INELASTIC NEUTRINO-HELIUM SCATTERINGS AND STANDING ACCRETION SHOCK INSTABILITY IN CORE-COLLAPSE SUPERNOVAE

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ABSTRACT

We present the results of numerical experiments, in which we have investigated the influence of the inelastic neutrino-helium interactions on the standing accretion shock instability supposed to occur in the postbounce supernova core. The axisymmetric hydrodynamical simulations of accretion flows through the standing accretion shock wave onto the proto-neutron star show that the interactions are relatively minor and the linear growth of the shock instability is hardly affected. The extra heating given by the inelastic reactions becomes important for the shock revival after the instability enters the nonlinear regime, but only when the neutrino luminosity is very close to the critical value at which the shock would be revived without the interactions. We have also studied the dependence of the results on the initial amplitudes of perturbation and the temperatures of mu and tau neutrinos.

Subject headings: hydrodynamics — instabilities — neutrinos — supernovae: general

1. INTRODUCTION

Most of the supernova modelers are currently concerned with the multidimensional aspects of the dynamics, pushed by the accumulating observational evidence that the core-collapse supernovae are generally aspherical (Wang et al. 1996, 2001, 2002). Various mechanisms to produce the asymmetry have been considered so far. Among them are the convection (e.g., Herant et al. 1994; Burrows et al. 1995; Janka & Mueller 1996), growth of asymmetry seeds generated prior to core-collapse (Burrows & Hayes 1996; Fryer 2004), rotation, and magnetic fields (see Yamada & Sawai 2004; Kotake et al. 2004; Takiwaki et al. 2004; Sawai et al. 2005; Ardeljan et al. 2005; Kotake et al. 2006 for collective references).

Recently, the standing accretion shock instability (SASI) has been attracting the interest of researchers. The instability was originally studied for transonic accretion flows to black holes (e.g., Foglizzo 2001, 2002) and was rediscovered by Blondin et al. (2003) in the context of core-collapse supernovae. Blondin et al. (2003) found that their two-dimensional (2D) numerical simulations of the spherically symmetric, isentropic, steady accretion flows that a standing shock wave is unstable to nonspherical perturbations and that the perturbations grow up to the nonlinear regime with a clear dominance of the $\ell = 1$ mode at first and the $\ell = 2$ mode later, leading to a global deformation of the shock wave, as has been observed. Here $\ell$ stands for the azimuthal index of the Legendre polynomials.

The mechanism of the instability is still controversial. Blondin & Mezzacappa (2006) took cooling into account in a simple analytic way following Houck & Chevalier (1992) and claimed that the repeated propagations of pressure fluctuations are responsible for the instability. On the other hand, Ohnishi et al. (2006) did 2D numerical experiments, implementing more realistic heating as well as cooling by neutrinos and found that the original idea by Foglizzo (2001, 2002) that the nonradial instability is driven by the cycle of the advection of entropy and velocity fluctuations and propagation of pressure perturbations seems to be more appropriate. Obviously, detailed linear analyses of the instability are needed further (Galletti & Foglizzo 2005; Yamasaki & Yamada 2007; Laming 2007).

It is important that such a low-$\ell$-mode deformation of the shock wave has been also observed in more realistic simulations (Scheck et al. 2004) and that the asymmetric explosion following the instability might reproduce various nonspherical features of SN 1987A (Kifonidis et al. 2006). It should be also emphasized that the instability is helpful for the shock revival just as the convection is (Ohnishi et al. 2006). The problem is whether the instability enhances the neutrino heating sufficiently to revive the stalled shock. Recent numerical investigations by Janka et al. (2005) seem to say “no” to this question. It is true that we have to wait for detailed three-dimensional (3D) simulations before drawing a conclusion, but we had better continue to seek for some other processes that would further facilitate the shock revival. As such a potential boost, we focus in this paper on the interplay between the inelastic neutrino-nucleus interactions and the SASI.

