White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***06/19/2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	P
• Interactions of plasmas and waves	S
• Plasma self-organization	
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	X
Poster	
Either Oral or Poster	
Will not attend	

Title:	Long Duration Directional Drives for Star Formation and Photoionization
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- ***Describe the research frontier*** **and importance of the scientific challenge.**

The research frontiers are

- The dynamics of star forming structures in molecular clouds, for example the famous pillars of the Eagle Nebula (Figure 1).
- Ablative hydrodynamics and hydrodynamic instabilities in the presence of directional illumination.
- Hydrodynamic evolution and development of pillar structures in situations where ablative stabilization strongly mitigates the Rayleigh-Taylor instability.
- The evolution of dense star forming regions in these molecular clouds.
- Atomic physics of low-density photoionized plasmas.

For over fifteen years astronomers at the University of Maryland and theorists and experimentalists at LLNL have investigated the origin and dynamics of the famous Pillars of the Eagle Nebula (Pound 1998, Kane 2005), and similar parsec-scale structures at the boundaries of HII regions in molecular hydrogen clouds. Eagle Nebula was selected as one of the National Ignition Facility (NIF) Science programs, and has been awarded four NIF shots to study the 'cometary model' of pillar formation. These experiments require a long-duration drive, 30 ns or longer, to drive deeply nonlinear ablative hydrodynamics. The NIF shots will feature a new long-duration x-ray source prototyped at the Omega EP laser, in which multiple hohlraums are driven with UV light in series for 10–15 ns each and reradiate the energy as an extended x-ray pulse. The new source will be used to illuminate science packages with directional radiation mimicking a cluster of stars.

The Rayleigh-Taylor (RT) instability (Sharp 1984), familiar in the context of inertial confinement fusion (Takabe 1985), is not considered a viable explanation for the Eagle pillars; modeling by our group has shown that ablative stabilization strongly suppresses RT (Mizuta 2005). For this reason, our group is investigating the 'cometary model' of pillar formation, in which the pillar at least superficially resembles a comet, and consists of a combination of material ablated from a dense clump in a molecular cloud by UV radiation from nearby O-type stars (Figure 1), then confined by behind the clump by ablative pressure; and material from the surrounding cloud that is driven behind the clump by shocks. Astrophysical modeling by our group (Figure 2) has shown that the cometary model can produce a pillar structure, and comparisons to millimeter wave observations have shown the cometary model can produce column density and velocity profiles similar to those in the Eagle Pillars (Kane 2015). However, because the pillar structures evolve over hundreds of thousand of years, it has only been possible to simulate the evolution of these pillars, without experimental verification.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

The approach is to experimentally test the cometary model for pillar formation as follows.

- Develop a novel long duration (60-100 ns), directional laser-driven x-ray source (Figure 2, left panels.)
- Use the new source to create a scaled 'cometary model' pillar in the laboratory using the National Ignition Facility laser (Figure 3, bottom right).
- Using radiography, confirm the morphology of the pillar predicted in hydrodynamic simulations of the experiments.
- Deduce the velocity and density structure of the pillar from the validated simulation.
- Repeat the experiments in the presence of a fixed background magnetic field that is expected to change the hydrodynamics of the evolving pillar.
- Feed the results back to collaborating astronomers and astrophysics for comparison with millimeter-wave column density and Doppler shift observations of Eagle and other molecular clouds, and assess the validity of the cometary model.
- Propose new observations of those clouds to further refine the model.

The research uses the NIF and its currently available diagnostics, including x-ray radiography, DANTE flux measurement, and spectrometry. For prototyping experimental concepts, such as the multi-hohlraum source, the Omega EP laser at the University of Rochester Laboratory for Laser Energetics is being used. Standard target fabrication capabilities at General Atomics (GA) in San Diego and Albuerque are employed. GA has performed new target fabrication research and development for this effort, including for the low density CH_2 foam that fills the hohlraums to delay closure and mitigate glint.

