Long Duration Directional Drives for Star Formation and Photoionization

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Physical and Life SCIENCES

NIF

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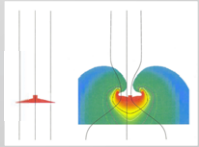
Star-forming molecular clouds and the platforms used to study them offer access to multiple frontiers and challenges in plasma physics research

Long duration, directional laboratory x-ray sources

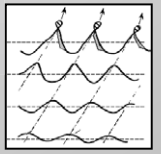
Ablatively confined hydrodynamic flows

Pillars, comets, and deeply nonlinear hydrodynamic flows

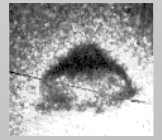
Magnetohydrodynamic flows



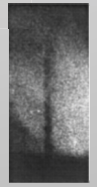
Hydrodynamic instabilities due to directional illumination



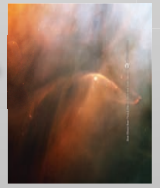
Cloud crushing and star formation



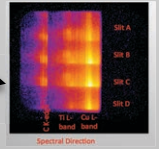
Radiative collapse and star formation



Stellar outflows and bow shocks



Photoionization in accretion disks and molecular clouds



Summary

Eagle Nebula / pillars
Laser facilities (NIF & Omega EP); hohlraums
Astrophysical modeling / comparison to observations
Cometary / other models / RT / magnetic fields
Directional instabilities / TR / DR
Photoionization experiments / accretion disks
Long duration directional multi-hohlraum source
Omega EP high density pillar EP results
NIF high density pillar results
Future proposals / low density comets / magnetic fields

Collaborators and Acknowledgements

Participants	Institution	Roles
Marc Pound, Mark Wolfire	U MD	Eagle Nebula millimeter-wave observation, theory
David Martinez	LLNL	Experimentalist on Omega EP and NIF shots
Bob Heeter	LLNL	Multi-hohlraum concept, photoionization experiment
Alexis Casner, Bruno Villette	CEA	μDMX and mini-DMX spectrometers at Omega EP
Roberto Mancini	U NV	Photoionization experiment
Jim Emig	LLNL	Omega EP experimental support
Reny Paglio, Diana Schroen, Mike Farrell, Abbas Nikroo	GA	Omega EP and NIF multi-hohlraum source, hohlraum foam fill, Eagle and photoionization science packages
Russ Wallace, Alex Hamza	LLNL	NIF and Omega EP source and package assembly
Bruce Remington, Dmitri Ryutov	LLNL	Laboratory astrophysics, Eagle Nebula physics

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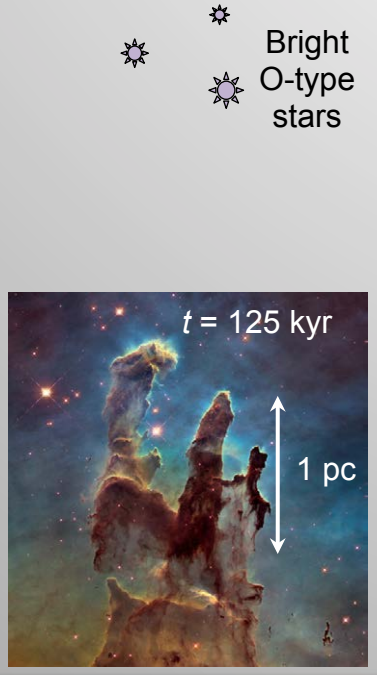
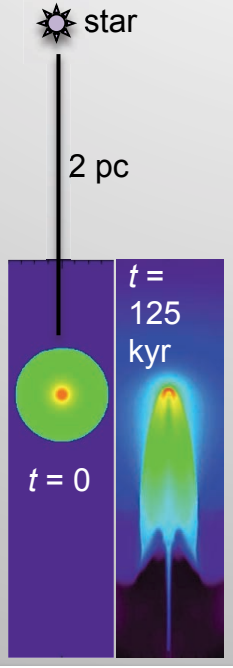
NIF Discovery Science Eagle Nebula studies models for the formation of pillar structures in star-forming molecular clouds, in particular the 'cometary' model