The potential importance of the inelastic neutrino-nucleus interactions was first pointed out by Haxton (1988), who paid attention to the heating and dissociations of nuclei in the matter ahead of the shock wave via these reactions, the so-called preheating. Taking the reactions into account in their one-dimensional (1D) spherically symmetric numerical simulations, Bruenn & Haxton (1991) found that the effect of preheating is quite minor, mainly because $\nu_e$ energies obtained in the simulation were much lower than the ones assumed in Haxton (1988). They also discussed the possibility of shock revival by enhanced heating of the postshock material by inelastic $\nu_e$, $\mu^+e^-$He scatterings, an idea similar to the one pursued in this paper. They found that the reactions are not very important. It should be emphasized, however, that the conclusion will be sensitive to the background model, and they considered a single snapshot after the bounce. Furthermore, in the spherically symmetric models most of the nuclei are photodisintegrated after passing through the shock, and the reactions will rarely occur anyway. The situation may be different in nonspherical cases.
Since the shock wave hovers at larger radii in general, not all the nuclei are dissociated and the heating region will be wider. In this paper we pay particular attention to the interplay between the SASI and the inelastic reactions.

The plan of this paper is as follows. We describe the numerical methods, input physics, and models in § 2. The main numerical results are shown in § 3. We conclude this paper with § 4.

2. NUMERICAL METHOD, INPUT MICROPHYSICS, AND MODELS

In this paper we study the effects of the inelastic neutrino-helium interactions on the evolution of accretion flows through a shock wave onto a proto-neutron star, in particular, the growth of SASI. We assume axisymmetry of the system and do 2D numerical simulations.

The numerical methods employed in this paper are essentially the same as those used in our previous paper (Ohnishi et al. 2006). The following equations describe the compressible accretion flows of matter attracted by the proto-neutron star and irradiated by neutrinos emitted from the neutrino sphere:

\[
\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0, \quad (1)
\]

\[
\frac{d\mathbf{v}}{dt} = - \nabla P - \rho \nabla \Phi, \quad (2)
\]

\[
\rho \frac{d}{dt} \left( \frac{e}{\rho} \right) = - \mathbf{P} \nabla \cdot \mathbf{v} + Q_E + Q_{\text{inel}}, \quad (3)
\]

\[
\frac{dY_e}{dt} = Q_N, \quad (4)
\]

\[
\Phi = - \frac{GM_n}{r}, \quad (5)
\]

where \(\rho\), \(v\), \(e\), \(P\), \(Y_e\), and \(\Phi\) are the density, velocity, internal energy, pressure, electron fraction, and gravitational potential, respectively. The Lagrangian derivative is denoted by \(d/dt\), and \(r\) is the radius. The self-gravity of matter in the accretion flow is ignored (see Yamasaki & Yamada 2006 for the effect). The parameters of \(Q_E\) and \(Q_N\) are related to the interactions of neutrinos and free nucleons (see also Ohnishi et al. 2006), and \(M_n\) is the mass of the central object.

In addition to the standard heating and cooling via neutrino absorptions and emissions by free nucleons, here we consider the inelastic neutrino-helium interactions. The heating rates denoted by \(Q_{\text{inel}}\) were estimated by Haxton (1988) for the inelastic scatterings on nuclei via neutral currents, \(\nu + (A, Z) \rightarrow \nu + (A, Z)'\), as

\[
Q_{\text{inel}} = \frac{\rho X_A}{m_B} \frac{31.6 \text{ MeV}}{(r/10^7 \text{ cm})^2} \times \left[ \frac{L_{\nu_\mu}}{10^{52} \text{ ergs s}^{-1}} \right] \left( \frac{5 \text{ MeV}}{T_{\nu_\mu}} \right) A^{-1} \left( \sigma^0_{\nu_\mu} E_{\nu_\mu} + \sigma^0_{\nu_\mu} E_{\nu_\mu}' \right) r_{\nu_\mu} + \left[ \frac{L_{\bar{\nu}_\mu}}{10^{52} \text{ ergs s}^{-1}} \right] \left( \frac{5 \text{ MeV}}{T_{\bar{\nu}_\mu}} \right) A^{-1} \left( \sigma^0_{\bar{\nu}_\mu} E_{\bar{\nu}_\mu} + \sigma^0_{\bar{\nu}_\mu} E_{\bar{\nu}_\mu}' \right) r_{\bar{\nu}_\mu} + \left[ \frac{L_{\nu_\tau}}{10^{52} \text{ ergs s}^{-1}} \right] \left( \frac{10 \text{ MeV}}{T_{\nu_\tau}} \right) A^{-1} \left( \sigma^0_{\nu_\tau} E_{\nu_\tau} + \sigma^0_{\nu_\tau} E_{\nu_\tau}' \right) r_{\nu_\tau}, \quad (6)
\]

