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The Impact of a Supernova Explosion in a Very Massive Binary

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ABSTRACT
We consider the effect of a supernova (SN) explosion in a very massive binary that is expected to form in a portion of Population III stars with the mass higher than $100M_{\odot}$. In a Population III binary system, a more massive star can result in the formation of a BH and a surrounding accretion disc. Such BH accretion could be a significant source of the cosmic reionization in the early universe. However, a less massive companion star evolves belatedly and eventually undergoes a SN explosion, so that the accretion disc around a BH might be blown off in a lifetime of companion star. In this paper, we explore the dynamical impact of a SN explosion on an accretion disc around a massive BH, and elucidate whether the BH accretion disc is totally demolished or not. For the purpose, we perform three-dimensional hydrodynamic simulations of a very massive binary system, where we assume a BH of $10^3M_{\odot}$ that results from a direct collapse of a very massive star and a companion star of $100M_{\odot}$ that undergoes a SN explosion. We calculate the remaining mass of a BH accretion disc as a function of time. As a result, it is found that a significant portion of gas disc can survive through three-dimensional geometrical effects even after the SN explosion of a companion star. Even if the SN explosion energy is higher by two orders of magnitude than the binding energy of gas disc, about a half of disc can be left over. The results imply that the Population III BH accretion disc can be a long-lived luminous source, and therefore could be an important ionizing source in the early universe.

Key words: accretion discs — PopIII stars — early universe — hydrodynamics — binaries: general — cosmology: theory

1 INTRODUCTION

The studies on the formation of Population III (Pop III) stars have shown that first stars in the universe are likely to be as massive as $100 - 1000M_{\odot}$ (Bromm, Coppi & Larson 1999; Abel, Bryan, & Norman 2000, 2002) or to form in a bimodal initial mass function (IMF) with peaks of several $100M_{\odot}$ and $\sim 1M_{\odot}$ (Nakamura & Umemura 2001). Recently, it has been revealed that a significant fraction of Pop III stars can be expected to form in binary systems (Saigo et al. 2004). Heger & Woosley (2002) have studied the nucleosynthetic evolution of Pop III stars, and have shown that Pop III stars in the mass range of $m \gtrsim 260M_{\odot}$ result in direct black hole formation, while the mass range of $25M_{\odot} \lesssim m \lesssim 140M_{\odot}$ leads to the supernova (SN) explosions. Hence, if there is mass difference in a Pop III binary, there can form a binary system composed of a BH with $m \gtrsim 260M_{\odot}$ and a massive star with $25M_{\odot} \lesssim m \lesssim 140M_{\odot}$. Also, recent general relativistic simulations on a supermassive star ($m \gtrsim 10^3M_{\odot}$) have shown that if a star possesses large angular momentum, a massive gas disc is left over around a forming black hole (Shibata & Shapiro 2002; Shibata 2004; Shapiro 2004; Sekiguchi & Shibata 2004). The mass fraction of gas disc is $10^{-4} - 10^{-1}$ of the initial stellar mass, depending on the equation of state and the degree of rotation. This disc can fuel the BH in the later evolutionary stage. Even if a disc left over is quite small, the Roche lobe overflow from a companion star may also fuel the BH in a close binary system (Lawlor et al. 2008).

On the other hand, it is suggested that Pop III BH accretion may be an important clue for the reionization of the universe (Madau et al. 2004; Ricotti & Ostriker 2004b). For a BH of $\approx 10^3M_{\odot}$, the accretion disc can emit a blackbody radiation with an effective temperature of 10^{6-7} K, if the mass accretion rate is close to the Eddigton rate (e.g. Kato et al. (1998)). When the disc mass is several $10M_{\odot}$,

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the accretion timescale is several 10^6 years. Therefore, the accreting BH can be an ultraviolet radiation source in a longer timescale than the lifetime of a massive companion star. Then, the accreting BH can be a significant contributor for the early reionization(Hirose & Umemura 2007). However, if the accretion disc is blown off by the SN explosion of a companion star, the accretion timescale may be too short to play a significant role for the reionization.

In this paper, we explore the disruption and stripping of a gas disc around a BH by a SN explosion of a massive companion star. For the purpose, we perform three-dimensional hydrodynamic simulations with a second-order scheme, AUSM-DV. In particular, to resolve the propagation of a blast wave and the deformation of a gas disc with high accuracy, three-dimensional generalized curvilinear coordinates are used. Such a three-dimensional simulation on the collision of SN blast wave with a BH accretion disc has been never performed so far. With the simulations, we study the stripping efficiency as a function of the kinetic energy of the SN blast wave, by changing the separation of binary and the mass of gas disc. Then, the dependence on the ratio of the blast wave kinetic energy to the binding energy of gas disc is analysed in detail.

The paper is organized as follows. In Section 2, the details of present numerical model and method are presented. In Section 3, we show the numerical results for the deformation and stripping of gas disc around a BH by the collision with a SN blast wave. Also, the dependence on the model parameters is studied, and the resultant remaining mass fraction of disc is argued. Section 4 is devoted to conclusions.

2 NUMERICAL MODEL AND METHOD

2.1 Model

We consider a binary system composed of a black hole of $1000M_\odot$ and a Pop III companion star of $100M_\odot$. In the present analyses, the model parameters are the separation between the BH and the companion star, the mass of gas disc surrounding the BH, and the density profile of gas disc. Based on the analysis by Saigo et al. (2004), we set the binary separation, a, to be 700 AU as a fiducial case, and a half or one-fifth of the fiducial separation is also examined. As for the mass of gas disc, considering the disc formation around a black hole (Shibata & Shapiro 2002; Shibata 2004; Shapiro 2004; Sekiguchi & Shibata 2004) and also the mass loss from a Pop III star before a SN explosion (Heger & Woosley 2002), we set the disc mass to be $30M_\odot$, $10M_\odot$ or $3M_\odot$. Regarding the density distribution of gas disc, we assume a power-law type distribution like $\rho(r) \propto r^n$ on the equatorial plane. The power-law index n is assumed to be $n = 0$, -1, or -2. The temperature of gas disc is presumed to be 10^4K, since the gas disc is irradiated by ultraviolet radiation from a companion star before the explosion. The rotation of the disc is assumed to be Keplerian, because the self-gravity is negligible in all the cases considered. In vertical directions of the disc, we determine the density distributions by solving a hydrostatic balance. Also, taking the tidal effect into account, the gas disc is truncated at the tidal radius given by Paczynski (1977) and Boffin (2001). The tidal radius is ~ 0.7 Roche lobe radius of the BH. For instance, the outer radius of the gas disc is set to be 280AU for a fiducial case. The space out of the gas disc is filled with tenuous and high temperature gas, since we cannot treat a vacuum in the present hydrodynamic scheme. In order to minimize its dynamical effect, we set the density to be negligibly small. Here, the density and temperature are assumed to be 2.5×10^{-16}g cm^{-3} and 10^7K, respectively. The parameters adopted are summarized in Table 1.