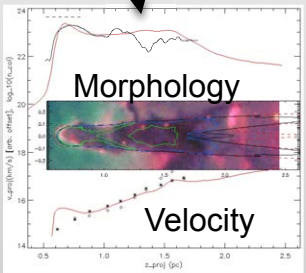
The Eagle Nebula



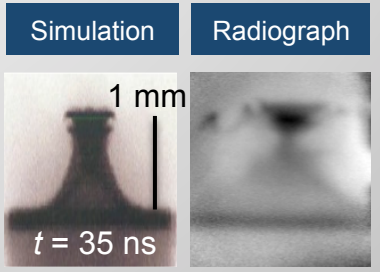
'Cometary' simulation of Eagle pillar

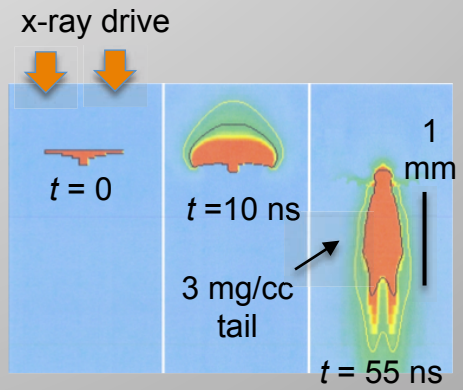


Comparison to observations



Laboratory astrophysics experiment



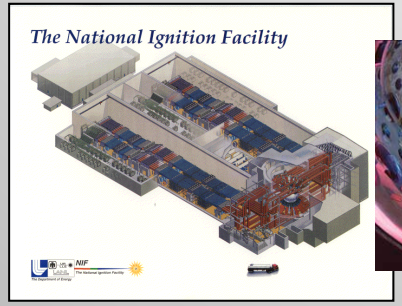


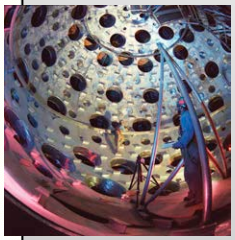
The Eagle Nebula experiments use two large laser facilities capable of producing ablating ionized plasmas

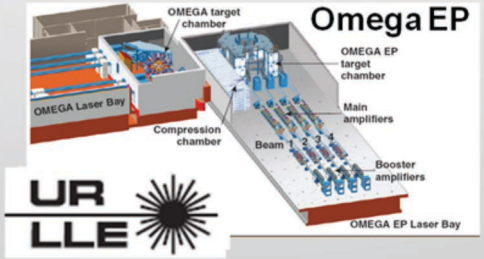
National Ignition Facility (NIF) laser
- 192-beam
- 1.8 MJ
- Inertial confinement fusion (ICF) and fundamental science

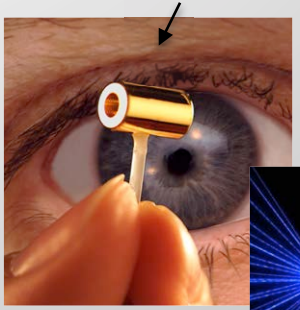
Omega EP laser
- 4-beam
- 16 kJ
- Eagle experiments prototyped

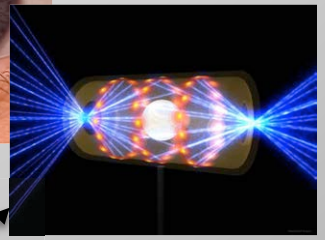
Hohlraum (Au radiation cavity)
- converts 0.35 μm laser energy to soft x-ray blackbody (100-300 eV)
- ICF applications







