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THE RING AROUND SN 1987A AND ROTATION OF THE PROGENITOR

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ABSTRACT

The ring discovered around SN 1987A is likely to be related to the rotation of the progenitor. We have studied two rotational effects of the progenitor of SN 1987A: (1) mass-shedding from the equator and (2) an aspherical mass distribution in a stellar wind due to the direction-dependent mass loss. With approximate models for a rotating star and a wind, we have obtained the following results.

First, if the rotational velocity of the progenitor at the main sequence exceeds 270 km s^{-1}, mass-shedding can occur (i.e., the angular velocity can exceed the critical angular velocity) at the blue supergiant stage. This is due to the decreasing moment of inertia along the evolution with increasing mass concentration toward the center. However, the observed elemental abundances and the expansion velocity of the ring provide rather severe constraints on the time of mass-shedding, which suggests that the mass-shedding scenario is probably less likely the case.

Second, the stellar wind combined with the rotation forms an aspherical mass distribution in the distant region from the star. The nonsphericity can be 10%–20% depending on the ratio of the rotational energy to the gravitational energy. This mild asphericity in the slow wind can be a seed of the ring formation due to the interaction with the fast wind at later stages, which should be studied with full hydrodynamical calculations of the wind-wind interaction.

Subject headings: stars: individual (SN 1987A) — stars: rotation — supernovae: individual (SN 1987A)

1. INTRODUCTION

The discovery of ringlike circumstellar matter around SN 1987A (Jakobsen et al. 1991) has raised a new question about the ring-formation mechanism. It is natural to consider that such a ring structure is closely related to a certain nonspherical structure of the progenitor due to its rotation and magnetic field. Aspherical structure of SN 1987A has been suggested from the polarization observations (Cropper et al. 1988) and the speckle image of the ejecta (Papaliolios et al. 1989).

In the present paper we explore possible effects of rotation of the progenitor on the formation of the ring around SN 1987A. The rotation can reveal itself in several different phenomena. Here we study two effects of rotation: One is the mass-shedding, where the rotation directly induces the ring formation. The other is the rotational effect on the mass loss that would provide a seed of the ring formation through the wind-wind interaction (see below).

The mass-shedding scenario is based on the following thought. The rotation velocity at the stellar surface changes significantly as the internal structure of the progenitor changes during its evolution from the main sequence to the blue giant. Because of the decrease in the moment of inertia during the expansion, there may exist some stage(s) where it reaches a critical rotation state, i.e., a mass-shedding which occurs when the centrifugal force overwhelms the gravity at the equatorial surface (see, e.g., Eriguchi 1978; Eriguchi & Müller 1985; Hachisu 1986). The shed mass will expand slowly and may be observed as a ringlike circumstellar matter. Such a possibility of mass-shedding during the *expansion* stage has not been studied in detail. Therefore, we will describe the basic mechanism of such a mass-shedding with polytropic models in § 2.1 and examine the realistic evolutionary model of the progenitor of SN 1987A in § 2.2. Comparison with the observed features of the ring will be discussed in § 2.3.

The second scenario to form a small asymmetry in the red supergiant wind is motivated by the recent analyses of observations and the modeling of the ringlike structure (Wampler et al. 1990; Wang & D'Odorico 1991; Luo & McCray 1991; Wang & Mazzali 1992). Their hourglass model has shown that, if there is a nonspherical stellar wind at the red supergiant phase, the fast wind at the blue supergiant phase catches up with the slow red wind and the resulting interaction between the two winds greatly enhances the pre-existing aspherical structure. In their models, however, the existence of the asphericity in the wind at the red supergiant phase is simply *assumed*. Thus far little has been known quantitatively about the rotational effect on the mass loss. In the present study described in § 3, therefore, we will make rather simple models, i.e., polytropic models, to see how much the rotation affects the distribution of the matter in a wind.

