Measurement of the Decay Rate of Single-Frequency Perturbations on Blast Waves

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To explore the validity of theories forwarded to explain the dynamics of hydrodynamic perturbations on high Mach number blast waves, we have studied the decay rate of perturbations on blast waves traveling through nitrogen gas. In our experiments, 1 kJ pulses from the Z-Beamlet laser at Sandia National Laboratories illuminated solid targets immersed in gas and created blast waves. The polytropic index implied by comparing experiment to theoretical predictions is compared to simulation results.

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High Mach number radiative shocks in astrophysics, such as those in certain supernova remnants, can exhibit a large amount of structure and may play a role in star formation [1,2]. One possible explanation of this structure was proposed by Ryu and Vishniac who used perturbation analysis to develop a comprehensive theory [3–5] for the hydrodynamic evolution of perturbations on the surface of a blast wave. These waves can be described as a thin shell of gas bounded on one side by ram pressure arising from expansion into an external medium and on the other by the thermal pressure of hot gas inside the blast wave. Ryu and Vishniac determined theoretical growth and decay rates [4] for spatial perturbations on thin shell blast waves and found that these rates depend on two factors, the mode number of the perturbation and the thickness of the blast front. The thickness of the blast front is determined by its compressibility, which is measured by the polytropic index.

Various groups have attempted to confirm the predictions of Vishniac's theory via computer simulations [6,7] and scaled experiments [8–11]. MacLow and Norman used the 2D gas hydrodynamics code Zeus2D to examine the growth rate of perturbations on blast waves traveling through low polytropic index gases [7] and found agreement with the theoretically predicted growth rates. In addition, there have been some preliminary experiments that examined radiative shocks via laser-driven blast wave experiments [8,10,12,13]. These experiments take advantage of a laser's ability to deliver a large amount of energy to a small focal spot in a time span short compared to the evolution time of the resulting explosion. One feature common to previous experiments is that they attempted to look at the growth of perturbations from noise. As blast waves expand, they cool, reducing the amount of line radiation, increasing the effective polytropic index, and reducing the growth rate of perturbations. This means that the time period over which growth can be observed is limited, and experimental observation is limited to perturbations with mode numbers where growth occurs. In this Letter we describe experiments where we have induced perturbations with a dominant primary frequency on blast waves traveling in nitrogen. This allows us to induce perturbations with a wide range of mode numbers and compare the evolution of these perturbations with theory. We find that our measurements are consistent with the Vishniac theory [4] for blast waves with a polytropic index near 1.4 but that simulations suggest a polytropic index closer to 1.25.

We performed our experiments on the Z-Beamlet laser at Sandia National Laboratories [14]. Laser pulses with 527 nm wavelength, up to 1 kJ pulse energy, and 1 ns duration irradiated one side of a solid 500 μm diameter nylon target pin immersed in 10 Torr of nitrogen gas. The resulting explosion from the laser heated pin created a nearly spherical blast wave in the background gas. The setup we used for this experiment is illustrated in Fig. 1. Perturbations were induced on some blast waves by means of a regularly spaced wire array. This array had a square clear aperture approximately 3 cm on a side, through which were strung 30 gauge tin-copper wires at regular intervals. The wires were spaced 2, 4, or 6 mm apart, corresponding to spherical harmonic ℓ numbers of ~28, 14, and 9 given the size of the blast wave at the time it intersected the arrays. The evolution of the induced perturbation was tracked as a function of time over several hundred nanoseconds using a probe laser which fired 80 mJ, 150 ps pulses at 1064 nm. The blast waves were imaged with both a dark-field telescope and a Mach-Zender interferometer in which the probe light was isolated by means of 2 4 nm bandwidth interference filters. The dark-field diagnostic is an imaging telescope with an obscuring block at the focal point, and images probe light refracted at density gradients such as those that occur at the edge of a blast wave. There is an illustration of such a device in the inset of Fig. 1. Phase

