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HYDROGEN MOLECULES AND THE RADIATIVE COOLING OF PREGALACTIC SHOCKS II: LOW VELOCITY SHOCKS AT HIGH REDSHIFT

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ABSTRACT. The nonequilibrium radiative cooling, recombination, and molecule formation behind steady-state shock waves in a gas of primordial composition have been calculated in detail for a number of cases. We have solved the rate equations for these processes, together with the hydrodynamical conservation equations. Shock waves such as these are relevant to a wide range of theories of galaxy and pregalactic star formation. We have described elsewhere our calculations for shock velocities ranging from 50 to 400 km s^{-1} for shocks occurring in pregalactic gas at redshifts z = 5, 10 and 20. We present results here for a different range of cases, focusing on shocks of relatively low velocity (v_s = 20, 30, 50 km s^{-1}) occurring at high redshift (z = 20, 100). Such shocks may occur, for example, in primordial cloud-cloud collisions, in the gravitational collapse of cosmological density fluctuations of subgalactic mass, and in the wakes of cosmological strings. A purely atomic gas of H and He which is shock-heated to temperatures above 10^4K and is assumed to remain in ionization equilibrium as it cools in the postshock flow will not in general be able to cool radiatively to temperatures much below 10^4K. When proper account is taken of departures from ionization equilibrium, however, the nonequilibrium recombination which occurs as such a gas cools makes possible H_2 formation which can enable the gas to cool to much lower temperatures. At redshifts as low as z = 5, the low velocity shocks considered here do not generally form enough H_2 rapidly enough to cool the postshock gas to 10^2 K within a Hubble time, in contrast to our previous results for higher velocity shocks. Our results indicate that at <u>high</u> redshift, however, even for shock velocities as low as this, H_2 molecules can form in the postshock gas with concentrations ~ 10^{-3} sufficient to cool the gas to ~ 10^2K within a time comparable to the age of the universe at the redshift of shock-heating. This extra cooling from 10^4K to 10^2K at nearly constant pressure greatly reduces the characteristic gravitational scale length in the cooled gas. The spherical Jeans length, for example, is reduced by two orders of magnitude. This has important implications for theories involving primordial star formation at high redshift.

Key words: COSMOLOGY — HYDRODYNAMICS

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I. INTRODUCTION

Shock waves in primordial composition gas occur in a wide range of circumstances in the theory of galaxy and pregalactic star formation. These include the intergalactic blast waves of the explosive galaxy formation model (Ostriker and Cowie 1981) whose properties have been studied by a number of authors (e.g. Schwartz, Ostriker, and Yahil 1975; Ikeuchi, Tomisaka, and Ostriker 1983; Bertschinger 1983; Carr and Rees 1984; Vishniac, Ostriker and Bertschinger 1985). They also include the accretion shocks which occur in the gravitational collapse of cosmological pancakes (e.g. Zel'dovich 1970, 1978; Sunyaev and Zel'dovich 1972; Binney 1977 a,b; Doroshkevich, Shandarin and Saar 1978) recently studied in detail in the context of a dark-matter-dominated universe (Shapiro, Struck-Marcell, and Melott 1983; Shapiro 1984; Bond *et al.* 1984; Shapiro and Struck-Marcell 1985). Recently, the wakes of cosmic strings have been added to the list of suggestions for galaxy or pregalactic star formation involving shocks in primordial composition gas (cf. Rees 1986; Bertschinger 1986). In all of these examples, the radiative cooling of the postshock gas is crucial to the successful production of gravitationally bound fragments. Without such fragmentation, the models do not form stars and galaxies.

