Radiative shell thinning in intense laser-driven blast waves*

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Abstract. The structural evolution of blast waves launched by intense laser pulses in gases is investigated. These blast waves exhibit significant energy loss through radiation while propagating in xenon as evidenced by interferometric imaging revealing radiative precursors and deceleration parameters well below those of an energy-conserving wave. Thinning of the blast wave shell from radiative cooling is observed through comparison of shocks launched in gases of differing atomic number. Shell thinning is also measured when the gas density is altered, indicating the influence of conditions within the preshock medium. These results are compared with radiative-hydrodynamic simulations.

An energetic explosion in a gas can drive a blast wave as ejected mass sweeps up the surrounding matter. A well-known example of such a wave occurs in the circumstellar medium around a supernova \cite{1}. These blast waves can often enter a radiative phase if the surrounding medium is of high enough density and $Z$, and the shock velocity is sufficient \cite{2}. This radiative phase, which occurs for some supernova remnants, sets in when the blast wave shell loses a significant

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amount of energy by radiation on a time scale faster than the hydrodynamic time scale. Radiation emitted from the hot expanding shell can ionize gas ahead of the shock wave, leading to a radiative ionization precursor [3]. Furthermore, energy loss by radiation in an optically thin system will increase the rate of deceleration of the wave. Whereas a spherical, energy conserving blast wave will expand outward according to the self-similar Sedov–Taylor (ST) solution [4] with a radius that increases as \( t^{2/5} \), where \( t \) is the time from the initial explosion (\( r \propto t^{1/2} \) in cylindrical blast waves), the deceleration rate of a strongly radiating wave will be higher. In the limit of very fast radiation loss, the blast wave radial trajectory is determined simply by momentum conservation, and the shock shell expands as \( t^{1/4} \) [2] (\( t^{1/3} \) in cylindrical waves).

Another major consequence of strong radiation in a high Mach number blast wave is an increase in the compressibility of the gas caused by a reduction in its polytropic index, \( \gamma \). This means that radiative cooling in a layer ahead of the viscous shock transition will lead to a thinning of the blast wave shell as the preshock ram pressure and the back pressure of the hot postshock gas drive its collapse [5]. This is well known from some radiative supernova remnants such as the Vela SNR [6]. One important consequence of this shell thinning can be instabilities emerging on the shock front [7], such as the thin shell overstability described by Ryu and Vishniac [8]. This effect is thought to be important in the structural evolution of many radiative supernova remnants [5].

To date, there have been a number of experiments on shock waves in the radiative regime, most conducted by driving a strong shock or blast wave into a low-density gas with an intense laser pulse [9]–[18]. For example, Grun et al [9] reported evidence for Vishniac overstability on spherical blast waves driven in Xe gas by a 200 J laser pulse. Edens et al [10] performed similar experiments but added well-defined perturbations on the blast wave to test quantitatively the predictions of the Vishniac theory. Both of these experiments inferred that their blast waves in Xe entered the radiative regime. The shape of shock structures driven with continuous energy injection from high-energy, long-pulse (~1 ns) laser beams has also been investigated. Measurements of the precursor generated by a radiative shock were consistent with hydrodynamic simulations [11, 12] and a highly compressed collapsed layer caused by radiative losses from the shocked material has been measured [13].

Direct experimental evidence for radiative energy losses in Xe blast waves has also been reported. Edwards et al [16] found that cylindrical shocks driven by an ultrashort pulse laser focused onto a Xe cluster jet showed a slight deviation of the blast wave trajectory from the energy conserving ST self-similar solution. This experiment also observed a strong radiative precursor, though the waves were only weakly radiative. To date, there has been no examination of the shape of both the ionization precursor and the blast wave shell itself in a regime in which the shock radiates strongly and deviates substantially from the energy-conserving case. In this work, we report on experimental measurements of laser-driven cylindrical blast waves in Ar and Xe gases in which the shape of the wave for both upstream and downstream of the shock is investigated. We observe blast waves in Xe that deviate strongly from ST trajectories and exhibit thinner shock shells than in those seen in Ar because of radiative energy loss. Furthermore, in Xe we measure a change in the thickness of the blast wave shell depending on the density of the target medium. We interpret this as a consequence of higher energy loss from the shock because of a change in the opacity of the gas.