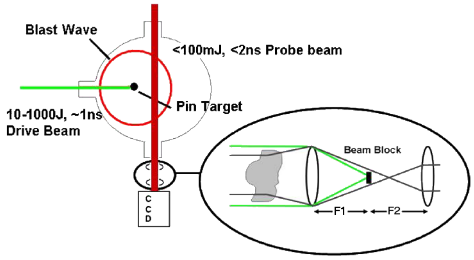

FIG. 1 (color online). Experimental setup of laser shock experiments. 1000 J, 527 nm drive beam enters the chamber from left and illuminates a pin target. This creates a blast wave that is imaged by the ~70 mJ, 1064 nm probe laser onto a dark-field imaging telescope, shown in the inset. The dark-field telescope blocks light that passes through the chamber undeflected, but any light that encounters a density gradient is deflected around the beam block at the center of the telescope and shows up as a bright area.

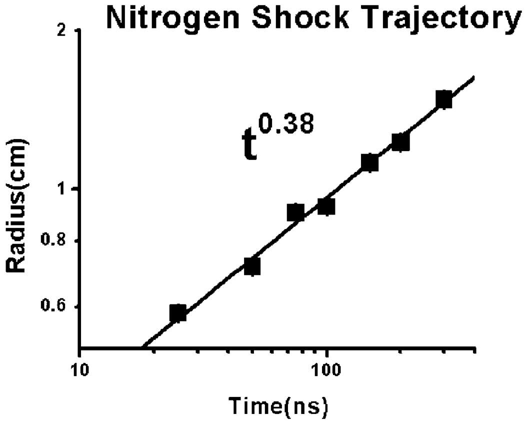

FIG. 2. Blast wave trajectory through nitrogen gas. The best fit for the blast wave trajectory follows $t^{0.38}$, indicating a small but non-negligible energy loss through radiation. Error bars are smaller than the data points.

shift information from the interferometer can be used to obtain line integral information of the electron density in the plasma. Assuming cylindrical symmetry, this information can then be Abel inverted [15] to obtain an estimate of the electron density as a function of radius.

The effective polytropic index of a gas depends on the relative importance of radiation as an energy loss mechanism. One means of gauging the relative importance of radiation as a loss mechanism as opposed to hydrodynamic cooling is to look at the radial expansion of the blast wave. For a self-similar blast wave, the position of any feature, such as the blast wave front, will evolve as $R(t) = \beta t^{\alpha}$. Blast waves that do not lose or gain a significant fraction of their initial energy during their evolution, i.e., those that are not radiative, follow the Taylor-Sedov solution, where $\alpha = 0.4$ [16,17]. Because radiative blast waves lose energy and therefore slow more quickly, they follow a solution with a lower α. The blast wave trajectory in nitrogen with a 1 kJ laser pulse in 10 Torr of nitrogen is illustrated in Fig. 2. The best fit to the data points gives an α of 0.38 ± 0.02, which is within error of the $\alpha = 0.4$ Taylor-Sedov solution. The fact that any deviation from the Taylor-Sedov is small indicates that while there may be a modest amount of radiation emitted from the blast front, it does not greatly affect the evolution of the blast wave. However, the amount of radiation emitted by the blast wave was sufficient to create a radiative precursor in front of the shock front. Evidence for the radiative precursor is present in the interferometry data, which shows that the nitrogen gas directly in front of the shock has been ionized roughly two and a half times on average at 400 ns. In addition to this, the dark-field images of Fig. 3 show probe light surrounding the blast waves which results from refraction by the electron density gradient preceding the shock front.

The linear theory of thin shell (in)stability published by Vishniac and co-workers [3–5] for spherical shock waves evolving as $R \propto t^{\alpha}$ has any given mode growing as a power law in time, $\delta \propto t^{p}$. They find that only for gases with a polytropic index <1.2 will there be a range of wavelengths for which perturbations will grow. Perturbations on gasses with higher polytropic indices always decay. The growth rate increases slowly as a function of mode number until the wavelength approaches the thickness of the blast front, at which point the growth rate rapidly falls off with increasing mode number.

