Instabilities in Taylor-Sedov Blast Waves

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ABSTRACT

The stability of Taylor-Sedov blast waves in low-density gases was investigated. Theoretical results have shown that the stability of propagation in uniform gases depends on the adiabatic index of the gas. This was verified with a LASNEX simulation. Both stable and unstable propagation was observed in experiments at the Trident laser facility. The experimental verification of the adiabatic index criterion for stability is not yet completed.

INTRODUCTION

In a series of papers[1-3] in the *Astrophysical Journal,* Vishniac and Ryu showed theoretically that under certain conditions the propagation of shock waves can be unstable even in a uniform gas. The criterion for instability was an adiabatic index (g) below 1.2, where $g = C_p/C_v$ of the gas into which the wave propagates. Here C_p and C_v are the molar specific heats at constant pressure and volume. A low g can occur at certain densities and temperatures when excitation, ionization, and radiation processes increase the number of degrees of freedom.

In the above papers, the instability was modeled by starting with a spherical harmonic perturbation on the radius of the expanding wave.

$$R \propto t^{2/5}\left(1+bt^{s}Y_l^m(\theta,\phi)\right)$$

The hydrodynamic equations linearized in the perturbation were solved for the growth rates of the perturbation as a function of l. The equations do not depend on m, and b is a constant. The results show a positive s for a range of l values and $\gamma < 1.2$. For example, a peak growth rate of $s \approx 0.5$ for $l \approx 30$ is calculated for $\gamma = 1.1$.

In a subsequent paper, J. Grun et al.[4] demonstrated an instability of Taylor-Sedov blast waves propagating through a uniform gas. In this experiment, blast waves were generated by laser-driven ablation on a polystyrene foil in 5 torr of gas. For nitrogen, the blast waves appeared to be stable, expanding with the characteristic Taylor-Sedov $t^{2/5}$ law. In the case of xenon, no stable propagation occurred. This result was attributed to the above-mentioned instability. Presumably, the radiation from the laser/foil interaction or the blast wave itself heats the background gas sufficiently to result in a γ below 1.2 in xenon but not in nitrogen. From these results and previous measurements, J. Grun et al.[4] quoted a $\gamma = 1.3 \pm 0.1$ for nitrogen and a $\gamma = 1.06 \pm 0.02$ for xenon.

The intent of our experimental program is to verify the Vishniac theory in more detail by mapping out the transition from stable to unstable propagation in a gas by changing its γ. We accomplish this by varying the temperature of the gas using different ablator foils or secondary sources to control the radiation spectrum which heats the gas. For example, the γ of the noble gases can be driven from 5/3 at room temperature to below 1.2 near 1 eV.

LASNEX TEST

To test whether this instability is observed in our hydrocalculations, we performed LASNEX computer simulations of Taylor-Sedov blast waves propagating in $\gamma = 1.4$ and $\gamma = 1.06$ gases.[5] The calculation followed a spherical blast wave for several millimeters in 5 torr of gas. We chose the initial energy input to approximate the expansion of the wave in Ref. 4. For the $\gamma = 1.4$ case, the propagation was stable with an initial perturbation of 0.01 $P_{l=30}$ in the energy, whereas the $\gamma = 1.06$ case resulted in a growing instability for a initial perturbation of 10^{-4} $P_{l=30}$. Figures 1 and 2 show the results. A perturbation of 10^{-6} $P_{l=30}$ is required to remain stable within the region of interest for the $\gamma = 1.06$ case.

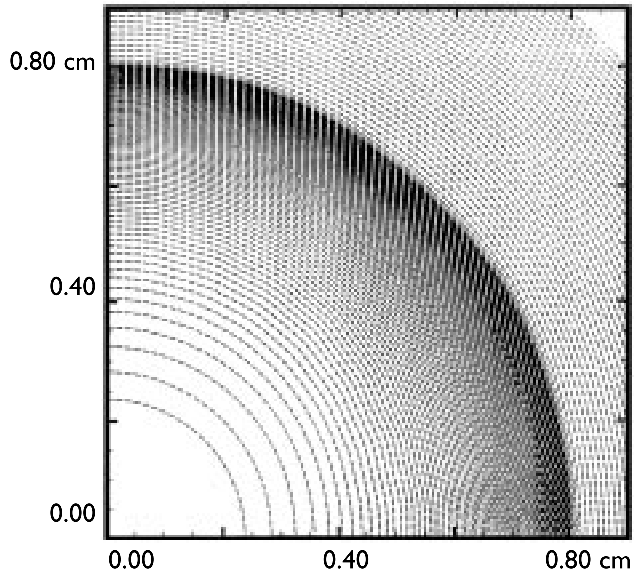

Figure 1. Lasnex calculation of a spherical Taylor-Sedov blast wave in a gas with $\gamma = 1.4$ and a perturbation of .01 $P_{l=30}$.