To simulate a SN explosion, we employ a method similar to that taken by Kitayama & Yoshida (2005), and Bromm, Yoshida & Hernquist (2003), where the explosion energy is inserted as the thermal energy of the gas ejected from a SN. The ejected gas has no initial velocity and is accelerated by the gas pressure. The temperature is assumed to be 1.0×10^8K for all cases, and the density and extent of hot gas is adjusted so that the explosion energy is 10^{51}erg (Heger & Woosley 2002). If the separation is shorter, the density of hot gas is higher and the extent is smaller. For model A1, the density of the hot gas is set to be $\rho_{\rm SN} = 1.0 \times 10^{-11}$g cm^{-3} and the extent is to be 50AU. We tested the cases of different density and extent and confirmed that the impact of a SN explosion on the gas disc does not have a strong dependence on the choices, but is basically determined by the explosion energy. Also, we regulate the duration of SN explosion so that the total mass ejected by SN explosion is $50M_\odot$ (Heger & Woosley 2002).

2.2 Numerical Method

We solve the three-dimensional Euler equation for inviscid gas. Basic equations can be written in the conservative form as

$$\frac{\partial \tilde{Q}}{\partial t} + \frac{\partial \tilde{E}}{\partial x} + \frac{\partial \tilde{F}}{\partial y} + \frac{\partial \tilde{G}}{\partial z} + \tilde{H} = 0, \tag{1}$$

where $\tilde{Q}$, $\tilde{E}$, $\tilde{F}$, $\tilde{G}$ and $\tilde{H}$ are respectively the following vectors,

$$\tilde{Q} = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ e \end{pmatrix}, \quad \tilde{E} = \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ \rho uw \\ (e+p)u \end{pmatrix}, \quad \tilde{F} = \begin{pmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ \rho vw \\ (e+p)v \end{pmatrix},$$
$$\tilde{G} = \begin{pmatrix} \rho w \\ \rho uw \\ \rho vw \\ \rho w^2 + p \\ (e+p)w \end{pmatrix}, \quad \tilde{H} = \begin{pmatrix} 0 \\ \rho f_x \\ \rho f_y \\ \rho f_z \\ \rho\left(u f_x + v f_y + w f_z\right) \end{pmatrix}, \tag{2}$$

(e.g, Vinokur 1974), where ρ is the density of gas, u, v and w are respectively the x-, y- and z- components of velocities, and f_x, f_y and f_z are the x-, y- and z- components of gravity force by a black hole. As the gravity force, we take into account only the effect of black hole, since it is a major component. The pressure p and the total energy per unit volume e are related by the equation of state,

$$p = (\gamma - 1)\left\{ e - \frac{\rho}{2}\left(u^2 + v^2 + w^2\right)\right\}, \tag{3}$$

where γ is the ratio of specific heats of gas, which is $\gamma = 5/3$ here.

The Reynolds number based on the molecular viscosity is very large for the present case. Therefore, we have neglected the effect of viscosity (and only considered the effect of ram pressure), i.e. solved the Euler equations. However, we should note that possible turbulence would provide a tendency to reduce the remaining disc mass or to extinguish the disc. Solving such case accounting for turbulent eddy viscosity will be our future work (Takeda et al. 1985).

To solve the governing equation (1) numerically, AUSM-DV scheme (Wada & Liou 1994) is employed. To properly adjust the boundary and solve the flow with high accuracy, we use the three-dimensional generalized curvilinear coordinates as shown in Fig. 1. Because we assume the system is in a plane-symmetric with respect to the equatorial plane, we perform simulations in the computational domain that is composed of a hemisphere and an adjacent protuberant region. The BH and the SN explosion are placed on the equatorial plane, where the BH is located at the center of hemisphere, and the SN explosion occurs at the center of protuberant region. In Fig. 1, only a half of the computational domain is shown after the domain is cut by a plane perpendicular to the equatorial plane that connects the BH and the SN explosion. The number of grid points is $51 \times 101 \times 31$. We treat a black hole as a small central hole with absorbing boundary, whose radius is 20AU for the case of $a = 700$AU. The gas disc is set up around the small hole, and the inner radius of the disc is assumed to be 50 AU. The grids are generated with higher resolution near the black hole and the equatorial plane of the gas disc. Such coordinates allow us to treat accurately the flow of the gas disc. The computations are carried out only in the upper half domain relative to the equatorial plane, because we assume that the system is symmetric about this plane. The leftward meshes are built up to represent a SN explosion. A free boundary condition on outer and inner boundaries is adopted in these meshes.

3 RESULTS

When a SN explosion produces a supersonic flow with the mass of $50M_\odot$ and the velocity of 4000 km/sec, the kinetic energy of the blast wave is $\sim 1.1 \times 10^{50}$ erg for the solid angle of a disc viewed from the SN explosion. In the fiducial case, the binding energy of gas disc is evaluated to be $\sim 3.1 \times 10^{48}$ erg. Hence, the kinetic energy of a SN blast wave is much larger than the disc binding energy. Then, the collision of the blast wave with a disc is anticipated to be devastating. However, the disc is deformed by the collision, and also streamlines are bent significantly. Therefore, it is unclear whether the whole of disc gas is stripped out by the collision of the SN blast wave.

3.1 Disc Deformation and Stripping

Figure 2 shows the numerical results at early stages for model A1. The density distributions and velocity fields are shown in the $x - y$ plane with $z = 0$ (*lower panels*) and in $x - z$ plane with $y = 0$ (*upper panels*). Figure 2(a) shows the initial state, where high-density hot gas is ejected at 700AU from a BH. The hot gas expands almost radially (Fig. 2(b)) and rushes toward the gas disc (Fig. 2(c)). At ~ 0.47 years, as seen in Fig. 2(d), the bulk of flow is bent to go through the disc. In this stage, some of gas disc is stripped out, but much of the blast wave energy can escape owing to the bending of gas flow. On the other hand, the flow directed to the disc center is strongly decelerated by the collision with the disc, and begins to deform the disc (Fig. 2(e)(f)).

