Creating the Eagle Nebula Pillars in the Lab

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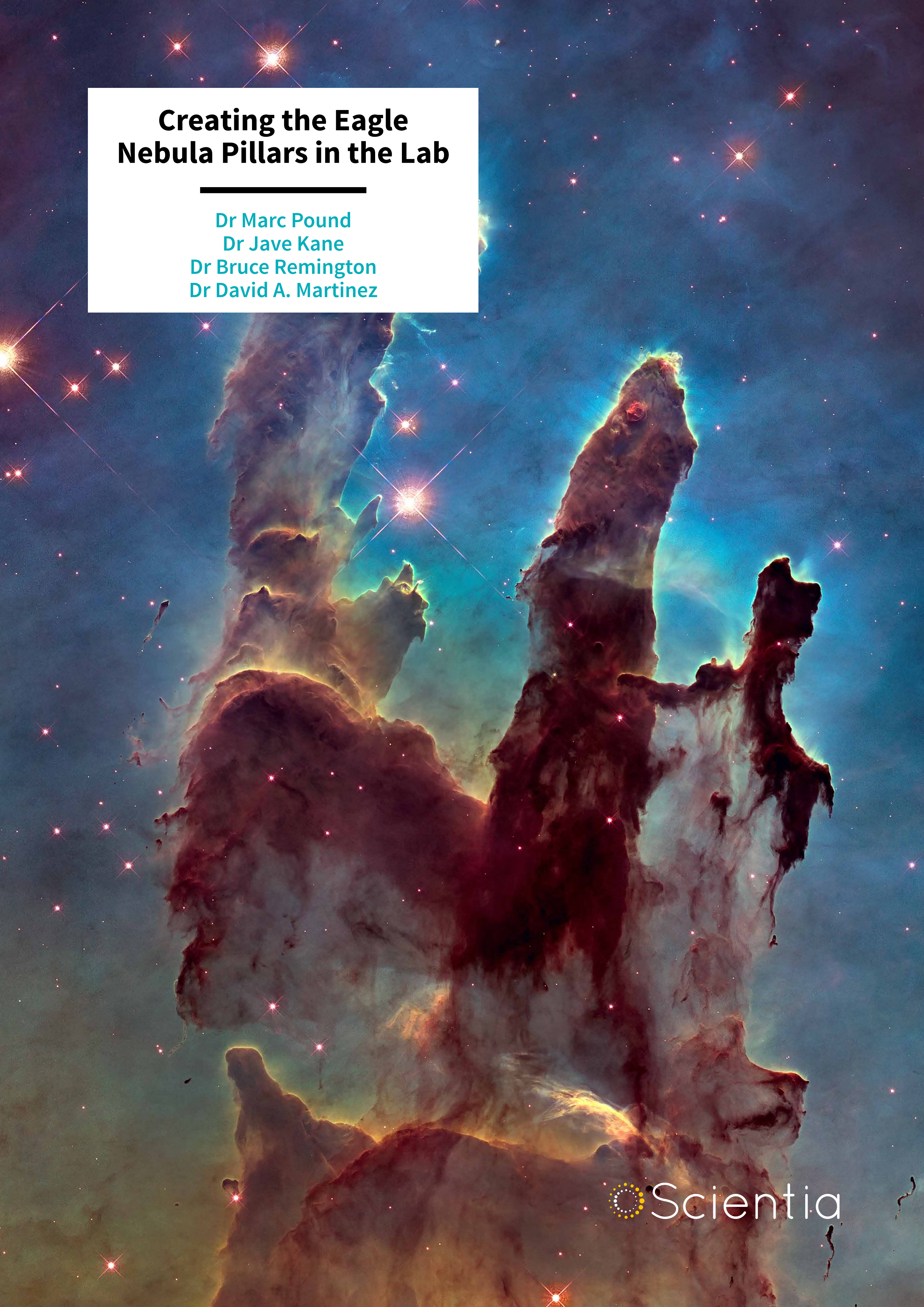