2. MASS-SHEDDING FROM ROTATING STARS

2.1. *Mass-Shedding Mechanism During Expansion*

In this section, we describe the basic mechanism of mass-shedding during an *expansion phase* of the evolution of a rotating star. To clarify the mechanism with simple models, we use rotating polytropic models and assume that the total angular momentum is conserved and that the angular velocity remains uniform. The evolution of the polytrope is roughly approximated by the increase in the polytropic index N due to the increasing mass concentration toward the central region. (In a realistic stellar evolution mass is lost in a stellar wind which necessarily carries away the angular momentum from the star, whose effect is discussed in the next section.)

For uniformly rotating polytropes a critical equilibrium state has been found to appear (see, e.g., Eriguchi 1978; Hachisu 1986). A rotating star maintains its equilibrium state by the balance among the centrifugal force, the gravitational force, and the pressure gradient. As the rotation rate increases, there appears an equilibrium state where the pressure gradient vanishes and the centrifugal force balances the gravity on the equatorial surface. If the star rotates more rapidly, there is no equilibrium state and matter will flow out from the equatorial surface of the star. We call this phenomenon *mass-shedding* and the most rapidly rotating state as a critical state or critical equilibrium.

The angular velocity for the critical state is approximately given as

$$\frac{GM}{R_{\rm eq}^2} = R_{\rm eq}\Omega_{\rm cr}^2 , \tag{1}$$

where M, $R_{\rm eq}$, and $\Omega_{\rm cr}$ are the mass, the equatorial radius and the critical angular velocity, respectively. From equation (1) dimensionless critical angular velocity ($\omega_{\rm cr} \equiv \Omega_{\rm cr}/\sqrt{4\pi G\rho_c}$) can be written as

$$\omega_{\rm cr}^2 = \frac{1}{3}\frac{1}{k^3}\frac{\rho_{\rm av}}{\rho_c} , \tag{2}$$

where $\rho_{\rm av}$ and ρ_c are the averaged density and the central density, respectively, and

$$k \equiv \frac{R_{\rm eq}}{R_s} . \tag{3}$$

Here R_s is the radius of the spherical star. If we choose

$$k = 1.4 , \tag{4}$$

which is a typical value for the rotating polytropes with a large polytropic index (Eriguchi 1978), then the obtained critical angular velocities for the polytropes are approximately equal to those obtained from axisymmetric computation (Eriguchi 1978; Hachisu 1986) as shown in Table 1. In this table $\omega_{\rm max}$ is the critical angular velocity obtained from full axisymmetric computation. Also shown are the ratio, f, of the moment of inertia I to MR_s^2. From this table we can find that

$$f^2 \frac{\rho_c}{\rho_{\rm av}} \sim 0.3 . \tag{5}$$

As the evolution of a star proceeds in the direction of increasing $\rho_c/\rho_{\rm av}$, the f-value becomes smaller. Thus we can get a rather accurate relation for the critical rotation state as

$$\Omega_{\rm cr} = \left(\frac{GM}{k^3}\right)^{1/2} \frac{1}{R_s^{3/2}} . \tag{6}$$

The angular velocity of the star during its evolution can be estimated as follows. Since we have assumed that the angular momentum is conserved during the evolution, the following relation holds:

$$fMR_s^2\,\Omega = {\rm constant} = J_0 , \tag{7}$$

where Ω and J_0 are the angular velocity at a certain stage of evolution and the initial angular momentum, respectively. This equation can be expressed as

$$\Omega = \frac{J_0}{M}\frac{1}{f}\frac{1}{R_s^2} . \tag{8}$$

In the expansion phase the radius increases, so that the critical angular velocity and the angular velocity of the star decrease according to equations (6) and (8), respectively. The factor f also decreases according to equation (5), which increases the angular velocity of the star. Thus if the decrease in f is large enough during some stage of evolution, the star reaches the critical state for mass-shedding.

2.2. *Possibility of Ring Formation by Mass Shedding for SN 1987A*

In this section we examine whether or not the mass shedding mechanism did work during the actual evolution of the progenitor of SN 1987A (see, e.g., Nomoto et al. 1991 for a review of the progenitor evolution).

