Formation of Elephant Trunks in H II Regions

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Introduction

Dense elongated pillars of gas are one of the most striking features of massive star-forming regions (e.g. the Eagle (M16) and Carina (NGC3372) Nebulae). Despite extensive study in recent years, there is still no firm consensus as to the lifetimes of these *elephant trunk*-like structures or the mechanisms by which they form.

We have developed a radiation-MHD code to study the possible formation scenarios of such pillars. We confirm previous work in finding that it is very difficult for the shadowing of ionising radiation by a single clump to produce a dense pillar on a timescale of 0.1Myr. We have performed 2D and 3D numerical simulations where we have investigated the evolution of a random distribution of dense clumps exposed to an ionising radiation source. The 3D results are presented here and we describe the mechanisms which produce the pillars. We assess the properties of the density fields that are required in this model to produce the large pillars which are observed.

Brief Description of Code

We have developed a grid-based, finite volume, fluid dynamics code, with a dimensionally unsplit second order accurate update, similar to Falle, Komissarov & Joarder (1998). We use Riemann solvers to calculate the fluxes for the Euler and Ideal MHD equations, with the *mixed-GLM* divergence cleaning method for dealing with $\nabla \cdot \mathbf{B}$ (Dedner et al., 2002). Following Falle, Komissarov & Joarder (1998), we add some bulk and shear viscosity to ensure stability and accuracy in multi-dimensional simulations. The code was parallelised using domain decomposition on multiple processors (with MPI communication).

On top of the dynamics module we have added an operator-split microphysics/ray-tracing module, where for each cell we update the internal energy and ionisation state via an adaptive sub-stepping integrator. Ionising radiation is traced from a discrete source on or off the domain (or at infinity) using the *Short Characteristic Tracer* method. Diffuse radiation is not treated (the "On-the-Spot" approximation). Ion fractions are tracked with passive tracer variables. The integration uses the photon-conserving formalism developed by Abel, Norman, & Madau (1999), and is similar to the C^2-ray method (Mellema et al., 2006).

In this work we track hydrogen ionisation/heating/cooling explicitly, and cooling due to other elements via a pre-calculated cooling function ($\propto n_e$, T). Molecular cooling is not considered.

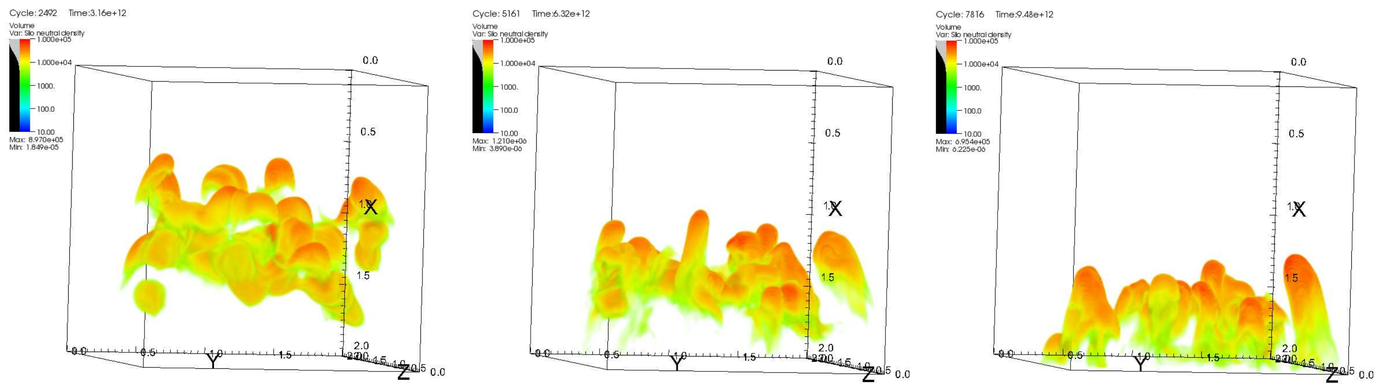

Figure 1: Volume rendering of 3D models. Neutral gas density is plotted, with gas at $n_H \lesssim 10^4\,\mathrm{cm}^{-3}$ made transparent to show the difference between neutral tails and dense pillars. Images are at simulation times 100, 200, and 300kyr. Note the pillar front and centre in the second panel, and another at right back in the third panel.