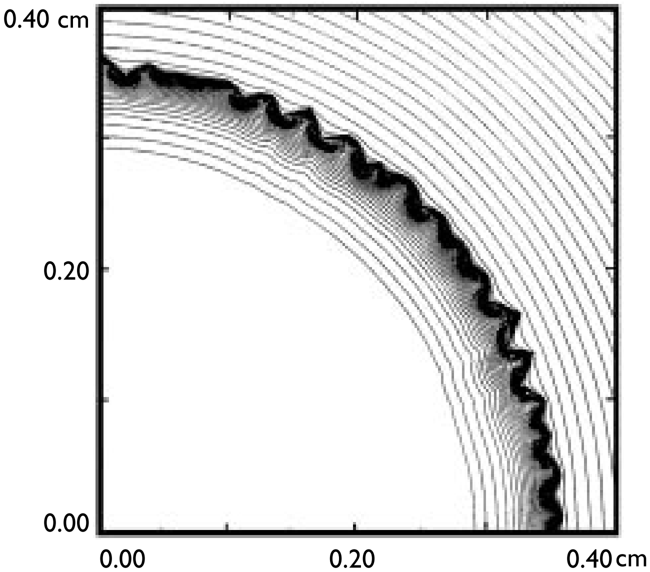

Figure 2. Lasnex calculation of a spherical Taylor-Sedov blast wave in a gas with $\gamma = 1.06$ and a perturbation of 10^{-4} $P_{l=30}$.

Close inspection of Fig. 2 shows that the angular wiggles of the instability do not exhibit the 15 zero crossings expected from a $P_{l=30}$ polynomial in one quadrant.

LASNEX solves the nonlinear hydroequations that lead to significant mode coupling and hence to a more complicated perturbed structure. The growth rate of the perturbation calculated by LASNEX is within 10% of that given by the linearized theory of Vishniac and Ryu. Without knowledge of this effect, this instability in a LASNEX calculation could easily have been mistaken for a numerical instability rather than a real hydrodynamic effect.

EXPERIMENTAL SETUP

The experiments were performed at the Trident laser facility, which has three available beams and is ideal for this kind of experiment. Beams A and B are used to drive the blast wave. Each beam can have a maximum energy of up to ~100 J at 527 nm in a several-ns pulse. For this experiment, beam C is used to image the blast waves in a dark-field-shadowgraph setup. The beam is operated in either single-pulse mode or as a train of 100-ps pulses separated by 30 or 60 ns with a total energy of 1 J at 1054 nm. Operating in pulse train mode allows multiple framing of the blast wave and permits determination of the blast wave's temporal development.

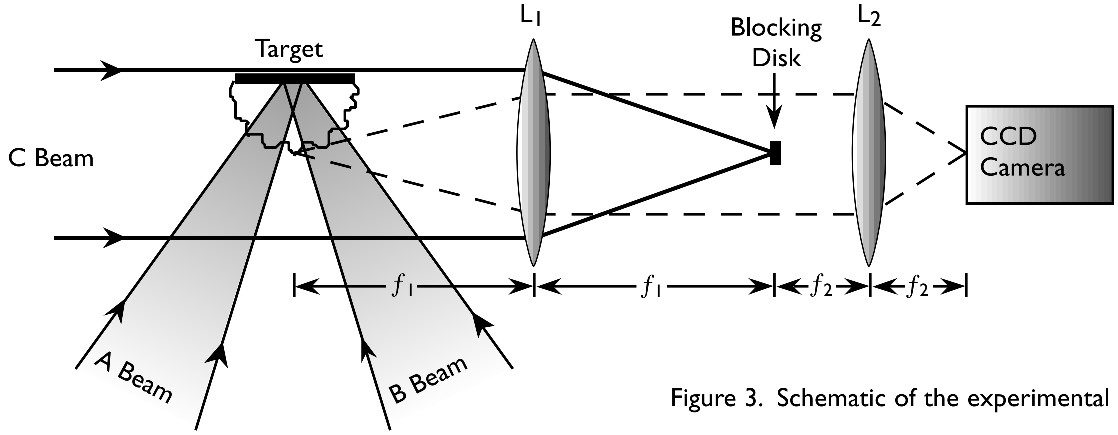

Figure 3. Schematic of the experimental setup.