It is well known that a shock-heated gas composed only of atomic H and He is very inefficient at radiatively cooling below 10^4K. Such a gas in collisional ionization equilibrium is mostly recombined at temperatures below about 2 x 10^4K. The resulting paucity of free electrons and the exponential cut-off in the temperature dependence of the H Ly α excitation rate combine to reduce the cooling rate below 10^4K abruptly by many orders of magnitude. It is for this reason that such a gas when cooling from a higher temperature is generally believed to relax to a thermally stable temperature just below 10^4K. Without metals, such an atomic gas would not radiatively cool below about 10^4K. When a gas of H and He cools radiatively from a temperature well above 10^4K, however, it cools faster than it can recombine. As a result, the recombination is out of equilibrium, and a greatly enhanced ionized fraction exists at temperatures below 10^4K compared to the equilibrium value. This ionized fraction makes possible the gas-phase formation of H_2 molecules by the creation of the intermediaries H^- and H_2^+, as follows:

$$H + e \rightarrow H^- + \gamma \qquad (1.1)$$

$$H + H^- \rightarrow H_2 + e \qquad (1.2)$$

and

$$H + H^+ \rightarrow H_2^+ + \gamma \qquad (1.3)$$

$$H_2^+ + H \rightarrow H_2 + H^+. \qquad (1.4)$$

The presence of the small concentration of H_2 molecules which results from reactions (1.1) - (1.4) then makes possible the further radiative cooling of the gas by H_2 rotational - vibrational line excitation to temperatures as low as ~ 10^2K.

In a previous paper, (Shapiro and Kang 1987; henceforth Paper I), we considered the nonequilibrium radiative cooling, recombination, and molecule formation behind steady-state shock waves in a gas of primordial composition (i.e. H and He only). In that paper, we solved the rate equations for these processes, together with the hydrodynamical conservation equations, for shock velocities v_s in the range $50 \leq v_s \leq 400$ km s^{-1} for shocks occurring at redshifts z = 5, 10 and 20. For z = 5, we also considered the effect of external photoionizing, photodissociating radiation on the flow. Our results indicated that, for a significant range of shock velocities, if the shock-heated gas is able to cool to 10^4K within the age of the universe, then it quite commonly forms an H_2 fraction in

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excess of 10^{-3} and cools at nearly constant pressure to less than 10^2K. We also found that, while too high an external-radiation flux level can prevent cooling below 10^4K, a substantial intermediate range of flux levels exists comparable to that expected from the UV background of quasars at lower redshift (i.e. z ~ 2-3) which actually enhances the H_2 concentration in the cooling flow to values well above 10^{-3}. For this range of flux levels (or less), the postshock flow shields itself and is, therefore, able to cool to temperatures as low as 10^2K just as it does with no external radiation. These results are consistent with our earlier calculations of isobaric radiative cooling, recombination and molecule formation in a shock-heated primordial gas in a few cases of interest (Shapiro and Kang 1986; Shapiro 1986). Calculations similar to those of Paper I have been reported independently by MacLow and Shull (1986).

In this paper, we focus on a new range of cases which was not considered in Paper I, those of relatively low velocity shocks (v_s = 20, 30 and 50 km s^{-1}) occurring at high redshift (z = 20, 100). Such shocks may occur, for example, in primordial cloud-cloud collisions when the relative cloud velocities are of this order, in the gravitational collapse of cosmological density fluctuations of small enough mass that infall velocities of this order arise, and in the wakes of cosmological strings (e.g. Rees 1986). At redshifts as low as z = 5, shocks of velocity v_s < 50 km s^{-1} do not generally form enough H_2 rapidly enough to cool the postshock gas within a Hubble time to the low temperatures (T ~ 10^2K) found in Paper I for higher velocity shocks. Our purpose here is to demonstrate that at high enough redshift, even such low velocity shocks can succeed in forming enough H_2 rapidly enough to cool to T ~ 10^2K within the age of the universe at the epoch of shock heating.

We describe our calculations and present our results in § II. In § III, we briefly summarize this work.