Since rotational equilibrium configurations of the realistic stars have not been computed, we assume that equations (1) and (2) together with equation (4) approximately hold for realistic stars. Thus we use equation (6) for the critical angular velocity of realistic stars.

During the post main-sequence evolution, the core shrinks while the envelope expands, which increases the mass concentration toward the central region. This reduces the moment of inertia and possibly increases the ratio between the angular velocity and its critical value as mentioned in the previous section.

For the blue-red-blue evolution of the progenitor of SN 1987A we adopt the 21 $M_\odot$ model at the zero age main sequence (Saio, Nomoto, & Kato 1988; Yamaoka et al. 1991). For this model we calculate the factor f at four representative stages: (1) the main-sequence phase (MS), (2) the blue supergiant phase (BSG), (3) the red supergiant phase (RSG) and (4) the second blue supergiant phase (r-BSG). The model parameters—the total mass and the radius—and the obtained factor f are shown in Table 2. In this table the critical angular velocities are also given.

TABLE 1

PHYSICAL QUANTITIES FOR THE POLYTROPES

N	$\omega_{\rm max}^2 = \Omega^2/\sqrt{4\pi G\rho_c}$	$\omega_{\rm cr}^2 = \rho_{\rm av}/(3k^3\rho_c)$	$\rho_c/\rho_{\rm av}$	$f = I/(MR^2)$
1.5	2.18E-2	2.03E-2	5.99	2.04E-1
3	2.04E-3	2.24E-3	54.2	7.53E-2
4	1.63E-4	1.95E-4	6.22E2	2.26E-2
4.9	1.0E-7	1.25E-7	9.73E5	4.96E-4

TABLE 2

PHYSICAL QUANTITIES FOR THE REALISTIC MODELS

Stage	$M/M_\odot$	R (cm)	$\Omega_{\rm cr}$ (s^{-1})	$f = I/(MR^2)$
MS	21.0	4.2E11	1.17E-4	8.72E-2
BSG	17.6	3.4E12	4.66E-6	1.12E-2
RSG	16.0	5.0E13	7.89E-8	4.58E-2
r-BSG	16.0	3.4E12	4.45E-4	1.52E-2

TABLE 3

FRACTION OF THE RETAINED MASS AND THE ANGULAR MOMENTUM

Stage	α	β
MS → BSG	0.5	0.83
BSG → RSG	0.5	0.90
RSG → r-BSG	1.0	1.0

It is interesting that even though the averaged density of the blue giant is larger than that of the red giant star, the factor f is smaller for the blue giant. This is because the mass distribution is more concentrated in the *radiative* envelope of the blue supergiant due to steeper density gradient than in the *convective* envelope of the red supergiant.

The angular velocities of the star at stages (1)–(4) are estimated as follows. During the evolution, stellar mass is lost in a wind, which also carries away the angular momentum. Although the mass loss is a continuous phenomena, we assume that mass loss takes place discretely at each stage with a loss of the angular momentum contained in the wind material. We denote the fractions of the lost angular momentum and the lost mass by $1-\alpha$ and $1-\beta$, respectively. The α values for the main-sequence stage and the blue supergiant stage are approximately obtained from the polytropic models of $N = 3$ and $N = 3.5$, respectively (Table 3).

The relation between two angular velocities corresponding to two different stages, 1 and 2, is given as

$$\alpha(f_1 M_1 R_1^2 \Omega_1) = f_2(\beta M_1) R_2^2 \Omega_2 \ . \tag{9}$$

The angular velocities are expressed in terms of the angular velocity at the main-sequence stage Ω_{MS} as

$$\Omega_{BSG} = 7.2 \times 10^{-2} \Omega_{MS} \ , \tag{10a}$$

$$\Omega_{RSG} = 4.5 \times 10^{-5} \Omega_{MS} \ , \tag{10b}$$

$$\Omega_{r-BSG} = 2.9 \times 10^{-2} \Omega_{MS} \ , \tag{10c}$$

where the subscript denotes the evolutionary stage.

