq v_{esc.}(t_0)$, with energy $E < 0$, will be successively returning to neutron star after $t > t_0$. In other words, all of the bound gas is confined in a shell $\frac{\pi}{2}(GM_* t_0^2)^{1/3} < r_0 < 2(GM_* t_0^2)^{1/3}$ which borders on the central hot bubble. Within a reasonable range of t_0-value (hours or at most days) the thickness scale of the shell is small, $\sim 10^{11} cm$. The escape velocity $v_{esc.}(t_0) \sim$ several $10^7 cm/sec.$ is also low compared with the typical radial velocities $v \approx 1000 km/sec$ in the main part of the expanding envelope.

In order to obtain the infall rate, and thence the accretion luminosity, we should know the density distribution of the gas in the shell at t_0. So far none of available models predicts the distribution in such a thin shell where the velocities are as low as $0 \leq v_0(t_0) \lesssim$ several $10^7 cm/sec.$ However, the density profiles (ρ vs. v curves) given by 10HM and 10HMM models (Pinto & Woosley 1988a, 1988b) enable us to infer a reasonable density distribution in this region. Bethe (1990) suggested that the gas density increases outward near the outer surface of the central bubble. According to the 10HM model, the density profile at 300d after explosion (Fig. 1) shows a sharp increase of density with radius in a small sphere, i.e. in the low ejection velocity region. It finally reaches a constant value $5 \times 10^{-14} g/cm^3$. The 10HMM model (Fig. 2) gives a similar result, which shows that the density increases sharply with expansion velocity and becomes constant when $v \approx 5 \times 10^7 cm/sec.$

Combining the results of Fig. 1 and Fig. 2, and taking the relation $\rho \propto t^{-3}$ in free expansion, we obtain a reasonable distribution of density in the inner shell of envelope at the moment t_0 as

$$\rho_0 = 5 \times 10^{-14}(\frac{t_0}{300d})^{-3}(\frac{v_0}{5 \times 10^7})^m g/cm^3$$
$$(v_0 \leq 5 \times 10^7 cm/sec) \quad (6)$$

It is difficult to obtain the precise value of the index m. From Fig. 2 we can only estimate that the m value is restricted within the range $7 \lesssim m \lesssim 11$. Therefore, the index m in Eq. (6) is another adjustable parameter in our model in the restricted range.

For a given gas element with (t_0, r_0, v_0) in the inner shell of the envelope at t_0, i.e. in the infall region where $0 \leq v_0(t_0) \leq v_{esc.}(t_0)$, the energy E per unit mass is negative which will remain constant at any time $t > t_0$:

$$E = \frac{1}{2}v^2 - \frac{GM_*}{r} = \frac{1}{2}v_0^2 - \frac{GM_*}{r_0} = E(v_0, r_0) < 0 \quad (7)$$

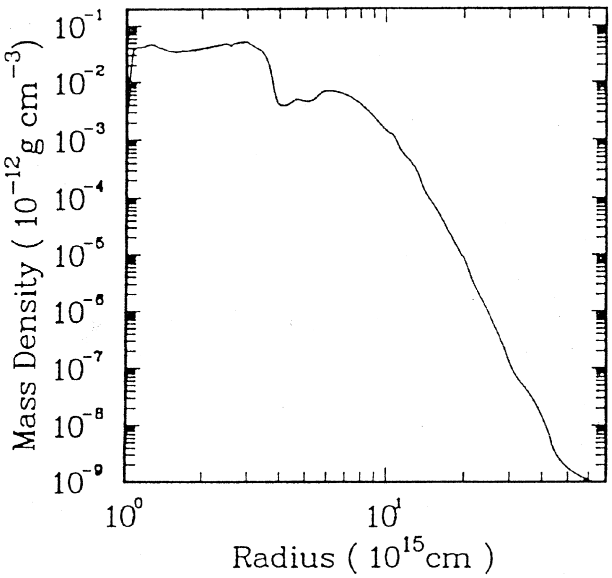

Fig. 1. Model 10HM for radial distribution of density in envelope of SN1987A at $t = 300d$ (Pinto & Woosley 1988a).