A schematic of the apparatus used for these experiments is shown in Fig. 3. The target consists of either a 6-µm Mylar foil or a 6-µm gold foil mounted on a washer. Before each shot, a new target is positioned in the Trident target chamber. The chamber is then evacuated to a few millitorr and filled with the desired gas to the desired pressure. The blast wave is created by simultaneously illuminating the center of the target with the A and B beams of the laser. The beams are focused onto the target with f/6 optics to give a spot size of ~800 µm.

To image the blast wave, the target is illuminated with the collimated C beam. For single-pulse imaging, the time delay between when the A and B beams hit the target and when the C beam reaches the target is adjusted to give a suitable image. For multiple-pulse imaging, the delay is set so that the first C beam pulse reaches the target at the same time as the A and B beams. The direction of the illumination is perpendicular to the target normal. The shadowgraph-imaging system is aligned along the C beam axis. The first lens, L_1, is a simple 1.5-m-focal-length optic located 1.5 m from the target. An ~2-mm solid disk supported on a thin stalk is located at the opposite focus of the lens to act as a block. Unscattered C beam light is focused onto the disk and kept from propagating through the rest of the system. However, C beam light scattering from the blast wave and the target is collimated by the first optic and passes by the block. A second lens, L_2, is placed after the disk to focus this light onto the image plane of a Pulnix TM-7CN charged coupled device (CCD) camera. The second lens is a Nikon f/5.6, 75- to 300-mm zoom lens and is positioned so that its focus coincides with the blocking disk. Several green-blocking filters and 1054-nm band-pass filters are placed in front of L_2 to prevent any scattered light from the A and B beams from reaching the camera. The camera image is digitized and stored using a Spiricon laser beam analyzer. For such an imaging system, the intensity of the image is a function of the second derivative of the index of refraction of the scattering media. Thus, the system is well suited for imaging the blast wave which has a strong density gradient.

RESULTS

The stability of blast wave propagation in nitrogen, xenon, neon, and helium was investigated. None of the blast waves in nitrogen, neon, and xenon resulted in a clean "hemispherical" wave without some extra structure. The most unstable propagation occurs in xenon. Figures 4 and 5 show single- and multiple-frame shadowgraphs, respectively, of a blast wave initiated in xenon from a Mylar foil.

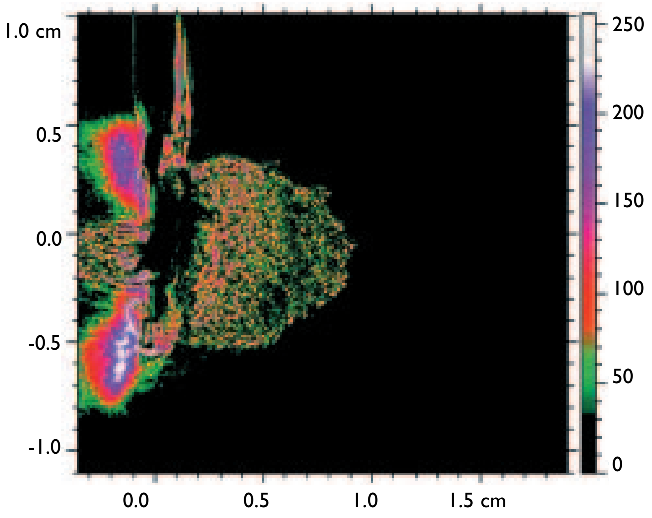

Figure 4. Single-frame shadowgraph of a blast wave in 5 torr of xenon initiated with 38 J at 152 ns.

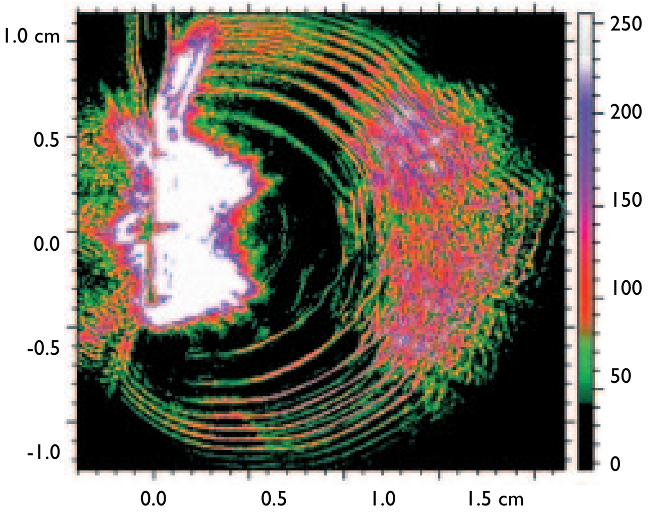

Figure 5. Multiple-frame shadowgraph of a blast wave in 0.5 torr of xenon with 66 J at 30-ns intervals.