The first of the NIF shots has been completed; the new x-ray source was tested at NIF scale and a pillar-like object was generated and radiographed (Figure 3). This pillar was deliberately designed to be dense and easily imaged, so that the multi-holraum source could be demonstrated and validated at NIF scale. The pillar consisted laregely of material from the pre-existing background pushed behind a dense clump, and partly from of ablated from the clump and swept in behind it. This type of pillar rapidly disassembles, and is its density and velocity profiles are not intended to be similar to those in the Eagle pillars, although perhaps similar to those in other pillars (possibly the Horsehead Nebula.)

In new NIF shots being proposed, a much lower density, longer-lived cometary structure will be generated, composed entirely of material ablated from a dense clump and ablatively confined behind the clump, and is expected to generate scaled density and velocity profiles that similar to those in the Eagle pillars.

In addition to studying the formation of pillar structures, the new long-duration platform can be used to study other physics relevant to molecular clouds and star formation:

- The surface of the molecular cloud illuminated by UV radiation is a 'photoionization' front, in which ionization of atoms is predominantly by photons, as opposed to the collisional effects that dominate in denser plasmas. In experiments that prototyped the multi-hohlraum concept at Omega EP, a photionization science package was fielded (Kane 2015), and may be fielded again in new NIF experiments being proposed. Photoionization is also of interest in the context of black hole accretion disks (Frank 1992, Mancini 2009, Liedahl 1999).
- Star formation in molecular clouds occurs by collapse of dense gravitational condensations within the cloud (Bertoldi 1990), as in the core of the cloud in our cometary simulation (Figure 2). The dense cores may be triggered to collapse through compression by shock waves, or by radiative losses (Bertoldi 1990.) The multi-hohlraum source and the Eagle science package is ideally suited to study both those mechanisms; the dense clump at the head of the pillar is traversed by shock waves generated by ablation pressure; and by doping the clump with high-Z material (Farley 1999, Shigemori 2000), radiative collapse of the clump could be triggered.
- Certain types of exotic hydrodynamic instabilities may occur at surfaces illuminated by directional radiation, the so-called 'Tilted Radiation' and 'Directed Radiation' instabilities (Ryutov 2003). The directionality of the multi-hohlraum source may be sufficient to study these instabilities experimentally.
- Magnetic fields of order a few μG to a few hundred μG are known to be ubiquitous clouds (Crutcher 1991, Bourke 2001, Ryutov 2004), and are likely to affect the evolution of structure in these clouds. It is possible to add a static background magnetic field in the NIF experiments. This field would be compressed by material collapsing onto the pillar axis, providing pressure support that could measurably increase the observed diameter of the pillar.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit***.

This research will

- Confirm the possibility of studying the structure and evolution of star-forming regions of molecular clouds in the laboratory.
- Test the cometary model for the formation of the pillar structures in molecular clouds.
- Assess the effect of magnetic fields on the evolution of structures in molecular clouds.
- Develop and demonstrate a new, long-duration (60-100 ns), directional source of x-ray radiation that can be used for the study of deeply nonlinear hydrodynamics, hydrodynamic instabilities that occur in the presence of directional radiation, shock-driven and radiatively-driven collapse of dense cores, and photoionization.

Due to the iconic status of the pillars of the Eagle Nebula, this research will bring popular attention to plasma physics, HED laboratory physics, and fundamental science at NIF and other experimental facilities. The result will be to both to bring new perspectives to the studies of hydrodynamics in inertial confinement fusion and HED scenarios in general, and to promote interest in the STEM disciplines.

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Figures (maximum 1 page)

Figure 1. 1st panel: Eagle Nebula Pillars. Blue: O++; green: H+ red: S. 2nd panel: near infrared. 3rd panel: NGC3603. 4th panel: Geometry and orientation of the Pillars. The nearest, brightest star provides most of the flux irradiating the Pillars. Adapted from Pound. Image credits: Eagle: NASA/ESA/Hubble/Hubble Heritage Team (2015). NCG3603: HST + VLT/ISAAC5 (2000).

