Thermal instability in a collisionally cooled gas

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ABSTRACT

Non-equilibrium (time-dependent) cooling rate and ionization state calculations are presented for a gas behind a shock wave with \( v \sim 50–150 \text{ km s}^{-1} \) (\( T_s \sim 0.5–6 \times 10^5 \text{ K} \)). Such shock waves do not lead to the radiative precursor formation; that is, the thermal evolution of a gas behind the shock wave is controlled by collisions only. We have found that the cooling rate in a gas behind a shock wave with \( v \sim 50–120 \text{ km s}^{-1} \) (\( T_s \sim 0.5–3 \times 10^5 \text{ K} \)) differs considerably from the cooling rate for a gas cooled from \( T = 10^8 \text{ K} \). It is well known that a gas cooled from \( T = 10^8 \text{ K} \) is thermally unstable for isobaric and isochoric perturbations at \( T \gtrsim 2 \times 10^8 \text{ K} \). We studied the thermal instability in a collisionally controlled gas for shock waves with \( v \sim 50–150 \text{ km s}^{-1} \). We found that the temperature range within which the post-shock gas is thermally unstable is significantly modified and depends on both gas metallicity and the ionic composition of the gas before the shock wave. For \( Z \gtrsim 0.1 Z_{\odot} \), the temperature range for which the thermal instability criterion for isochoric perturbations is not fulfilled widens in comparison with that for a gas cooled from \( T = 10^8 \text{ K} \), while that for isobaric perturbations remains almost unchanged. For \( Z \sim Z_{\odot} \), the gas behind a shock wave with \( v \lesssim 65 \text{ km s}^{-1} \) (\( T_s \lesssim 10^5 \text{ K} \)) is thermally stable to isochoric perturbations during all of its evolution. We have shown that the transition from isobaric to isochoric cooling for a gas with \( Z \gtrsim 0.1 Z_{\odot} \) behind a shock wave with \( T_s = 0.5–3 \times 10^5 \text{ K} \) occurs in a gas layer column density layer behind a shock wave than that for a gas cooled from \( T = 10^8 \text{ K} \). The ion states in a gas with \( Z \sim 10^{-3}–1 Z_{\odot} \) behind shock waves with \( T_s \lesssim 4 \times 10^5 \text{ K} \) demonstrate a significant difference from those in a gas cooled from \( T = 10^8 \text{ K} \). Such a difference is thought to be important for the correct interpretation of observational data, but is not very helpful for discriminating thermally stable gas.

Key words: atomic processes – plasmas – galaxies: general – intergalactic medium – galaxies: ISM.

1 INTRODUCTION

Thermal instability (TI), which has been comprehensively analysed by Field (1965), is frequently considered to be a good candidate to explain the evolution of planetary nebulae (Hunter & Sofia 1971), cooling flows (Nulsen 1986), the formation of interstellar clouds (Burkert & Lin 2000), the temperature distribution of the unstable interstellar gas in the Galactic disc (Gazol et al. 2001), the formation of high-velocity clouds in galactic corona (Binney, Nipoti & Fraternali 2009), and so on. An interesting question concerns the possibility of the development of TI behind shock waves. An analysis of stability in post-shock flow was performed by Shchekinov (1978, 1979) and Chevalier & Imamura (1982). Further progress was made by Yamada & Nishi (2001), who analysed TI behind radiative shock waves and studied its possible role in fragmentation. In numerical simulations, the role of TI behind radiative shock waves has been studied by many authors (e.g. Binette, Dopita & Tuohy 1985; David, Bregman & Seab 1988; Sutherland, Bicknell & Dopita 2003). In the above-mentioned papers, radiative shock waves with velocities \( \sim 150–1500 \text{ km s}^{-1} \) were considered, and the thermal/thermo-reactive instabilities were analysed in a diffuse interstellar photoionized gas with temperature below \( 10^4 \text{ K} \) (Corbelli & Ferrara 1995; Smith, Sigurdsson & Abel 2008). Shock waves with velocities \( \sim 50–150 \text{ km s}^{-1} \) are important in the evolution of dwarf galaxies. Such shock velocities can be associated with global star formation processes and winds in dwarf galaxies. Thus, it is interesting to study both the possibility of TI and the ionization and thermal evolution in a gas behind a shock wave with \( v \sim 50–150 \text{ km s}^{-1} \).

