Experimental study of the interaction of a strong shock with a spherical density inhomogeneity

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Summary

- Experiments have been conducted on the Omega Laser to study the interaction of a strong shock (M>10) with a spatially localized density inhomogeneity (Cu sphere)

- The interaction is diagnosed with x-ray radiography simultaneously from two orthogonal directions

- The evolution of the shocked sphere is observed to proceed as an initial roll-up into a double vortex ring structure followed by the appearance of an azimuthal instability which ultimately results in the three-dimensional breakup of the sphere.

- Numerical simulations are performed in both two and three-dimensions, and results are in good agreement with experiment.
These experiments recreate in a controlled setting the interaction of a strong shock with a dense molecular cloud.


“The Cygnus Loop is the classic example of a moderately old supernova remnant (SNR). Its structure and physical properties are the result of a supernova-generated shock wave interacting with the surrounding interstellar medium.”

“Comparisons with published shock models indicate significant differences between the models and observations …”
The interaction of a shock with a dense spherical inhomogeneity has previously been studied only at low mach number.

From M = 1.2 shock tube experiments of Haas & Sturtevant, JFM 181, 41 (1987)
Once formed, a vortex ring is subject to a 3D azimuthal bending mode instability. The mode number is a function of the ring radius $R$ and thickness $a$. From Widnall, Bliss, & Tsai, JFM 66(1), 35 (1974). The mode number is given by:

$$n = \frac{\ln(8R/a) - 1/4}{\Gamma}$$
Outline

• Background / motivation

• Omega Experimental Results

• Numerical simulations

• Conclusions
The Omega experiments are conducted in a very small Beryllium shock tube.

2D slice through target

3D view of target
Multiple beams of the Omega laser are used to both drive the strong shock and diagnose the interaction.

Target CAD drawing with Omega beam orientations

Side-on backlighter beams

Face-on backlighter beams

Drive beams
10 beams @ 500J
~ 600 µm spot
Simultaneous side-on and face-on images of shock / sphere interaction with 120 µm diameter Cu sphere

Omega data of April, 2000

# 19728

# 19736

# 19732

# 20637

# 20645

t = 13 ns

Omega data of Aug 2-3, 2000

t = 26 ns

# 19728

# 19736

# 19732

# 20637

# 20645

t = 39 ns

t = 52 ns

t = 78 ns
Simultaneous side-on and face-on images of shock/sphere interaction with 240 µm diameter Cu sphere

Omega data of Aug 2-3, 2000
Large-scale features appear repeatable from shot-to-shot, but small-scale details differ.
The two orthogonal diagnostic views help to reveal the 3D morphology of this flow.

Illustration of 3D morphology

Inner ring mode $\approx 5$

Outer ring mode $\approx 15$
Analysis of Omega shock / sphere data quantifies the three-dimensional instability and breakup of the sphere

From Robey et al., submitted to PRL (May, 2001)
Mode number spectra from face-on images of shock / sphere interaction reveal a dominant azimuthal mode.
The observed azimuthal mode number agrees well with the prediction from Widnall’s theory.

Power spectrum of circular line-out through outer feature ($r=127 \, \mu m$)

- Observed peak at 15

Mode number, $n$ vs. non-dimensional ring translation velocity, $\tilde{V}$

- Predicted Mode = 14-17

From azimuthal lineouts

- $a = 20 \, \mu m$
- $R = 127 \, \mu m$

$\tilde{V} = \ln (8R/a) - 1/4$

$\tilde{V} = 3.67$
SNR should be greatly improved using a backlit pinhole due to greatly decreased pinhole-to-target distance.

# photons / resolution element \(\sim u^{-2}\), and \(\text{SNR} = \sqrt{\# \text{ photons}}\)

Backlit pinhole increases SNR by factor of 11.
We have begun investigating the ability to seed the azimuthal instability with machined initial perturbations.

Face-on view using point projection backlighting.

Shot #24527

Machined Cu sphere
With mode 16 perturbation

120 µm

Beryllium tube

Shot #24527
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2D simulations of the experiment performed with CALE predict the basic evolution of the sphere into a vortex ring.

Simulations by J. O. Kane
3D simulations of the experiment have been performed with an AMR code

Simulated radiograph of side-on view

Simulated radiograph of face-on view

Transparent bubble

Outer ring

Inner ring

Transparent bubble

Simulations by J. A. Greenough
Mode number spectra of the experimental and the AMR face-on images are in good agreement.
Conclusion

• Experiments have been conducted on the Omega laser to explore the interaction of a strong shock with a dense sphere

• The experiment has been diagnosed simultaneously from two orthogonal directions

• The experimentally observed azimuthal mode number is in good agreement with both incompressible theory of Widnall and 3D numerical simulations.

• Future work will focus on shock interaction with less-dense objects and interactions with multiple objects