where \(X_A\) is the mass fraction of the nucleus, \(m_B\) is the atomic mass unit, \(L_{\nu}\) and \(T_{\nu}\) in the square brackets are the neutrino luminosity and temperature, respectively, and \(A\) is the mass number of the nucleus. The last term denotes the sum of the contributions from mu and tau neutrinos. The cross section for each neutral current is evaluated by the fitting formula

\[
A^{-1} \left( \sigma^0_{\nu} E_{\nu} + \sigma^0_{\nu} E_{\nu}' \right) r_{\nu} = \alpha \left( \frac{T_{\nu} - T_0}{10 \text{ MeV}} \right)^\beta, \quad (7)
\]

where \(\alpha\), \(\beta\), and \(T_0\) are given in Table I of Haxton (1988). Since we are concerned with the reactions with \(^4\)He, the only nucleus that is abundant in the postshock matter, these parameters are chosen to be \(\alpha = 1.24 \times 10^{-40} \text{ MeV cm}^2\), \(\beta = 3.82\), and \(T_0 = 2.54 \text{ MeV}\). In the first and second terms on the right-hand side of equation (6), the contributions from the charged-current reactions, \(\sigma_{\nu}^+\) and \(\sigma_{\nu}^-\), are also taken into account according to Table II of Haxton (1988). We ignore the variations of the electron fraction by these reactions, since they are minor and make no qualitative difference to the dynamics. Considering the uncertainties inherent to the theoretical estimation of the reaction rates, we multiply rather arbitrarily the rates obtained above and discuss the dependence of the outcomes on this factor.

The numerical code employed in this paper is based on the ZEUS-2D (Stone & Norman 1992) code, which is an Eulerian code based on the finite-difference method with an artificial viscosity of the von Neumann and Richtmyer type. We have made several major changes to the base code to include appropriate microphysics. For example, we have added the equation for electron fraction (eq. [4]), which is solved in the operator-splitting fashion. We have also incorporated the tabulated realistic equation of state (EOS) based on the relativistic mean field theory (Shen et al. 1998) instead of the ideal gas EOS assumed in the original code. The reason why only \(^4\)He is considered in this paper is that the abundance of other nuclei is negligibly small in the postshock matter. The mass fraction of \(^4\)He is obtained from the EOS.

Spherical coordinates are used. No equatorial symmetry is assumed, and the computation domain covers the whole meridian section with 60 angular mesh points, except for a model in which we have adopted 120 angular mesh points. Since the latter model did not produce any significant difference from other models, we report in the following the results obtained from the models with 60 angular mesh points. We use 300 radial mesh points to cover \(r_{in} \leq r \leq r_{out} = 2000 \text{ km}\), where \(r_{in}\) is the inner boundary and is chosen to be roughly the radius of the neutrino sphere.

The initial conditions are prepared in the same manner as in Ohnishi et al. (2006). The steady state solutions obtained by Yamasaki & Yamada (2005) for a fixed density at the inner boundary, \(\rho_{out} = 10^{11} \text{ g cm}^{-3}\), are utilized. In so doing, \(Q_{\text{inel}}\) is not taken into account. Hence, the initial state is not completely steady when the inelastic interactions are considered, and this slight inconsistency can be regarded as an additional radial perturbation. As shown below, however, the effect is small and limited to a very narrow region and matters little to the analysis of the following dynamics. To induce the nonspherical instability, we have added \(\ell = 1\) velocity perturbations to the initial state mentioned above.