Such shock waves are believed to play a significant role in the metal enrichment of the intergalactic medium (IGM). Metals (heavy...
elements) produced by stars are transported into the IGM by shock waves from galaxies and clusters of galaxies (Gnedin 1998; Madau, Ferrara & Rees 2001; Shchekinov 2002; Aguirre & Schaye 2007; Meiksin 2009). The efficiency of metal ejection depends on many factors and parameters, for example the mass of a parent (for metals) galaxy, the star formation rate and the density profile. On one hand, massive galaxies should produce and may throw out a significant amount of metals because of the high-velocity shock waves. On the other hand, the escape velocity is high for such galaxies, and metals may be confined inside them. During star formation burst, however, dwarf galaxies can expel a major part of their metal products into the IGM (Ferrara, Pettini & Shchekinov 2000). The velocity of shock waves produced by dwarfs is several dozens of kilometres per second. Low-velocity shock waves do not lead to the radiative precursor formation (Dopita & Sutherland 1996). The ionizing flux produced by the stellar population of a parent galaxy is expected to be insignificant owing to the burst character of star formation processes (massive stars explode as supernovae on short time-scales, whereas low-mass stars do not produce sufficient numbers of ionizing photons). Therefore, the ionization and thermal evolution of the gas behind low-velocity shocks is governed mainly by collisions between atoms, ions and electrons.

The dynamics of interstellar/intergalactic gas in general can be understood by studying the ionization states of metals. Indeed, the C IV, N v and O vi ions are sensitive tracers of hot gas with T approximately several times 10^5 K (e.g. Edgar & Chevalier 1986). Using theoretical models, Indebetouw & Shull (2004a) investigated the ionization ratios of the Li-like absorbers C IV, N v and O vi in the Galactic halo, and Gnat & Sternberg (2009) considered the ionic column densities as tracers of the thermal and ionization evolution behind strong radiative shocks with velocities of more than 100 km s^{-1}. Shock waves with different velocities can be identified using spectral lines (Cox & Raymond 1985). The growth of TIs can be detected by the associated X-ray and optical-ultraviolet lines (David et al. 1988). The analysis of the observed column densities of ions can give information about interstellar and intergalactic structures (e.g. Fox et al. 2005; Simcoe et al. 2006; Gnat & Sternberg 2007; Agafonova et al. 2007; Vasiliev, Sethi & Nath 2010). Theoretical models of the ionization mechanisms give different predictions for ions and their ratios (e.g. Spitzer 1996), and usually the ionic ratios do not remove the ambiguities regarding the ionization conditions (e.g. Indebetouw & Shull 2004b). However, we can expect that ionization states of metals may help us to recognize shock waves with v ~ 50–150 km s^{-1} and to determine the physical conditions in the post-shock gas.

In this paper we study TI in a collisionally controlled gas behind a shock wave with v ~ 50–150 km s^{-1}. A possible influence from the external ionizing radiation field will be considered elsewhere. The paper is organized as follows. In Section 2 we briefly describe the details of the model. In Sections 3 and 4 we present our results, which are summarized in Section 5.

2 MODEL DESCRIPTION

Here we briefly describe our method of calculation. The full description of the method and the references to the atomic data can be found in Vasiliev (2011). We study the ionization and thermal evolution of a Lagrangian element of cooling gas. In our calculations we consider all ionization states of the elements H, He, C, N, O, Ne, Mg, Si and Fe. We take into account the following major processes in a collisional gas: collisional ionization, radiative and dielectronic recombination, as well as charge transfer in collisions with hydrogen and helium atoms and ions.