For each of our arrays we acquired a time series of shots with temporal spacings of 100–300 ns. Raw data for the 4 mm spaced array corresponding to a primary mode number of 14 are seen in Fig. 3. In order to quantify the decay rates of the perturbations on the blast waves, we first traced out the edge of the waves in polar coordinates. As illustrated in Fig. 3, there is a sharp transition at the edge of the shock wave, making it clear where the shock boundary is located. The mode content of our induced perturbations is complicated by several factors. First, there is an ellipticity to the underlying blast wave that adds a low mode number component. In addition, the fact that we are using a planar array that intersects only a section of the solid angle of the sphere induces additional mode content. We Fourier decomposed our polar graph in order to isolate the perturbation mode number in which we are interested. The Fourier transform provided us with the amplitude of the induced perturbation, which we then plot relative to the radius of the blast wave as a function of time, and fit the result to a power law in time. The error in the amplitudes was set by the spatial resolution of the imaging system. Figure 4 shows the time evolution of a $\ell = 28$ perturbation induced on a spherical blast wave front, and the best fit gives a decay rate proportional to $t^{-1.2}$. Once we determine the decay rates for our induced perturbations, we compare the results to theory.

Growth or damping rates for the Vishniac overstability depend on two variables, the mode number, determined by the wire spacing of our arrays, and the polytropic index.

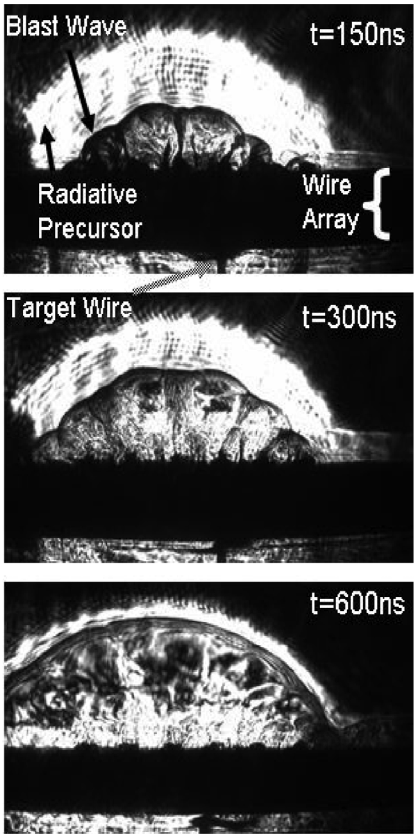

FIG. 3. Evolution of a blast wave traveling past a wire array with 4 mm spacing between wires. The laser comes in from the left and strikes the target wire indicated. The target chamber is filled with 10 Torr of nitrogen gas. The visible probe light preceding the blast front marks the location of a radiative precursor.

For the polytropic index we compared the value obtained from simulation to that implied by the matching of our experimental results to the theory of Ryu and Vishniac [4]. Estimates for the polytropic index were obtained from simulations reported in two papers by Laming and Grun [11,18] as well as simulations performed using the one-dimensional Lagrangian hydrodynamics code HYADES [19].

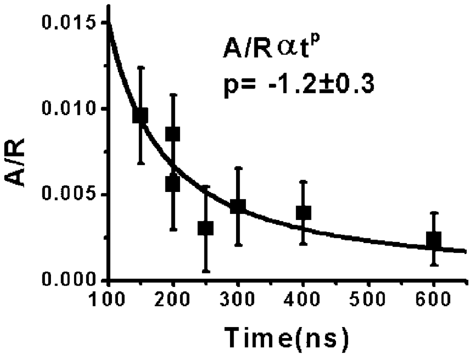

FIG. 4. The size of mode number 28 perturbations on a blast wave is plotted relative to the blast wave's radius as a function of time. The result is fit to a power-law decay in time.