Figure 3 shows the deformation and stripping of the disc at later stages. The figure zooms in the disc regions. The rotation period at the outer edge of gas disc is ~ 148 years. Fig. 3 (a) is the initial state again. As seen in Figures 3 (b) and (c), the blast wave pushes the left-side edge of gas disc and produces a dent within a few years, because the time-scale of the SN explosion is much shorter than the rotation period of the outer edge of gas disc. The rotation of disc transfers this dent, resulting in the overall deformation of the disc (Fig. 3 (d)). Through this deformation, the rotation balance breaks down, and resultantly some of gas is blow out by centrifugal force, as seen in Figure 3 (e). Eventually, the gas disc is settled in a quasi-steady state within about 100 years (Fig. 3 (f)). As a result, roughly 70% of an original disc around the BH is left over. In Figure 4, the deformation and stripping processes are shown with three-dimensional volume rendering visualization. The survival of the gas disc after the heaving and ruffling by the blast wave collision is clearly shown.

Previously, Wheeler et al. (1975) argued that in a binary system the mass stripping and ablation from a star by the impinging balastwave is well expressed by a non-dimensional parameter Ψ, which is defined as

$$\Psi \equiv \frac{1}{4}\frac{M_{\rm SN}}{M_{\rm c}}\frac{R^2}{a^2}\left(\frac{v_{\rm SN}}{v_{\rm es}} - 1\right), \tag{4}$$

where $M_{\rm SN}$ is the mass of gas expelled by a SN, $M_{\rm c}$ and R are respectively the mass and radius of object affected by blast wave, $v_{\rm SN}$ is the typical speed of the blast wave, $v_{\rm es}$ is the escape velocity. They obtained the mass fraction ejected by the stripping and ablation as a function of Ψ. We can evaluate Ψ in the present system, where $M_{\rm SN} = 50M_\odot$, $M_{\rm c} = M_{\rm disc} = 30M_\odot$, $R = 280$AU, $a = 700$AU and $v_{\rm SN} =$ 4000 km/sec. $v_{\rm es}$ is approximated to be

$$v_{\rm es} = \left(\frac{2GM_{\rm BH}}{R}\right)^{1/2}, \tag{5}$$

where $M_{\rm BH} = 1000M_\odot$. Then, we find $\Psi \simeq 3.28$ in our model A1. According to the criterion for a polytropic star with $n = 3$ given by Wheeler et al. (1975), it is predicted that about a half of mass is ejected in the case of $\Psi \simeq 3$. In the present simulation, about 30% of mass is ejected eventually. Therefore, we can conclude that Ψ is a fairly good measure for the mass ejection even in a disk system. However, in the disk system, a little more mass remains than the prediction for a spherical star. In the collision of blast wave with a gas disk, the streamline is more strongly bent above and below the disc. Hence, the momentum transferred to the gas in a disk is reduced, and more mass can be left over. Therefore, the difference from the spherical prediction can be reasonably understood in terms of the geometrical effect.

3.2 Dependence on Binary Separation

In order to investigate the dependence on the binary separation, we perform additional two simulations with $a =$ 350 AU (model B1), which is a half separation of model A1, and with $a = 140$ AU (model B2), which is a one-fifth separation of model A1. We assume the mass of the disc to be the same as model A1. Therefore, the disc radius becomes smaller and the density is higher for these models. Also, the energy of the SN explosion, the temperature, and the total mass of ejected gas to be the same as model A1. The rotation period of the outer edge of gas disc for model B1 and B2 is ~ 52 years and ~ 13 years, respectively. Figure 5 shows the density distributions and the velocity fields in the final quasi-steady state, which is reached at $t = 38.19$ years and 11.95 years for models B1 and B2, respectively. Hence, the time to reach the final state is shorter for the shorter separation. Interestingly, it is found that more mass is left over for shorter binary separation. Roughly 80 % of disc survives for model B1, and nearly 85 % of disc does for model B2. This can be understood in terms of the binding energy E_b of the disc relative to the kinetic energy E_k of the SN blast wave. The ratio E_b/E_k is ~ 0.1 and ~ 0.2 for models B1 and B2, respectively, while $E_b/E_k \sim 0.03$ for model A. Thus, E_b/E_k is thought to be a key physical quantity that determines the remaining mass of disc. This point is argued again later.

3.3 Dependence on Density Distribution

To check whether the deformation and stripping of disc depends on the density distribution of gas disc, simulations for discs with different density distributions are performed. One is a flat density distribution model with $n = 0$ on the equatorial plane (model C1), and the other is a centrally concentrated model with $n = -2$ (model C2). The mass of gas disc is the same as model A1. Figure 6 shows the results for a flat density distribution disc (model C1). The snapshots of density distributions and velocity fields at $t = 0.00, 10.32,$ and 110.16 years are presented. The results look similar those shown in Figure 3 at the same evolutionary stages. Actually, the remaining mass is not changed significantly. Figure 7 show the results for a centrally-concentrated disc (model C2). The snapshots of density distributions and velocity fields at $t = 0.00, 10.37,$ and 105.69 years are presented. It is found that, for model C2, the influence by the blast wave is slightly weaker in the central regions of the disc (Fig. 7 (b)), compared to model C1 (Fig. 6 (b)). But, the remaining mass increases by only several %. Therefore, we can conclude that the density distributions of disc do not influence the final mass of disc strongly.

3.4 Remaining Mass

In Figure 8, the time sequences of the disc mass are summarized by the ratio of the remaining disc mass to the disc mass without a supernova explosion of companion star. For model A1, C1 and C2, the disc is settled in quasi-steady states in 60 years, and $\sim 70\%$ of disc gas remains, almost regardless of density distributions of disc. For model B1 ($a = 350$AU), a quasi-steady state is attained in 20 years and $\sim 80\%$ of disc gas remains. For model B2 ($a = 140$AU), the disc reaches a quasi-steady state in 10 years and $\sim 85\%$ of disc gas remains.

As argued in Section 3.1, the remaining amount of gas can be understood in terms of the ratio of E_b to E_k, where E_b is the binding energy of the gas disc around the BH and E_k is the kinetic energy of the blast wave taking into account the solid angle of the disc viewed from the SN explosion point. E_b is evaluated by integrating potential energy of the gas around the BH. Figure 9 shows the remaining mass fraction against the E_b/E_k ratio. In this diagram, two more simulations are added with changing the disc mass: model D1 has the disc mass of $10M_\odot$, which is one-third of that in model A, and model D2 has the disc mass of $3M_\odot$, which is one-tenth of that in model A. Obviously, the remaining mass fraction correlates positively with E_b/E_k. Thus, a key physical parameter that determines the remaining mass fraction is the E_b/E_k ratio. Interestingly, even if the binding energy is less than 1% of the kinetic energy of SN blast wave, a considerable amount of mass remains. This is a three-dimensional effect of deformation and stripping, which is demonstrated in Figure 4.