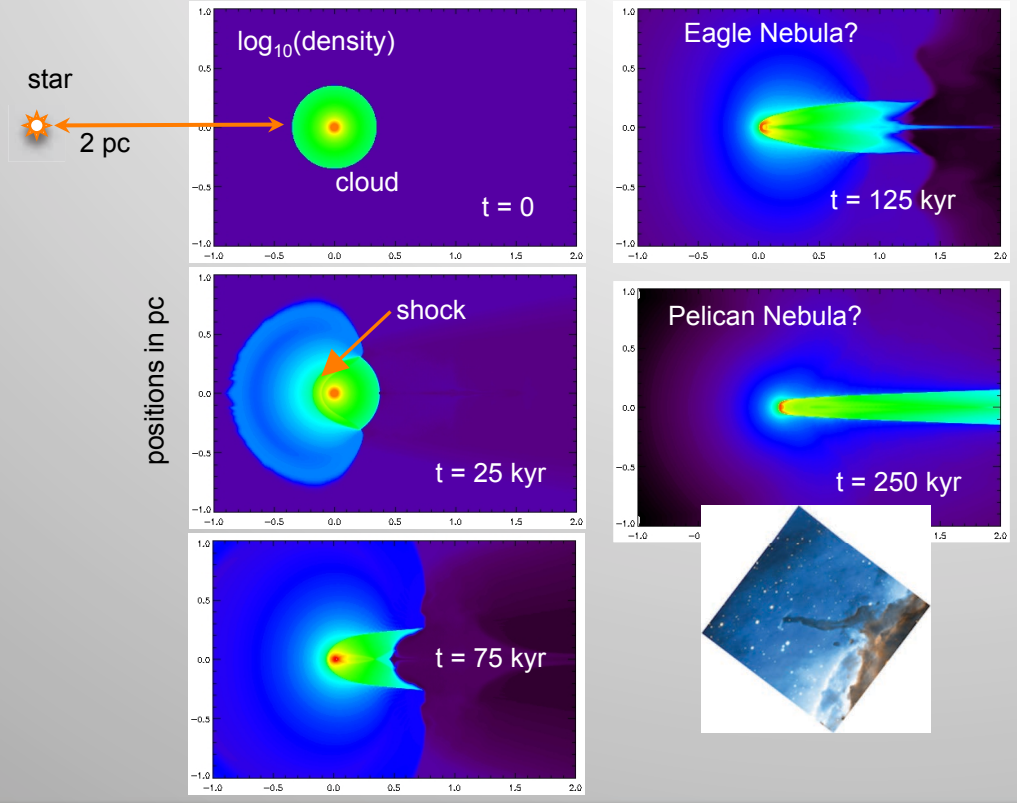


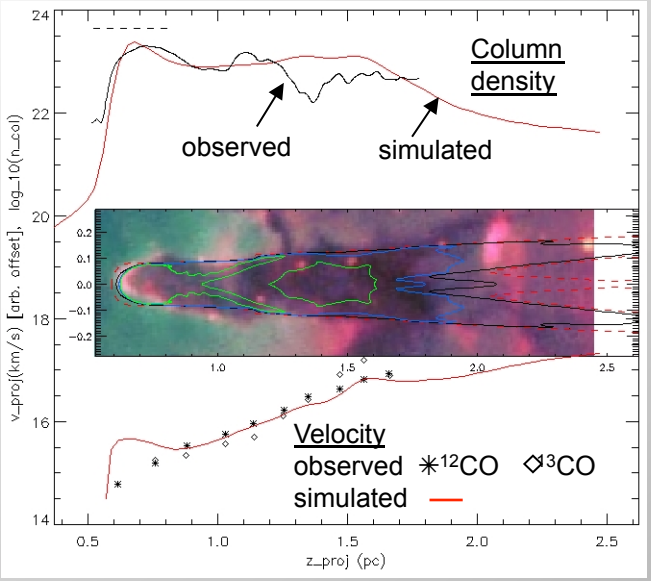


- Laser pulse lengths: 1-10 ns (1e-9 s)
- Target scales: 0.1–5 mm
- Temperatures: 1 eV (1 ev = 11605 K) to a few keV
- Hydrodynamic velocities: 1 km/s
- Typical target conditions: H fully ionized or Fe stripped to K shell

ICF
Hohlraum x-rays compress capsule of deuterium-tritium fuel to fusion conditions

Scientific basis for molecular cloud studies: our astrophysical simulations suggest that a 'cometary' model is reasonable for the famous pillars of the Eagle Nebula

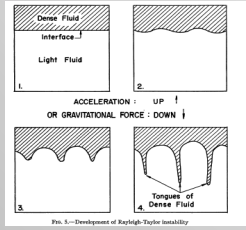




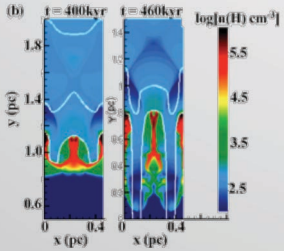
- Overall column density and velocity profile reproduced.
- Actual initial cloud was likely more clumpy and filamentary

Other physics could explain the formation of the Eagle pillars

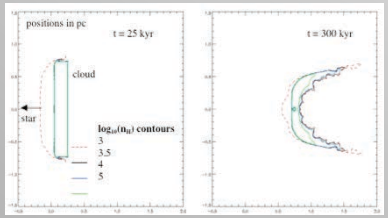
Modeling suggests Rayleigh Taylor instability is strongly ‘ablatively stabilized’



Spitzer, ApJ **120**, 1 (1954); Frieman, ApJ **120**, 18 (1954)

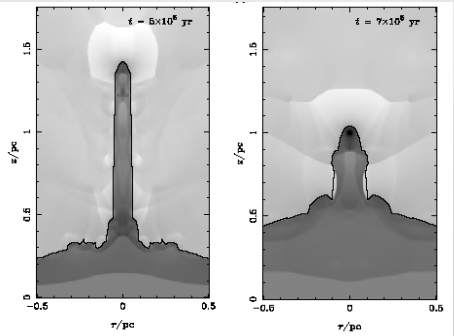


Mizuta (2005)



Kane (2006)

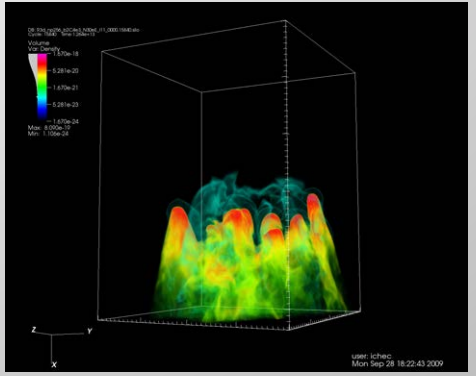
A pre-existing column of material could be shadowed behind a dense clump



Williams *et. al*. MNRAS 327, 788 (2001)

But actually shrinks; and velocity and density profiles not consistent with Eagle.

