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How Young Massive Stars Shape Their Surroundings

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Abstract

Nebulae around young massive stars are powered by high energy radiation and stellar winds from the stars. The behaviour of these nebulae is still a subject of active research due to the complexity of their interactions with the environment. In this project we will explore this problem in detail using the 1D hydrodynamic simulation code Weltgeist. We will simulate the time-dependent evolution of nebulae around young massive stars and their influence on star-forming clumps in the cloud. The results of this project will make predictions for the dynamics of dense structures in star-forming clouds and the resulting efficiency of star formation that can be compared to the results from full 3D hydrodynamic simulations.

Samenvatting

Gasnevels zoals de Orionnevel bevatten veel gasklonten. In deze klonten vindt stervorming plaats. Jonge zware sterren hebben veel invloed op het gedrag van de gasnevels waar ze zich in bevinden. De straling van zo'n ster duwt het gas van de nevel weg. Dit verlaagt de kans op stervorming in de directe omgeving van de zware ster. In dit project onderzoeken we de invloed van jonge zware sterren op de stervorming in hun omgeving. Dit doen we door te kijken naar de beweging van de gasklonten onder invloed van sterkte straling afkomstig van de ster.

Acknowledgements

This project has been quite weird due to Covid-19. All the meetings I had were over the internet, but despite this inconvenience the guidance I got from Sam was amazing. Its hard for me to describe how highly I think of Sam. Sam was incredibly patient with me. He answered all my emails within an hour, even in the weekends. And I never got the idea that he was rushing our meetings, he would take as long as it took for me to be able to continue working again. I really appreciate his calm and non judgemental attitude. He pushed me to choose my own path and I ended up making my own program which was incredibly fun! Thanks Sam, I hope to see you from time to time at Sciencepark.

Further I would like to thank Alex de Koter and Lex Kaper for guiding and reviewing this project. Your helpful comments during the project send me in the right direction.

I would also like to thank my parents and my brother for mental support and for letting me borrow their laptops to finish all the simulations in time. They also spoiled me during the last weeks of the project so I could focus all my energy on the project. Thanks, I really appreciate it.

And lastly I would like to thank my study friends Liz, Levi, Thomas, Appie, Auke, Mitchel, Jelle, Hoang and Matthijs. You all motivated me to keep continuing and pushing myself a little more.

Contents

Chapter 1

Introduction

Figure 1.1: The "Pillars of Creation". The dense gas clumps are at the top of the pillars. Strong radiation hits the clumps from above and push away gas from the clumps downwards, resulting in comet tails. Credit: NASA, ESA/Hubble and the Hubble Heritage Team.

Star formation is a very inefficient process with only 1-2% of the gas in galaxies forming stars each free-fall time [Kennicutt, 1989]. This is partly due to stars themselves. The radiation of young massive stars have a negative effect on the star formation of its surrounding gas. Star formation in galaxies happen mostly in molecular clouds. While some clumps seem to collapse on their own, others may be triggered by a collision with another gas clump [Duarte-Cabral et al., 2011]. Further when a young massive star is present in a molecular cloud, its radiation will push away the gas, lowering the chance of it forming new stars.

In this project we define gas clumps by regions of gas which have the potential to form stars, background gas does not have this potential. The background gas around a young massive star forms a structure called an HII region, more on this in section 1.1.

When looking at the influence of the strong ionizing radiation on a gas clumps, something called photoevaporation occurs. Photoevaporation is the process of radiation ionizing the neutral gas of a clump's surface, causing it to flow away and exposing more neutral gas. This process causes gas clumps to lose mass and accelerate away from the star, more on this in section 1.2.

In this project we did research to how young massive stars shape their surroundings. We wanted to know how much mass the gas clumps in a molecular cloud would lose due to the presence of a young massive star. Further we wanted to know more about the collisions between gas clumps which could trigger star formation.

We did this by combining two separate programs. The first program used was created by dr. Sam Geen and his program describes in one dimension how a gas cloud would behave in the presence of a radiation source (in our case a star). The star will ionize its surrounding gas and pushes it away, this is called a HII region and more on this later. We will use this program to describe the behavior of the background gas and we will refer to it as the 1D hydrodynamics program.

The other program was created during this project, it describes the motion of gas clumps. We will refer to this program as the clump dynamics program. The motion of the gas clumps is dependent on gravity, drag and photoevaporation. This project combines the 1D hydrodynamics program and clump dynamics program to describe the behavior of a molecular cloud with a young massive star in its center.