If the ring is formed directly by mass-shedding at the intermediate stage of the evolution, the following conditions should be satisfied:

$$\Omega_{MS} \le \Omega_{cr}^{MS} \ , \tag{11}$$

and

$$\Omega_{BSG} \ge \Omega_{cr}^{BSG} \ , \tag{12a}$$

or

$$\Omega_{RSG} \ge \Omega_{cr}^{RSG} \ . \tag{12b}$$

If we can find the allowed range of Ω_{MS} satisfying the conditions (11) and either of equation (12), we may expect that mass-shedding does occur.

In Figure 1, the solid line shows the critical angular velocity given by equation (6) against the radius of the spherical star models, and the dashed curves show the angular velocity of the star at different evolutionary stages that satisfies the above conditions. As seen from this figure there is a possibility of mass-shedding during the blue supergiant phase.

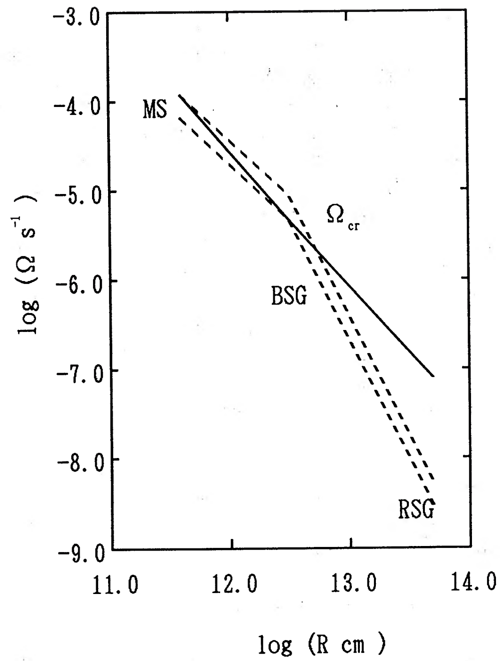

FIG. 1.—Critical angular velocity is plotted against the radius of the spherical star (*solid line*). The angular velocities of the star at each evolutionary stage which experiences mass-shedding at a certain stage are plotted by dashed lines. The upper dashed line corresponds to the most rapidly rotating model without mass-shedding at the main-sequence phase. The lower dashed curve corresponds to the slowest rotating model which experiences mass shedding at the blue supergiant phase.

The smallest angular velocity at the main-sequence stage which might lead to mass-shedding is obtained as

$$\Omega_{MS} = 6.5 \times 10^{-5} \ s^{-1} \ . \tag{13}$$

This corresponds to the surface velocity

$$V_{MS} = 270 \ km \ s^{-1} \ , \tag{14}$$

which implies that the star at the main-sequence stage was rotating rather rapidly but not extremely fast. It is important to note that, if the mass-shedding occurs, it determines the angular velocity of the blue giant star.

So far we have assumed that the angular velocity maintains uniformity during the evolution. However, in a realistic evolution, especially, from the main sequence to the blue supergiant phase, the angular velocity distribution could be differential. Although it is hard to calculate the angular momentum redistribution during the evolution, there remains a chance of mass-shedding as long as the surface angular velocity is larger than half of that for the uniformly rotating case.

One may consider a case that the differential rotation during the blue giant phase may prevent the mass shedding at that stage and convection in the red supergiant establishes the uniform rotation which increases the angular velocity near the surface. The increased angular velocity may exceed the critical angular velocity at the red giant stage. However, the final uniform angular velocity at the red supergiant phase cannot exceed the estimated value in equation (10b) because of the total angular momentum conservation.

2.3. *Observational Constraints*

In the above mass-shedding scenario, the ring was likely to be formed when the progenitor of SN 1987A was a blue supergiant rather than a red supergiant. This scenario should be consistent with the observed elemental abundances and expansion velocity of the ring. Elemental abundances of the ring estimated from the UV emission lines of CNO elements indicate large excesses of the N/C and N/O ratios over the solar values (Panagia et al. 1987; Fransson et al. 1989). The expansion velocity of the ring material was recently obtained as ~ 7 km s^{-1} (Wang & D'Odorico 1991).