II. CALCULATIONS AND RESULTS

The equations which we have solved, the method of their solution, and the atomic and molecular rates used are all as described in Paper I. We consider several representative cases, both with and without an external radiation flux. In all cases, we assume that $\Omega_b h^2 = 0.1$, where $h = H_o/(100 \text{ km s}^{-1}\text{Mpc}^{-1})$ and Ω_b is the mean baryon mass density in the pregalactic gas in units of the critical mass density of an Einstein-de Sitter universe. For the cases without external radiation, we consider v_s = 20, 30 and 50 km s^{-1} and z = 20 and 100. For the cases with an external flux of ionizing and photodissociating radiation, we consider v_s = 20 and 30 km s^{-1} and z = 100, with an external flux defined by $F_\nu = \varepsilon \{1.0 \times 10^{-21}(\nu/\nu_H)^{-0.7}\}$ erg cm^{-2} Hz^{-1} s^{-1}, where ν_H is the Lyman edge frequency for H atoms and ε = 0.02 or 1. (We have restricted our attention to a flux of this spectral shape so as to make comparisons with the results of Paper I at z = 5 possible.) In these cases with external radiation, we calculate the transfer of this radiation through the postshock layer and the self-shielding of that layer as described in Paper I.

For the cases with no external radiation flux, the preshock ionization levels are set as follows. For v_s = 50 km s^{-1}, $n(H^+)/n_H = 10^{-2}$ and $n(He^+)/n(He) = 10^{-5}$ as calculated for a shock of this velocity in a gas of solar metallicity by Shull and McKee (1979). For v_s = 20 and 30 km s^{-1}, we are guided by the results of Shull and McKee at higher shock velocities to estimate that $n(H^+)/n_H = 10^{-4}$ and $n(He^+)/n(He) = 10^{-7}$. Our results are not very sensitive to these ionization levels as long as they are small. For the cases with external radiation included, the preshock ionization level is determined by calculating the thermal and ionization equilibrium of the preshock gas at this redshift in the presence of the assumed external flux. This results in the following preshock ionized fractions independent of v_s. For ε = 0.02 at z = 100, $n(H^+)/n_H = 8.4 \times 10^{-2}$, $n(He^+)/n(He) = 7.8 \times 10^{-3}$, and $n(He^{++})/n(He) = 1.5 \times 10^{-5}$. For ε = 1.0 at z = 100, these fractions are 0.5, 4.6×10^{-2}, and 9.5×10^{-4}, respectively.

Our results are summarized in Figures 1 - 4. Figures 1(a) and (b) display the variation of temperature with time for each postshock fluid element, beginning with the moment of shock-heating. The horizontal axis is labelled in units of $tn_{H,2}$, where t is the time after passage through the shock and $n_{H,2}$ is the immediate postshock value

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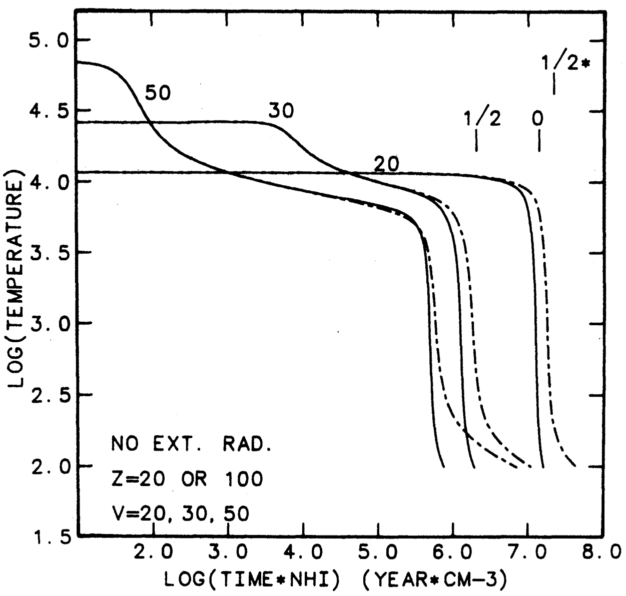