1.1 HII region

The presence of a young massive star in a molecular gas cloud will create a region called a HII region. These are called HII regions because they have HII (ionised hydrogen) in them, which can be detected in observations. A schematic image of a HII region is drawn in figure 1.2, this figure focuses solely on the background gas and ignores the gas clumps. The radiation of the star ionizes the hydrogen present in the gas and pushes the gas away from the star. A so called ionization front will move outwards sweeping up neutral background gas, the behaviour of ionization fronts is described by equations derived in [Kahn, 1954]. All radiation gets absorbed by the gas and can't go past the ionization front. This is since the ionization front is defined as the boundary between the ionized hot gas on the inside and the cold, dense, swept up gas on the outside. More about the behavior of spherical symmetric HII regions can be found at [Spitzer, 1978], [Dyson and Williams, 1980] and [Franco et al., 1990].

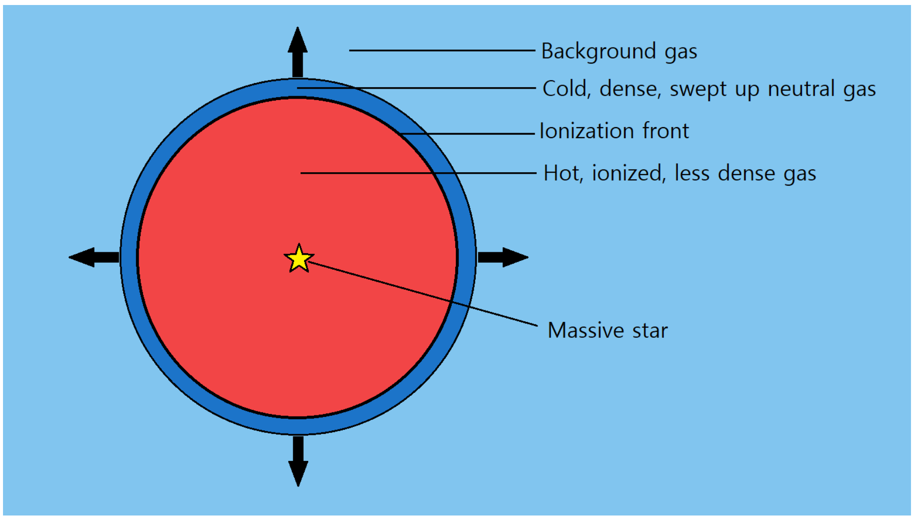


Figure 1.2: A schematic image of the HII region produced by a star in a molecular cloud. In this figure gas clumps are ignored and spherical symmetry is assumed. The radiation of the star ionizes the gas and pushes is away from the star. Cold neutral gas gets swept up by the ionization front. The expansion of the ionization front can come to a stop whenever forces such as gravity and gas pressure are balanced with the force produced by the radiation.

1.2 Photoevaporation

The most dominant force acting upon the clumps in this project is the force caused by photoevaporation [Bertoldi and McKee, 1990]. Photoevaporation occurs when hydrogen ionizing radiation hits a gas clump as shown in figure 1.3. The gas on the right side (in the case of figure 1.3) gets ionized and heated up, we call this gas evaporated gas. The evaporated gas expands and pushes itself away from the clump to the right. By doing so it also pushes the clump to the left, away from the star. The evaporated gas moves towards the star and spreads into the HII region. Photoevaporation of gas clumps results in comet tails behind the clumps away from the star, an example of this are the "Pillars of Creation"[1] shown in figure 1.1. These tails are made of dense gas from the clump that has been pushed away, more on this in [Mackey and Lim, 2010].

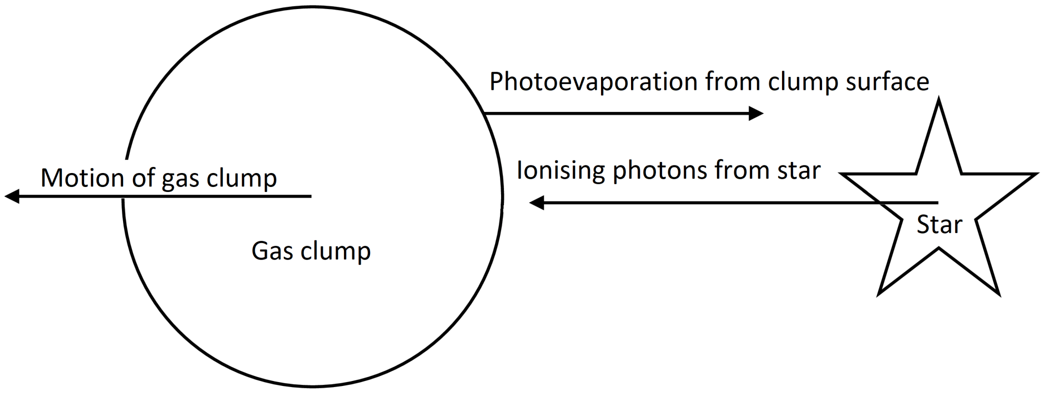


Figure 1.3: A schematic image describing photoevaporation. Radiation from the star hits the gas clump, ionizing hydrogen gas. The ionized gas expands and flows away, exposing more neutral gas. The gas clumps gets pushed away from the star by the evaporated gas.