In both cases the propagation is highly unstable. For the lower pressure, the wave propagated farther from the origin than expected from the density scaling in the Taylor-Sedov theory. To invoke the energy scaling requires the further assumption that the fraction of the incident laser energy coupled into the blast wave is independent of the laser energy. This assumption has not been demonstrated.

To obtain a stable blast wave, we investigated helium. With its high excitation and ionization energy, helium should be more difficult to drive into a low γ state. Figure 6 shows a multiple-frame shadowgraph of a blast wave in 5-torr helium driven by a Mylar foil with 90 J of laser energy. The frame spacing is 30 ns. The waves are not quite circular. This pattern is probably due to the foil ablation coupling to the gas, which favors the foil normal. The observed spacing between the wave fronts separated by 30 ns follows the Taylor-Sedov $t^{2/5}$ expansion to within 1.5%.

To observe an instability in helium, we initiated a blast wave using a gold foil. The x-ray yield from the laser/gold-foil interaction is higher than that from the carbon foil and hence should deposit more energy into the gas and lower its γ. The blast wave shown in Fig. 7 is clearly unstable and its structure is very different from the stable wave in Fig. 6. Whether or not the origin of the instability is due to driving γ below 1.2 is not proven. Future plans for this experiment include a spectroscopy-based measurement of the gas temperature ahead of the blast wave to determine the state and hence the γ of the gas.

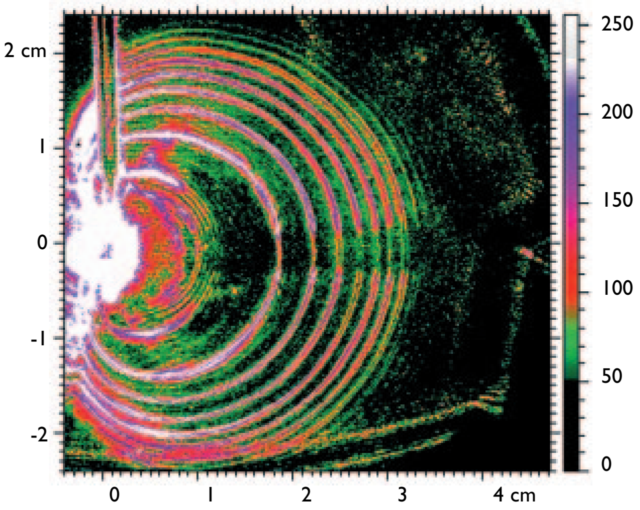

Figure 6. Multiple-frame shadowgraph of a stable blast wave in 5 torr of helium initiated with 90 J on Mylar foil framed at 30-ns intervals.

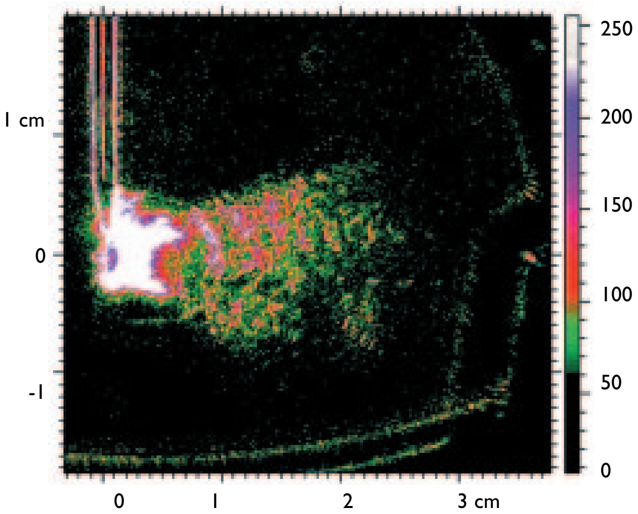

Figure 7. Multiple-frame shadowgraph of a blast wave in 2 torr of helium initiated with 205 J on gold foil framed at 30-ns intervals.

CONCLUSION

We have demonstrated that Taylor-Sedov blast waves can be driven from stable to unstable propagation by varying the conditions in the gas. More experiments with diagnostics to measure the conditions in the gas prior to the arrival of the wave are required to determine the nature of this instability. This preliminary experiment has shown that the Trident laser facility is an ideal facility to perform this type of measurement involving drive energies of up to a few hundred joules timed relative to a multiple-pulse diagnostic beam.

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