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III

A class of champagne flow H II regions with radiation pressure-driven dust waves

We investigate the evolution and the morphology a class of H II regions formed by champagne flow mechanisms in order to explain the cometary shape of the dust emission. We carry out hydrodynamical numerical simulations with radiation using the FLASH HC code. We set up a modified Bonnor-Ebert sphere density profile to represent the molecular cloud and change the location of the ionizing star offset from the center. We derive velocity and emission measure maps to compare to observations. The velocity of the gas inside the H II region reaches values up to 40 km s^{-1} at the star location, well above the minimum velocity required for a dust wave to form. We show that champagne flow models provide a natural mechanism to explain the presence of dust inside bubbles and its cometary shape. We are also able to reproduce the full range of observed morphological classes by setting the ionizing star offset from the center of the natal molecular cloud.

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to be submitted

3.1 Introduction

The presence of dust inside H II regions as discovered by the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) survey in the mid-infrared has recently raised a new enigma regarding the evolution of interstellar bubbles. The formation and expansion mechanisms of H II regions are still under debate. When a high mass star ionizes its surrounding, the ionization front reaches the Strömgren radius on short timescales. The following stages of expansion have been examined by many authors, each taking into account different physical processes. Spitzer (1978) studied the expansion due to the effects of overpressure caused by the ionization and heating of the H II region; Castor et al. (1975) considered the mechanical energy of the stellar winds as a main driving mechanism; and Krumholz & Matzner (2009) took into account the pressure of the radiation on the gas. Draine (2011) studied the structure of dusty H II regions in static equilibrium with an external bounding pressure and found a family of solutions for the density profiles, ranging from uniform to hollow-spheres.

Ochsendorf et al. 2013a (submitted) revealed the first detection of a radiation-pressure driven *dust wave* around a massive star (σ Ori, stellar spectral type O9.5V). They suggested that the cometary shape of the dust emission is the result of the interaction between radiation pressure from the star with the dust contained in the flow of ionized gas photo evaporated from the natal molecular cloud. Similar arc-like structures in 24 μ m emission of warm dust have been detected inside H II regions. Ochsendorf et al. 2013b (to be submitted) suggest that the dust distribution inside interstellar bubbles can be explained by similar dust waves. Radiation pressure from the ionizing star acts on the photo-evaporating flow from the swept up shell of the H II region. In the presence of a champagne flow, the ionized gas inside the H II region reaches velocities $\sim 10 \text{ km s}^{-1}$ at the star location setting up the conditions for a dust wave.

In this work, we extend the work of Ochsendorf et al. 2013b (to be submitted) to a broader range of parameters. We restrict our study to H II regions powered by stars that have weak stellar winds. Indeed, evidence is accumulating that winds from stars with stellar type later than O6.5V (ionizing luminosity $Q_0 \approx 48.8$ (Martins et al. 2005)) are weaker than predicted by theory (Vink et al. 2000, Puls et al. 2008, Najarro et al. 2011). We identify five H II regions following such criteria, and with different morphologies: from closed bubbles, to broken and fully open ones. In the first case, Draine (2011) theory predicts a ring-like structure in the emission measure of dust, while in the other cases we expect an arc-like structure pointing upstream of the gas flow. We investigate if H II bubbles can, without the inclusion of a stellar wind, reproduce the morphologies (as a function of density gradient and depth into the cloud) and create the conditions necessary to induce photo-evaporating flows in their interior.

The paper is organized as follows. We present a selection of five prototypical H II regions in Section 3.2 which cover well the range of morphology observed. We describe the numerical method in Section 3.4 and analyze the results in Section 3.5. In Section 3.6 we discuss how simulated H II regions compare with observed one, and what are the main implications of this work. We conclude in Section 3.7.

Table 3.1 – Bubble parameters. Electron densities are derived from the observed emission measure assuming spherical symmetry of the H II region with a uniform density distribution.

Name	l (deg)	b (deg)	d (kpc)	Diam. (pc)	$\dot{N}_{\text{Ly}\alpha}$ (s^{-1})	Spec. type	τ_{MS} (Myr)	n_e (cm^{-3})
N49 (C)	28.83	-0.23	5.5 ¹	4.0	48.35 ^{1,3}	O7-8	~ 7	72
N90 (C)	43.77	0.06	6.1 ¹	1.7	47.74 ^{1,3}	O9.5	~ 11	68
RCW120(B)	348.26	0.48	1.35 ²	3.5	48.58 ⁴	O7-7.5	~ 6	86
N73 (B)	38.74	-0.14	9.2 ¹	5.3	48.2	O8-8.5	~ 8	41
N69 (B/O)	36.29	0.72	4.9 ¹	30	48.0	O9	~ 10	13

(1) Deharveng et al. (2010), (2) Zavagno et al. (2007), (3) Beaumont & Williams (2010), (4) Martins et al. (2010). Spectral types from Martins et al. (2005) assuming dwarf type stars. Main sequence lifetimes (τ_{MS}) from Ekström et al. (2012). *Notes:* (N49 and N90) Flux density S taken from Beaumont & Williams (2010) but corrected for distance from Deharveng et al. (2010). (N73): S taken from the HRDS (Bania et al. 2010). (N69): S taken from the NVSS (Condon et al. 1998).

3.2 H II region morphology

H II regions are often classified by their morphology. Churchwell et al. (2006) and the ongoing Milky Way project (Simpson et al. 2012) used the Spitzer/GLIMPSE survey to collect a large sample of Galactic bubbles and classified bubbles as complete or closed (C) or broken (B) according to their appearance in the IRAC 8 μm band. We follow this classification, however adding the ‘open’ morphology (O). A morphological classification does not necessarily relate to the age of the bubble; as we will investigate below, the evolution could be dominated by the region in which the H II region expands. Furthermore, while some bubbles can appear broken in IRAC 8 μm band, dense condensations exposed at longer wavelengths by Herschel can exist in the parts of the apparent broken shell. For example, in N49 (Figure 3.1(a)) the broken parts of the IRAC shell correspond to the highest columns seen in SPIRE 250 μm .