Magnetic fields are likely to play a role depending on strength and orientation

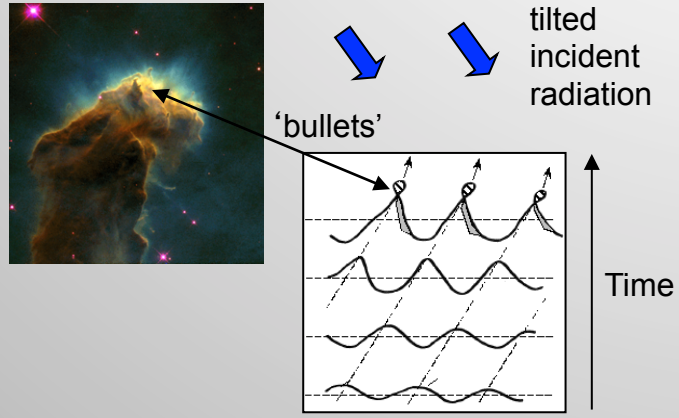


J. Mackey and A. J. Lim, MNRAS 403, 714 (2010); 412, 2079 (2011)

Magnetic fields could be studied in laboratory astrophysics experiments.

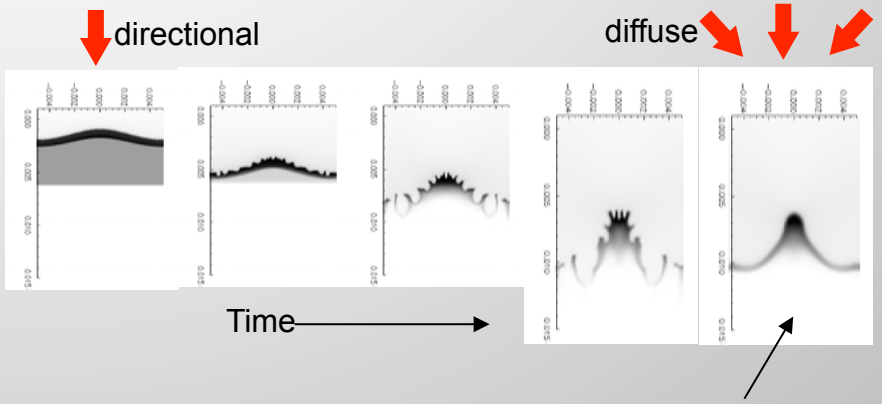
Additional physics frontier: where illumination is highly directional (from a star), exotic hydrodynamic instabilities may occur

‘Tilted Radiation’ (TR) instability



Can push surface waves, which can break. (Axford, 1964, Ryutov, 2003).

‘Directed Radiation’ (DR) short-wavelength instability



- Seen in astrophysical and other simulations (Kane, 2003), R. Williams (2001)
- Related to Landau-Darrius?

With multi-directional illumination, the short wavelengths do not grow

- These instabilities can occur in compression, not just in acceleration (unlike RT).
- They could potentially be studied in laboratory illumination astrophysics experiments using long duration directional.

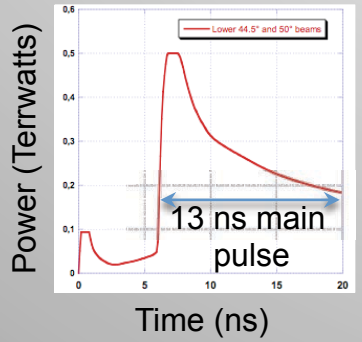
x (cm)

Plasma physics challenge: laboratory astrophysics exeriment studying Eagle hydrodynamics require a long duration (by laser standards), directional drive

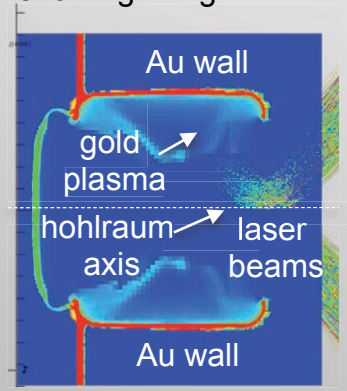
By 15 ns, even a large (5 mm diameter) hohlraum fills with ablated gold plasma, preventing the laser beams from entering the hohlraum, and choking off the x-ray drive.

We developed a novel, multi-hohlraum 160 eV x-ray source. Each holraum is laser-driven for only 10–15 ns until it begins to fill with gold plasma, then the next hohlraum is driven.