We produced cylindrical shock waves by exploiting the high absorption of femtosecond (fs) laser pulses that occur in a gas when large atomic clusters are present [15]. Laser pulses of 35 fs
Figure 1. (a) Schlieren images of blast waves in Xe at $2.47 \times 10^{-4}$ g cm$^{-3}$ after 17 ns (left) and $1.6 \times 10^{-4}$ g cm$^{-3}$ after 11 ns (right) with (b) corresponding radial electron density profiles extracted from interferometric images.

duration were focused to an intensity of up to $10^{18}$ W cm$^{-2}$ with an $f/7$ spherical mirror into a gas plume of clusters formed by expanding high-pressure gas through a supersonic, conical nozzle, creating a hot plasma filament approximately 65 $\mu$m in diameter and 4 mm long which developed into a strong cylindrical blast wave. Xenon clusters were irradiated at two different average gas densities: $2.5 \times 10^{-4}$ g cm$^{-3}$ with 360 mJ pulse energy and $1.6 \times 10^{-4}$ g cm$^{-3}$ with 440 mJ per pulse. Argon clusters with a slightly lower density of $1.4 \times 10^{-4}$ g cm$^{-3}$ were also irradiated with 440 mJ pulses. The evolution and morphology of the blast waves were monitored using imaging interferometric and Schlieren techniques. The plasma was imaged with $\sim 10 \mu$m resolution by illuminating it with a short, second-harmonic probe pulse directed perpendicular to the axis of symmetry of the plasma filament. Interferograms obtained with a shearing Michelson interferometer yielded phase information that could be directly transformed into absolute electron density as a function of radius, permitting direct time-resolved images of the entire shock structure. Complementary Schlieren imaging provided a measure for the spatial derivative of the electron density making it particularly sensitive to shock front modulations and the radiatively ionized precursor.

Typical Schlieren images of blast waves launched in high- and low-density xenon are shown in figure 1 along with radial electron density profiles at 17 and 11 ns, respectively, obtained from interferograms. The shock front is visible as a bright line and a radiative ionization precursor can be seen in the gas ahead of the shock. The precursor generated by the high-density shock extends further than in the lower density gas and reaches almost
Figure 2. Measured blast wave behaviour in Xe at a density of \(1.6 \times 10^{-4} \text{ g cm}^{-3}\) (red), Xe at \(2.47 \times 10^{-4} \text{ g cm}^{-3}\) (blue) and Ar at \(1.4 \times 10^{-4} \text{ g cm}^{-3}\) (black). (a) Shock front position versus time with best fits to the data after the time of blast wave formation, taken as the radius at which the accumulated mass exceeds the initial mass by a factor of 10 (dashed black). The dashed red lines indicate the transition visible in the low-density trajectory. (b) Shock shell thickness versus blast wave radius. Solid lines are linear fits to the data.

50% of the peak density at the shock front compared with about 35% in the lower density shock. Owing to the higher laser energy we use to launch the shock waves, the precursors are also much more prominent than those reported in the previous work [14]–[16] at a similar density. The precursors at this time precede the shock by as much as 800 µm and so are unlikely to be in local thermal equilibrium (LTE) considering that the time scale for the precursor to reach a steady state is \(\sim 50 \text{ ns}\) [19].

Measured shock front trajectories from Schlieren images for the two Xe densities and for Ar are shown in figure 2(a). The shock is fully formed after 4–6 ns and can be characterized
by measuring the deceleration parameter \( n \) and performing a least-square fit of functions of the form \( R(t) = \beta t^n \) through the data points after this time. The blast wave in Ar follows a trajectory with \( n \sim 0.5 \), consistent with an energy conserving ST solution. We also measured \( n \sim 0.5 \) in Xe driven with lower energy (35 mJ) laser pulses (not shown). By contrast, in the Xe blast waves irradiated with laser energies of 300–400 mJ, we measure significant deviations from an ST evolution with deceleration parameters below 0.5. At the higher density, \( n \) remains the same throughout our observation period at \( n = 0.43 \pm 0.01 \). However, in the lower density Xe the trajectory evolves through two distinct phases: (i) a strongly radiative phase between 7 and 30 ns in which \( n = 0.39 \pm 0.01 \), and during which time we estimate the fraction of energy radiated to be between 90–100% of the incoming energy flux [20], and (ii) at later times, when the shocked material is cooler, radiative losses become less significant causing the blast wave to revert to an energy-conserving (or energy gaining) trajectory of \( n = 0.51 \pm 0.01 \). The fact that the blast wave radius is similar between the sets of data indicates that the amount of energy per mass density deposited in each run remained approximately equal.