We will compare the outcome of our simulations with several prototypical examples outlined below. Limitations in the selection criteria of the prototypes include:

- 1) *Apparent size.* To simultaneously study the distribution of both gas and dust we need sufficient spatial resolution.
- 2) *Radio surveys.* High resolution radio continuum observations are needed to study the distribution of the ionized gas. $\text{H}\alpha$ is rarely observed towards faint H II in the Galactic plane. Therefore, we rely on radio observations. The recent MAGPIS radio survey offers radio images at 20 cm with a resolution 6''. However, this covers only a small part of the Galactic plane ($48.5 < l < 5$, $|b| < 0.8$). In addition, the MAGPIS is one of the most sensitive surveys up to date. For bubbles of large angular size (RCW 120), lower resolution data from the NVSS (Condon et al. 1998) is sufficient for our needs.

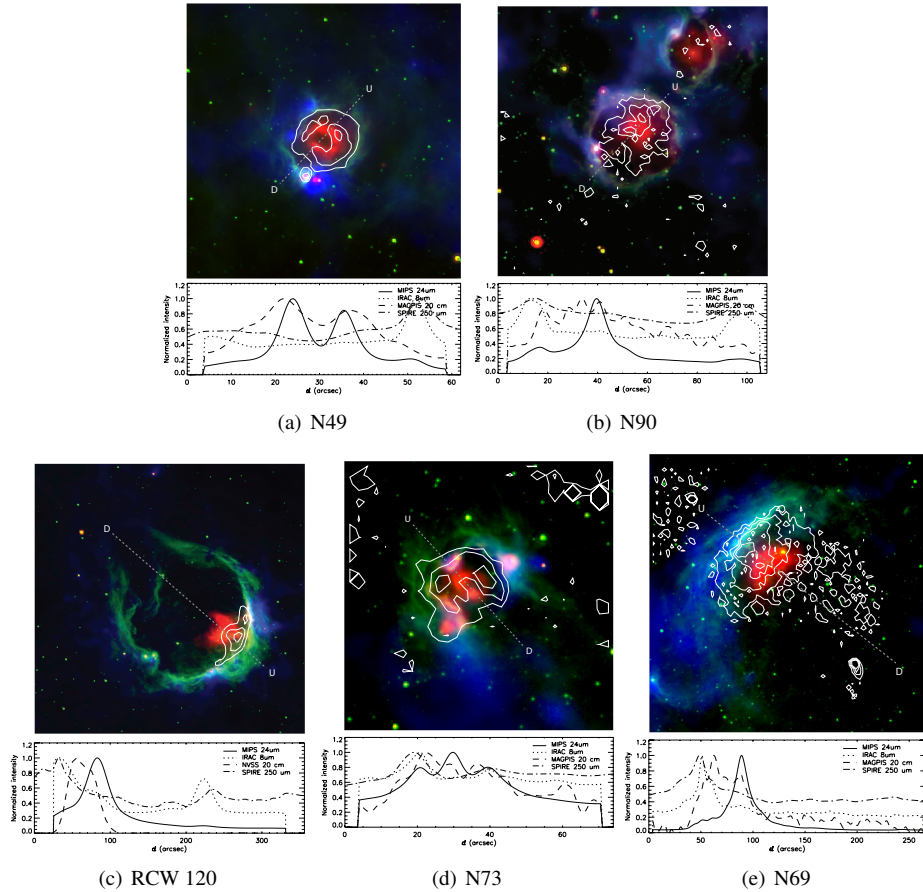


Figure 3.1 – Bubble prototypes. Red is MIPS 24 μm , green is IRAC 8 μm , and blue is SPIRE 250 μm . Overlaid are smoothed contours of radio emission of MAGPIS 20 cm (for RCW 120; NVSS). Contour levels are max-75%-50%, except for N69 where a 25% contour level is added to show the faint emission that traces the gas streaming out of the bubble. Lower panels show line profiles of cross-cuts through the maximum of the 24 μm emission, which corresponds to the apex of the arc (or ring; see N49 and N73) shaped 24 μm emission. The profiles are smoothed using a Gaussian function of width 7.5'' in order to reduce noise in the MAGPIS images. The cuts run from 'U', which stands for 'upstream', to 'D', which stands for 'downstream'.

- 3) *Distance*: Large scale surveys like the Green Bank Telescope H II region Discovery Survey (HRDS) (Bania et al. 2010) are trying to solve the near and far kinematic distance ambiguity by measuring radio recombination lines (RRL) (e.g., Anderson et al. 2012). However, the distance towards a lot of bubbles remain uncertain. In our sample selection we only use sources of which the distance ambiguity is resolved.

With the distance known, we estimate the amount of Lyman continuum photons, $\mathbb{N}_{\text{Lyc}}$, from the integrated radio fluxes necessary to maintain the ionization in the H II region, assuming optically thin free-free emission, using the following relation (Condon 1992):

$$\mathbb{N}_{\text{Lyc}} = 7.54 \times 10^{46} \left(\frac{F_\nu}{\text{Jy}} \right) \left(\frac{\nu}{\text{GHz}} \right)^{0.1} \left(\frac{d}{\text{kpc}} \right)^2 \left(\frac{T_e}{10^4 \text{ K}} \right)^{-0.45} \text{ s}^{-1}, \quad (3.1)$$

where F_ν is the flux at frequency ν , d is the distance of the source and T_e is the electron density.

Table 3.1 lists the properties of the selected bubble sample. For each bubble, we compare emission maps at a multitude of wavelengths:

- 1) *Spitzer*/IRAC 8 μm from the Glimpse survey (Benjamin et al. 2003), which traces PAH emission coming from the PDR located at the inner boundary of the swept up shell.
- 2) *Spitzer*/MIPS 24 μm from the MIPS GAL survey (Carey et al. 2009), which traces warm dust (50-150 K) emission mainly coming from both the swept up shell and the interior of the bubbles.
- 3) *Herschel*/SPIRE 250 μm from the Hi-Gal survey (Molinari et al. 2010), tracing cool (10-40 K) dust emission from dense condensation containing larger columns of material.
- 4) VLA 20 cm images from the MAGPIS survey (Helfand et al. 2006), tracing free-free continuum emission from ionized gas.