Shadowing by Dense Clumps

The photo-ionisation and evaporation of a single clump exposed to ionising radiation is a well-studied problem (e.g. Bertoldi, 1989; White, Nelson, Holland, et al., 1999; Williams, Ward-Thompson & Whitworth, 2001; Pound et al., 2007), but it is not easy for the shadowed region to gather and organise enough mass to form a pillar, at least not in a small fraction of a Myr. The problem is as follows: if ambient gas is compressed from a large cylinder into a smaller cylinder (pillar), the density increases as $\rho \propto 1/r^2$, so if we need to increase density by 50× the ambient value, then we need the gas to come from a cylinder 7× larger in radius. The observed mean density in the M16 pillars is $n_0 \sim 3-5\times10^4\,\mathrm{cm}^{-3}$ with radii $R \simeq 0.1-0.15pc$. It seems unlikely that all of this gas came from a cylindrical volume of $\simeq$ 1pc radius. We have run 3D simulations to verify this, and were not able to build up enough mass in 200kyr for the tail to constitute a pillar.

The alternative is that enough mass to form a pillar is already nearby. This could either come from the shadowing clump itself due to its dynamical response to the radiation, or from other nearby clumps which move into the shadowed region. We know molecular clouds are clumpy on a wide range of scales so we consider the second possibility to be the most promising to study. To this end, we set up simulations with lots of randomly placed clumps, some partially and fully shadowing others, to investigate how they evolve when exposed to ionising radiation. Ours is in many ways a similar model to that investigated by Raga, Henney, Vasconcelos et al. (2009), who studied a specific configuration of clumps on much smaller length scales.

There are at least three reasons why gas will move into the shadows:

- Pressure gradients (because the shadowed region is cold).
- A partially shadowed clump experiences a skewed 'Rocket Effect' directed both away from the star and into the shadows.
- If one clump is swept past another by the rocket effect, it moves more easily through the lower density medium, distorting its shape. The above two effects then come into play and mean most of the distorted clump material will end up in the shadow.

If the gas in the shadows is adiabatic it will tend to bounce back out of the shadows, but if it can cool efficiently there is a good chance it will 'stick' and remain there.

3D Simulations

We set up a number of 3D simulations at 128^3 resolution with various numbers and sizes of random clumps. Here we show results from one of these simulations, which we subsequently re-simulated at higher resolution (256^3). This model has a $(2\mathrm{pc})^3$ domain, with a star 2pc off the grid in one direction. The ionising photon flux is $10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at the front edge of the grid. There are initially 30 randomly placed dense clumps ranging in mass from $3-10\mathrm{M}_\odot$ with radii $0.06-0.14$pc (Gaussian density distribution). A volume rendering of the neutral gas density is shown in Figure 1, and slices of neutral density in the two main pillars in Figures 2 and 3.