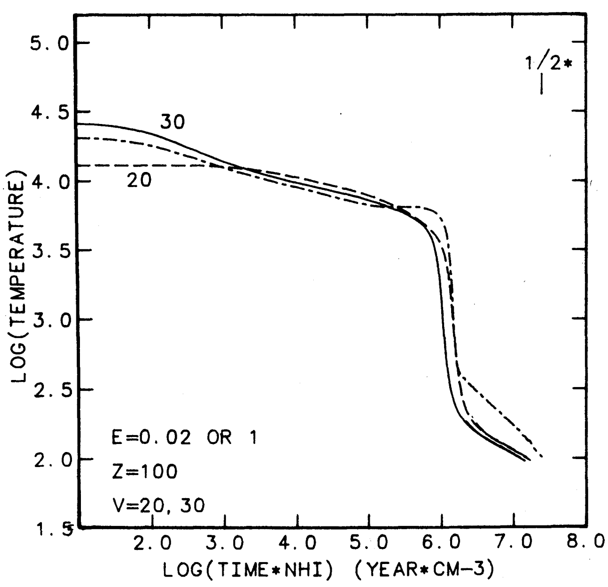

Fig. 1a. Temperature versus $tn_{H,2}$(years cm^{-3})(t = time and $n_{H,2}$ = H number density immediately behind shock) for models with z = 20 (solid lines) and 100 (combination of long and short dashed lines), with shock velocities of 20, 30 and 50 km s^{-1} without external radiation flux. The vertical markers labeled with "0" and "1/2" represent values of the age of the universe at z = 20, multiplied by $n_{H,2}$, with q_0 = 0 and 1/2, respectively, and h = 1. The vertical marker labeled with "1/2*" represents the age of the universe at z = 100 for q_0 = 1/2, while the corresponding age for q_0 = 0 is beyond the right hand edge of the plot. We have assumed $\Omega_b h^2$ = 0.1.

Fig. 1b. Temperature versus $tn_{H,2}$ for models with an external ionizing radiation flux at z = 100. The solid line represents the model with ε =1 and v_s = 30 km s^{-1}. The dashed line represents the case with ε = 0.02 and v_s = 20 km s^{-1}. ε is defined by $F_\nu = \varepsilon\{1.0 \times 10^{-21} (\nu/\nu_H)^{-0.7}\}$ erg cm^{-2} Hz^{-1} s^{-1}, where F_ν is the external radiation flux and ν_H is the H Lyman edge frequency. The vertical marker labeled with 1/2* represents the same value as in Figure 1a.

of the H number density. This makes comparison amongst shocks in gas of different preshock densities easier, since, as discussed in Paper I, there is an approximate scaling law such that the temperature versus $tn_{H,2}$ curve is relatively insensitive to changes of $n_{H,2}$. We have also marked the values of $tn_{H,2}$ which correspond to the age of the universe for various values of q_0 and h. Only those cases which cool in a time less than or equal to the Hubble time can be considered to be adequately described by the steady-state shock calculations presented here. As indicated by Figure 1(a), the lower the shock velocity (in this range), the longer is the cooling time. The higher the redshift, moreover, the smaller is the ratio of the cooling time to the Hubble time at that redshift. According to Figure 1(b), at z = 100 the introduction of the amount of external radiation flux described above increases the net cooling time, but does not prevent the cooling from occurring within a Hubble time.

Figures 2(a) and (b) show the time evolution of the H_2 concentration relative to the total density of H nuclei. The lower the shock velocity, the lower is the final concentration of H_2. The higher the redshift, the higher is the final H_2 concentration. Without external radiation, the final concentration values range from $10^{-3.4}$ for

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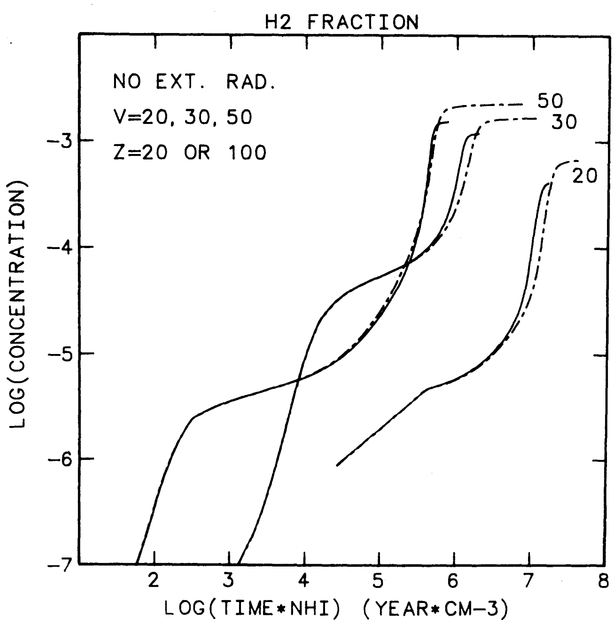