3.2.1 ‘Closed’ bubbles

As predicted by the Draine (2011) static solution, radiation pressure acting on dust grains inside the bubble pushes the dust towards the walls of the H II region, seen as a ring structure in emission measure. Several apparent closed bubbles, such as N49 (Fig 3.1(a), (Draine 2011)) and W3A (Salgado et al. 2012), show such ring features. The line profiles at 24 μm and 20 cm show that gas and dust inside the bubble are spatially coupled. We note that Draine (2011) concludes that the gradient inside N49 can not be due to radiation pressure on dust alone and that a stellar wind likely contributes to the inner cavity. Indeed, the N49 ionizing star is at the limit that defines stars with weak winds, making it difficult to exclude the effects of stellar winds without a more detailed investigation.

3.2.2 ‘Broken/open’ bubbles

From Figure 3.1(c) to 3.1(e), broken (B) and/or open (O) bubbles are shown in increasing stages of opening or shell-disruption. We find a clear separation of the ionized gas and dust inside H II regions, as traced by the cross cuts in Figure 3.1(c). The sequence could be interpreted as an age progression: the bubbles expand to large radii, which leads to an increasingly large ‘opening’ of the region (N73 and N69). Eventually, a bubble can

Table 3.2 – Initial Density

	$\log \max(n)$	$\log \bar{n}$	R_{cl} [pc]	M_{cl} [$M_{\odot}$]	P_{env} [$K \text{ cm}^{-3}$]
A	4.4	2.4	4.7	5.6×10^4	6×10^5
B	5.8	3.5	4.6	6.9×10^5	6×10^5
C	5.8	3.8	4.7	1.4×10^6	6×10^6
D	5.8	4.2	7.1	3.3×10^6	6×10^6

appear as a flat ionization front being evaporated by the ionizing source (σ Ori-like’: see Ochsendorf et al. 2013a, submitted).

3.3 Dust waves

Photo-evaporation flows inside H II bubbles can be caused by either a density gradient or the disruption of the swept-up shell, ultimately characterized by the ejection of the ionized gas in the surrounding medium. A flow of ionized gas will drag along dust in its way by coupling through the drag force. The coupling efficiency between dust and gas depends on the flow parameters (in particular, the velocity v_f and density n_H of the flow) and the intrinsic momentum of the grains. This allows us to derive properties of the dust as soon as the flow parameters are specified. Depending on the coupling efficiency, we can distinguish between a *dust wave*, where dust is stopped by radiation pressure from the ionizing source and decouples from the gas, and a *bow wave*, where dust is stopped and gas stays coupled. Thus, the former is characterized by an arc structure in the dust, while the latter has an arc structure in dust and gas emission. Regardless of the coupling between gas and dust, photo-evaporation flows provide a natural explanation for the presence and arc-like morphologies of dust within H II regions (Ochsendorf et al., 2013a submitted), typically observed at $24 \mu\text{m}$ (see Figure 3.1) and indicative of dust grains of temperature $\sim 50\text{--}100$ K residing within the harsh conditions of the H II regions.

3.4 Numerical method

We carry out hydrodynamical simulations using the code FLASH HC, a modified version of the FLASH code (Fryxell et al. 2000) that includes a Hybrid Characteristics radiative transfer scheme developed by Rijkhorst et al. (2006). The FLASH code is a publicly available, block-structured, adaptive mesh refinement (AMR) hydrodynamics code with modular design and scalable to tens of thousands of processors. The Hybrid Characteristics (hereafter HC) is a ray-tracing radiative transfer scheme designed specifically with FLASH block structure in mind. Since its introduction by Rijkhorst et al. (2006), we made several improvements to the HC scheme that are described in Raicevic (2010) and Chapter 2. The updated version of the scheme was employed in the radiative transfer code comparison project by Iliev et al. (2009).

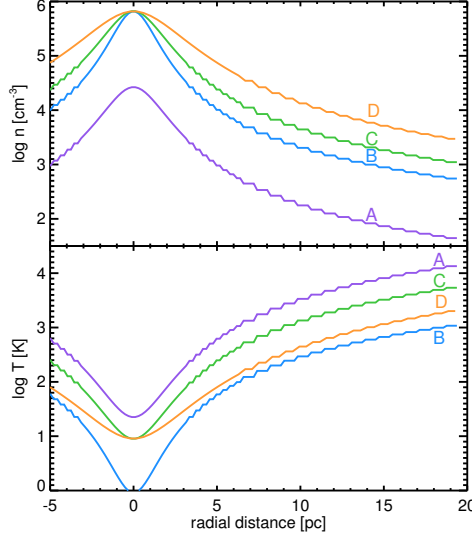


Figure 3.2 – Density and temperature profiles of the initial condition along the x-axis. We generate four clumps with a density profile similar to a Bonnor-Ebert sphere, but in pressure equilibrium.

3.4.1 Setup

The computational domain consists of a Bonnor-Ebert sphere density profile, modified to be in pressure equilibrium. A Bonnor-Ebert sphere is an isothermal gas sphere embedded in a pressurized medium in hydrostatic equilibrium. A number of isolated globules and cores have been studied in near infrared showing a good fit to the Bonnor-Ebert sphere profiles (Alves et al. 2001, Teixeira et al. 2005, Kandori et al. 2005). Since we do not want to study the formation from molecular cloud to birth of a star, but only the physics after the star is formed and starts ionizing the surrounding medium, we omit the force of gravity in the simulations. In order to have an equilibrium solution, we put the sphere in pressure equilibrium by changing the temperature appropriately. In this way we create a density profile that resembles the Bonnor-Ebert density structure without including gravity.