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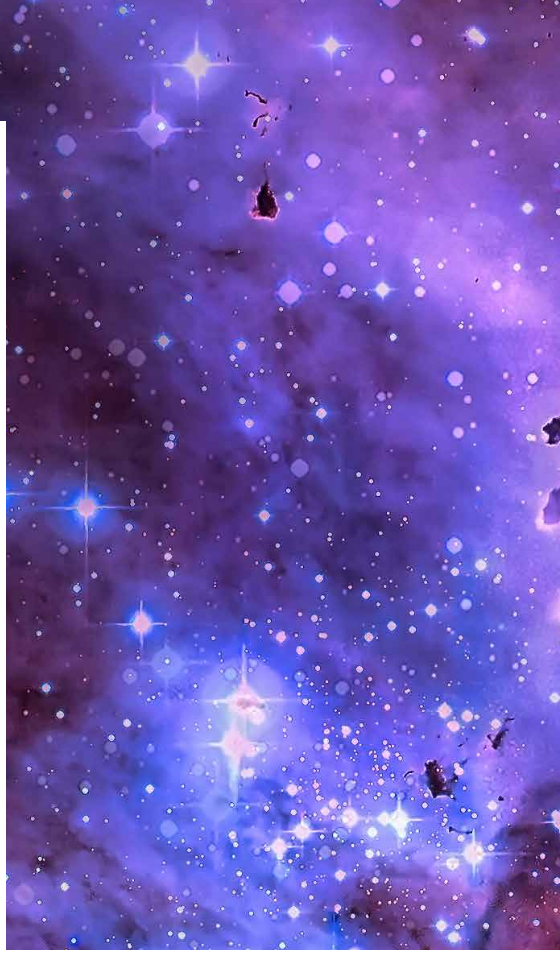


The 'Pillars of Creation' is one of the most iconic images ever taken by the Hubble Space Telescope, but the processes that formed these colossal tendrils of the Eagle Nebula are still not entirely understood. To test emerging theories, **Drs Marc Pound, Jave Kane, David Martinez** and **Bruce Remington** are using the National Ignition Facility, at Lawrence Livermore National Laboratory (LLNL) in Livermore, California, to recreate the conditions that formed the pillars, on a much smaller scale.

Situated some 6,200 lightyears from our Solar System, the Eagle Nebula contains a number of clouds composed of interstellar gas and dust. On a cosmic timescale, these clouds don't stay around for long, as denser areas formed inside the cloud collapse under their own gravity, giving birth to new stars. The material is so plentiful that massive O-type stars – those up to 90 times the mass of our Sun – can form. These stars burn hot and bright, emitting ultraviolet radiation at extremely high intensities.

This ultraviolet radiation from a young O-type star gets absorbed by the cloud material surrounding the new hot star. Hydrogen atoms on the outer surface of the cloud become ionised by the radiation, and 'photoevaporate' away from the cloud towards the hot star, forming a low-density gas between the star and the cloud. A localised high-pressure region is thus created near the surface of the cloud through a process called the 'rocket effect', where the photoevaporated ions correspond to the 'exhaust'. The net result is a shock wave launched through the cloud, pushing the cloud away from the star.

Made famous by the Hubble Telescope's iconic image, the 'Pillars of Creation' or 'Eagle Pillars' are elongated clouds of gas and dust stretching five lightyears, which are situated within the Eagle Nebula. The cloud that originally came to form these pillars contained clumps of denser material, which hadn't yet collapsed to form stars. While shock waves pushed lower density cloud material away, the dense clumps ultimately stayed in place, as shock waves travelled through them much more slowly.

The clumps, therefore, provided a safe haven from both the intense radiation from the star and the resulting shock waves from photoevaporation of the clump, allowing gas and dust to collect behind them, forming pillars. This scenario is the basis of the so-called 'shielding model' of formation of the Eagle pillars.