Typical long pulse drive for a current NIF experiment

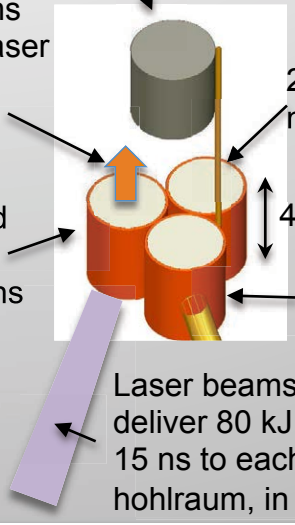


Cross section of hohlraum at end of typlaser drive showing filling



Science package is stood off 5-20 mm to see directional illumination

Hohlraums convert laser energy to x-rays



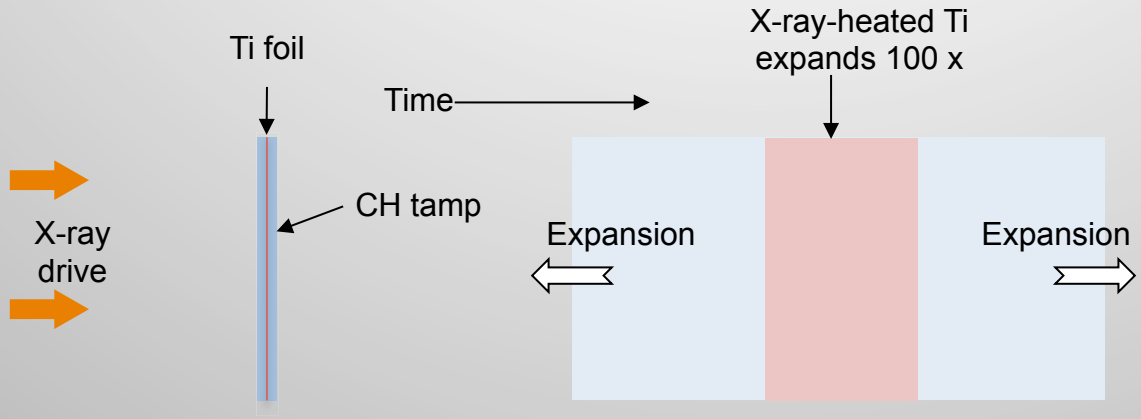
heated from 0–10 ns

Laser beams deliver 80 kJ in 10–15 ns to each hohlraum, in series

Separate laser-heated radiography target generate a few ns of keV-range x-rays for imaging the evolving science package

Frontier: the long duration of the new drive also makes it useful for laboratory astrophysics studies of photoionization

In the limit of strong X-ray flux and low density, the atomic kinetics rate equations are greatly simplified and one can validate, in relative isolation, the photoionized plasma equilibrium driven by photoionization and radiative and dielectronic recombination in the absence of multibody effects.



The approach to conditions where photoionization dominates collisional ionization and equilibrium is achieved requires 20+ ns x-ray drives, and even better, 40+ ns drives

R.C. Mancini *et. al*., “Accretion disk dynamics, photoionized plasmas and stellar opacities” , Physics of Plasmas **16,** 041001 (2009).

Liedahl, D.A. 2005, “Resonant Auger Destruction and Iron Ka Spectra in Compact X-ray Sources,” in *X-ray Diagnostics of Astrophysical Plasmas,* ed., R.K. Smith, (American Institute of Physics), p. 99.

The scaling between the Eagle Nebula (parsec, 100 kyr) and laboratory hydrodynamics (mm, 50e-9 s) has been established

- The thickness of the absorbing layer near the surface of the target is small compared to other geometrical dimensions, and details of the absorption processes essentially drop out of the problem.
- The density and structure of the clump drop out since for the cometary model the clump mainly acts to
  - Hold back the head of the comet.
  - Provide a reservoir of material that releases down to a low density determined by the drive flux.

Under such circumstances, the similarity between the two systems requires a similar value of the parameter

$$A = \frac{\tau^*}{L^*}\sqrt{\frac{p^*_{\mathrm{abl}}}{\rho^*}}$$

where p_{abl}, ρ^*, L^* and τ^* are the characteristic ablation pressure, density, scale length, and time for evolution. As shown in the following table, the scaling is reasonable.

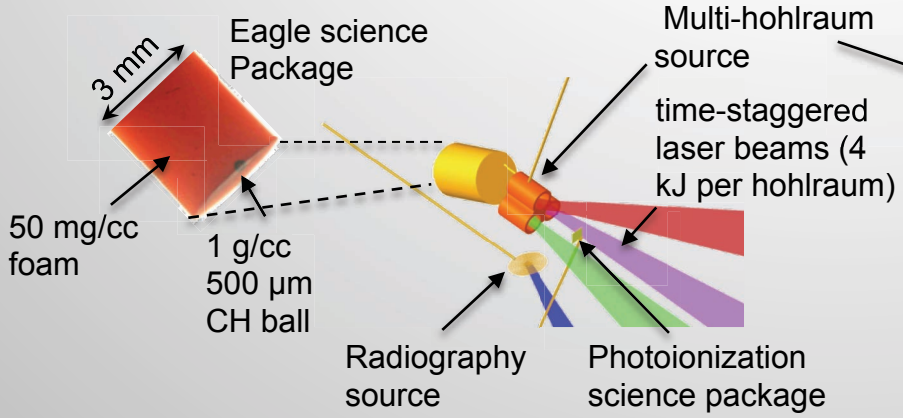
Parameter	Eagle pillar	Laboratory experiment
L^* (cm)	3E+18	0.1
p_{abl} (dyne cm^{-2})	5E-09	1e+10
ρ^* (g cm^{-3})	5E-21	10e-3
τ^* (s)	4e+12	1e-07
A	**1.33**	**1**