3.4.2 Initial conditions

We carried out a parameter study to investigate what determines the shape and size of H II regions during their dynamical evolution. We also want to establish whether the ionized gas moves inside the H II region and is able to set the right conditions for a dust wave.

We keep the type of star fixed with $\dot{N}_{\text{Ly}\alpha} = 10^{48} \text{ s}^{-1}$, without stellar winds, and the box size 26 pc by 19.5 pc. We modify the density profile: we generate four clumps with the modified Bonnor-Ebert sphere with properties listed in Table 3.2. The average density and the mass in the clump spans two orders of magnitude. The ambient pressure has a low

and high value. In Figure 3.2 we illustrate the one-dimensional density and temperature profile of the four clumps.

Additionally to the density, we also change the location of the source with respect to the center of the clump. We consider three cases: the star at the center of the clump, the star offset along the x-axis of 1.3 pc and 4.9 pc. We run a total of twelve two-dimensional simulations by combining the four clumps and the three locations of the ionizing star. We assume that the star is not moving in respect to the ambient medium.

3.5 Results of the simulations

3.5.1 Morphology

We carried out a parameter study to determine the effects of the density of the ambient medium and the location of the star on the resulting H II region size, morphology and characteristics. We plot in Figure 3.3 and 3.4 the results of our twelve simulations at age 1 Myr and 2 Myr respectively. We note that H II regions in the lower density medium reach a larger radii in a shorter time. This is expected: the recombination timescale goes as $1/(\alpha_B n)$, where α_B is the recombination rate, and the expansion depends on the amount of gas that gets ionized and stays as such. In a lower density medium a larger volume of gas is ionized.

The position of the star with respect to the clump determines the shape of the H II region. When the star is at the center of the clump the H II region is perfectly spherical. The Strömgren radius is reached in a recombination timescale, before the gas has time to react. Later, the increase in pressure due to the increase in temperature ($\sim 10^4$ K) drives the shock to larger radii. However, the pressure of the ambient medium stops such a shock and material builds up into a thick shell that radiation cannot penetrate anymore. The result is an inner region of gas highly ionized and of low density at temperature $\sim 10^4$ K surrounded by a almost neutral, denser shell propagating into the medium.

The same physics happens when the star is offset with respect to the clump center, with the difference that there is no more symmetry in the H II region. The result is an elongated H II region towards the low density side, that can eventually evolve into an open H II region. The increasing distance of the star to the center of the clump increases the asymmetry of the morphology of the H II region.

In the offset cases, simulations show Rayleigh-Taylor instabilities in a zone between the ionization front and the dense shell towards the low density medium. When the ionized gas at higher pressure is accelerated towards the medium at lower pressure, the instability sets in and the typical gas mushroom-like features characteristic of the Rayleigh-Taylor instability becomes visible.

Finally we note that the location of the star with respect to the slope of the density of the medium creates differences in the evolution of the H II region. Looking at clump C and D, where the main difference is the slope of the radial decay in density, we see that the asymmetries evolve faster in the less steep case (clump D) creating a more elongated H II region.

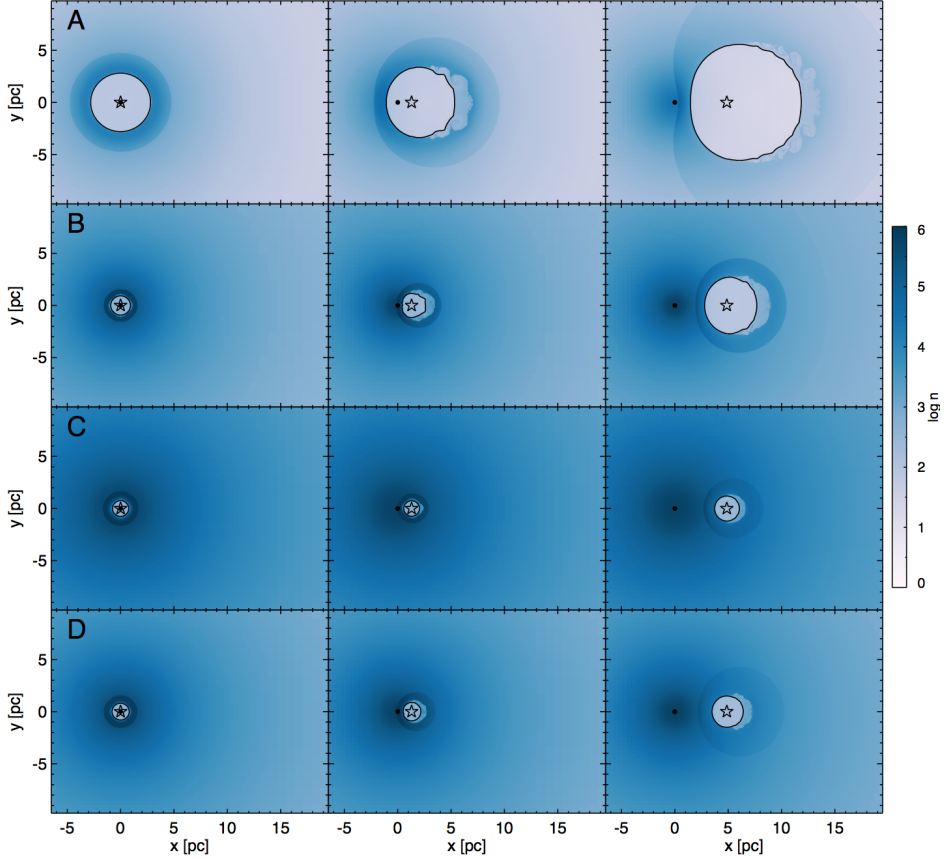


Figure 3.3 – Logarithm of the number density (in cm^{-3}) after 1 Myr from the start of the simulations. The location of the ionizing star is marked by the star symbol, while the clump center is marked by a dot. We also mark the ionization front (black line), defined as the location where the ionization fraction has dropped to a value of 0.5. From top to bottom we show clump A, B, C, D respectively. On the columns we plot the three stars offset: centered, offset by 1.3 pc, and offset by 4.9 pc.