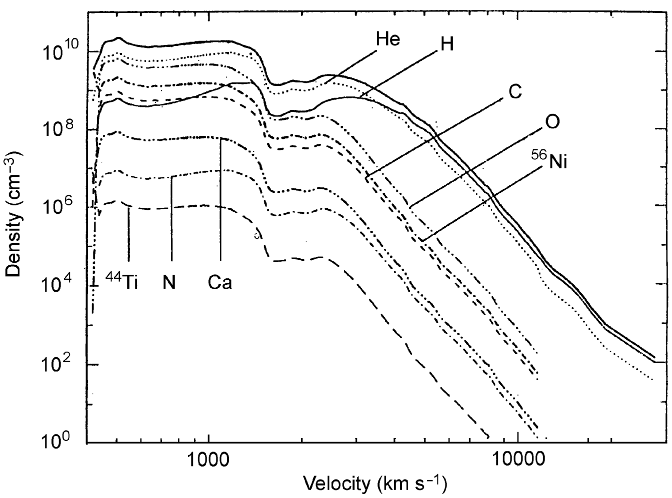

Fig. 2. Model 10HMM for radial distribution of average density and composition in envelope of SN1987A at t=1yr (Pinto & Woosley 1988b).

From Eq. (7), we obtain the required time t_1 for the given gas element reaching the maximum distance $r_{max.}$:

$$t_1 = t_0 + \int_{r_0}^{r_{max}} \frac{dr}{v} = t_0 + \int_{r_0}^{r_{max}} (2E + \frac{2GM_*}{r})^{-1/2} dr \quad (8)$$

where

$$r_{max.} = \frac{-GM_*}{E(v_0, r_0)} = \frac{-GM_*}{\frac{1}{2}v_0^2 - \frac{GM_*}{r_0}} = r_{max}(r_0)$$

Therefore, the returning time t for the gas-element back to the neutron star is:

$$t \approx 2t_1 = 2t_0 + 2\int_{r_0}^{r_{max}} (2E + \frac{2GM_*}{r})^{-1/2} dr \quad (9)$$

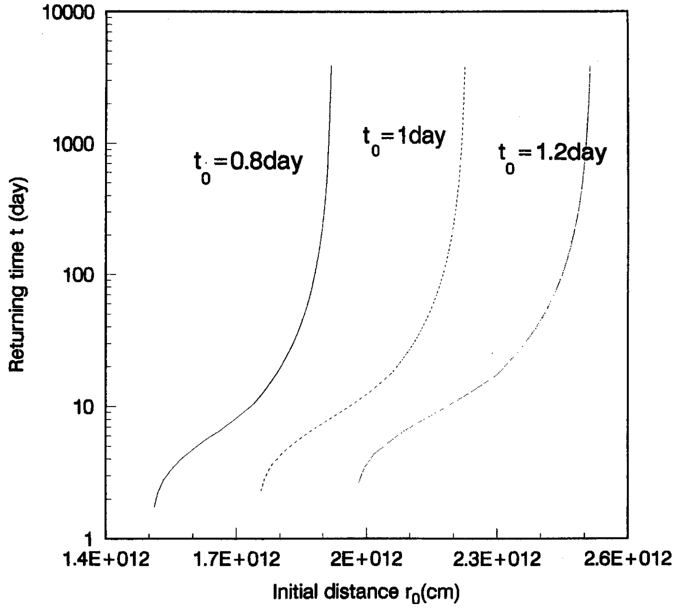

Fig. 3. The dependence of returning time t on the initial position r_0 at the moment t_0. The parameter t_0 are set as 0.8day (plain line), 1day (dashed line), 1.2day (dotted line).

Thus $t = t(r_0, v_0, t_0) = t(r_0, t_0)$ (see Eq. (1) and Eq. (2)). The calculated $t\ vs. r_0$ curves are shown in Fig. 3, and t_0 is taken as a free parameter. We take $t_0 = 0.8day, 1day, 1.2day$, respectively.