4 CONCLUSIONS

We have explored the dynamical impact of SN explosion in a very massive binary system. We have simulated the deformation and stripping of a gas disc around a BH, using three-dimensional generalized curvilinear coordinates. Also, the dependence on the binary separation, the density distribution of disc, and the mass of disc have been studied. As a result, we have found that a SN blast wave is not so devastating that a disc around a BH is totally evaporated. It has turned out that the remaining mass fraction is basically determined by the ratio of the disc binding energy to the SN kinetic energy. As a matter of importance, even if the binding energy of gas disc is much smaller than the kinetic energy of blast wave, a significant amount of mass can remain. For instance, when the binding energy is about 1% of the kinetic energy of SN blast wave, about a half of mass is left over. We have found that the three dimensionality of the disc deformation is essential to make a disc around a BH survive.

The present results imply that in a massive binary system like a Pop III binary, the BH accretion activity can be long-lived even after a massive companion star explodes. Such BH accretion can emit ultraviolet radiation, and therefore a Pop III BH accretion disc can be an important candidate as a reionization source in the early universe.

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Table 1. Adopted parameters for model calculations. In this table, a represents the binary separation, $M_{\rm disc}$ does the mass of gas disc, and n does the power-law index of density distributions on the equatorial plane.

Model	a [AU]	$M_{\rm disc}$	n	Remarks
A1	700	30	-1	Fiducial model
B1	350	30	-1	Half of the separation in model A1
B2	140	30	-1	One-fifth of the separation in model A1
C1	700	30	0	Flat density distribution disc
C2	700	30	-2	Centrally concentrated density distribution disc
D1	700	10	-1	One-third of the disc mass in model A1
D2	700	3	-1	One-tenth of the disc mass in model A1

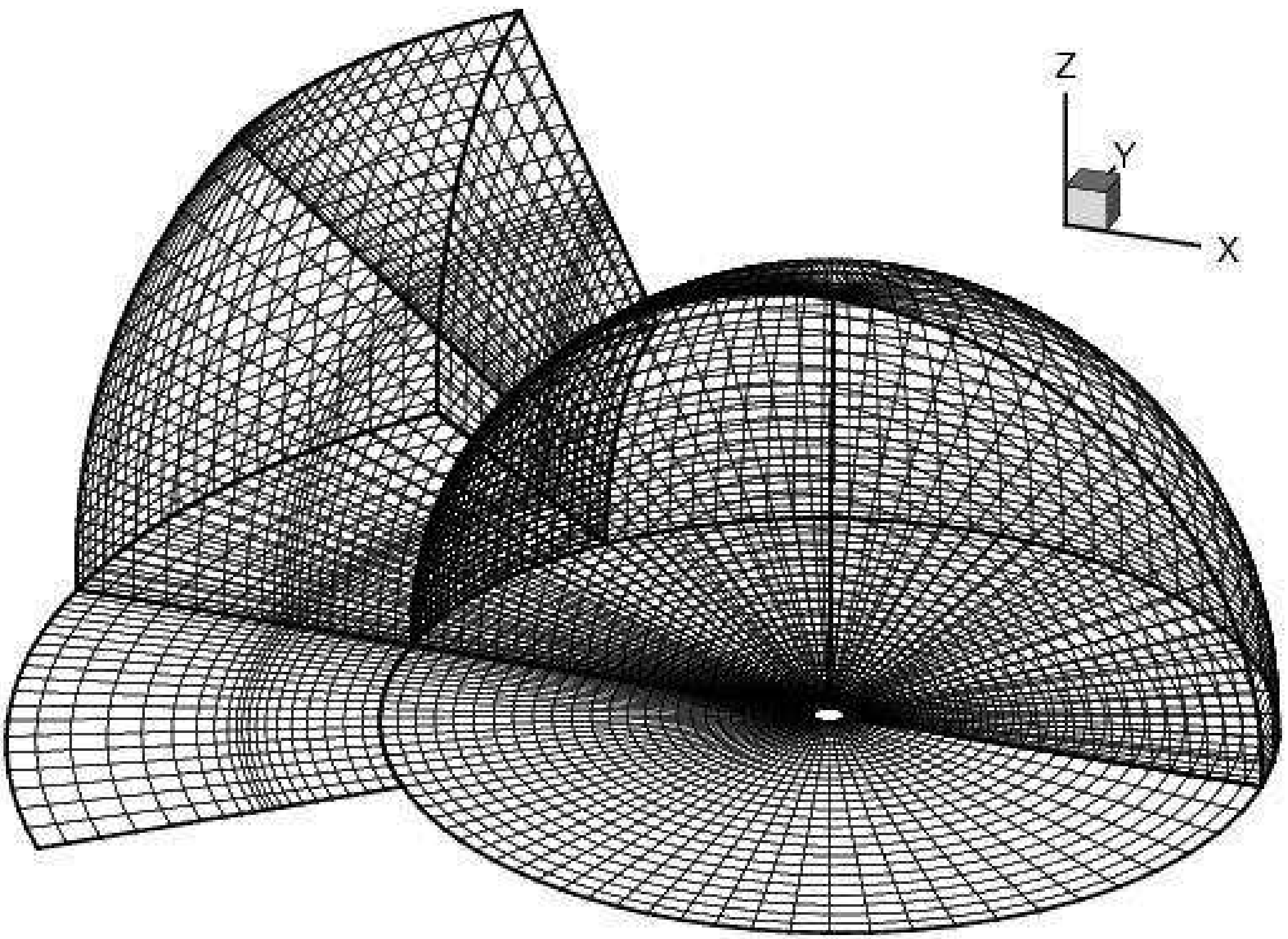

Figure 1. The three-dimensional generalized curvilinear coordinate system used in this paper. The bottom plane is the equatorial plane. The center of the gas disc, i.e. the BH, is placed at the center of a rightward hemisphere, and the SN explosion occurs at the center of an adjacent protuberant region. A half of grids in the computational domain are shown, after the whole domain is cut by a plane including the BH and the SN explosion point perpendicular to the equatorial plane. The number of grid points is $51 \times 101 \times 31$.