3.5.2 Velocity of the ionized gas

Figure 3.5 illustrates the total velocity of the gas for the twelve runs at age 2 Myr. For the low density case (clump A) the swept up shell expands at about 5 km s^{-1} into the medium, while the ionized gas inside the H II region has a velocity strongly dependent on the morphology of the region. For the offset cases at low density, most similar to the broken and fully open observed cases, the velocity of the ionized gas reaches value of $20\text{--}35 \text{ km s}^{-1}$. For the higher density clumps, the velocities reached inside the bubbles is

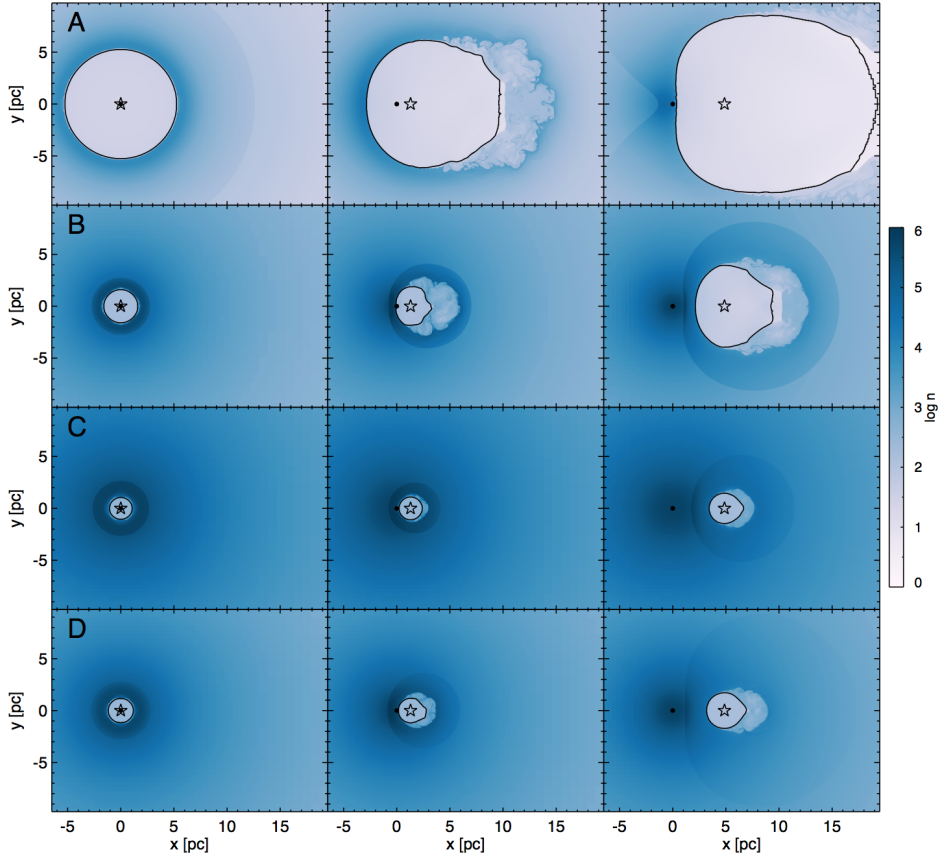


Figure 3.4 – Logarithm of the number density (in cm^{-3}) after 2 Myr from the start of the simulations. The location of the ionizing star is marked by the star symbol, while the clump center is marked by a dot. We also mark the ionization front (black line), defined as the location where the ionization fraction has dropped to a value of 0.5. From top to bottom we show clump A, B, C, D respectively. On the columns we plot the three stars offset: centered, offset by 1.3 pc, and offset by 4.9 pc.

from 5 to 20 km s^{-1} . We note that the ionized gas moves down the density gradient even before the H II region opens up, in some cases, the H II region is close to spherical, but has already the gas moving towards what will be the opening.

Figure 3.6 shows the ranges of velocities reached along the x-axis passing through the star at different ages. The spherical case shows a very symmetric profile characteristic of a sphere expanding outwards. The neutral shell expands at maximum 5 km s^{-1} in radial direction. When the star is offset from the cloud center, the gas is accelerated up to 20 to 25 km s^{-1} (according to the offset) at the location of the star, creating the perfect