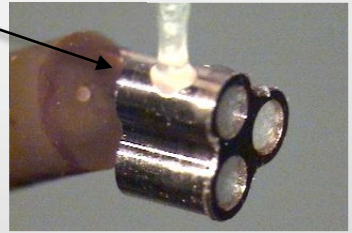
References

D.D. Ryutov and B.A. Remington, "Scaling astrophysical phenomena to high-energy-density laboratory experiments," Plasma Phys. Control. Fusion 44, B407 (2002).

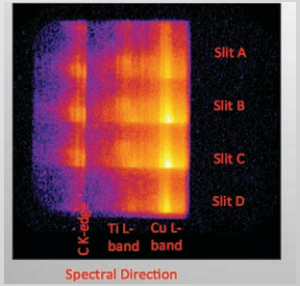
D.D. Ryutov, B.A. Remington, H.F. Robey and R.P Drake, *Phys.Plasmas* 8, 1804 (2001)

1st Eagle experiments: low energy Omega EP laser shots prototyped the new long duration directional source and demonstrated application to scientific packages

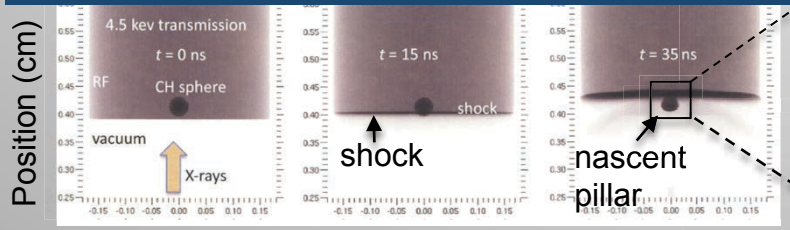




Photoionization science package Ti spectrum

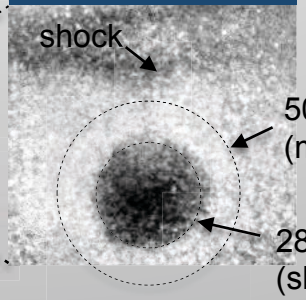


Simulated x-ray radiographs from HYDRA radiative hydrodynamics design simulation

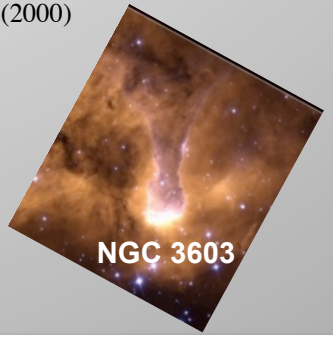


t = 0 t = 15 ns t = 35 ns

Radiograph



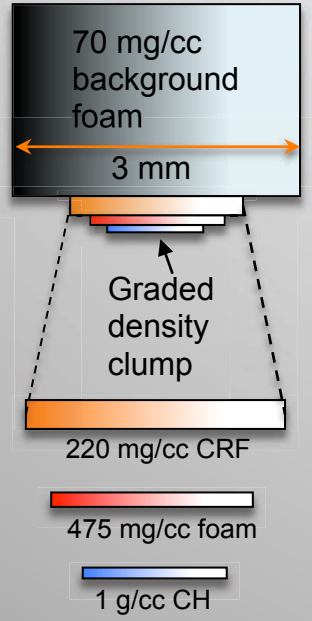
W. Bradner *et. al.* Astron. J 301, (2000)

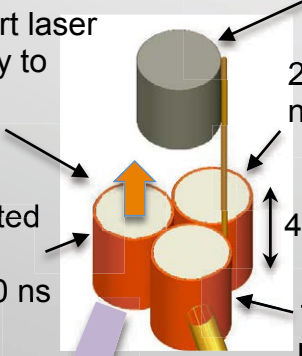


At 20 x higher energy, the 1st NIF laser Eagle shot demonstrated the full-scale source and formation of a dense, easily imaged 'shadowing' pillar

initial condition: graded-density cylindrical clump on background foam

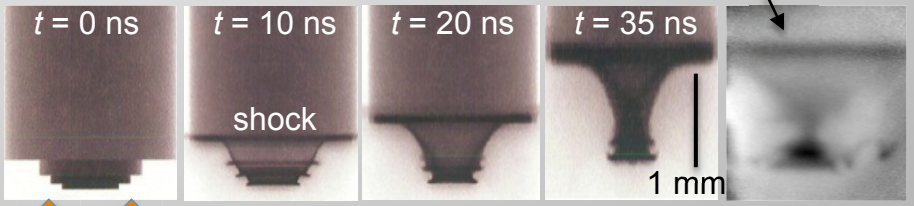
Eagle science package is driven by 30 ns laser-produced x-ray source