Laming and Grun wrote two papers [11,18] that give theoretical predictions for the properties of a blast wave in nitrogen gas produced by a 100 J laser pulse. They included predictions for the shock velocity, the polytropic index, and the percent of energy lost to radiation. For our experimental blast waves at 100 ns (approximately the time the blast wave encounters the wire array in our experiments), our blast wave is traveling at ~35 km/s. The estimates for the polytropic index in the two papers by Laming and Grun [11,18] yield predictions of 1.23 in the original paper and 1.1 with an improved model for a blast wave with a similar velocity and radius to that in our experiment at 100 ns, implying a compression ~10.

Another estimate of the polytropic index resulted from calculating the density ratio across our shocks using HYADES simulations. The HYADES code employs a tabular equation of state (EOS) and diffusive radiation transport with photon groups. For our simulations we used sesame EOS number 5000 from Los Alamos National Laboratory. We simulated a 1 kJ, 1 ns, 527 nm laser pulse incident on a 0.25 mm radius plastic target which was immersed in 10 Torr of nitrogen. From this we determined the density ratio across the shock during the period when the perturbations were evolving, ~200 ns–700 ns. The density ratio observed in the simulations corresponds to a polytropic index of 1.25. This result is quite similar to the prediction from the original paper of Laming and Grun [11].

These estimates of the polytropic index were compared to that implied by matching our experimental results to the predictions from Vishniac's theory. Figure 5 shows the comparison of our experimentally measured perturbation decay rates to theoretical predictions for several different adiabatic indices. There is good agreement between the data and the theoretical predictions for polytropic indices

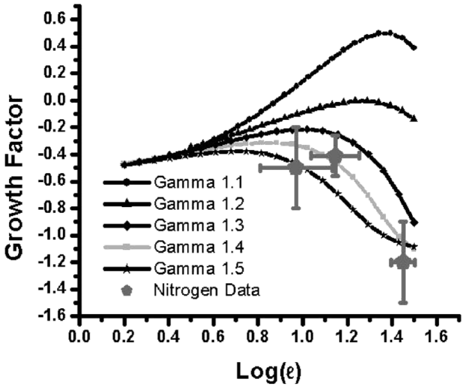

FIG. 5. Comparison of experimentally determined decay rates to theoretical curves from Ryu and Vishniac [3]. Shown are growth rate theory curves for gasses with polytropic indices (gamma) of 1.1, 1.2, 1.3, 1.4, and 1.5. The experimental data agrees most strongly with the 1.4 curve.

of 1.3–1.5. This is somewhat higher then the polytropic indices suggested by simulations. There are several possibilities for this discrepancy. The first possibility is the experimental data could be in error, possibly due to the sources of modal noise mentioned earlier. Alternately, the simulation predictions could be in error. One possible source of error in the simulations is suggested by the strong degree of ionization in the radiative precursor. The fact that the precursor is ionized 2.5 times on average indicates that the precursor region is heated to several eV. This degree of ionization and the implied temperature are significantly higher than appear in the simulation results. The fact that this gas is hotter than expected may make it less compressible and thus raise the effective polytropic index. One other thing to note is that the earlier simulations of Laming and Grun seem to be in better agreement with the data and HYADES simulations than the newer predictions.

In conclusion, we have performed experiments measuring the decay rates of induced perturbations with a primary frequency on blast waves. Our measurements allow for quantitative comparison to the theory of Vishniac and coworkers and simulation results. There is a disagreement between the polytropic implied by the experiment, 1.3–1.5, and the simulation results which range from 1.1–1.25. One possible explanation for the discrepancy in the polytropic index between simulation and experiment lies in the higher than expected ionization in the radiative precursor preceding the shock front. It should be noted, however, that both simulation and experiment predict that perturbations on blast waves in nitrogen gas should decay, which is in agreement with previous experiments where blast waves traveling in nitrogen remained smooth throughout their lifetime.

Future work should include looking at blast waves traveling through gasses with different adiabatic indices, including one for which growth is expected and one for which radiative effects are expected to play a smaller role, reducing the possible sources of discrepancies. Additionally, experiments in which the compression ratio across the shock front is directly measured would resolve the discrepancy in the polytropic index between simulation and experiment.

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