All the numerical models are summarized in Table 1. The mass accretion rate and the mass of the proto-neutron star are fixed to be \(\dot{M} = 1 M_\odot \text{ s}^{-1}\) and \(M_n = 1.4 M_\odot\), respectively. The temperatures of electron-type neutrinos are also constant and set to be \(T_{\nu} = 4 \text{ MeV}\) and \(T_{\bar{\nu}} = 5 \text{ MeV}\), which are the typical values in the postbounce phase. For most of the models, the temperature
TABLE 1
MODEL PARAMETERS

| Model   | $L_{\nu_e}$ ($10^{52}$ ergs s$^{-1}$) | $Q_{\text{inel}}$ (eq. [6]) | $\delta_{\nu_e}/\nu_{\text{th}}$ (%) | $T_{\nu_e}$ (MeV) | Shock Revival |
|---------|--------------------------------------|-------------------------------|------------------------------------|------------------|---------------|
| L590... | 5.9                                  | ...                           | 1                                  | 10               | X             |
| L591... | 5.9                                  | 1                             | 1                                  | 10               | X             |
| L593... | 5.9                                  | 3                             | 1                                  | 10               | O             |
| L59110... | 5.9                                  | 10                            | 1                                  | 10               | O             |
| L5913... | 5.9                                  | 30                            | 1                                  | 10               | O             |
| L590d5... | 5.9                                  | ...                           | 5                                  | 10               | X             |
| L591d5... | 5.9                                  | 1                             | 5                                  | 10               | X             |
| L5913d5... | 5.9                                  | 3                             | 5                                  | 10               | O             |
| L590d10... | 5.9                                  | ...                           | 10                                 | 10               | O             |
| L59T15... | 5.9                                  | 1                             | 1                                  | 15               | X             |
| L59T20... | 5.9                                  | 1                             | 1                                  | 20               | X             |
| L59T25... | 5.9                                  | 1                             | 1                                  | 25               | O             |
| L580... | 5.8                                  | ...                           | 1                                  | 10               | X             |
| L581... | 5.8                                  | 1                             | 1                                  | 10               | O             |
| L5815... | 5.8                                  | 5                             | 1                                  | 10               | O             |
| L58110... | 5.8                                  | 10                            | 1                                  | 10               | O             |
| L5815... | 5.8                                  | 15                            | 1                                  | 10               | O             |
| L5820... | 5.8                                  | 20                            | 1                                  | 10               | O             |
| L5830... | 5.8                                  | 30                            | 1                                  | 10               | O             |
| L5840... | 5.8                                  | 40                            | 1                                  | 10               | O             |
| L5850... | 5.8                                  | 50                            | 1                                  | 10               | O             |
| L581100... | 5.8                                | 100                           | 1                                  | 10               | O             |
| L571... | 5.7                                  | ...                           | 1                                  | 10               | X             |
| L5711... | 5.7                                  | 1                             | 1                                  | 10               | X             |
| L57110... | 5.7                                  | 10                            | 1                                  | 10               | X             |
| L57130... | 5.7                                  | 30                            | 1                                  | 10               | X             |
| L571100... | 5.7                                | 100                           | 1                                  | 10               | O             |
| L550... | 5.5                                  | ...                           | 1                                  | 10               | X             |
| L551... | 5.5                                  | 1                             | 1                                  | 10               | X             |
| L5510... | 5.5                                  | 10                            | 1                                  | 10               | X             |
| L5530... | 5.5                                  | 30                            | 1                                  | 10               | X             |
| L55110... | 5.5                                  | 100                           | 1                                  | 10               | X             |
| L551100... | 5.5                               | 1000                          | 1                                  | 10               | X             |

Notes.—The variable $L_{\nu_e}$ represents the luminosity of the electron-type neutrino. For $Q_{\text{inel}}$, only the multiplicative factor is given. The term $\delta_{\nu_e}/\nu_{\text{th}}$ denotes the initial relative amplitude of the velocity perturbation. The variable $T_{\nu_e}$ is the temperature of mu and tau neutrinos. The “successful shock revival” is defined as a continuous increase of the shock radius by $\approx 500$ ms.