The system of time-dependent ionization state equations should be complemented by the temperature equation. Neglecting the change in the number of particles in the system (for fully ionized hydrogen and helium it remains approximately constant) the gas temperature is determined by

\[ \frac{dT}{dt} = -\frac{n_e n_H \Lambda}{A_\text{nk}} \]

where n_e, n_H and n_A are the electron and total hydrogen number densities, \( \Lambda(x, T, Z) \) is the cooling rate, A is a constant equal to 3/2 for isochoric and to 5/2 for isobaric cooling, and k_B is Boltzman’s constant. Cooling is isobaric when the cooling time is much greater than the dynamical time of a system, t_c/\tau_d  1, and it is isochoric when t_c/\tau_d  1.

The total cooling rate is calculated using the photoionization code CLOUDY (ver. 08.00, Ferland et al. 1998). For the solar metallicity we adopt the abundances reported by Asplund, Grevesse & Sauval (2005), except for Ne, for which the enhanced abundance is adopted (Dake & Testa 2005). In all our calculations we assume that the helium mass fraction Y_{He} = 0.24. We solve a set of 96 coupled equations (95 for ionization states and one for temperature) using a variable-coefficient ordinary differential equation solver (Brown, Byrne & Hindmarsh 1989).

We consider the pure collisional ionization model, so we should constrain the shock wave velocity by a value that does not lead to the radiative precursor formation. The precursor is photoionized by the radiation field emitted by a shocked gas, and consequently the initial ionization states in gas behind a shock depend on the spectrum emitted by the shock wave. A stable photoionization precursor will be formed when the ionization front velocity in the gas approaching the shock becomes larger than the shock velocity. This condition is satisfied for shock velocities higher than \( v_s \geq 175 \text{ km s}^{-1} \) (Dopita & Sutherland 1996) or shock temperatures \( T_s = 3 m_p v_s^2 / 16 k \geq 7 \times 10^5 \text{ K} \). Thus, we study shock waves with temperature \( T_s \equiv T_0 \). We constrain our calculations by the lower value \( v = 155 \text{ km s}^{-1} \) corresponding to \( T_s \approx 6 \times 10^5 \text{ K} \). We assume that the gas temperature just behind a shock front instantaneously becomes equal to \( T_0 \), but the ionization composition relaxes from that corresponding to temperature \( T_0 \) before the front. During the relaxation period, the gas cools more efficiently owing to the higher collisional ionization rates of the low ionic states that exist in the post-shock gas, and the ionization composition tends to fit such thermal evolution. In general, for fixed other parameters (density, metallicity), the ionization composition tends to that of the corresponding temperature in a gas collisionally cooled from \( T_{0} \). However, depending on the relation between \( T_s \) and \( T_0 \), the relaxation period lasts a different time.

The ionization times of H and He are longer than those of metals, so the influence of H and He on the thermal evolution of the gas just behind a shock is expected to be dominant. As an example, Fig. 1 presents the H and He ionization states in a gas isochorically cooled from \( T = 10^8 \text{ K} \) for \( 10^{-3}, 0.1 \) and solar metallicities. There is no significant dependence of the hydrogen states on metallicity; in contrast, the helium states vary considerably. The considerable dependence of the H and He states on temperature is clearly seen. Thus, for different ionization compositions corresponding to \( T_s = T_1 \) in a gas before the shock wave one can expect differences in the thermal evolution of the post-shock gas. However, the closer \( T_s \) is to \( T_1 \), the smaller is the distinction of the thermal evolution from that for a gas collisionally cooled from \( T = 10^8 \text{ K} \).
The gas temperature before a shock wave can vary over a wide range. For example, a gas can be relaxed from some previous shock interaction or heated by galactic or extragalactic ionizing radiation. It is therefore difficult to choose a more or less common initial temperature. The gaseous temperature in HI regions is \(\sim 2-4 \times 10^4\) K, and the typical temperature of the IGM is \(\sim 2 \times 10^4\) K. To constrain calculations we suppose that the initial temperature of a gas before a shock wave equals \(T_i = 2 \times 10^4\) K, and that the gas has the ionization composition obtained in the non-equilibrium (time-dependent) model at this temperature and given metallicity. In several sets of models, however, we study the dependence of the gas evolution on \(T_i < T_s\). For these models the ionization composition corresponds to \(T_i\).