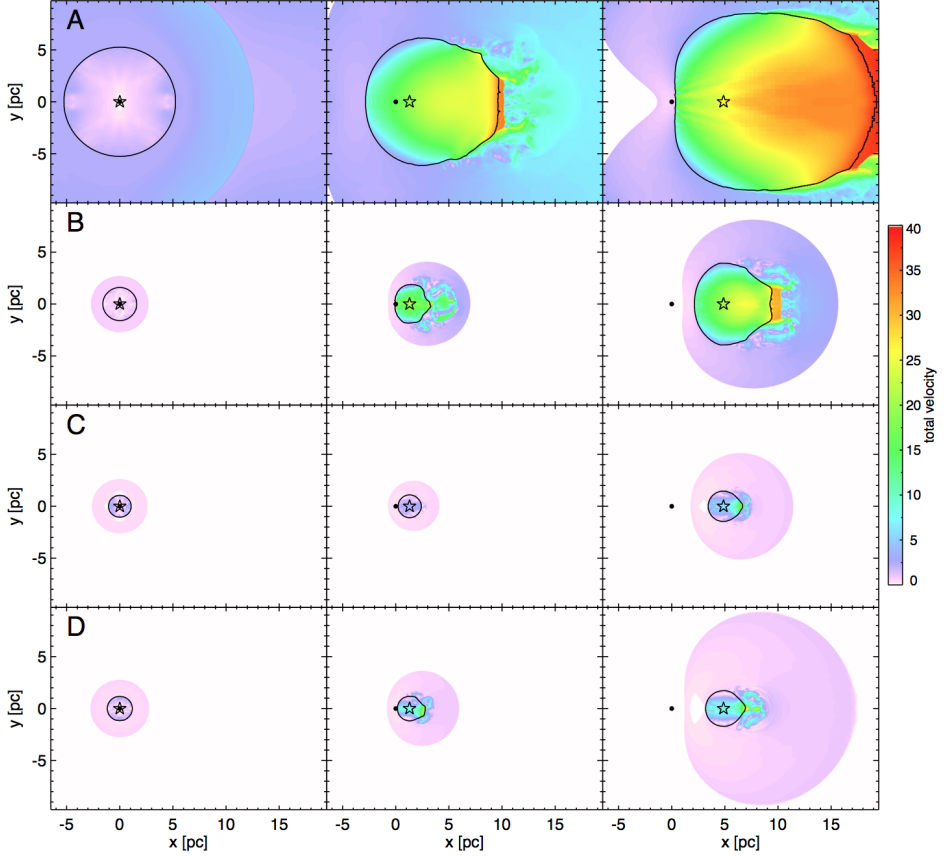


Figure 3.5 – Total velocity (in km s^{-1}) after 2 Myr from the start of the simulations. The location of the ionizing star is marked by the star symbol, while the clump center is marked by a dot. We also mark the ionization front, defined as the location where the ionization fraction has dropped to a value of 0.5. From top to bottom we show clump A, B, C, D respectively. On the columns we plot the three stars offset: centered, offset by 1.3 pc, and offset by 4.9 pc.

conditions for the dust wall to set up.

3.6 Discussion

3.6.1 Comparison with observations

We selected two simulations that are representative of the two classes of bubbles that are observed: closed and broken/open bubbles. We choose clump B with star offset of 1.3 pc

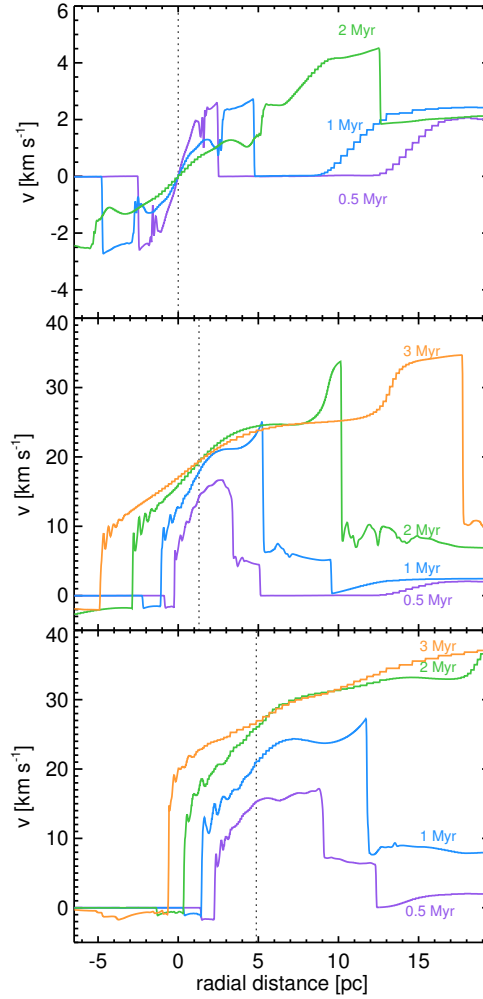


Figure 3.6 – Time evolution of the total velocity of the gas along the x-axis passing through the star for clump A. The ionizing star location is indicated by the dotted line, the clump is at zero coordinate. From top to bottom we show clump three stars offset: centered, offset by 1.3 pc, and offset by 4.9 pc. The velocity of the gas along the cut is shown for times 0.5, 1, 2 and 3 Myr after the start of the simulation. Note the different y-axis range for the top panel.

to represent the closed bubbles and clump A with stellar offset 4.9 pc as an example of the broken bubbles. We run those two cases in three dimensions and produce maps similar to the observables. We create emission maps of the ionized gas to estimate the radio emission. We select gas with a column density from the central star up to 10^{21} cm^{-2} that

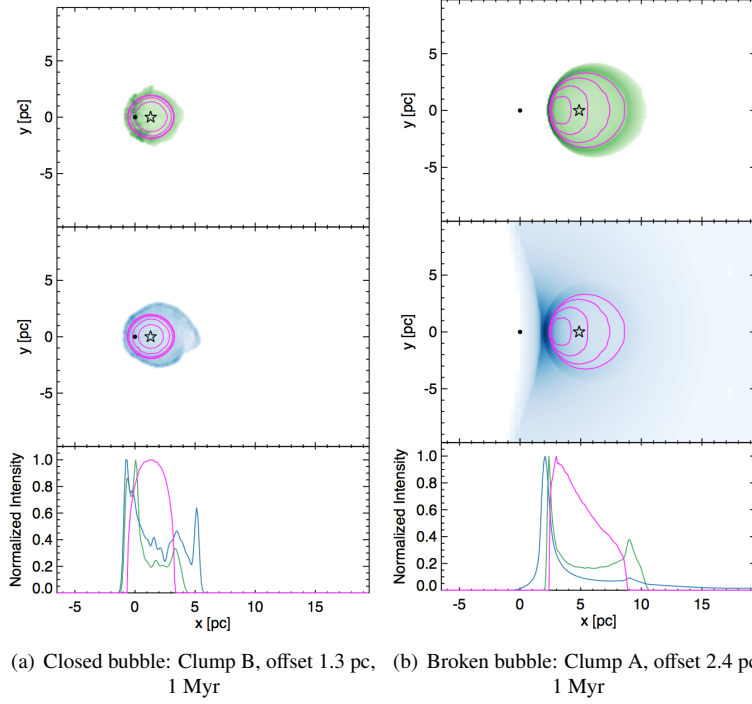


Figure 3.7 – Synthetic emission of the PAH feature (top panel), the cold dust component (middle panel) and ionized gas (contours) for a typical (a) closed bubble and (b) broken bubble. We also show cross-cut through the center of the star of the three components (bottom).

represents the PAH emission, and gas with a column density up to 10^{22} cm^{-2} to represent the PACS observation of the dust. Then, we integrate along a line of site and generate column density maps of the selected region as would be observed. We plot the results in Figure 3.7.