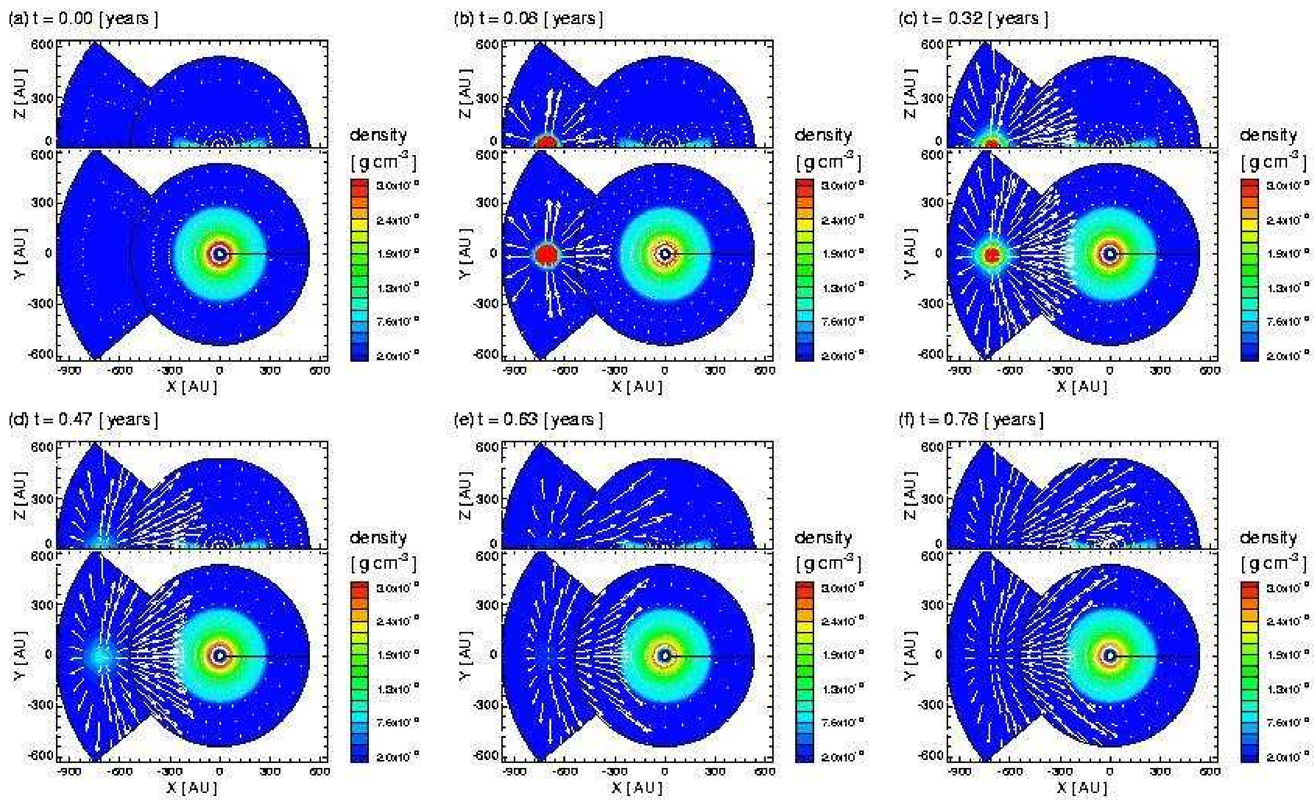

Figure 2. Early stages of the interaction of a SN blast wave with a disc around a BH for model A1. Snapshots show density distributions and velocity fields in the $x - y$ plane with $z = 0$ (*lower panels*), and in $x - z$ plane with $y = 0$ (*upper panels*).

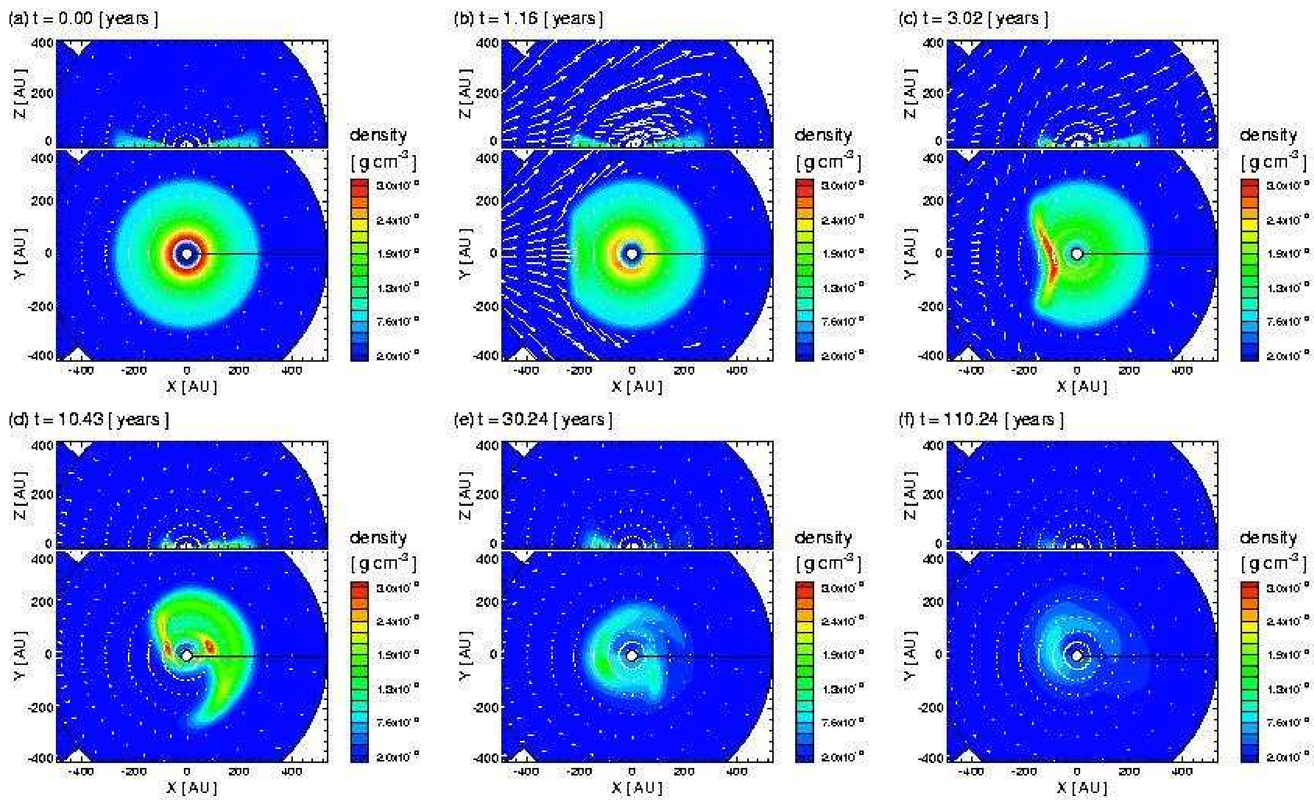

Figure 3. Later stages of the interaction of a SN blast wave with a disc around a BH for model A1, where the deformation and stripping processes of the gas disc are shown. The density distributions and the velocity fields are shown with zooming in disc regions.