### 3 COOLING RATES AND THERMAL INSTABILITY

The TI criteria for a gas cooled isochorically and isobarically are (Shchekinov 1978)

\[
\frac{d \ln \Lambda}{d \ln T} < 1, \quad f = \frac{d \ln \Lambda}{d \ln T} < 2,
\]

respectively. The isochoric and isobaric cooling rates for a gas cooled from \(T = 10^4\) K are similar to each other (Gnat & Sternberg 2007). The temperature range, where a gas is unstable to isochoric perturbations, is very close to that, where a gas becomes unstable to isobaric ones. However, the cooling rate of the gas behind a shock wave may depend on the physical conditions of the gas before the shock front, for example the ionization composition and temperature of the gas, so that the temperature range for which a gas becomes thermally unstable can be modified.

Fig. 2 presents the isochoric cooling rates, the TI criterion, \(f\), and the characteristic scale for a gas with \(10^{-3}\), 0.1 and 1 \(Z_\odot\) behind a shock with \(T_s\). Below, we present our calculations in terms of a shock temperature \(T_s = 3m_pv_{10}^2/16k \simeq 2.3 \times 10^3v_{10}^2\), where \(v_{10} = v_p/10\,\text{km s}^{-1}\). In addition, for a given metallicity, the isochoric cooling rate for \(T_s = T_{s1} = 10^8\) K, the fiducial model, which corresponds to tabulated cooling rates (e.g. Sutherland \\& Dopita 1993; Gnat \\& Sternberg 2007), is plotted by the thin solid line. First of all we should note that no significant difference between isobaric and isochoric cooling rates for \(T_s \lesssim 6 \times 10^5\) K is found. Thus we present results for the isochoric case only, but, because of the different TI criteria, we analyse both cases.

Fig. 2 (upper panels) shows that the cooling rates for the whole shock temperature range considered here, \(T_s = 0.5-6 \times 10^5\) K, tend to the fiducial one and equal it at low temperatures. For gas with \(Z = 10^{-3}Z_\odot\), this occurs almost at \(T_s\) owing to the fast ionization of hydrogen for \(T_s \lesssim 7 \times 10^4\) K and both H and He ionization for higher initial temperatures (the vertical part of lines in upper left-panel). For higher metallicities, other chemical elements, mainly carbon and oxygen, can dominate in cooling. This is clearly seen in Fig. 3, which presents the contributions to the total cooling rate from each chemical element for \(T_s = 8 \times 10^4\) K (upper panel) and \(T_s = 3 \times 10^5\) K (lower panel) in a gas with solar metallicity. It can be seen that the difference between cooling rates behind shock waves and the rate for the fiducial model reaches a maximum for solar metallicity and depends strongly on \(T_s\), but for any \(T_s\) the cooling rates coincide at \(T \lesssim 3 \times 10^5\) K. Thus, we can conclude that the cooling rate in a gas behind a shock wave differs considerably from the cooling rate for the fiducial model, \(T_s = 10^5\) K, which is usually used to study the thermal evolution of a gas.