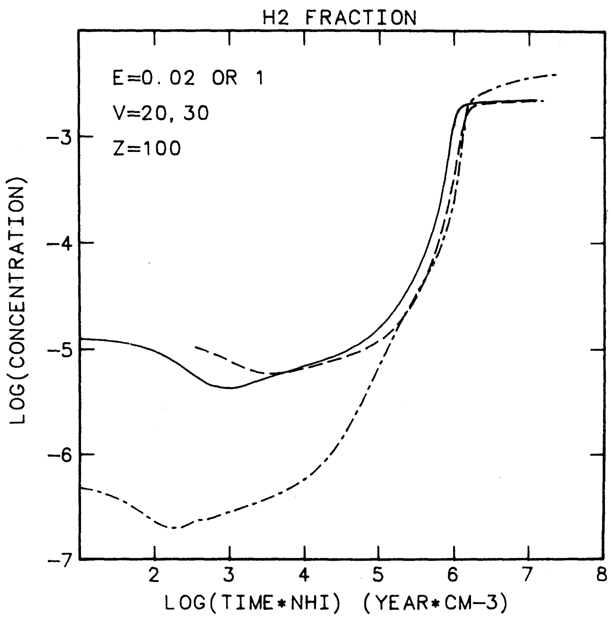

Fig. 2a. The H_2 molecular concentration $n(H_2)/n_H$ versus $tn_{H,2}$ for the same models as in Figure 1a, using the same conventions for identyfing the different cases.

Fig. 2b. H_2 molecular concentration $n(H_2)/n_H$ versus $tn_{H,2}$ for the same models as in Figure 1b.

$v_s = 20$ km s^{-1} at $z = 20$ to $10^{-3.2}$ for the same shock at $z = 100$, to $10^{-2.8}$ for $v_s = 50$ km s^{-1} at $z = 20$ to $10^{-2.6}$ for the same shock at $z = 100$. With the assumed levels of external radiation, the values at $z = 100$ are increased, reaching a value of $10^{-2.4}$ for $v_s = 30$ km s^{-1} and $\varepsilon = 1$.

The ionized fraction of hydrogen is shown plotted against temperature in Figures 3(a) and (b). Without external radiation, the lower the shock velocity, the lower is the mazimum ionized fraction. In all cases without external radiation, the cooling time of the shocked gas is less than the time required to ionize up to the ionization equilibrium value of the ionized fraction. Hence, the gas is underionized at $T \sim 10^4$K compared to shock-heated gas which cools from a significantly higher temperature, as in a higher velocity shock. As in the case of the higher velocity shocks, however, the ionized fraction once the temperature drops below 10^4K is substantially higher than the ionization equilibrium value. This results from the fact that recombination lags cooling and is essential to the success of the H_2 formation via H^- and H_2^+ intermediaries. The same is true of the cases shown in Figure 3(b), which include an external ionizing flux, although in this case each fluid element must flow downstream until the column density between it and the shock is large enough to shield it from the ionizing effects of the external radiation before recombination and further cooling are possible.