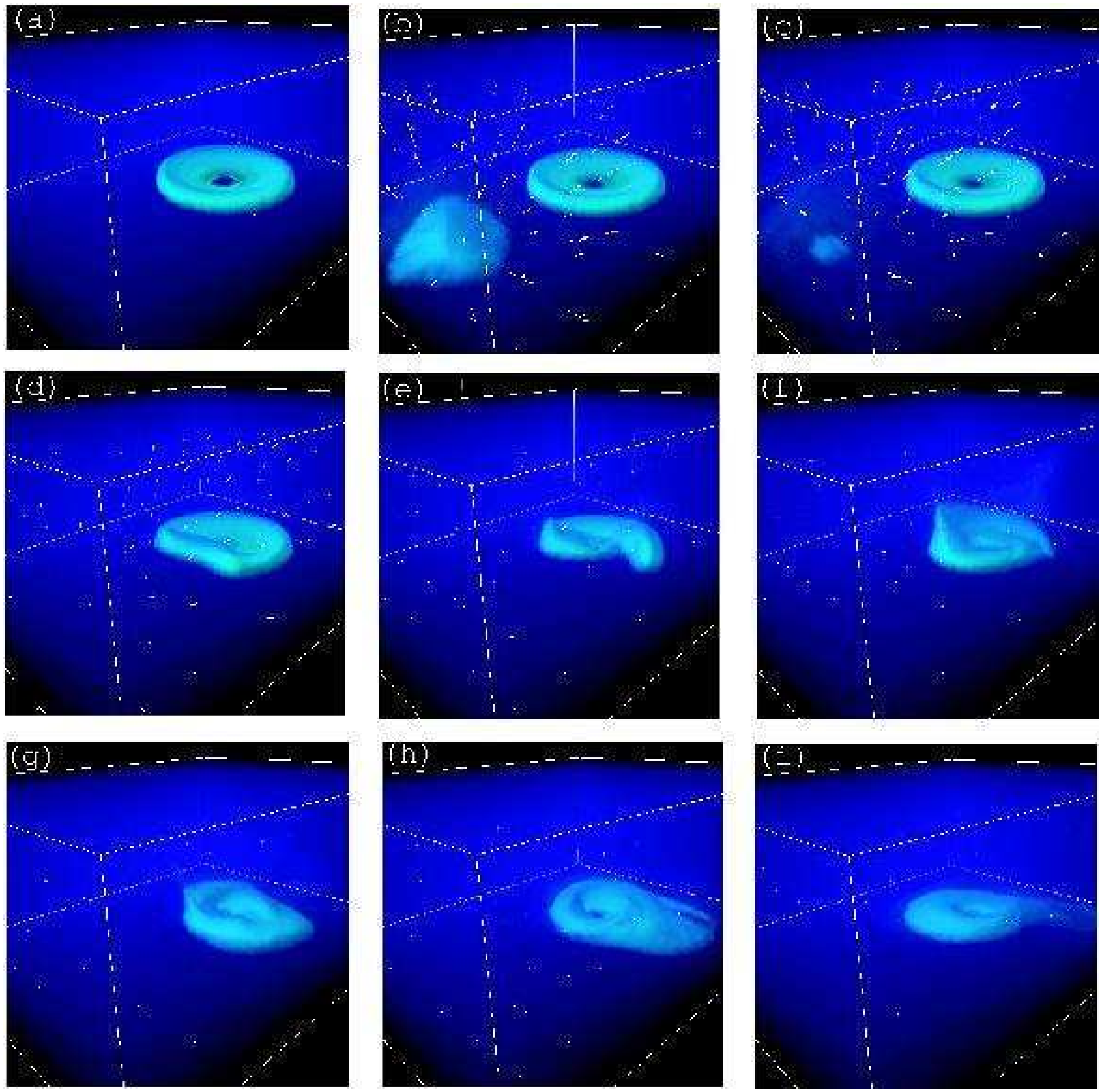

Figure 4. 3D volume rendering visualization of density distributions with velocity fields for model A1. Figures (a), (b), (c), (d), (e), (f), (g), (h) and (i) represent the snapshots at $t = 0.00, 0.63, 0.78, 2.90, 11.17, 35.72, 53.98, 72.98,$ and 110.24 yrs, respectively.

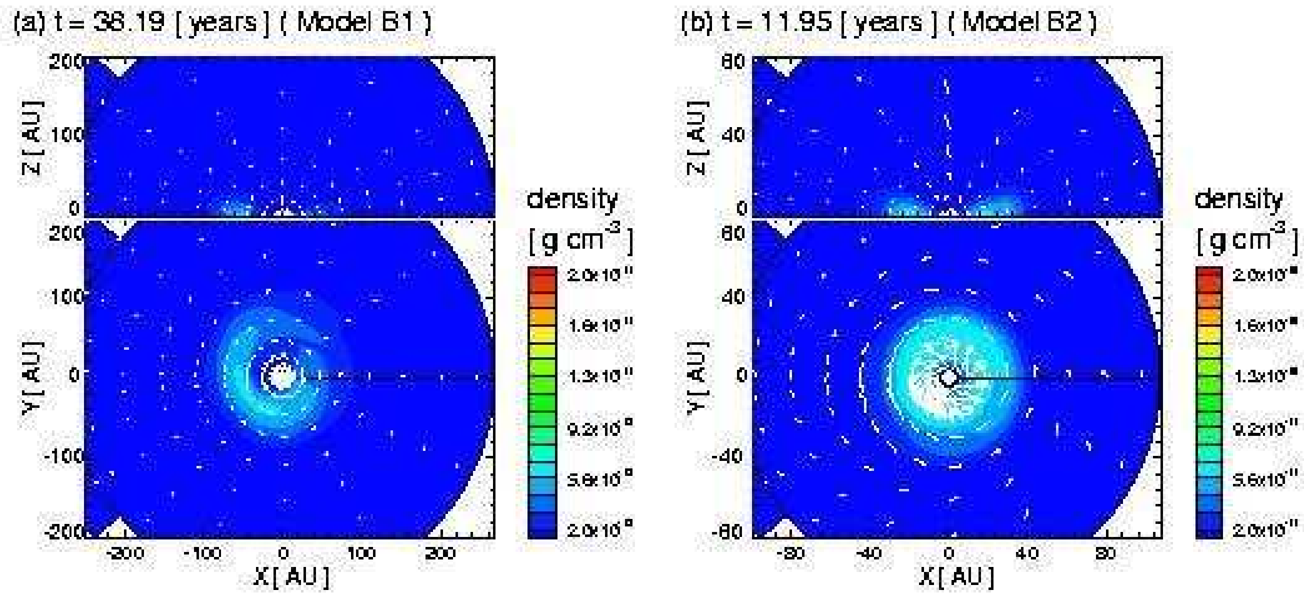

Figure 5. The density distributions and the velocity fields in the final state for shorter separation models; model B1 is a model with $a = 350$ AU (*left panel*) and model B2 is a model with $a = 140$ AU (*right panel*). The snapshots at $t = 38.19$ years and 11.95 years are presented for model B1 and B2, respectively.

