The impact of a supernova explosion in a very massive binary

Jun’ichi Sato,1⋆† Masayuki Umemura1 and Keisuke Sawada2

1Centre for Computational Sciences, University of Tsukuba, Tsukuba 305-8577, Japan
2Department of Aeronautics and Space Engineering, Tohoku University, Sendai 980-8579, Japan

Accepted 2008 April 15. Received 2008 April 7; in original form 2008 January 7

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 100 M⊙. In a Population III binary system, a more massive star can result in the formation of a black hole (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 103 M⊙ that results from a direct collapse of a very massive star and a companion star of 100 M⊙ 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, accretion discs – 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 100–1000 M⊙ (Bromm, Coppi & Larson 1999; Abel, Bryan & Norman 2000, 2002) or to form in a bimodal initial mass function (IMF) with peaks of several 100 M⊙ and ∼1 M⊙ (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, Matsumoto & Umemura 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 ≥ 260 M⊙ result in direct black hole formation, while the mass range of 25 ≤ m ≤ 140 M⊙ 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 black hole (BH) with m ≥ 260 M⊙ and a massive star with 25 ≤ m ≤ 140 M⊙. Also, recent general relativistic simulations on a supermassive star (m ≥ 103 M⊙) 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; Sekiguchi & Shibata 2004; Shapiro 2004; 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 2004). For a BH of m ≈ 103 M⊙, the accretion disc can emit a blackbody radiation with an effective temperature of 106–107 K, if the mass accretion rate is close to the Eddington rate (e.g. Kato, Fukue & Mineshige 1998). When the disc mass is several 10 M⊙, the accretion time-scale is several 106 years. Therefore, the accreting BH can be an ultraviolet radiation source in a longer time-scale than the lifetime of a massive companion star. The accreting BH can then be a significant contributor for the early
reionization (Ricotti & Ostriker 2004). However, if the accretion disc is blown off by the SN explosion of a companion star, the accretion time-scale 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. The dependence on the ratio of the blast wave kinetic energy to the binding energy of a gas disc is then analysed in detail.

This 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 1000 M\(_\odot\) and a Pop III companion star of 100 M\(_\odot\). 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; Sekiguchi & Shibata 2004; Shapiro 2004; 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 30, 10 or 3 M\(_\odot\). Regarding the density distribution of gas disc, we assume a power-law type distribution like \(\rho \propto r^n\) on the equatorial plane. The power-law index \(n\) is assumed to be \(-0.7\) to 0.

The temperature of gas disc is presumed to be 10\(^7\) K, 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 Booth (2001). The tidal radius is \(\sim 0.7\) Roche lobe radius of the BH. For instance, the outer radius of the gas disc is set to be 280 au 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 \(\times 10^{-16}\) g cm\(^{-3}\) and 10\(^7\) K, 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 \(\times 10^7\) K 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 \(\rho_{SN} = 1.0 \times 10^{-11}\) g cm\(^{-3}\) and the extent is to be 50 au. 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 50 M\(_\odot\) (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

\[ \frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} + \frac{\partial \rho}{\partial t} \left( \frac{e}{\rho} + p \right) = 0, \]

where \(\rho\), \(u\), \(v\), \(w\), \(E\), \(F\), \(G\) and \(\dot{H}\) are, respectively, the following vectors:

\[
\begin{align*}
Q &= \begin{pmatrix} \rho & \rho u & \rho v & \rho w \end{pmatrix}, \\
E &= \begin{pmatrix} \frac{\rho u}{\rho} & \rho u^2 + p & \rho u v \end{pmatrix}, \\
F &= \begin{pmatrix} \frac{\rho v}{\rho} & \rho v w \end{pmatrix}, \\
G &= \begin{pmatrix} \frac{\rho w}{\rho} \end{pmatrix}, \\
\dot{H} &= \begin{pmatrix} 0 \end{pmatrix}.
\end{align*}
\]

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

| Model | \(a\) [au] | \(M_{disc}\) | \(n\) | 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 |

(e.g. Vinokur 1974), respectively, where \(\rho\) 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

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

where \(\gamma\) 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), that is, 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 a 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 that 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 centre of hemisphere, and the SN explosion occurs at the centre 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. 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 20 au 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 $50 \, M_\odot$ and the velocity of $4000 \, \text{km} \, \text{s}^{-1}$, 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. The collision of the blast wave with a disc is then 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

Fig. 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 the $x$–$z$ plane with $y = 0$ (upper panels). Fig. 2(a) shows the initial state, where high-density hot gas is ejected at 700 au from a BH. The hot gas expands almost radially (Fig. 2b) and rushes towards the gas disc (Fig. 2c). At $\sim 0.47$ yr, 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 centre is strongly decelerated by the collision with the disc, and begins to deform the disc (Figs 2e and f).

Figure 1. The three-dimensional generalized curvilinear coordinate system used in this paper. The bottom plane is the equatorial plane. The centre of the gas disc, that is, the BH, is placed at the centre of a rightward hemisphere, and the SN explosion occurs at the centre 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 $51 \times 101 \times 31$. 

© 2008 The Authors. Journal compilation © 2008 RAS, MNRAS 387, 1517–1524
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.
Fig. 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 $\sim 148$ yr. Fig. 3(a) is the initial state again. As seen in Figs 3(b) and (c), the blast wave pushes the left-hand 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. 3d). Through this deformation, the rotation balance breaks down, and resultant some of gas is blow out by centrifugal force, as seen in Fig. 3(e). Eventually, the gas disc is settled in a quasi-steady state within about 100 yr (Fig. 3f). As a result, roughly 70 per cent of an original disc around the BH is left over. In Fig. 4, the deformation and stripping processes are shown with three-dimensional volume rendering visualization. The survival of the gas disc after the heating and ruffling by the blast wave collision is clearly shown.