In Figure 4(a), the total cooling rate is plotted against temperature for one of the cases without external radiation, that of $v_s = 30$ km s^{-1} at $z = 100$. The dominant contributors to the total are shown separately, as well. Initially, H Ly α collisional excitation dominates as the gas ionizes up. Once the temperature drops below about $10^{3.8}$K, H_2 rotational-vibrational line cooling dominates. Figure 4(b) shows the same curves for the same shock velocity and redshift as in Figure 4(a) except with an external flux added with $\varepsilon = 1$. Once again, the cooling is initially dominated by H Lyα excitation. Once the temperature drops below 10^4K, however, there is a phase where inverse Compton cooling by cosmic background radiation is the dominant cooling process, almost balanced by the

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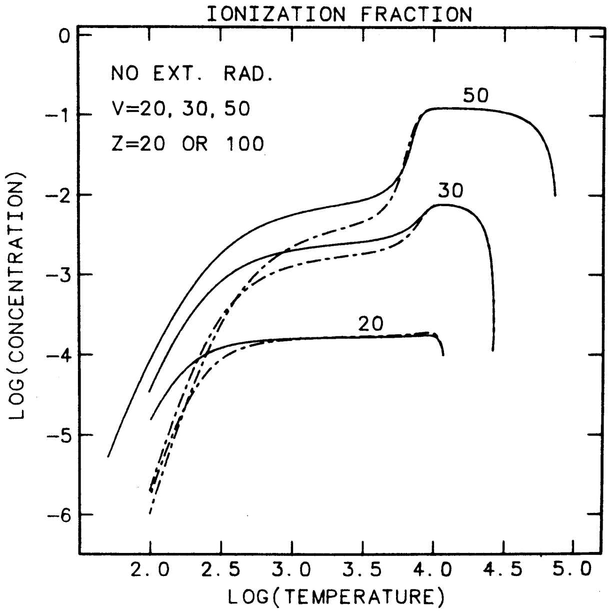


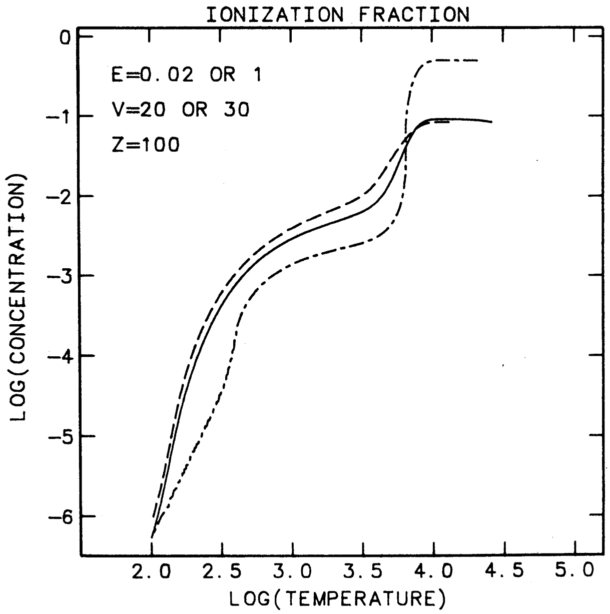
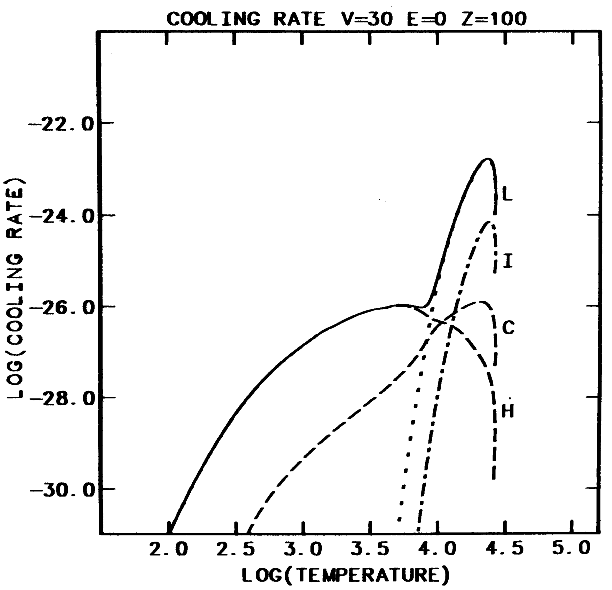


Fig. 3a. Non-equilibrium ionized fraction of hydrogen, n_H+/n_H, versus temperature, calculated for the same models as in Figure 1a.