Simulated x-ray radiographs from HYDRA radiative hydrodynamics design simulation

Radiograph data



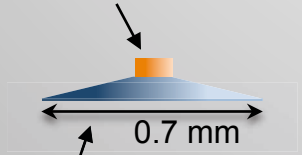
X-ray drive

This pillar forms from background material compressed behind clump, and clump material released by shock

Frontier: proposed new experiments would determine column density and velocity profile in a low density cometary tail instead of a dense ‘shadowing’ pillar

Eagle cometary model science package

Dense core
- Cu, 8.99 g/cm^3
- Holds back head
- shields tail

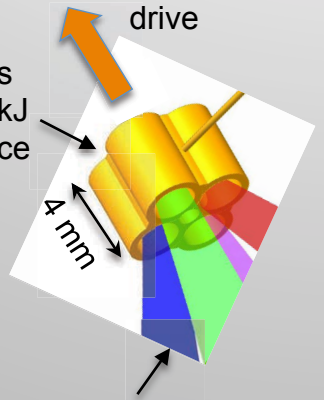


Reservoir
- CH, 1 g/cm^3
- Edge ablates first
- Deeper layers ablate later

160 eV x-rays

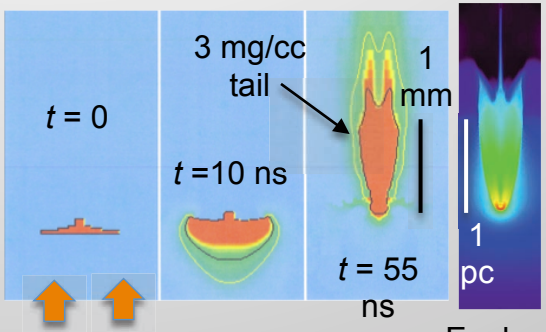
Large standoff distance, very long drive

10–20 mm standoff: highly directional illumination



A cometary target was prototyped at Omega EP

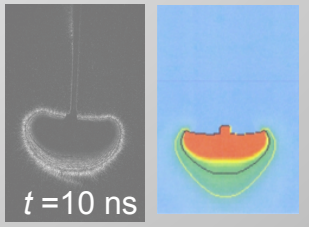
HYDRA radiative hydrodynamics simulation



X-ray drive

Eagle at t = 125 kyr

Shadography image

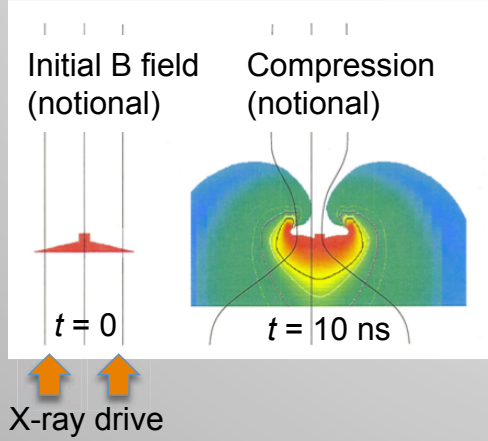


X-ray drive

- No ‘background’ material pre-existing behind the core.
- Tail is confined behind the head by its ablative pressure.

Frontiers: these experiments can access other physics of interest in star-forming molecular clouds: pre-existing magnetic fields, stellar winds, and radiative collapse

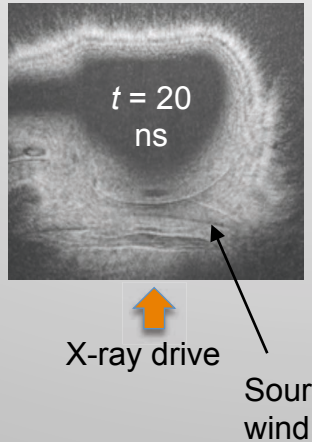
A 2T coil-generated background magnetic field could alter the laboratory pillar dynamics



Frozen-in field lines could generate sufficient magnetic pressure to widen pillar

A 'wind' of ablated foam fill from the source reaches the science package in 20+ ns