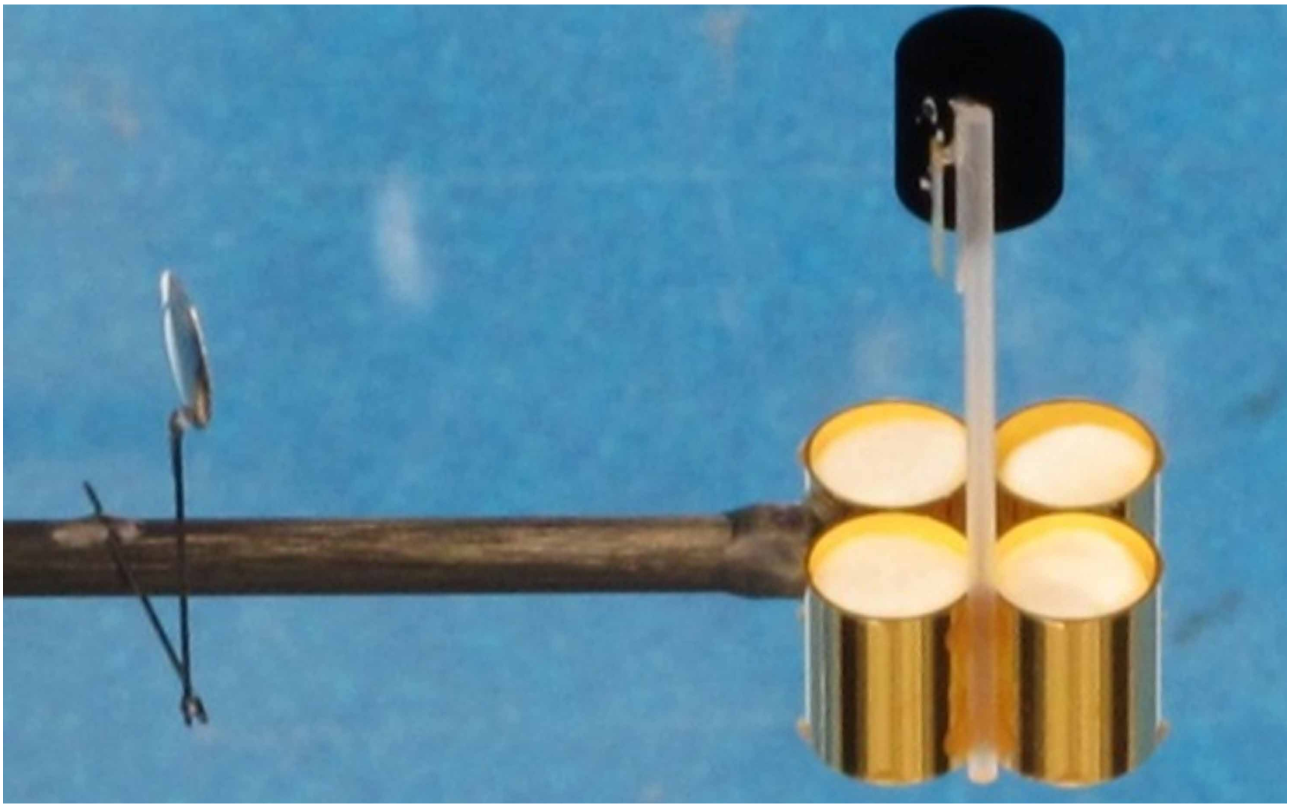
'High mass stars will disrupt the clouds through powerful streams of high energy photons (particles of light) that break apart the molecules and ionise the gas,' explains Dr Marc Pound, of the University of Maryland. 'The Eagle Pillars and features like them are a particularly dynamic manifestation of this interaction as the photons sculpt the dense gas, and push it into elongated shapes.' The shielding model is one interpretation of the early formation of the Eagle Pillars, but Dr Pound and his colleagues, Drs Jave Kane, David Martinez and Bruce Remington at the Lawrence Livermore National Laboratory, believe there is more involved with the structures that we observe today.

Introducing the Cometary Model

The four researchers think that as an initial shock wave wrapped around behind a clump of material, it gained a lateral component, causing it to collide with itself when it reached the axis of one of the pillars. Material travelling with the shock wave rebounded off the pillar's axis, while also moving away from the clump and cooling by radiation and expansion. There are a number of effects, such as the 3D nature of this interaction, that make the situation slightly more complicated. Thus, the team propose a far more comprehensive model.

'At later times, material that is photoevaporated from the clump, or released when the shock exits the clump, collects behind the clump, creating a second, late-time source of material for the pillar,' the researchers claim in their report. 'This process of the clump releasing material downstream is the beginning of the formation of a secondary, "cometary" structure.' This secondary source of material maintains the continuous, elongated structures that we see in the Eagle Pillars today.