The large N/C and N/O ratios imply that the ring contains the material which had been processed by the CNO cycle in the interior and brought to the surface by convection at the red supergiant phase. If mass-shedding occurred at the blue supergiant phase, there might be two possible scenarios to account for the N-rich materials in the ring.

One is to get the N-rich material from the wind at the red supergiant stage that could catch up with the ring. The collision of the red-giant wind with the ring would necessarily accumulate the N-rich materials, which could make the ring materials a mixture of materials with low and high nitrogen abundances. This scenario predicts some variation of CNO elements within the ring.

The other possible scenario adopts a model that the progenitor underwent a blue-red-blue-red-blue evolution, which was found to occur if the degree of mixing in the semi-convection zone is very finely tuned (Langer, El Eid, & Baraffe 1989). If mass-shedding to form the ring occurred at the *second* blue supergiant phase (i.e., after the first red-supergiant stage), the ring must be N-rich.

In the mass-shedding scenario, the expansion velocity of the ejected ring may be estimated by using a test particle as follows. Although the angular momentum of the ejected particle is uncertain, we parameterize it by introducing a factor γ as

$$j_1 = \gamma j_{\rm cr}\,, \quad (\gamma \geq 1)\,, \tag{15}$$

where j_1 and $j_{\rm cr}$ are the angular momentum of the ejected test particle and the specific angular momentum at the critical state of mass shedding, respectively. If the test particle is ejected from the surface at the radius r_0, then the radial velocity of the particle at the distance r can be expressed as

$$v^2 = v_{\rm esc}^2\left(1 - \frac{1}{r/r_0}\right)\left[\frac{\gamma^2}{2}\left(1 + \frac{1}{r/r_0}\right) - 1\right], \tag{16}$$

where v and $v_{\rm esc}$ are the velocity of the particle at r and the escape velocity from the surface of the star, respectively. If γ is near unity, the ejected mass expands very slowly compared with the escape velocity and almost stands still not far from the surface of the star.

In a realistic situation, the ring must have been accelerated by the wind. We assume that the constant velocity wind continuously collides with the ring and a small fraction of the wind is taken into the ring. Then the linear momentum conservation gives

$$v_r = \left(1 - \frac{M_0}{M}\right)V_w + \frac{M_0}{M}\,v\,, \tag{17}$$

where M_0, M, v_r, and V_w are the initial mass of the ring, the ring mass after collision, the velocity of the ring, and the wind velocity, respectively. The mass of the colliding wind against the ring can be estimated by considering the solid angle of the ring with respect to the central star, which is roughly 1/20. However a large fraction of the wind in that solid angle does not necessarily hit the ring directly as mentioned above, considering the shape of the ring and the collision which is not head-on. Thus only a fraction μ of the wind mass—a percent or less—may be accumulated in the ring:

$$M - M_0 = \mu M \sim M/100\,. \tag{18}$$

Therefore the final expansion velocity can be written as

$$v_r \sim \frac{1}{100}\,V_w + v \sim {\rm O}(1 \text{ km s}^{-1})\,. \tag{19}$$

This implies that the acceleration by the red supergiant wind ($V_w \sim 10$ km s^{-1}) is negligible while the blue supergiant wind of $V_w \sim 500$ km s^{-1} may lead to $v_r \sim 5$ km s^{-1}. This might explain the observed expansion velocity of 7 km s^{-1}.

However, the observed expansion velocity sets a rather severe constraint that the time interval between the onset of ring acceleration by the *blue wind* and the supernova explosion is $\sim$30,000 yr (Wang & D'Odorico 1991). To satisfy this condition in both scenarios of nitrogen enrichment, the ring formation must have occurred just before the transition of the progenitor from the blue to the red supergiant and the significant acceleration must have taken place during the final excursion of the progenitor from the red to the blue supergiant.