Fig. 3b. Non-equilibrium ionized fraction of hydrogen, n_H+/n_H, versus temperature, for the same models as in Figure 1b.



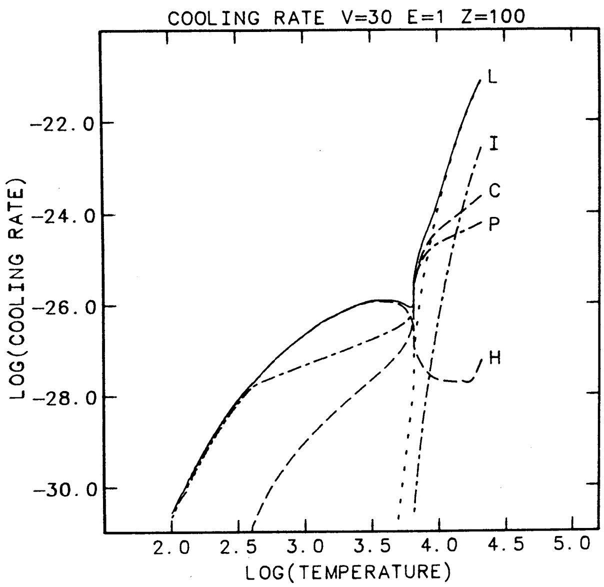


Fig. 4a. Cooling rate coefficients Λ/n_H^2(erg cm^3/sec), for the dominant $z = 100$, $\varepsilon = 0$ and $v_s = 30$ km s^{-1}. The solid line represents the total cooling, the short dashed line labeled with 'L' represents atomic line cooling, 'I' represents collisional ionization cooling, 'C' represents Compton cooling by cosmic background radiation, and 'H' represents H_2 vib-rotational excitation cooling.

Fig. 4b. Same as Figure 4a, except $\varepsilon = 1$. The combination of long and short dashed line labeled with 'P' represents the photoionization heating rate. Other lines are assigned in the same way as in Figure 4a. The total cooling curve is Λ/n_H^2, not $(\Lambda-\Gamma)/n_H^2$, where Γ is the heating rate.

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photoionization heating rate. Once the gas becomes self-shielded and the heating rate drops, however, H_2 line cooling dominates at T $\lesssim 10^{3.8}$K as it did for the case in Figure 4(a). At late times, the cooling slows as the H_2 line cooling rate drops almost to the level of the residual photoionization heating rate.

III. CONCLUSIONS

We have calculated the time-dependent nonequilibrium recombination, molecule formation, and radiative cooling behind low velocity shocks ($20 \leq v_s \leq 50$ km s^{-1}) at high redshift ($z > 20$) in a gas of primordial composition. We find that such shocks succeed in forming an H_2 concentration ~ 10^{-3} rapidly enough to cool the postshock flow to temperatures T ~ 10^2K within a Hubble time at the epoch of shock-heating. The presence of a level of external radiation sufficient to produce an ionized fraction of 50% in the preshock gas does not prevent these shocks from cooling and forming H_2 molecules.

The ability of this shock-heated gas to cool to temperatures as low as 10^2K contrasts with the situation expected for a gas composed of H and He cooling radiatively in ionization equilibrium. In the latter case, the canonical temperature generally assumed to be the thermally stable endpoint of this cooling is ~ 10^4K. The fact that the postshock flow is nearly isobaric implies that the extra cooling to 10^2K found here dramatically reduces the characteristic gravitational scale length in the cooled gas. As measured by the spherical Jeans length, in fact, this reduction by a factor of 10^2 in the temperature translates directly into a reduction factor of 10^2 in the Jeans length. While the fragmentation of the postshock gas is a complicated problem involving a combination of dynamical, thermal and gravitational instabilities which are not adequately represented by the Jeans criterion, the Jeans length provides some indication of the much increased importance of gravity relative to pressure in the cooled gas. This result will have important implications for theories involving primordial star formation at high redshift.

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