3. RESULTS

Figure 1 shows the mass fractions of protons, neutrons, and helium (top panel) and the profiles of $Q_E$ and $Q_{\text{inel}}$ (bottom panel) at the initial time for the reference model L5910, where $L_{\nu_e}$ is set to be $5.9 \times 10^{52}$ ergs s$^{-1}$ and $T_{\nu_e} = 10$ MeV. The helium abundance is small except for a narrow region inside the shock wave. All the nuclei are completely dissociated to nucleons after passing through the shock wave, because the standing shock is located deep inside the gravitational potential well in spherically symmetric accretions, and as a result, the postshock temperature becomes too high for nuclei to survive. There is also a small population of helium ahead of the shock owing to the partial decomposition of nuclei by adiabatic compressions. This small abundance is the main reason why most of the detailed numerical simulations have not incorporated the reactions of neutrinos with helium so far. The heating by the inelastic interactions is appreciable only inside the shock wave accordingly. Note also that the value of $Q_{\text{inel}}$ is multiplied by a factor of 30 in Figure 1. It is thus expected that the inelastic reactions will not affect the dynamics at least in the initial phase. This may not be the case for later phases, however. After the nonspherical instability grows, the shock radius becomes larger in general, and as a result, the helium abundance will be increased in a wider region. Moreover, most of this helium will be populated in the so-called heating region (see Fig. 5).

We first summarize the basic feature of the temporal evolution of the reference model L5910 after 1% of the $\ell = 1$ single-mode velocity perturbation is added. The exponential growth of the perturbation is observed at first, and the shock surface is deformed by the increasing amplitude of the nonradial mode. When the nonlinear regime is reached, the shock begins to oscillate with large amplitudes. As shown in Figure 2, where the time evolution...
of the angle-averaged shock radius is presented, the oscillation becomes quasi-steady by $\sim 150$ ms. Note that the shock radius in this phase is larger than the initial value, as pointed out by Ohnishi et al. (2006). We have found no shock revival for this model. In fact, as mentioned above, the shock revival is found only for $L_{\nu e}/C_{23} > 6 \times 10^{52}$ ergs s$^{-1}$ if the inelastic interactions are not taken into account. In the last column of Table 1, we summarize for each model if the shock revival is found by 500 ms after the onset of computation. It should be noted that the shock revival, if observed in our models, does not guarantee the explosion in more realistic settings, since the neutrino luminosity will not be constant in time as assumed in our models and will decline in reality. Hence, our criterion for the shock revival should be regarded as a minimum requirement for explosion.

Now we proceed to consider the effect of the inelastic interactions of neutrinos with helium. The time evolution of shock radius for models L59I1, L59I3, and L59I10 are presented in Figure 2 together with that for the reference model L59I0. These models have the same neutrino luminosity and initial velocity perturbation as the reference model. The difference is the assumed cross sections for the inelastic reactions. As mentioned above, considering the uncertainties that the theoretical estimation inherently has, we multiply the nominal values of the cross sections given by equations (6) and (7) by the factors given in Table 1. Except for model L59I10, the shock oscillations accompanied by the growth of SASI are settled to quasi-steady states by $\sim 150$ ms just as in the reference model. The final shock radii are not very different from each other among these no-revival models and are larger than that of the initial condition. Model L59I10, whose $Q_{\nu e}$ is multiplied by a factor of 10, gives a shock revival after a rather long time, $\sim 450$ ms. As seen in Figure 2, the evolution in the early phase is essentially the same as for other models, as expected from the helium abundance in the initial condition. This is also seen in the growth rates of the $\ell = 1$ and 2 modes presented in Figures 3 and 4, respectively. Here we decompose the deformation of the shock surface into the spherical harmonic components,

$$ R_\ell (\theta) = \sum_{\ell=0}^\infty a_\ell \sqrt{\frac{2\ell + 1}{4\pi}} P_\ell (\cos \theta). $$  