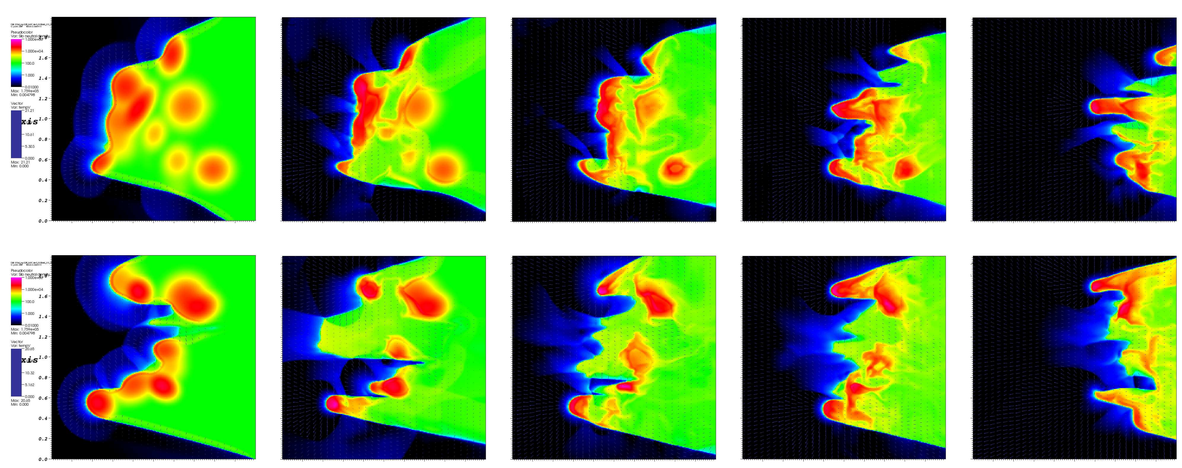

Figure 2: Slices through the dense pillar at the front of panel 2 of Figure 1. The top sequence shows $x-y$ slices with the pillar just above centre, and the bottom sequence is $x-z$ slices with the pillar near the top. Slices are at times, 10, 50, 100, 150, and 250kyr. The pillar is gone at 300kyr, succumbing to the rocket effect.

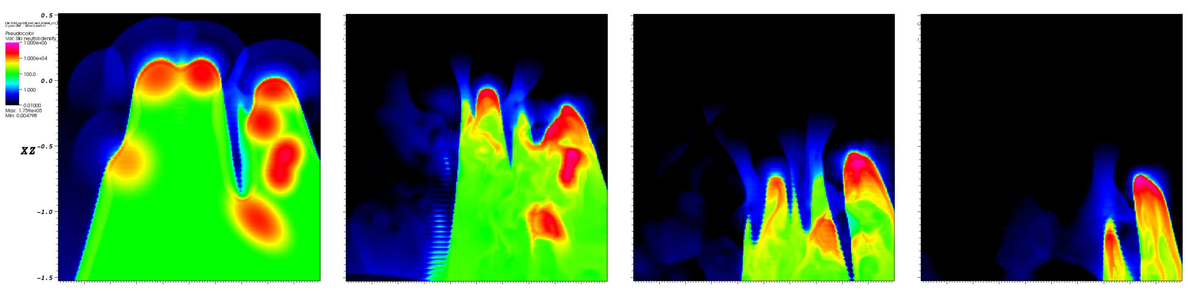

Figure 3: Slices through the dense pillar at back right of panel 3 of Figure 1. The slices are at an angle to the grid, so that rays from the source stay in the slice. No interpolation is done within grid cells, leading to striping as cell boundaries are crossed. Slices are at times, 10, 100, 200, and 300kyr.

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Discussion of Results

- Looking at Figure 1, there are no structures like elephant trunks after 100kyr. There are only dense clumps with low density tails. The first pillar-like structure forms after about 150kyr, and they last about $50-100$kyr. In this simulation the two elephant trunks are $\sim 0.5-0.7$pc long, similar to the smaller two M16 pillars.
- Figure 2 shows that the first elephant trunk forms in a way we didn't originally anticipate. A massive clump is shadowed by two smaller clumps. These are accelerated past the massive clump (top line, second panel), and wrap around it forming a dense pillar. The massive clump protrudes because it is not subject to the rocket effect until the shielding clumps are pushed past it. It rejoins the main mass of gas by 300kyr since the rocket effect acts more effectively on clumps closer to the source.
- A pillar closer to what we expected forms in the back right corner of Figure 1. A cut through this is shown in Figure 3. There are a few clumps through the volume, partially shadowed, and they gradually merge into a dense pillar after $\sim$ 250kyr.
- A general feature of our results is that low density regions are needed around clumps for pillars to form. The ionisation front has to propagate far beyond the leading clump for anything like a pillar to form because (1) it takes up to $\sim$ 100kyr to organise gas into a pillar; and (2) The rocket effect efficiently accelerates all but the most massive clumps on a similar timescale.
- Ionisation front instabilities are another possible formation mechanism for trunk-like and cometary features. On the scales of M16, where the trunks are parsec-scale, and the radiation sources are only about 2pc away, the inverse-square law drop-off in flux becomes a significant damping factor on any instabilities, just as it is on our multiple clumps model.

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