From the calculated t vs. r_0 curves, we obtain the infall rate of mass $\dot{M}_{inf.}(t)$ at any moment t:

$$\dot{M}_{inf.}(t) = 4\pi r_0^2 \rho_0 dr_0/dt \tag{10}$$

Here, dr_0/dt can be obtained from Eq. (9) or Fig. 3. ρ_0 is obtained from Eq. (6). As an example, the calculated $\dot{M}_{inf.}(t)$ curve with selected parameters $t_0 = 1$ day, $m = 8.22$ is shown in Fig. 4.

As we discussed in Sect. 2, in the earlier stage, when the calculated $\dot{M}_{inf.}(t) \geq \dot{M}_{Edd.}$, the real accretion rate is expected to be restricted as follows:

$$\dot{M}_{acc.}(t) = \dot{M}_{Edd.} \qquad (for \quad t_{*1} < t < t_{*2}) \tag{11}$$

The total mass of the excess infalling material, i.e. the extra-Eddington material, which will be delayed to be accreted is:

$$\Delta M = \int_{t_{*1}}^{t_{*2}} [\dot{M}_{inf.}(t) - \dot{M}_{Edd.}]dt \tag{12}$$

Here we emphasize again that the saturated accretion $\dot{M}_{acc.}(t) = \dot{M}_{Edd.}$ in $t_{*1} < t < t_{*2}$ will persist for a longer period Δt after $t > t_{*2}$ due to the continuous supplement of accretion material provided by the deposited mass ΔM, thus Eq. (11) will be valid in a much longer period $t_{*1} < t < t_{*2} + \Delta t$. Δt can be estimated from the equation

$$\Delta M = \int_{t_{*2}}^{t_{*2}+\Delta t} [\dot{M}_{Edd.} - \dot{M}_{inf.}(t)]dt \tag{13}$$

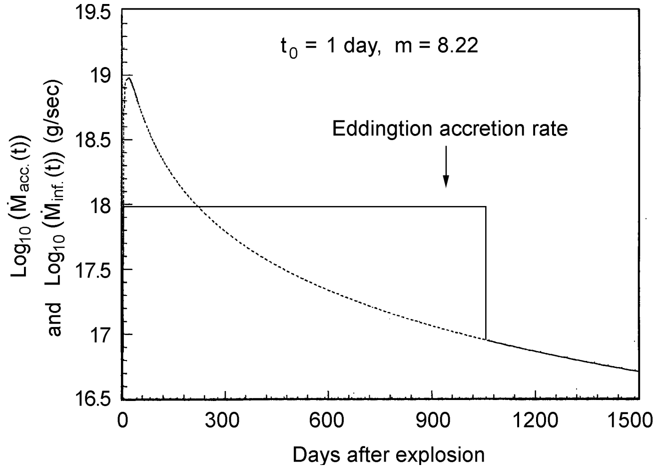

Fig. 4. The curves of $\dot{M}_{inf.}(t)$ and $\dot{M}_{acc.}(t)$. $\dot{M}_{inf.}(t)$ reprents the infall rate in unit g/sec. $\dot{M}_{acc.}(t)$ reprents the accretion rate in unit g/sec. The dashed curve is $\dot{M}_{inf.}(t)$, and the plain is $\dot{M}_{acc.}(t)$. For clearness, only the curves with the selected parameters $t_0 = 1$ day and $m = 8.22$ are shown in this figure.

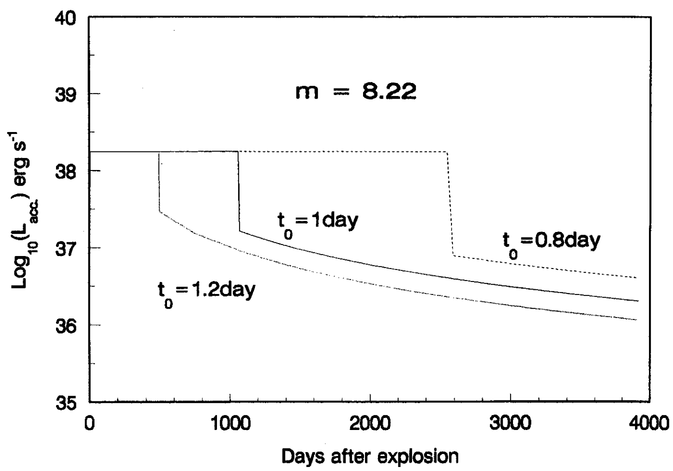

Fig. 5. The variation curves $L_{acc.}(t)$ with different t_0 while $m = 8.22$. t_0 are set as 0.8day (dashed line), 1day (plain line), 1.2day (dotted line).