Since the system is axisymmetric, only $m = 0$ harmonics, which are nothing but Legendre polynomials, show up. The coefficients $a_\ell$ can be calculated by the orthogonality of the Legendre polynomials,

$$ a_\ell = \frac{2\ell + 1}{2} \int_{-1}^{1} R_\ell (\theta) P_\ell (\cos \theta) \, d\cos \theta. $$  

The position of the shock surface $R_\ell (\theta)$ is determined as the isentropic surface of $\mathbf{s} = 5$. No essential difference between the results with the inelastic interactions and the results without them can be seen in both the linear phase lasting for $\sim 150$ ms and the early nonlinear phase. Therefore, the additional heating from the inelastic interactions does not play an important role in the growth of SASI.

Figure 5 shows in the meridian section the contours of the mass fractions of nucleons and helium and the neutrino heating rates for model L59I10. Note that the heating rates for the inelastic reactions (the right half of the right panels of Fig. 5) are plotted in the logarithmic scale, whereas those for the others (the left half) are plotted in the linear scale. At 100 ms when the perturbation is still growing in the linear regime, the mass fraction of helium is not so large in most of the region. One can see some minor heating via the inelastic interactions both inside and ahead of the shock wave; the latter of which is the preheating considered by Haxton.
At 300 ms, however, the shock front wobbles and is deformed substantially by the SASI in the nonlinear regime, a part of the shock reaches larger radii from time to time, and the region behind the portion of the shock front contains a nonnegligible fraction of helium. This is simply because the temperature becomes lower there and nuclei are not completely dissociated. As a result of this increased helium population, the neutrino heating is also enhanced, which then pushes the shock wave further outward and increases the volume, in which the helium is abundant. This positive feedback finally leads to the shock revival around 500 ms in this model. One can see at this time that most of the region behind the shock contains a large fraction of helium.

We point out here that the shock revival is rather sensitive to the initial amplitude of perturbation, as demonstrated in Figure 6, where we show the evolution of the angle-averaged shock radius.
for models L59I0d5, L59I1d5, and L59I3d5. In these models we have imposed 5%, instead of 1%, of the initial velocity perturbation. We can observe that the perturbation grows more rapidly in these models. The nonlinear regime is reached in ~100 ms. More importantly, the shock revival occurs even for model L59I3d5 with the cross sections of the inelastic reactions multiplied by a factor of 3 rather than 10, the value required for the initial perturbation of 1%. Note, however, that the shock revival is achieved without inelastic reactions if we add 10% of velocity perturbation initially (model L59I0d10).

It should be also mentioned that the inelastic interactions lose their importance very quickly as the neutrino luminosity is decreased. As shown in Table 1, the models with $L_{\nu} = 5.5 \times 10^{52}$ ergs s$^{-1}$ have not led to the shock revival even if we have multiplied the reaction rates by a factor of 100 (in fact, we have found a factor of 300 is required at least in this model). An interesting thing is that for models with $L_{\nu} = 5.8 \times 10^{52}$ ergs s$^{-1}$, the shock revival has been found for model L58I10 that has a multiplicative factor of 10, whereas the models with the factors of 15, 20, 30, and 40 (models L58I15, L58I20, L58I30, and L58I40, respectively) have not produced a shock revival (see Fig. 7). As shown in Figure 1, the mass fraction of helium just ahead of the shock is ~0.2 initially, and the preheating is actually operating. The preheating has both a positive effect, that is, the reduction of energy losses via dissociations of nuclei as pointed out by Bruenn & Haxton (1991), and a negative effect, that is, the increase of pressure ahead of the shock, but it turns out that both effects are quite minor and that they are too subtle to say which is more important. In fact, what happens here seems to be as follows. The shock revival is triggered by a rather accidental “local increase in the shock radius” in the nonlinear phase of SASI. The evolution of the instability proceeds in general via (1) the linear growth that is subject to the random fluctuations during the relaxation, leading to the nonmonotonic behavior observed for the L58I series. In fact, models L58I20, L58I30, and L58I40 do not explode in 500 ms as shown in Table 1, but they do explode in 800–900 ms (the elapsed times do not correlate with the multiplicative factors). On the other hand, model L58I15 does not explode even after 1 s. Thus, we think that these models are so close to the shock revival that the final outcome is subject to the random fluctuations during the relaxation. It is then admittedly difficult to determine very precisely the minimum multiplicative factor for the shock revival. However, as demonstrated by the L57I series, the general trend is unmistakable: as the neutrino luminosity is lowered, the inelastic scatterings lose their leverage very quickly.