We studied the compression of the shocked material by measuring the full-width at half-maximum shell thickness from the blast wave electron density profiles obtained from interferograms, presented as a function of the shock front radius in figure 2(b). Plotting as a function of the shock radius is a good indicator of the effects of radiation because if the shocks evolved into self-similar blast waves with no significant energy losses, the shell thickness would be equal at equal shock radii. The energy loss suffered by a strongly radiative blast wave causes a reduction in the polytropic index making the gas more compressible and so thinning the shock shell. In Ar the thickness of the shell increases linearly from the onset of blast wave formation, suggesting a constant compression. In contrast, for both Xe densities there is an initial period until \(~30 \) ns when the shell does not thicken, corresponding to the strongly radiative phase identified in the low-density trajectory when \( \gamma \) is lowered. Subsequently, the cooling gas radiates less becoming harder to compress and so the shell broadens as it expands. The shell thickness in Xe blast waves is smaller than in Ar blast waves until fairly late in their evolution. This is consistent with the trajectory measurements that show that while the Xe is strongly radiative, the energy losses from Ar are not sufficient to reduce \( \gamma \) and alter the blast wave evolution. Additionally, the shock shells are thinner in the low-density Xe compared with the high-density Xe. This is consistent with the trajectory data, suggesting a higher energy loss from the blast wave. This could be caused by a reduction in the opacity of the gas ahead of the shock.

One-dimensional simulations of blast wave evolution in xenon were carried out using the radiation hydrodynamics code NYM [21], in which radiation transport was calculated using a multi-group implicit Monte Carlo (IMC) technique, and the individual plasma components are treated in LTE. The simulation was initiated as a 65 \( \mu \)m diameter cylindrical plasma surrounded by unheated room-temperature gas of density equal to that used in the experiment. An energy absorption fraction of 50% was used, and no further attempt was made to tune the input conditions to match the data. Figure 3 shows the simulated radial profiles of the electron density compared with the experimental data at different times in the blast wave evolution. The radial coordinate for the simulated results has been multiplied by 0.87 to achieve a better match to the measured shock front position. For an ST solution, scaling as \( r(t) = (E_L/\rho)^{1/4}t^{1/2} \) would mean that the estimated ratio of deposited energy to gas density \( (E_L/\rho) \) was 1.75 times higher which is within our experimental uncertainty. The decay of the blast wave shell is well represented by the simulation although the shell thickness is considerably underestimated at early times. This discrepancy is likely a result of non-LTE effects associated with the ion fluid.
Figure 3. Radial profiles of electron density from interferometric measurements (solid) and NYM simulations (dotted). The simulations were conducted with the same gas densities as used in the experiment: (a) $1.6 \times 10^{-4}$ and (b) $2.47 \times 10^{-4}$ g cm$^{-3}$. The radial coordinate in the simulation results has been multiplied by 0.87.

since the ions typically take several nanoseconds to thermalize. The radiative precursor is larger for the higher density in agreement with the experimental profile but extends further ahead of the shock than measured. This indicates that in the precursor region the code does not accurately model the physics because of a significant departure from LTE caused by the detailed atomic physics of the radiating shock.

Simulated shock front trajectories are shown in figure 4(a), which again display two stages in the blast wave evolution: a radiative phase characterized by a deceleration parameter $n < 0.5$, followed by a phase with $n > 0.5$ that indicates that the blast waves enter an energy recovery stage [16, 18, 20]. Radiative losses in the low-density gas simulations are more severe, as
Figure 4. Simulated blast wave behaviour using a density of $1.6 \times 10^{-4}$ g cm$^{-3}$ (red) and $2.47 \times 10^{-4}$ g cm$^{-3}$ (blue). (a) Shock front position versus time with best fits to the two expansion stages as solid lines. (b) The main plot shows the shock shell thickness versus shock position. The inset shows the shock compression, $\rho_{\text{shell}}/\rho_0$ as a function of time.

evidenced by the lower deceleration parameter of $n = 0.44$ compared with $n = 0.47$ with high density. Both trajectories evolve with $n = 0.53–0.54$ in the second stage. The time at which the transition between these phases occurs ($\sim30$ ns), is in good agreement with the behaviour seen in the measured low-density data (figure 2) although the experimental data suggest a higher radiative loss ($n = 0.39$) and less energy gain ($n = 0.51$). A change in gradient is not visible in the high-density experimental data.