The middle panels present the \(f\) value for the considered models. The two horizontal lines correspond to the isobaric and isochoric TI criteria. Note that both criteria are satisfied for the fiducial model at \(T \gtrsim 3 \times 10^4\) K for any metallicity considered here. For \(Z = 10^{-3}Z_\odot\), both the isobaric and isochoric criteria for models with \(T_s = 0.5-6 \times 10^5\) K are also satisfied (the region below the horizontal lines) in the same temperature range as that for the fiducial model, except for the very early evolution of a gas behind a shock wave (the almost vertical tails of the cooling curves correspond to that period of the evolution). An increase in the metallicity leads to a widening temperature range where the isochoric criterion is not satisfied, but does not change the range for the isobaric case. A gas evolving from \(T_s = 0.5-6 \times 10^5\) K is thermally unstable to isobaric perturbations during almost all of its evolution. In a gas cooled isochorically, the value \(f\) for the solar metallicity demonstrates a significant difference from that for the fiducial model. The temperature range for which a gas is unstable behind a shock wave with \(T_s \gtrsim 6 \times 10^5\) K is very close to that for the fiducial model. However, such a temperature range becomes narrower for lower \(T_s\); for example, for \(T_s = 3 \times 10^5\) K a gas is unstable at \(T \sim 2.6-5.4 \times 10^5\) K, and for \(T_s = 10^5\) K a gas becomes unstable at \(T \sim 2.8-4 \times 10^5\) K. For \(T_s \lesssim 10^5\) K, a gas remains thermally stable to isobaric perturbations during all of its evolution.

The bottom panels present the column density of a gas layer, which can be thermally unstable, \(N_i = n_i\lambda_i\), where \(\lambda_i = c_i\lambda_{cool}\) is the thermal length. We have plotted the dependence of \(N_i\) where the instability criterion is satisfied, namely, for any \(T_s\) at \(T \gtrsim 2 \times 10^4\) K in the isobaric case (shown by thin solid lines) and for \(T_s \gtrsim 10^5\) K in the isochoric one (shown by thick solid lines). Note that the criterion for the fiducial model with \(T_s = 10^5\) K is satisfied for \(T \gtrsim 2 \times 10^5\) K (dashed line). The difference between column densities for \(T_s = 0.5-3 \times 10^5\) K and those for the fiducial model reaches a factor of 2–3 for \(Z \gtrsim 0.1\); it is at a maximum for the early stages of evolution, when the cooling rate is changed considerably (the almost vertical tails of the cooling curves correspond to this period of the evolution).
Figure 2. The cooling rates (upper panels), thermal instability criterion (middle) and characteristic scale (lower) for a gas with $10^{-3}, 0.1$ and $1 Z\odot$ metallicities (from left to right). Upper panels. The cooling rates for $T_s = 5 \times 10^4, 6 \times 10^4, 7 \times 10^4, 8 \times 10^4, 9 \times 10^4, 10^5, 2 \times 10^5, 3 \times 10^5, 10^6$ K are depicted by solid lines from left to right, respectively. For solar metallicity (right column of panels), the cooling rates for $T_s = 4 \times 10^5, 5 \times 10^6$ and $6 \times 10^5$ K are added. The cooling rate for the fiducial model is shown by the dashed line. Middle panels. As above, for the thermal instability criterion. The two horizontal lines correspond to the criteria for isobaric (upper) and isochoric (lower line) perturbations. A gas is unstable below the lines. Lower panels. The column density of a thermally unstable gas layer, $N_t = n/\lambda_t$, for isobaric (shown by thin solid lines) and isochoric (shown by thick solid lines) perturbations, where $\lambda_t = c_{st}/\lambda_{cool}$ is the thermal length. The lines from bottom to top correspond to higher shock temperatures, $T_s$. For $Z = 10^{-3} Z\odot$ the lines coincide.

Following Gnat & Sternberg (2007), we consider the transition from isobaric to isochoric cooling for the interaction of a shock wave with a cloud in terms of the critical column density, $D_{n,n}$, and temperature, where $D_{n}$ is the critical size of a cloud. Fig. 4 presents such a dependence for the set of models with $T_s = 0.5-6 \times 10^5$ K (solid lines) and for the fiducial model (dashed line) for solar metallicity. The cooling becomes isochoric for temperatures and cloud column densities left of and above the curves. Here $D_{n,n} \propto c_s$, so that $D_{n,n}$ should be multiplied by the Mach number $M$ for a shock wave with $v_s = Mc_s$.