Finally, we discuss the dependence of the results on the neutrino temperature. As can be understood from equation (7), the inelastic scattering rates are very sensitive to the energy of the incident neutrino ($\propto T_{\nu}^{3/2}$). This naturally leads us to the question of what will happen if the energy spectra of neutrinos are harder than commonly assumed. Since higher energy neutrinos are more important, here we modify only $T_{\nu}$. The results are given in Table 1 as the L59T series of models. Unfortunately, the results are not so sensitive to the neutrino temperature as the cross sections themselves. It is found that for $L_{\nu} = 5.9 \times 10^{52}$ ergs s$^{-1}$ the extra heating by the inelastic interactions is large enough to revive the stalled shock only when the temperature of mu and tau neutrinos is higher than $T_{\nu} = 25$ MeV. This is much larger than the canonical value $\approx 10$ MeV and is highly unlikely to be obtained in the supernova core (e.g., Liebendörfer et al. 2001).

4. SUMMARY AND DISCUSSION

We have investigated the possible effects of the inelastic interactions of neutrinos with helium on the shock revival in the postbounce supernova core. In particular, we have paid attention to their influence on the SASI, one of the major causes for the asymmetry of dynamics and a possible trigger of explosion. For the spherically symmetric models, Bruenn & Haxton (1991) found that both the preheating of matter ahead of the shock and heating of matter behind the shock via these reactions are quite minor. In fact, most of the nuclei are photodisintegrated after passing through the shock, and the reactions will scarcely occur anyway in the spherically symmetric models. The situation may be different in nonspherical cases, where the shock wave hovers at larger radii in general, not all the nuclei are dissociated, and the...
heating region is wider. In fact, these reactions have never been explored in a multidimensional context so far. We have done 2D numerical experiments on the postbounce accretion flows through the stalled shock wave onto the proto-neutron star, systematically changing the luminosity and temperature of the neutrinos and the initial amplitude of perturbation as well as the reaction rates.

We have found that the incorporation of the inelastic interactions has essentially no influence on the growth of the SASI, since very little helium exists in the postshock matter initially. However, these reactions become appreciable later when the SASI enters the nonlinear regime and the shock oscillates with large amplitudes. It has been shown that the extra heating by these interactions is helpful for the shock revival in principle. This is, however, true in practice only when the shock revival is not obtained with a slight margin without the interactions. In fact, we have observed that a small (~10%) reduction of the neutrino luminosity makes the interactions entirely negligible. Hence, it is understandable that larger initial amplitudes of perturbation make the interactions more important for shock revival. It is, however, mentioned that even if the luminosity is very close to the critical value, the cross sections estimated by Haxton (1988) seem to be too small. Although it is not easy to evaluate the uncertainties of the theoretical prediction, recent new calculations by Gazit & Barnea (2004) can be used as a guide. They predicted a bit larger $\beta$ than Haxton (1988). However, the enhancement of the heating rate for our reference model is only 15%, much too small for the interactions to have some influence on the shock revival. The fact that the dynamics is rather insensitive to the neutrino temperature is not encouraging either. Hence, we conclude that the inelastic interactions of neutrinos with helium will be important only in determining the shock revival point and the explosion energy precisely. In this sense, the inelastic interactions of neutrinos with other nuclei should be also incorporated in the realistic simulations.