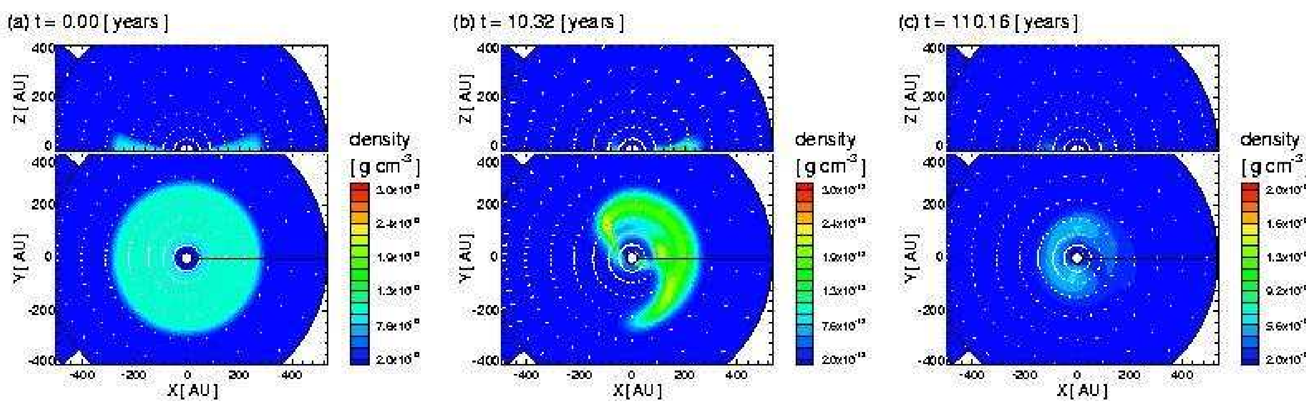

Figure 6. Same as Fig. 3 but for a flat density distribution model with $n = 0$ (model C1). The snapshots at $t = 0.00, 10.32,$ and 110.16 years are presented.

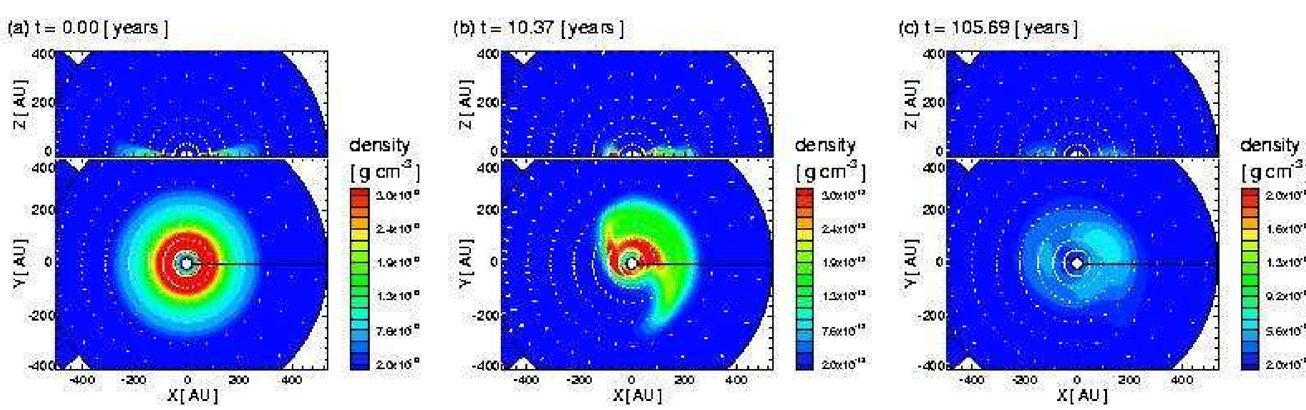

Figure 7. Same as Fig. 3 but for a central-concentration density distribution model with $n = -2$ (model C2). The snapshots at $t = 0.00, 10.37,$ and 105.69 years are presented.