In the above set of models, we start from the ionization composition corresponding to $T_i = 2 \times 10^4$ K. However, a gas behind a shock wave can have another ionization composition. Fig. 5 presents the isochoric cooling rates, TI criterion and characteristic scale for $T_s = 10^5$ K depending on the initial ionization composition, which corresponds to $T_i = (2-9) \times 10^4$ K. Fig. 5 (upper panel) shows that the cooling rates gradually approach the fiducial one, the difference being negligible for $T_i \gtrsim 7 \times 10^4$ K. The TI criterion and the value $n\lambda_t$ also demonstrate the same behaviour.

4 IONIZATION STATES AND THEIR RATIOS

Figs 6–8 show the $N_{N_{III}}/N_{O_{III}}, N_{C_{IV}}/N_{Si_{IV}}$ and $N_{C_{IV}}/N_{O_{VI}}$ ionization ratios in a gas with $10^{-3}, 0.1$ and $1 Z\odot$ metallicities behind a shock wave with temperature $T_s$. The temperature before the shock wave is taken as $T_i = 2 \times 10^4$ K. Here we consider isochoric ionization...
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Figure 3. The contributions to the total cooling rate from each chemical element for $T_i = 8 \times 10^4$ K (upper panel) and $T_i = 3 \times 10^5$ K (lower panel) in a gas with solar metallicity. The cooling rate for the fiducial model, $T_i = 10^8$ K, is shown by the thin dotted line.

Figure 4. The critical column density, $D_{cr}$, for models with $T_s = 5 \times 10^4$, $6 \times 10^4$, $7 \times 10^4$, $8 \times 10^4$, $9 \times 10^4$, $10^5$, $2 \times 10^5$, $3 \times 10^5$, $4 \times 10^5$, $5 \times 10^5$ and $6 \times 10^5$ K (thick solid lines from left to right, respectively) and for the fiducial model (thin dash line) at solar metallicity.

ratios. Although the difference from isobaric ratios is non-negligible, their temperature dependences show similar behaviour.

The ionization ratios for the metallicities considered here demonstrate a significant dependence on $T_s$ and difference from the ratios in the fiducial model. The difference in some temperature ranges reaches several orders of magnitude. The difference of the $N_{CV}/N_{OVI}$ ratio increases with increasing $T_s$ and reaches a maximum (up to two orders of magnitude) for $T_s = 2-3 \times 10^5$ K in a gas with $Z = 10^{-3}-1 Z_\odot$ (see the lower panels in Figs 6–8). Further increases of $T_s$ diminish the difference rapidly, and the ratios for $T_s = 4-5 \times 10^5$ K almost coincide with the fiducial one. Stronger shock waves (higher $T_s$) lead to the ionization of higher states, and the difference from the fiducial model should decrease with increasing $T_s$. The two other ratios exhibit similar behaviour.

The difference of the ionic ratios from the fiducial ones is a maximum for the lowest metallicity, $Z = 10^{-3} Z_\odot$. For example, the $N_{CV}/N_{OVI}$ ratio for $T_s = 2 \times 10^5$ K differs by about four orders of magnitude from that in the fiducial model. In a solar

Figure 5. As Fig. 2, but for a shock wave with $T_i = 10^8$ K depending on the initial ionization composition, which corresponds to $T_i = 2 \times 10^4$, $3 \times 10^4$, $4 \times 10^4$, $5 \times 10^4$, $6 \times 10^4$, $7 \times 10^4$, $8 \times 10^4$, $9 \times 10^4$ K from top to bottom, respectively.
metallicity gas, this difference reaches two orders only. Obviously, the ionic fractions decrease rapidly in a low-metallicity gas (e.g. Gnat & Sternberg 2007), and the recombination lag increases with increasing metallicity. So the comparison of two ions with a large gap between ionization potentials, such as C IV and O VI (47.9 and 113.9 eV for C III→C IV and O V→O VI, respectively), gives higher values for lower metallicity. The ratio between C IV and Si IV demonstrates a weaker dependence on metallicity owing to the proximity of their ionization potentials (34 eV for Si III→Si IV).