We are thankful to T. Yamasaki and M. Watanabe for providing us with the information on their models. K. K. expresses thanks to K. Sato for continuing encouragement. The numerical calculations were partially done on the supercomputers at RIKEN and KEK (KEK supercomputer projects 02-87 and 03-92) and also carried out on VPP5000 and the general common-use computer system at the Center for Computational Astrophysics (CfCA), the National Astronomical Observatory of Japan. This work was supported in part by Grants-in-Aid for Scientific Research from the Ministry of Education, Science, and Culture of Japan (S14102004, 14079202, and 14740166) and a Grant-in-Aid for the 21st century COE program “Holistic Research and Education Center for Physics of Self-organizing Systems.”

REFERENCES

Ardeljan, N. V., Bisnovatyi-Kogan, G. S., & Moiseenko, S. G. 2005, MNRAS, 359, 333
Blondin, J. M., & Mezzacappa, A. 2006, ApJ, 642, 401
Blondin, J. M., Mezzacappa, A., & DeMarino, C. 2003, ApJ, 584, 971
Bruenn, S. W., & Haxton, W. C. 1991, ApJ, 376, 678
Burrows, A., & Hayes, J. 1996, Phys. Rev. Lett., 76, 352
Burrows, A., Hayes, J., & Fryxell, B. A. 1995, ApJ, 450, 830
Foglizzo, T. 2001, A&A, 368, 311
———. 2002, A&A, 392, 353
Fryer, C. L. 2004, ApJ, 601, L175
Galletti, P., & Foglizzo, T. 2005, in Semaine de l’Astrophysique Francaise, ed. F. Casoli et al. (Les Ulis: EDP Sciences), 487
Gazit, D., & Barnea, N. 2004, Phys. Rev. C, 70, 048801
Haxton, W. C. 1988, Phys. Rev. Lett., 60, 1999
Herant, M., Benz, W., Hix, W. R., Fryer, C. L., & Colgate, S. A. 1994, ApJ, 435, 339
Houck, J. C., & Chevalier, R. A. 1992, ApJ, 395, 592
Janka, H.-T., Buras, R., Kitaura Joyanes, F. S., Marek, A., Rampp, M., & Scheck, L. 2005, Nucl. Phys. A, 758, 19
Janka, H.-T., & Mueller, E. 1996, A&A, 306, 167
Kifonidis, K., Plewa, T., Scheck, L., Janka, H.-Th., & Mueller, E. 2006, A&A, 453, 661
Kotake, K., Sato, K., & Takahashi, K. 2006, Rep. Prog. Phys., 69, 971
Kotake, K., Sawai, H., Yamada, S., & Sato, K. 2004, ApJ, 608, 391
Laming, J. M. 2007, ApJ, 659, 1449
Liebendo¨rfer, M., Mezzacappa, A., Thielemann, F.-K., Messer, O. E., Hix, W. R., & Bruenn, S. W. 2001, Phys. Rev. D, 63, 103004
Ohnishi, N., Kotake, K., & Yamada, S. 2006, ApJ, 641, 1018
Sawai, H., Kotake, K., & Yamada, S. 2005, ApJ, 631, 446
Scheel, L., Plewa, T., Janka, H.-T., Kifonidis, K., & Muller, E. 2004, Phys. Rev. Lett., 92, 011103
Shen, H., Toki, H., Oyamatsu, K., & Sumiyoshi, K. 1998, Nucl. Phys. A, 637, 435
Stone, J. M., & Norman, M. L. 1992, ApJS, 80, 753
Takiwaki, T., Kotake, K., Nagataki, S., & Sato, K. 2004, ApJ, 616, 1086
Wang, L., Howell, D. A., Höfflich, P., & Wheeler, J. C. 2001, ApJ, 550, 1030
Wang, L., Wheeler, J. C., Li, Z., & Clocchiatti, A. 1996, ApJ, 467, 435
Wang, L., et al. 2002, ApJ, 579, 671
Yamada, S., & Sawai, H. 2004, ApJ, 608, 907
Yamasaki, T., & Yamada, S. 2005, ApJ, 623, 1000
———. 2006, ApJ, 650, 291
———. 2007, ApJ, 656, 1019

No. 1, 2007

INELASTIC $\nu$-HE SCATTERINGS AND SHOCK INSTABILITY