where ΔM represents the total deposited mass during $t_{*1} < t < t_{*2}$ given by Eq. (12). After $t > t_{*2} + \Delta t$, the real accretion rate equals the calculated infall rate, i.e.

$$\dot{M}_{acc.}(t) = \dot{M}_{inf.}(t) \qquad (when \quad t \geq t_{*2} + \Delta t) \tag{14}$$

The calculated curve of $\dot{M}_{acc.}(t)$ with selected parameters $t_0 = 1$ day, $m = 8.22$ is also shown in Fig. 4, which shows a saturated accretion $\dot{M}_{acc.}(t) = \dot{M}_{Edd.}$ in the interval $t_{*1} < t < t_{*2} + \Delta t$, and can be called the "Eddington platform". The accretion luminosity is given by:

$$L_{acc}(t) = \frac{GM_* \dot{M}_{acc.}(t)}{r_*} \tag{15}$$

where r_* is the radius of the neutron star. Taking $M_* = 1.4 M_\odot$, $r_* \sim 10^6 cm$ and adjusting the values of (m,t_0), we obtain the calculated $L_{acc.}(t)$ curves shown in Fig. 5 and Fig. 6.

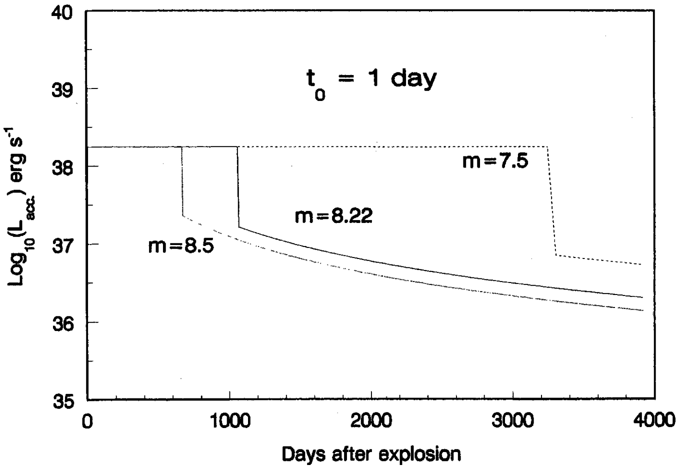

Fig. 6. The variation curves $L_{acc.}(t)$ with different m while t_0 is invariable, $t_0 = 1$ day. m are set as $m = 8.22$ (plain line), $m = 7.5$(dashed line), $m = 8.5$(dotted line).

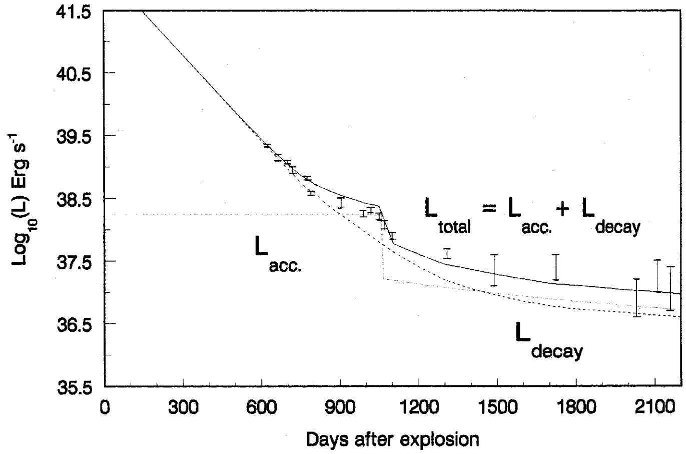

Fig. 7. The calculated total bolometric light curve (plain line) where the accretion luminosity (dotted line with $t_0 = 1$ day, $m = 8.22$) is added to that given by Frasson & Kozma (1993) (dashed line, here the $^{56}Co/^{57}Co$ ratio has been taken as 2× solar, and "the frozen effect of ionization fraction" have been considered to compute the energy output from radioactive decays).