Such a strong dependence on T s may lead to some uncertainties or inaccuracy in determining the physical conditions in the post-shock gas using the tabulated collisional ionization states (e.g. Sutherland & Dopita 1993; Gnat & Sternberg 2007). In the solar metallicity gas, the most remarkable dependence is within the temperature range where the post-shock gas can be thermally stable for isochoric perturbations (see Fig. 2) and the transition from isobaric to isochoric cooling is more probable (Fig. 4). Moreover, the post-shock material can be efficiently mixed owing to hydrodynamical instabilities (Slavin, Shull & Begelman 1993; de Avillez & Breitschwerdt 2009), and the degree of uncertainty in determining the physical conditions may increase. Thus the strong dependence of ionic states does not help to identify this transition and it should be taken into account for the correct interpretation of observational data and synthetic data models obtained from numerical simulations.

We have also analysed the dependence on the initial ionization composition of a gas. Fig. 9 shows the same ionization ratios, NNV/NOV, NCIV/NSIV and NCIV/NOV, in a gas behind a shock wave with Ts = 3 × 10^5 K for various initial ionization compositions corresponding to T i. An increase in T i leads to a smaller difference of the ionic ratios from those in the fiducial model. As noted above, such differences are more pronounced for ions with larger deviation in their ionization potentials.

Fig. 10 (lower panel) presents the dependence of NCIV/NOVI versus NNV/NOVI column densities on the temperature behind a shock wave with T s for a gas with solar metallicity and an initial ionization composition corresponding to T i = 2 × 10^5 K. All tracks start from the same point corresponding to the initial ratio at T i = 2 × 10^5 K. Further evolution depends on the collisional ionization rate of ions behind a shock with T s. As expected from the above results, the tracks differ significantly from the fiducial model: the largest deviation can be found for T s ~ 2–3 × 10^5 K, while the tracks for T s ≥ 10^5 K are close to each other, and the tracks for T s ≥ 4 × 10^5 K become closer to that for the fiducial model. The difference becomes negligible at T s ≥ 6 × 10^5 K.

Finally, we again consider the dependence on the initial ionization composition of a gas. Fig. 10 (upper panel) shows the dependence of the column densities behind a shock wave with T s = 3 × 10^5 K on the initial ionization composition corresponding to T i. It should be noted that the tracks for the shock models tend gradually to
the fiducial track, but these tracks coincide at $T \lesssim 4 \times 10^5$ K. At $T \gtrsim 4 \times 10^5$ K, however, a significant difference can be found even for the track $T_i = 10^5$ K, so that even a small deviation of the initial ionic composition leads to remarkably different tracks. In both panels we add the observational data for the high-velocity clouds in the Galactic halo (see table 8 in Fox et al. 2005). Although several tracks are within the error bars of the observational data, the majority of the points cannot be fitted by any track presented in Fig. 10. These observational points are believed to be explained by turbulent mixing behind shock waves (Slavin et al. 1993; de Avillez & Breitschwerdt 2009).

5 CONCLUSIONS

In this paper we have studied the TI, non-equilibrium cooling rates and ionization states in a collisionally controlled gas behind a shock wave with $v \sim 50$–150 km s$^{-1}$ ($T_s \sim 0.5$–$6 \times 10^5$ K). Such shock waves do not lead to the radiative precursor formation, and gas evolution is governed by collisions only.

Our results can be summarized as follows.

(i) The cooling rate in a gas behind a shock wave with $T_s \sim 0.5$–$6 \times 10^5$ K differs considerably from the cooling rate for a gas cooled from $T_i = 10^5$ K.