Figure 4(b) shows the thickness of the shell extracted from the simulated electron density profiles plotted against the shock radius, and was determined by measuring from the shock front to the position inside the blast wave where the mass density drops to the ambient density. The shell compression ($c = \rho_{\text{shell}}/\rho_0$), defined as the ratio of the maximum mass density within the shell to the ambient gas density, is displayed in the inset using 3-point average smoothing to
reduce fluctuations. Consistent with the experimental findings, the simulated blast waves in the lower density gas exhibit thinner shock shells and higher compression until \( \sim 65 \text{ ns} \). At this later time, the compression drops and becomes similar to that of the higher density.

The measurement of a larger precursor and a slower deceleration in a higher density gas target are indicative of a change in the properties of the preheated gas ahead of the shock. One effect of increasing the density is to make the gas more optically thick to the radiation emitted from the shocked material. This means that more energy is absorbed in the precursor, raising its average ionization and also reducing the overall energy loss from the system. In the lower density case when the precursor is more optically thin, large radiative losses cause the blast wave to become almost fully radiative. The consequent reduction in \( \gamma \) makes the shocked material more compressible leading to thinner shock fronts. Other factors such as ionization may also affect the structure of the shock and contribute to shell thinning.

The compression we measure for Xe of \( c \approx 2 \) is lower than the strong shock limit for an ideal gas (\( \gamma = 5/3 \)) of \( c = (\gamma + 1)/(\gamma - 1) = 4 \) rather than exceeding 4 as would be expected for a radiating gas with a lowered \( \gamma \). This is a consequence of the ionization and heating of the preshock gas by radiation from the shock which raises the local sound speed in the precursor to a substantial fraction of the shock speed \([14, 16, 17]\) reducing the Mach number to \( \sim 1.6 \). An analytical estimate for shock compression can be obtained by using the generalized Rankine–Hugoniot jump relations including the contributions of the radiation and ionization energy \([22]\). However, because in our case the preshock gas is optically thin to the radiation, the ionization must be calculated without using an LTE approximation. Therefore, an analytical or numerical treatment that takes into account departures from LTE is needed to fully understand the role of radiation and ionization in these blast waves.

The simulations suggest that late in the evolution \((t > 30 \text{ ns})\) the shocked material starts to recover energy previously deposited in the ionized precursor and the shock follows a trajectory with \( n > 0.5 \). At these later times, the shell in the low-density gas becomes of similar thickness to that in the high-density gas; formerly, it was thinner because of higher energy losses. This could be because for the low-density gas, in addition to the preshock gas being more optically thin, the energy that is absorbed in the precursor is shared between fewer particles leading to a hotter precursor at early time. Consequently, the gas being swept up by the blast wave at late time is less compressible leading to the greater shell thickness. In the experimental data, we do not measure a deceleration parameter significantly above 0.5 nor do we see the shock shell magnitudes converge (although the late time data are limited). These effects are possibly too subtle to be detected on a multiple shot basis. They may be observable using a streaked technique where the entire evolution of the blast wave is measured on a single laser shot \([18]\). It should also be noted that the energy recovery phase of the blast wave evolution is largely determined by the properties of the precursor. Since this is far from equilibrium, it would be of great benefit to perform simulations using the non-LTE version of the hydrocode.

In conclusion, we have studied the behaviour and morphology of radiative blast waves launched in clustered gases by intense laser pulses. By increasing the energy of the laser pulse, we have measured blast waves with more pronounced precursors and faster decelerations than those reported in previous experiments \([14]–[16]\). A detailed study of the blast wave structure revealed that a lower target density led to thinner shock shells and a faster shock deceleration. We suggest that both observations are consequences of a less opaque precursor leading to higher radiative energy losses, but further simulations are needed to investigate other possible contributory factors. Finally, we note that the heating of the preshock gas by radiation lowered
the Mach number of the shock and reduced the compression of the gas significantly below the strong shock prediction.

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