For the closed bubble (Figure 3.7(a)), the radio emission measure is symmetric and peaks at the center of the bubble. Our hydrodynamic simulations with radiative transfer exclude the effects of radiation pressure on the gas or on the dust. Therefore the ionized gas inside the bubble is uniform and the emission measure peaks at the center due to projection effects. The profile follows Draine (2011) dustless case. If we assume the presence of dust and radiation pressure acting on the gas and dust, we would expect the gas and dust to clear out the central part of the H II region and pile up towards the ionization front, as seen in N49 (Figure 3.1(a)) and N90 (Figure 3.1(b)). The PAH feature has its maximum just outside the ionized gas region and marks the location of the ionization front. Further out in radius, there is the location of the cold dust emission, tracing the dense material of the swept up shell.

In the case of broken/open bubbles, the ionized gas piles up towards the highest den-

sity of the ISM, as seen in observed bubbles (Figures 3.1). Cold dust, PAH feature, and ionized gas emission have distinctive peaks of emission, respectively from the high density part to the low density part. In the case of RCW120 (Figure 3.1(c)), the emission of each component behave as expected from theory. The sequence from partially broken bubbles to open is a result of the combined effects of density and time. If the density gradient is quite steep or the average density is not very high, the H II region expands to larger radii and breaks up quite fast. However, at early stages the H II region has a spherical shape.

3.6.2 Location of the dust wave

Ochsendorf et al., 2013a (submitted) developed a model to study the interaction of a dusty evaporative flow with the radiation pressure of the star. In this work, the equation of motion of the dust and the gas are calculated by solving a coupled set of differential equations, which includes the radiation pressure force and momentum transfer through the drag force.

When dust and gas decouple, dust piles up in front of the star, and a dust wave forms. The conditions necessary for such dust wave to generate can be quantified by the dimensionless coupling strength parameter, $C = 1 - v_g/v_{g,0}$, where $v_{g,0}$ is the initial velocity of the gas (i.e., the velocity of the photo-evaporation flow) and v_g is the velocity of the gas at the location where the dust is stopped. C is a measure of the efficiency of momentum transfer between gas and dust through the drag force and is regulated by the flow velocity and the density of the gas. For $C = 1$, gas and dust are tightly coupled in a photo-evaporation flow and a bow wave forms (Ochsendorf et al. 2013b, submitted).

We plot in Figure 3.8(a) the coupling strength C for a grid of models that have the same ionizing source (10^{48} s^{-1}) and varying density and velocity of the flow. We show also the time dependent results for the simulated H II regions. As Figure 3.8(a) displays, the coupling between gas and dust is least effective in high velocity photo-evaporation flow. Therefore, dust waves are expected to form in particular in Model A and B, which reaches high velocities near the star soon after ionization of the cloud material: indeed, these models also reproduce the observations best.

Similarly, Figure 3.8(b) shows the coupling strength C for a grid of models that have the same ionizing source (10^{48} s^{-1}), but for varying density and H II region radii. We can compare Model A and B – that have the right conditions for a dust wave to form – directly with observations. We note that there is overlap between observed H II regions and models. This indicates that broken/open bubbles have photo-evaporative flows above $15\text{--}20 \text{ km s}^{-1}$. The source N69 is the completely open source for which it is difficult to define both radius and density; uncertainties on the observations may cause the offset found in Figure 3.8(b). All models have a similar dependence between ionized gas density and radius of the H II region, with the exception of Model A2. The general trend is expected, as the H II region radius increases with time, the gas inside the bubble is diluted in a progressively larger volume, causing the density to decrease. Instead, Model A2 expansion is stopped by the presence of the clump, while the gas is flowing out of the region at considerable speed.

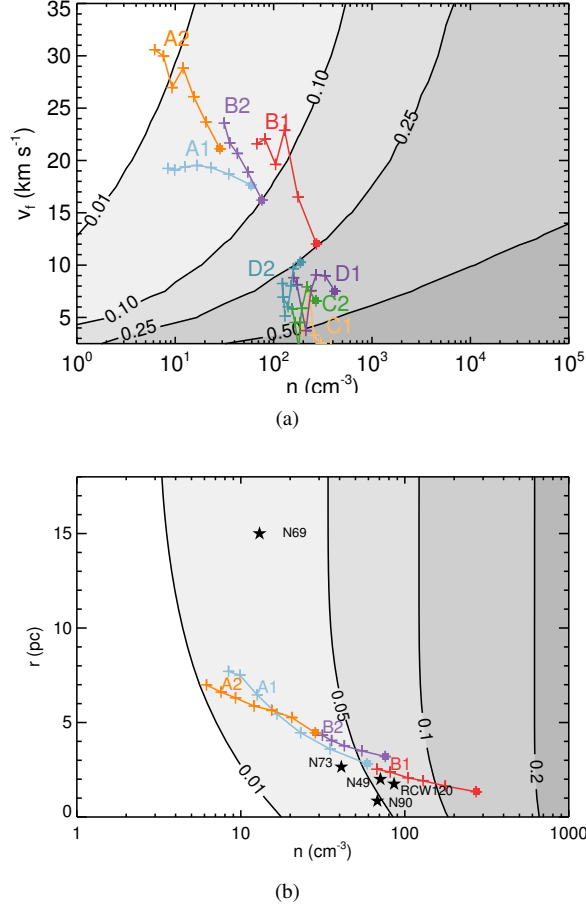


Figure 3.8 – Gray scale with marked contours of the coupling strength, C , for a grid of models with fixed ionizing source luminosities $\dot{N}_{\text{Ly}\alpha} = 10^{48} \text{ s}^{-1}$ and varying (a) velocity of the flow, v_f , and ambient densities, n ; (b) radius of the H II region, r , and ambient densities, n . Time dependent tracks from the H II region simulations are over plotted. Cross symbols mark time intervals of 0.5 Myr starting from the filled square symbols. The letter correspond to the clump, as in Table 3.2, and the numbers refer to the offset of the source in respect to the clump center, with ‘1’ being 1.3 pc offset, and ‘2’ 4.9 pc offset. The five selected typical H II regions are shown in (b) with star symbols. Low coupling strength will lead to dust wave, while high coupling strength results in bow wave.