(ii) The temperature range for which the post-shock gas is thermally unstable is significantly modified and depends on gas metallicity. For $Z \sim 10^{-3} Z_{\odot}$, both isobaric and isochoric criteria for

![Figure 8](https://example.com/fig8.png)

Figure 8. As Fig. 6, but for $Z = Z_{\odot}$.

![Figure 9](https://example.com/fig9.png)

Figure 9. The $N_{N_4}/N_{O_6}$, $N_{C_6}/N_{Si_4}$, and $N_{C_6}/N_{O_6}$ ionization ratios for a solar metallicity gas with $T_i = 2 \times 10^4$ K (thin solid line), $3 \times 10^4$ K (dashed line), $5 \times 10^4$ K (short-dash line), $7 \times 10^4$ K (dotted line), $9 \times 10^4$ K (dash-dot line), $10^5$ K (short-dash-dot line) behind a shock wave with $T_s = 3 \times 10^5$ K. The ratios for the fiducial model, $T_s = 10^5$ K, are depicted by the thick solid line.

shock waves with $T_s \sim 0.5$–$6 \times 10^5$ K and $T_i = 10^5$ K are satisfied in the same temperature range. An increase of metallicity leads to a widening temperature range for which the thermal instability criterion for isochoric perturbations is not fulfilled. For the solar metallicity, a gas behind a shock with $v \sim 50$–120 km s$^{-1}$ ($T_s \sim 0.5$–$3 \times 10^5$ K) is thermally unstable to isobaric perturbations during almost all of its evolution. However the temperature range within which a gas is unstable to isochoric perturbations becomes narrower for lower $T_s$, and a gas remains thermally stable to isochoric perturbations behind shock waves with $v \lesssim 65$ km s$^{-1}$ ($T_s \lesssim 10^5$ K) during all its evolution.

(iii) The column density of a gas layer, which can be thermally unstable, also depends on the gas metallicity. The difference between column densities for $T_s = 0.5$–$3 \times 10^5$ K and those for a gas cooled from $T = 10^5$ K reaches a factor of 2–3 for $Z \gtrsim 0.1 Z_{\odot}$.

(iv) The transition from isobaric to isochoric cooling for a gas with $Z \gtrsim 0.1 Z_{\odot}$ behind shock waves with $T_s = 0.5$–$3 \times 10^5$ K occurs earlier (in a lower column density layer) than it does in a gas cooled from $T = 10^5$ K.

(v) The ion ratios in a gas with $Z \sim 10^{-3} Z_{\odot}$ behind shock waves with $T_s \lesssim 4 \times 10^5$ K demonstrate a significant dependence on $T_s$ and a difference from the ratios in a gas cooled from $T =$
Figure 10. Upper panel. The dependence $N_{CII}/N_{OVI}$ versus $N_{NV}/N_{OVI}$ for a solar metallicity gas with $T_i = 2 \times 10^4$ K (label '24'), $3 \times 10^4$ K (label '34'), $5 \times 10^4$ K (label '54'), $7 \times 10^4$ K (label '74'), $9 \times 10^4$ K (label '94'), $10^5$ K (label '15') behind a shock wave with $T_s = 3 \times 10^5$ K. The ratios for the fiducial model, $T_s = 10^8$ K, are marked by the label 'cc'. Lower panel. The dependence $N_{CII}/N_{OVI}$ versus $N_{NV}/N_{OVI}$ for a solar metallicity gas with $T_i = 2 \times 10^4$ K behind a shock wave with $T_s = 5 \times 10^4$ K (label '54'), $9 \times 10^4$ K (label '94'), $10^5$ K (label '15'), $2 \times 10^5$ K (label '25'), $3 \times 10^5$ K (label '35') and the fiducial model, $T_s = 10^8$ K (label 'cc'). Gas temperature is indicated by a grey-scale along the trajectories: from hot (light grey) to cold (black) gas. The data points show the ionic ratios observed in the metal absorbers (see table 8 in Fox et al. 2005).

$10^8$ K. The difference becomes negligible at $T_s \gtrsim 6 \times 10^5$ K in the metallicity range considered here.

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