3. EFFECT OF ROTATION ON THE STELLAR WIND

As mentioned in § 1, the effect of rotation on the stellar mass loss has been poorly investigated so far quantitatively. Here we use *axisymmetric stationary polytropic* stars for simplicity in order to estimate the asymmetry of the mass loss from the rotating red supergiant.

Since we assume that the system is in a stationary state, we can use the Bernoulli's theorem as follows:

$$(1 + N)\lambda + \phi + \frac{1}{2}(u_R^2 + u_z^2) + \frac{1}{2}\frac{j_0^2}{R^2} = C\,, \tag{20}$$

where C is *a constant value along a stream line*, $\lambda \equiv \rho^{1/N}$, ϕ is the gravitational potential, j_0 is the specific angular momentum, and R is the distance from the rotation axis. Here u_R and u_z are R- and z-components of the flow velocity, respectively, for the cylindrical coordinates (R, z, φ).

We can assume that there is a region in the interior of the star where velocity components u_R and u_z are negligibly small compared with the gravitational potential or the rotational velocity term. In such a region, D, the matter can be considered to be in a rotational equilibrium, so that the equilibrium condition must hold on the boundary of this region (∂D) as follows:

$$(1 + N)\lambda_0(\theta) + \phi_0(\theta) - \frac{1}{2}\frac{j_0^2(\theta)}{R_0^2(\theta)} = C_0\,, \tag{21}$$

where C_0 is *a constant throughout the region D* and other quantities with subscript 0 are quantities on the boundary which depend on θ. Here the polar coordinates (r, θ, φ) are used.

Let us choose one stream line which starts from a certain point on the boundary. Along this stream line we can get the following relation from equation (20):

$$(1 + N)\lambda + \phi + \frac{1}{2}(u_R^2 + u_z^2) + \frac{1}{2}\frac{j_0^2}{R^2} = (1 + N)\lambda_0 + \phi_0 + \frac{1}{2}\frac{j_0^2}{R_0^2}\,. \tag{22}$$

By making use of equation (21), we obtain

$$(1 + N)\lambda + \phi + \frac{1}{2}(u_R^2 + u_z^2) + \frac{1}{2}\frac{j_0^2}{R^2} = C_0 + \frac{j_0^2(\theta)}{R_0^2(\theta)} . \quad (23)$$

At a distant region from the star, $r = r_1$, the gravitational potential behaves almost spherically and the j_0^2/R^2 term can be neglected. Thus we obtain

$$(1 + N)\lambda + \frac{1}{2}(u_R^2 + u_z^2) = C_0' + \frac{j_0^2(\theta)}{R_0^2(\theta)} , \quad (24)$$

where

$$C_0' \equiv C_0 - \phi(r) . \quad (25)$$

Let us consider two directions, the direction of the rotational axis and the equatorial direction. If we assume that the velocity depends little on the direction, the density becomes

$$\lambda_{\rm pole} \equiv \lambda(r_1, 0) = \frac{1}{1 + N}\left(C_0' + \frac{j_0^2(0)}{R_0^2(0)} - \frac{1}{2}u_z^2\right) \quad (26a)$$

for the rotational axis direction, and

$$\lambda_{\rm eq} \equiv \lambda(r_1, \pi/2) = \frac{1}{1 + N}\left(C_0' + \frac{j_0^2(\pi/2)}{R_0^2(\pi/2)} - \frac{1}{2}u_R^2\right) \quad (26b)$$

for the equatorial direction.