Previously, Wheeler, Lecar & McKee (1975) argued that in a binary system the mass stripping and ablation from a star by the impinging blast wave is well expressed by a non-dimensional parameter $\Psi$, which is defined as

$$\Psi = \frac{1}{4} \frac{M_{SN} R^2}{M_c a^2} \left( \frac{v_{SN}}{v_{es}} - 1 \right),$$

(4)

where $M_{SN}$ is the mass of gas expelled by a SN, $M_c$ and $R$ are, respectively, the mass and radius of object affected by blast wave, $v_{SN}$ is the typical speed of the blast wave, and $v_{es}$ is the escape velocity. They obtained the mass fraction ejected by the stripping and ablation as a function of $\Psi$. We can evaluate $\Psi$ in the present system, where $M_{SN} = 50 M_\odot$, $M_c = M_{\text{disc}} = 30 M_\odot$, $R = 280$ au, $a = 700$ au and $v_{SN} = 4000$ km s$^{-1}$, $v_{es}$ is approximated to be

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

(5)

where $M_{BH} = 1000 M_\odot$. We then find $\Psi \approx 3.28$ 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 $\Psi \approx 3$. In the present simulation, about

![Figure 4. Three-dimensional 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 yr, respectively.](image-url)
30 per cent of mass is ejected eventually. Therefore, we can conclude that $\Psi$ is a fairly good measure for the mass ejection even in a disc system. However, in the disc system, a little more mass remains than the prediction for a spherical star. In the collision of blast wave with a gas disc, the streamline is more strongly bent above and below the disc. Hence, the momentum transferred to the gas in a disc 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 models B1 and B2 is $\sim 52$ and $\sim 13$ yr, respectively. Fig. 5 shows the density distributions and the velocity fields in the final quasi-steady state, which is reached at $t = 38.19$ and $11.95$ yr 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 per cent of disc survives for model B1, and nearly 85 per cent 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 $\sim 0.1$ and $\sim 0.2$ 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. Fig. 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 $110.16$ yr are presented. The results look similar those shown in Fig. 3 at the same evolutionary stages. Actually, the remaining mass is not changed significantly. Fig. 7 show the

![Figure 5](https://academic.oup.com/mnras/article-abstract/387/4/1517/1088830)

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

![Figure 6](https://academic.oup.com/mnras/article-abstract/387/4/1517/1088830)

**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 $110.16$ yr are presented.
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 yr 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. 7b), compared to model C1 (Fig. 6b). However, the remaining mass increases by only several per cent. Therefore, we can conclude that the density distributions of disc do not influence the final mass of disc strongly.

3.4 Remaining mass

In Fig. 8, the time-sequences of the disc mass are summarized by the ratio of the remaining disc mass to the disc mass without a SN explosion of companion star. For model A1, C1 and C2, the disc is settled in quasi-steady states in 60 yr, and ~70 per cent 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 yr and ~80 per cent of disc gas remains. For model B2 ($a = 140$ au), the disc reaches a quasi-steady state in 10 yr and ~85 per cent 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. Fig. 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 10 $M_\odot$, which is one-third of that in model A, and model D2 has the disc mass of 3 $M_\odot$, 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 per cent 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 Fig. 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 per cent 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.

ACKNOWLEDGMENTS
We thank K. Hiroi for many useful comments. Numerical simulations have been performed with computational facilities at Centre for Computational Sciences in University of Tsukuba. This work was supported in part by Grants-in-Aid for Specially Promoted Research by MEXT in Japan (16020203), Grant-in-Aid for Scientific Research (S) by JSPS (20224022).

REFERENCES
Abel T., Bryan G. L., Norman M. L., 2000, ApJ, 540, 39
Abel T., Bryan G. L., Norman M. L., 2002, Sci, 295, 93
Boffin H. M. J., 2001, in Boffin H. M. J., Steeghs D., Cygters J., eds, Lecture Notes in Physics Vol. 573, Astrotomography. Springer, Heidelberg, p. 69
Bromm V., Coppi P. S., Larson R. B., 1999, ApJ, 527, L5
Bromm V., Yoshida N., Hernquist L., 2003, 596, L135
Heger A., Woosley S. E., 2002, ApJ, 567, 532
Kato S., Fukue J., Mineshige S., eds, 1998, Black Hole Accretion Discs. Kyoto Univ. Press, Kyoto
Kitayama T., Yoshida N., 2005, ApJ, 630, 675
Lawlor T. M., Young T. R., Johnson T. A., MacDonald J., 2008, MNRAS, 384, 1533
Madau P., Rees M. J., Volonteri M., Haardt F., Oh S. P., 2004, ApJ, 604, 484
Nakamura F., Umemura M., 2001, ApJ, 548, 19
Paczynski B., 1977, ApJ, 216, 822
Ricotti M., Ostriker J. P., 2004, MNRAS, 352, 547
Saggo K., Matsumoto T., Umemura M., 2004, ApJ, 615, L65
Sekiguuchi Y., Shibata M., 2004, Phys. Rev. D, 70, 084005
Shapiro S. L., 2004, ApJ, 610, 913
Shibata M., 2004, ApJ, 605, 350
Shibata M., Shapiro S. L., 2002, ApJ, 572, L39
Takeda H., Matsuda T., Sawada K., Hayashi C., 1985, Prog. Theor. Phys. 74, 272
Vinokur M., 1974, J. Comput. Phys., 14, 105.
Wada Y., Liou M. S., 1994, AIAA Paper, 94-0083
Wheeler J. C., Lecar M., McKee C. F., 1975, ApJ, 200, 145

This paper has been typeset from a TeX/LaTeX file prepared by the author.