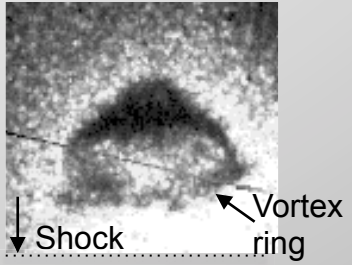
Omega EP shadography image



Bow shock in Orion Nebula

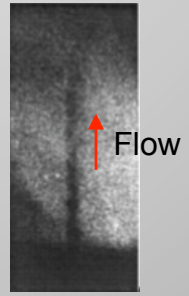
The dense core is subject to 'cloud crushing' and radiative cooling

Crushed sphere in Nova laser epxeriment



Klein, R. I., *et al.*, ApJS **127**, 379 (2000); Robey H. F. *et al.* PRL 89, 085001 (2002)

Radiatively collapsed high-Z jet in Nova laser experiment

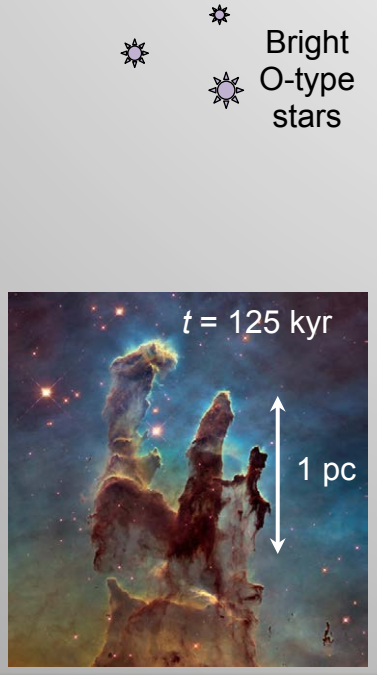


D. R. Farley et. al., PRL 83, 1982 (1999)

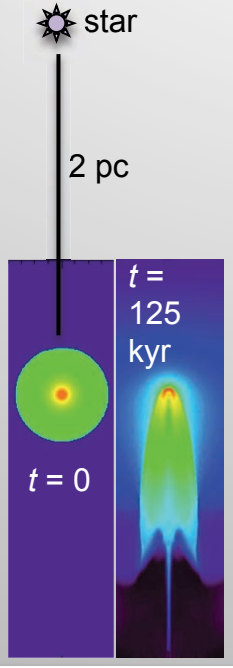
A high-Z dense core could radiatively collapse

NIF Discovery Science Eagle Nebula studies models for the formation of pillar structures in star-forming molecular clouds, in particular the 'cometary' model

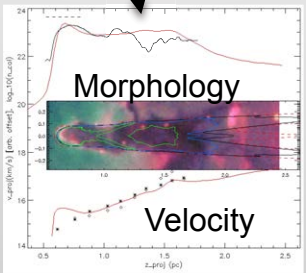
The Eagle Nebula



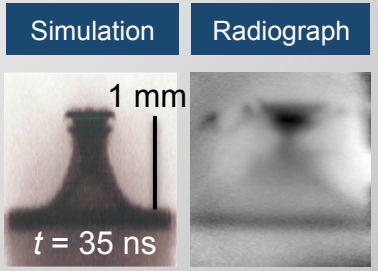
'Cometary' simulation of Eagle pillar

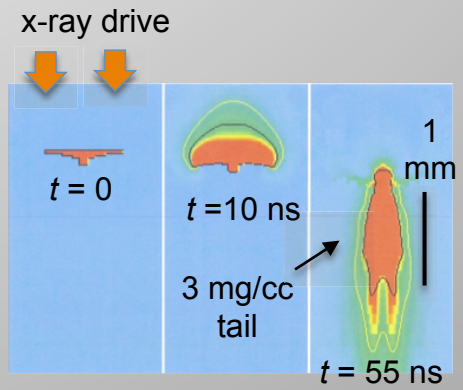


Comparison to observations



Laboratory astrophysics experiment





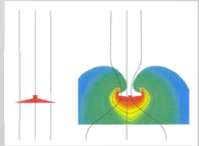
Star-forming molecular clouds and the platforms used to study them offer access to multiple frontiers and challenges in plasma physics research

Long duration, directional laboratory x-ray sources

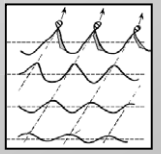
Ablatively confined hydrodynamic flows

Pillars, comets, and deeply nonlinear hydrodynamic flows

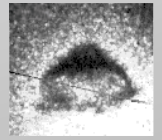
Magnetohydrodynamic flows



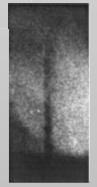
Hydrodynamic instabilities due to directional illumination



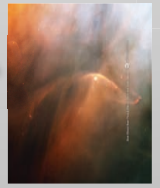
Cloud crushing and star formation



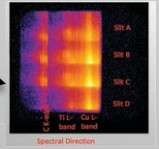
Radiative collapse and star formation



Stellar outflows and bow shocks



Photoionization in accretion disks and molecular clouds



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