This cometary model gets its name from its similarity with the tails of comets. The centres of comets emit particles that are 'blown down stream' by solar winds, leaving a 'tail' that continually points away from the Sun. Similarly, although on a much larger scale, material from the clumps in the Eagle Pillars is released in a 'tail' that points away from the pillar-forming star. Drs Pound, Kane, Martinez and Remington suggest that this process may be what created the structures that we see in the Eagle Pillars today, but unfortunately, they can't confirm it solely from direct astronomical observations. To test their theory, they decided to recreate the conditions that formed the pillars inside an experimental laboratory. To do this, they would need a radiation source powerful enough to play the role of the intense radiation given off by massive, young stars.



The Eagle experimental setup. The NIF laser beams hit the interiors of the hollow gold cylinders from below, which produces intense thermal x-rays out the tops, to simulate the powerful ultraviolet radiation given off by massive, young stars. This intense, protracted source of x-rays irradiates the foam target above.

The Laser that Simulates Starlight

About an hour's drive from San Francisco is a resource capable of meeting the team's requirements. The National Ignition Facility (NIF), located at the Lawrence Livermore National Laboratory (LLNL), contains a 192-beam laser that can deliver an energy of 2 megajoules – equivalent to the energy given off by half a kilogram of TNT – to an area of just a few square millimetres. The facility allows a select number of scientists to conduct their own research there each year. 'The NIF Discovery Science program allocates 8% of its facility time to basic science, based on an international call for proposals,' says Dr Remington, 'Through this program, new regimes of science are being experimentally studied at NIF.'

This facility has previously been used to recreate extreme astrophysical conditions in the lab. In 2014, a team of researchers led by Dr Ray Smith at LLNL wished to recreate the extremely high densities of material found in the cores of giant planets, such as Saturn. To do this, they fired the laser onto the inner surface of a gold cylinder called a 'hohlraum' that was 6 mm in diameter, with a small diamond plate mounted over a hole in the wall of the hohlraum. When hit by the laser, the hohlraum produced high-intensity bursts of x-ray photons – photons of even higher energy than ultraviolet photons.

When the x-ray photons hit the diamond, they generated intense photoevaporation (ablation), which resulted in a pressure of 5 terapascals – 50 million times larger than the Earth's atmospheric pressure. The impact created a compression wave inside the diamond – compressing it to almost a quarter of its original size and four times its density. This artificially high density gave the scientists a brief glimpse into the interiors of massive objects in space.

Another experiment at the NIF, conducted by a team of scientists including Drs Hye-Sook Park and Hans Rinderknecht from LLNL and Frederico Fiuza from SLAC, used the NIF

Simulated image (right) of the evolved target show similar evolution to the data (left). The dark band at the top of the image is the shock in the low-density foam and is moving up, away from the radiation source. The shock colliding behind the clump created a triangular band near the top of the image. At the bottom of the image is the dense clump and above the clump is a shock, moving away from the column of plasma.

laser to irradiate two pieces of foil separated by a few millimetres. Each piece of foil generated high speed (~1000 km/s) flows of plasma (highly charged matter), which interacted with each other at the midplane between the foils. As the two plasmas collided, bursts of subatomic particles called protons and neutrons were generated, as well as x-rays. The presence of these particles suggested that strong heating was occurring at the midplane between the foils, which over time allowed deuterium (a type of hydrogen atom containing one proton and one neutron) to undergo nuclear reactions.

These nuclear reactions implied extremely high temperatures, and suggested the formation of a shock. But the plasma densities were too low for a conventional ('collisional') shock to form. This meant that a 'collisionless' shock had formed, much like astrophysical shocks that exist in supernovae (exploding stars) and other energetic astrophysical phenomena. This observation showed the scientists that thin shockwaves were forming in each collective plasma flow, without the flows interacting with each other by direct two-body particle collisions.

Conducting experiments with the NIF laser is an exacting process, and Dr Park and her team needed to be confident that their experimental setup would yield high quality scientific results. To do this, they used a simulation code named HYDRA, developed at LLNL to predict the outcome of the plasma collision and interactions. Similarly, the recent experiments devised by Drs Pound, Kane, Martinez and Remington to examine the cometary model of pillar formation would rely on HYDRA simulations over many months of preparations to avoid costly mistakes.