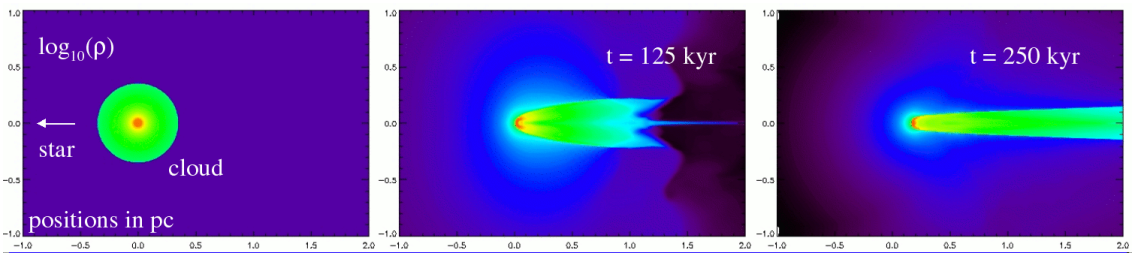

Figure 2. Log density from a 2D cylindrical radiative hydrodynamics astrophysics simulation of a cometary pillar. A 30 solar mass cloud with a power law density core is photoevaporated by an O-type UV star 2 parsecs away. An ablatively confined cometary pillar forms behind the clump. Eagle Pillar 2 has column density and velocity like the 125 kyr structure.

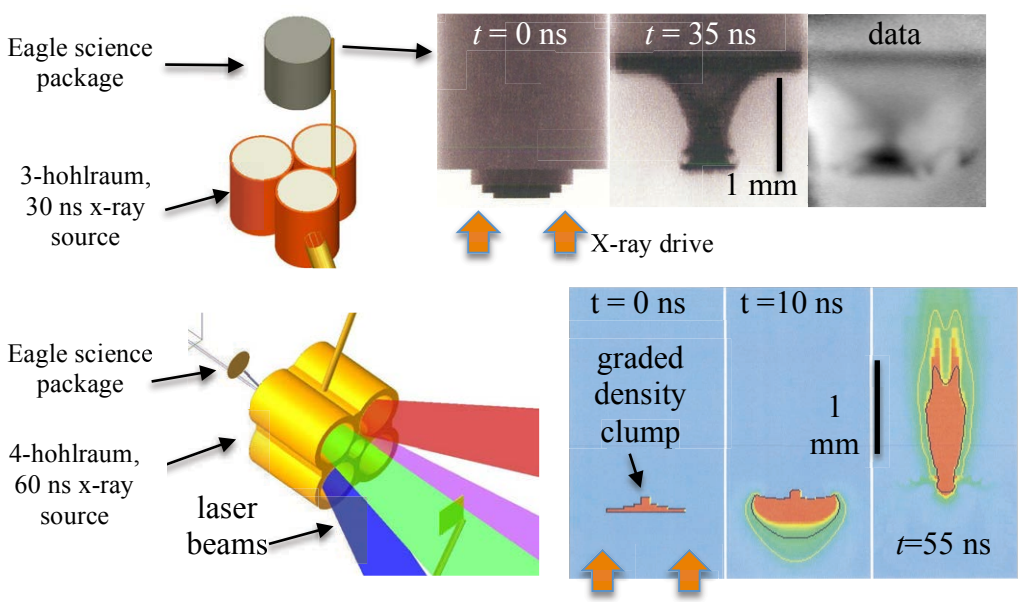

Figure 3. Top: First NIF experiment. Top left: A three-tube, 30 ns duration laser-driven x-ray source directionally illuminates a graded-density clump bordering a background foam 'cloud'. Top right: a short-lived dense pillar forms, similar to the structure predicted by the radiative design code HYDRA. Bottom: proposed NIF experiment. Bottom left: a four-tube 60 ns drive illuminates a graded density clump with a dense core, with no background foam: Bottom right: HYDRA predicts a low-density comet-like structure will form and can be imaged with radiograpgy. A pre-existing magnetic field parallel to the axis of the pillar would be expected to increase MHD pressure in the pillar, measurably increasing the diameter of the pillar.