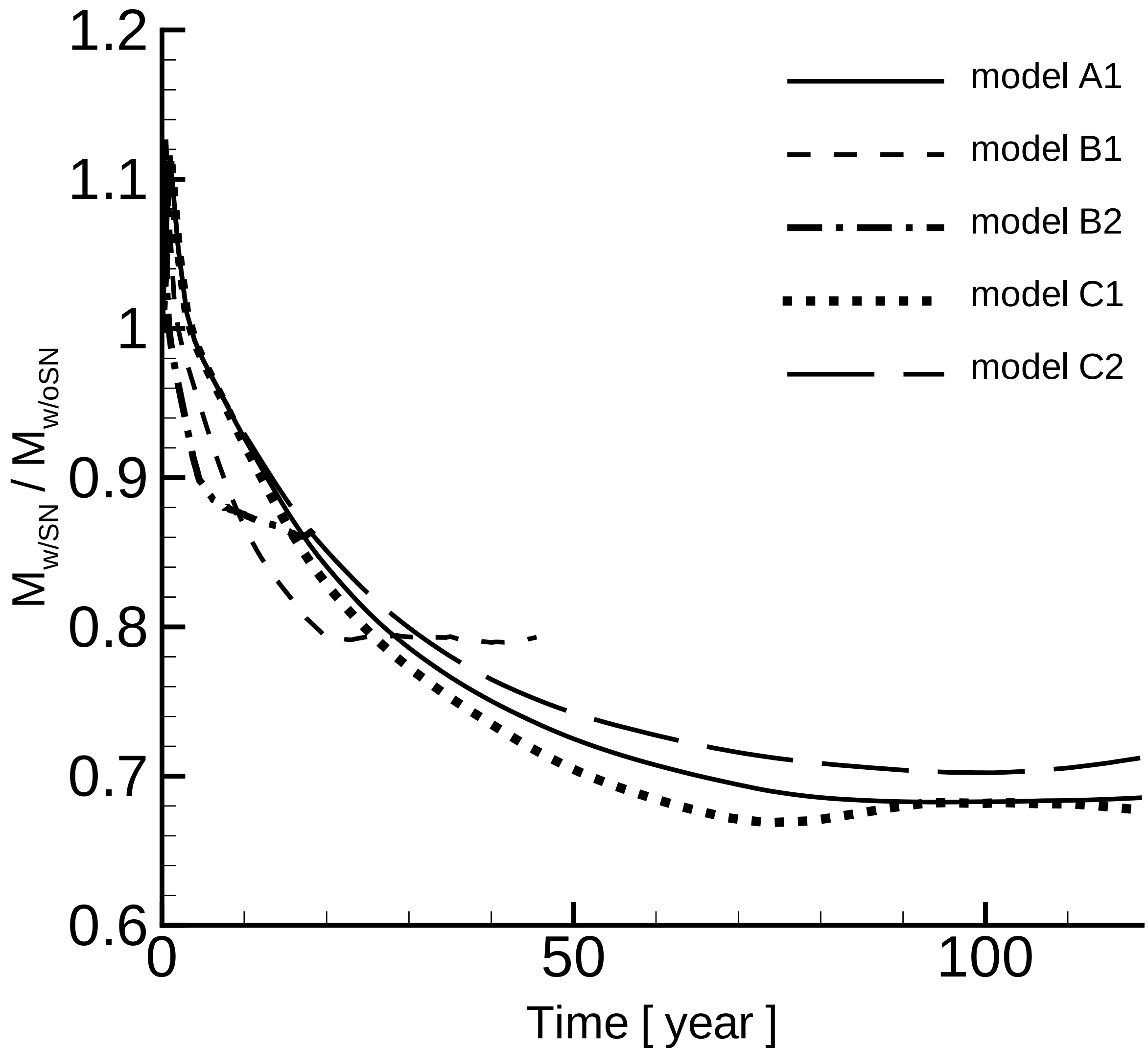

Figure 8. The time variation of the remaining mass of a disc affected by SN explosion, where the ratio of remaining mass to the mass of an undisturbed disc is shown. The horizontal axis is time in units of years. A solid line, a dashed line, a dash-dotted line, a dotted line and a log-dashed line show model A1, B1, B2, C1 and C2, respectively. Note that the ratio for each case starts exactly from unity. But, the strong inflow by supernova explosion causes the transient rapid growth of ratio by about 10% at the very early stage.

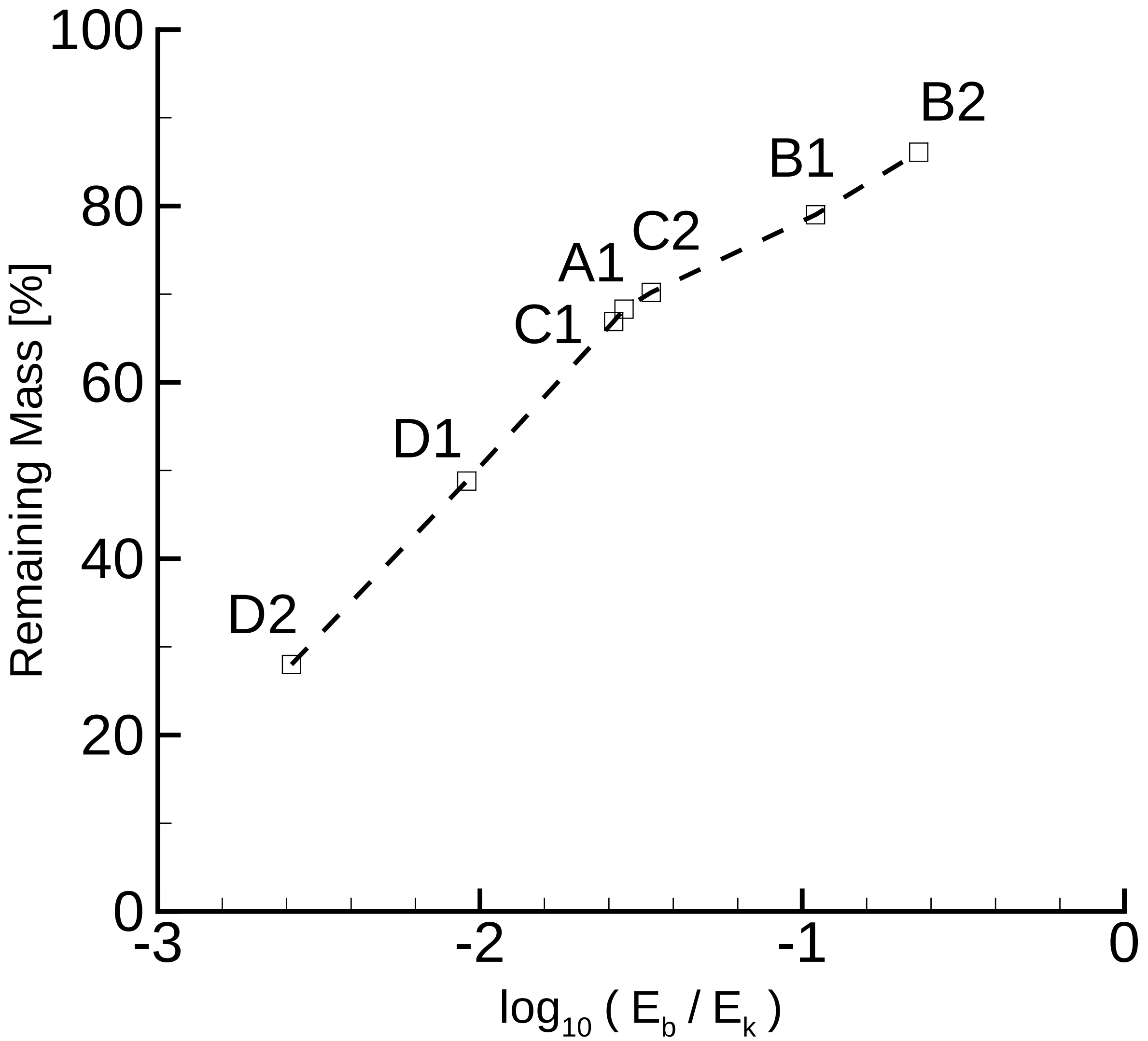

Figure 9. The resultant remaining mass fraction is shown against the ratio of E_b to E_k, where E_b is the binding energy of the gas disc around a BH and E_k is the kinetic energy of blast wave taking into account the solid angle of the disc viewed from the SN explosion point. The names near the symbols are model names.