In conclusion, models seem to indicate that champagne flow H II regions that can produce gas flows at the source location above 15-20 km s⁻¹ are likely to show a dust wall. The morphology of such H II regions can vary from almost spherical shapes to broken and open bubbles.

3.6.3 Champagne flow H II regions

Our assumption of small influence of the stellar winds on the H II region evolution is based on recent observation that revealed weak-wind strength for stars with $\log(L/L_{\odot}) \leq 5.2$ (Martins et al. 2005, Marcolino et al. 2009). Beaumont & Williams (2010) studied an unbiased sample of H II regions and most of their ionizing stars have luminosity $\log(L/L_{\odot}) \leq 5.2$, even after correction of the distance (Anderson & Bania 2009), indicating that a large population of H II regions might simply be explained without the effects of stellar winds. We argue that the arc-structures seen in infrared emission inside H II regions can be explained as dust waves induced by photo-evaporating flows inside H II bubbles. We revisit the champagne flow model, as first suggested by Mac Low et al. (1991), and calculate the flow velocity of the ionized gas. Dust waves require a gas velocity $> 10 \text{ km s}^{-1}$ near the star. By placing the ionizing star offset from the center of a Bonnor-Ebert sphere, the ionized gas flows in a champagne flow kind of fashion towards the low density part, or tail of the region. We show that the gas velocities are enough to explain the creation of dust waves. This mechanism provides a natural explanation for the presence and morphology of dust emission seen in the interior of H II bubbles (Deharveng et al. 2010, Anderson et al. 2012) and the morphology of the H II region itself.

3.6.4 Kinetic energy

In some models, the swept-up shell of the H II region breaks open and the ionized gas is injected directly into the surrounding ISM. The flow can reach velocity up to 40 km s^{-1} , with a total of kinetic energy released into the ISM up to 10^{49} erg . A typical supernova explosion has an energy of about 10^{51} erg , 10% of which gets transformed into kinetic energy of interstellar gas (Veilleux et al. 2005). Therefore the energy released by single H II regions is one order of magnitude smaller, considering that the lifetime of late type O stars is about 6-7 Myr. Nevertheless, their contribution to the kinetic energy in the ISM might be relevant particularly when considering scale sizes of $\sim 1\text{-}3 \text{ pc}$ in regions of massive star formation.

3.6.5 Triggered star formation

The theory of triggered star formation was first introduced by Elmegreen & Lada (1977). The ionization shock front of a massive star or group of stars provides the external pressure to compress a nearby molecular cloud and start its collapse. However, recent observations of single H II regions showed that triggered star formation can happen also at smaller scales. The swept-up shell produced by an ionizing star can be gravitationally unstable and fragment into small clumps that will generate low-mass stars. The ionizing radiation can induce condensation of preexisting overdensities due to turbulence and produce fingers and pillars and eventually a star. Examples of triggered star formation by the H II region bubble have been shown by Deharveng et al. (2009), Deharveng et al. (2010) and Zavagno et al. (2007)

The simulations we carried out in this work show that all the conditions for triggered star formation are met. During the evolution of H II regions, the swept-up gas becomes quite dense and contains up to $10^4 M_{\odot}$ in gas. The simulations with the ionizing star offset from the molecular cloud show a denser swept-up shell towards the highest density of the medium. Studied of RCW 120 showed that most of the condensation of material and possible formation of new stars is on the densest shell, opposite to the opening. Under the conditions of the swept-up shell, the Jeans length is about 0.5 pc that is smaller than the shell thickness, making this mechanism possible within the shell. The Jeans mass is $\sim 15 M_{\odot}$. We have showed that fragmentation might be possible, however detailed studies are needed to determine how efficient such mechanisms would be in generating new star.

3.7 Conclusions

We analyze a class of H II regions that show dust emission at $24 \mu\text{m}$ in their interior. We identify five typical H II regions with luminosity $\log(L/L_{\odot}) < 5.2$ to ensure that their stellar winds are weak. Each H II region represents a morphological class: closed, broken and open shells. We use *Spitzer*/IRAC $8 \mu\text{m}$ from the Glimpse survey to trace PAH emission coming from the PDR located at the inner boundary of the swept up shell; *Spitzer*/MIPS $24 \mu\text{m}$ from the MIPS GAL survey, which traces warm dust (50-150 K) emission mainly coming from both the swept-up shell and the interior of the bubble; *Herschel*/SPIRE $250 \mu\text{m}$ from the Hi-Gal survey to trace cool (10-40 K) dust emission from dense condensation; and VLA 20 cm images from the MAGPIS survey to trace free-free continuum emission from ionized gas.

We carried out hydrodynamical simulations using FLASH HC code of a class of champagne flow H II regions to explore the role of the environment and age on the morphology of the bubble. We set up an ionizing star at the center and offset from the center of four typical clumps. Each clump has a Bonnor-Ebert density profile modified to be in pressure equilibrium.

We find that all the morphological classes of observed H II regions can be explained with a champagne flow model. Closed bubbles are either young or evolving in a symmetric environment. The ionizing star of broken and open bubbles is in a non-uniform, and asymmetric medium.

The velocity of the gas inside the bubble reaches values up to 30 km s^{-1} at the star location that allows a dust wave to form. We find that a classical champagne flow model can explain both the presence of the dust inside the bubble. As suggested by (Ochsendorf et al., 2013a submitted), the cometary shape of the dust emission is the result of the interaction between radiation pressure from the star with the dust contained in the flow of ionized gas.

We limited this study to the case when stellar winds are negligible. Clearly, more massive stars have strong stellar winds and those change the structure and evolution of H II regions. However, dust emission has been found inside bubbles that have strong stellar winds. We leave to a future work the analysis of this class of H II regions.