In these figures, all the curves decline sharply at the age $t = t_{*2} + \Delta t$, This is because the calculated curves $\dot{M}_{inf.}(t)$ are obtained under the approximation of free infall motion. Actually, the radiation pressure will delay accretion, it cannot be ignored particularly when the accretion luminosity is near to $L_{Edd.}$. Therefore we expect a smoother decline of light curves around $t = t_{*2} + \Delta t$. The best fit with the observed bolometric light curve is obtained if we take $t_0 = 1$ day and $m = 8.22$. Fig. 7 shows the best calculated accretion light curve $L_{acc}(t) \sim t$ (dotted line) and the light curve of $L(t) \sim t$ (dashed line) resulting from Frasson and Kozma's model(1993). The solid line in Fig. 7 is the sum of the two lines, which includes the contribution both of the accretion and the radioactive decay, and the "frozen effect in ionization structure" has been taken into consideration. The observed points of bolometric luminosity are also shown in Fig. 7.

4. Conclusions and discussion

1. Our calculation in this paper gives a good fit to the observed light curve of SN1987A, particularly in the late stage from ~ 900 days to $\gtrsim 2000$ days. Both the obvious flattening of the light curve after $t \gtrsim 900$ days and the peculiar bump around day ~ 1050 can be explained satisfactorily by accretion onto the assumed central neutron star. In our consideration, the accreted material is nothing but the ejected gas in envelope with velocities less than the escape velocity $v_{esc.}$ This is directly confirmed by the observation of line profile and nearly independent of the explosion mechanism. Therefore the accretion suggested in this paper is totally different from other models as mentioned in Sect. 1. The good quantitative coincidence of our calculation with observation seems to be a strong support to this mechanism.

2. It is known that the radiation from the surface of the accreting neutron star is mainly released in the soft X-ray band $\sim 1kev$. For a homologously expanding envelope of SN1987A, the optical depth in X-rays is $\tau = \tau_1 t^{-2}$, where t is the time in unit year since explosion, and τ_1 is the optical depth from the supposed central neutron star to the surface of the envelope at age $t = 1yr$ and $E = 1kev$ (McCray 1993). The absorption of X-rays will transfer most of the accretion energy into UVOIR during a long time after explosion. However, at a later stage, the accretion luminosity in soft X-ray band will be increasing with age t in the form of an exponential law $e^{-\tau} = e^{-\tau_1 t^{-2}}$. This is the main prediction of our accretion model. G.Hasinger et al. (1996) show that the observed X-ray flux is really continuously increasing with age t, which may be an observational support for the suggestion of the central neutron star. Besides, the expected $e^{-\tau_1 t^{-2}}$ increasing of X-ray flux would be the main difference between the previous models (Woosley et al. 1989, Kumagai et al. 1989, Clayton et al. 1992, Fransson & Kozma 1993) and ours. They only considered the contribution of the radioactive elements to the bolometric luminosity, and the remarkable increase of X-ray flux in the later stage will be suppressed and replaced by the leakage of γ-ray radiation. Other possibilities for the contribution to the observed X-ray emission of SN1987A have been suggested by some authors, e.g. A contribution from the shock interaction with material inside the inner ring when the supernova shock sweeps up material (e.g. Chevalier 1982, Beuerman et al. 1994, Gorenstein et al. 1994, Suzuki et al. 1993, Masai & Nomoto 1994, Luo et al. 1994). However, the currently observed X-ray luminosity and its temporal behaviour does not exclude the possibility of X-ray emission produced from a compact object (Hasinger et al. 1996). We expect that future observations will decide the issue.

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