Pillars of Foam

In the team's Eagle experiment, the NIF laser was used to create high-intensity radiation, corresponding to that emitted by young O-type stars in the Eagle Nebula. They used a similar gold cylinder setup as that used in Dr Ray Smith's experiment, creating an intense, long-duration burst of x-rays to fire at their target. The NIF laser would do the job nicely, but the target itself required some more thought.

The team's setup could only fire x-rays at an area of a few square millimetres – around 10^{38} times smaller than the real Eagle Pillars! In earlier experiments, they embedded 'clumps' of solid material inside 'clouds' of foam a few millimetres across, representing the structure from which the pillars were formed. When the x-ray photons hit the outer surface of the target, a layer of foam particles was photoevaporated (ablated), in reaction to which a shock wave was launched into the foam. On timescales of 20 nanoseconds (20 billionths of a second), the foam formed into elongated pillars behind the clump, consistent with the shielding model.

These foam targets were incredibly intricate and delicate to make, yet they were vaporised with each shot of the laser. To make sure every shot counted, the researchers used the HYDRA computer code to predict the speed and density of the plasma flow at different points in the structure as it evolved. They could then compare their predictions with real observations of the speeds and densities of gas and dust in the Eagle Pillars, allowing them to perfect the design of the target.

The team's early experiments showed mature foam pillars forming on shorter timescales, consistent with the shielding model. The next step was to adapt the target to test their predictions about the cometary model from a clump embedded in a larger cloud. For this to work, the x-rays would need to last long enough for the shockwave to pass through the clump, allowing the photoevaporated material to collect behind it. The clump itself would also need to be adapted to dynamically add plasma to the pillar after the shock wave had passed through it.

To do this, the researchers adapted the shape and design by adding more x-ray producing gold cylinders that were then illuminated in sequence, lengthening the timescale of the x-ray pulse representing the hot, young O-star to 60 nanoseconds – long enough for cometary structures to form. For the clump, they used a series of denser foam disks, which became successively less dense away from the x-ray source. When the shock wave exited the back side, the clump contributed plasma to the earlier-formed pillar.

So far, the researcher's results have been promising for the cometary model, with the beginnings of cometary structures being observed in the foam pillars after 60 nanoseconds. In the future, they would like to adapt the clumps to more realistically represent those in the Eagle Pillars. This would involve creating spherical clumps that become denser towards the middle – a difficult task that is only now becoming possible with improvements in 3D printing technology.

Dr Pound would also like to explore how magnetic fields could have influenced the formation of the Eagle Pillars. 'Strong magnetic field lines could provide a "tension" that forces the gas to expand in a certain direction and prevent it from expanding in another,' he explains. 'Alternatively, a weak magnetic field would get swept along as the gas moves. We have proposed astronomical observations to measure the existing magnetic field in the Eagle Pillars using NASA's SOFIA airborne observatory. The results of these observations will guide the design a new generation of lab experiments that include the addition of a magnetic field.' Whichever direction the research takes, it's intriguing to think that we can make genuine advances towards understanding astrophysical processes, by recreating them on scales we can measure from the comfort of a lab.

Meet the researchers

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Dr Marc Pound is a principal research scientist at the University of Maryland, where he primarily studies molecular gas clouds and star formation. He completed his PhD in astronomy at the University of Maryland in 1994, after working as a radio astronomer at AT&T Bell Laboratories. He worked as a postdoctoral fellow at the University of California at Berkeley, before returning to Maryland in 1997. Outside of his research, Dr Pound develops software for astronomers using the Atacama Large Millimeter Array, and is involved many university committees on campus, aiming to improve career opportunities for non-tenured faculty members.

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Dr Jave Kane is a staff physicist at the Lawrence Livermore National Laboratory, where he first worked as a graduate member of staff in 1995. He completed his PhD in physics at the University of Arizona in 1999 and went on to study advanced computer security at Stanford University. He received a graduate certificate in mining massive data sets in 2014. Dr Kane has also worked as a technical advisor for the National Nuclear Security Administration.

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Dr Bruce Remington is a staff physicist at the Lawrence Livermore National Laboratory, where he has worked since 1988. He is now the program leader for Discovery Science at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). Dr Remington received his PhD in experimental heavy-ion nuclear physics from Michigan State University in 1986, and his research has since focused on using lasers to study plasma hydrodynamics, high pressure materials science, and laboratory astrophysics.

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