Comparing these two equations and noting that $u_z(r_1, 0) \sim u_R(r_1, \pi/2)$ and $j_0(0) = 0$, we have

$$\frac{\lambda_{\rm eq}}{\lambda_{\rm pole}} = 1 + \frac{R_0^2(\pi/2)\Omega^2}{C_0''} , \quad (27)$$

where

$$C_0'' \equiv C_0' - \tfrac{1}{2}u_1^2 , \quad (28)$$

$$u_1 \equiv u_R(r_1, \pi/2) = u_z(r_1, 0) . \quad (29)$$

Since at the distant region from the star the constant C_0'' is roughly equal to C_0 and C_0 can be evaluated from the gravitational potential of the pole on the boundary ∂D, we can write

$$\frac{\lambda_{\rm eq}}{\lambda_{\rm pole}} \sim 1 + \frac{T}{|W|} , \quad (30)$$

where T and W are the rotational energy and the potential energy of the fluid element on the equator of the boundary ∂D, respectively. Although we do not know the precise location of the boundary ∂D, we estimate the value of $T/|W|$ from the results of uniformly rotating polytropic equilibrium computations. The ratio $T/|W|$ may be 10%–20% or less for uniformly rotating polytropes with $N = 3$–4.

Wang & Mazzali (1992) have assumed that there is an asymmetry of order 20% in the mass distribution and have shown that its asphericity grows considerably by the expansion of and the interaction with the fast wind at the later stage. Therefore the effect of the rotation on the mass-loss flow studied in this section can become the seed of the ring formation in the model by Wang & Mazzali (1992). However it seems very hard to give 80% nonsphericity adopted by Luo & McCray (1991).

The mass concentration towards the equatorial plane is contradicted with the results obtained by Phillips & Reay (1977) who have shown the mass concentration is towards the rotation axis. However, Phillips & Reay (1977) have obtained their conclusion by assuming special velocity field and trajectory of the mass element. The velocity of the flow was assumed to be decomposed into the rotational component, i.e., ϕ-component, and the *normal* component to the deformed stellar surface. The velocity field in the meridional plane need not be normal to the surface but is likely to be inclined to the equatorial plane due to the rotational effect. Concerning the flow pattern, fluid dynamical calculation was not carried out but the trajectory of the mass element was assumed to be *hyperbolic*. Therefore their treatment was not fluid dynamical but geometrical so that it is natural for the mass to be concentrated towards the rotation axis.

So far we assumed that the velocity field is isotropic as was done by Wang & D'Odorico (1991) or Kahn & West (1985) who presented models for planetary nebulae by assuming the directional dependent mass flux. We can consider that the density is isotropic and the flow velocity has direction dependence as another extreme case. For such a situation equations (26a)–(26b) show that the flow velocity can be faster in the equatorial region. We may thus believe that the mass-loss rate is larger near the equatorial plane comparing with the polar direction. In order to get a definite answer we need to compute models of rotating polytropes with stationary outflow.

4. CONCLUDING REMARKS

We have studied two possible roles of rotation of the progenitor in forming the ringlike circumstellar matter around SN 1987A: (1) mass-shedding from the equator due to the decreasing moment of intertia along the evolution, and (2) an aspherical mass distribution in a stellar wind due to the direction dependent mass loss. Though our models are approximate regarding the angular momentum redistribution during the evolution and the flow pattern of the wind, our following results are quite suggestive for the ring formation mechanism.

Firstly, we have shown that mass-shedding can occur (i.e., the angular velocity exceeds the critical angular velocity) at the blue-supergiant stage if the rotational velocity of the progenitor at the main-sequence stage exceeds 270 km s^{-1}. To be consistent at least with the elemental abundances and the expansion velocity of the ring, however, mass-shedding must have occurred during the transition from the blue to the red supergiant. This requirement would restrict the parameters of the progenitor's initial configuration to a rather narrow range, which suggests that the mass-shedding scenario is probably less likely.

Secondly, we have shown that the stellar wind combined with rotation may form an aspherical mass distribution in the distant region from the star. Nonsphericity can be 10%–20% depending on the ratio of the rotational energy to the gravitational energy. This mild asphericity in the slow wind can be a seed which will be enhanced to the ringlike configuration later due to the interaction with the fast wind (Luo & McCray 1991; Wang & Mazzali 1992). Whether or not this amount of asphericity is enough for the seed should be studied by full hydrodynamical calculations of the wind-wind interaction.

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