The evaporated gas flows away from the clump resulting in a mass loss of the clump. The acceleration due to photoevaporation is called rocket acceleration [Oort and Spitzer, 1955]. The magnitude of clump evaporation is dependent on how many photons hit the clump, thus clump size, clump mass, luminosity of the star and distance between the clump and the star have a influence on the rocket acceleration and the mass loss.

[1] https://hubblesite.org/image/3862

Chapter 2

Method

2.1 1D hydrodynamics

The 1D hydrodynamic program, written by dr. S. Geen, describes the behavior of HII regions in one dimension (section 1.1). This program can be found on his GitHub[1]. We will apply the data obtained from this program to describe our background gas. In this program the background gas gets divided into N amount of cells, see figure 2.1. Each cell is a certain distance removed from the radiation source and has its own properties such as particle density and temperature. All the cells are giving an initial condition. Then the program calculates what the properties of each cell are after a time step "dt". The properties of each cell can only be influenced by its neighbour cells and the amount of radiation it receives from the radiation source. These properties are calculated using a multidimensional hydrodynamics code called VH-1[2] [Colella and Woodward, 1984]. By calculating the properties of each cell for a lot of time steps the behavior of the entire background gas is mapped.

For each cell we wanted to know what the particle density was and what the rate of photons reaching that cell was. The radiation source emits a constant rate of photons. Each cells absorbs a certain amount of photons depending on the cells properties. The amount of photons reaching a cell is the total amount of photons emitted by the radiation source, minus all the photons which got absorbed by cells in between. We need this data to calculate the gravity inflicted by the background gas on the gas clumps, the drag caused by the movement of the clumps relative to the background gas and the intensity of the photoevaporation of the clumps.

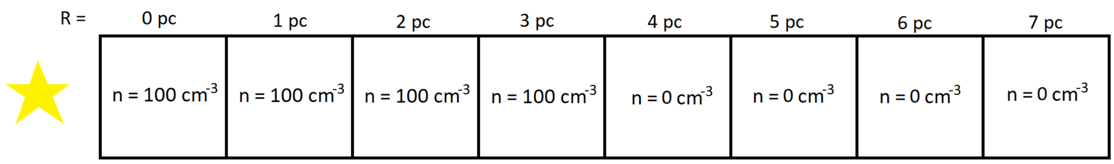


Figure 2.1: A schematic image explaining the mechanics of the 1D hydrodynamic program. Each square is a 1D cell with a certain distance to the star on the left side of the image. Each cell has its own properties, in this image only the particle density is shown.

Different parameters in the code can be toggled. The cooling of the gas is taken into consideration, however we decided to turn off the gravity. In this project the cloud will rotate around it axis, this is done to make the cloud more stable. In the 1D hydrodynamic program it is not possible to implement the rotation of the gas cloud. Further in practice there will also be turbulence within the cloud. The turbulence will also support the cloud against gravity. The motions of the clumps traces this turbulent flow a little. However we can't produce turbulence in one dimension, thus to

[1] https://github.com/samgeen/weltgeist
[2] http://wonka.physics.ncsu.edu/pub/VH-1/

compensate for the absence of centripetal force and turbulence we turned off the gravity. We made the assumption that these forces cancel each other out.

Further it is assumed the background gas is evenly distributed and fixed if there is no radiation source present. It is also assumed the background gas is spherical symmetric. And lastly for simplicity we decided the behavior of the background gas will not be affected by the the gas clumps in it.

2.2 Clump dynamics

In this project we are interested in how much mass the gas clumps lose due to photoevaporation. Photoevaporation is dependent on the size of gas clumps and their distance to the radiation source. These properties keep changing over time and thus we had to make a program which calculated the position of each gas clumps for each moment in time. This is done by using the Euler method. The program places N amount of gas clumps within a certain volume and calculates all forces acting upon each clump. These forces consist of a gravitational force due to the background gas, a gravitational force due to the central star, gravitational forces amongst clumps themselves, drag and the force inflicted by photoevaporation (each force will be discussed in depth later on). For each clump all the forces will be added and the acceleration is then calculated. By knowing the acceleration, velocity and position of a clump, a new velocity and a new position can be calculated. By repeating this process for x amount of time steps the motion of gas clumps is described.

The motion of clumps results in collisions. When two clumps collide it's assumed they will merge 100% of the time. This is not realistic so to compensate for this we added a collision parameter:

$$dr < \alpha(r_1 + r_2) \tag{2.1}$$

with dr the distance between object 1 and object 2, r_1 and r_2 the radius of both objects and α the collision parameter. When the distance between the objects get smaller than the summed radii times the collision parameter, the objects will collide. The collision parameter for clump with clump collisions is $\alpha = 0.6$ and the collision parameter for clump and star collisions is $\alpha = 0.8$. These values were handpicked based on what looked most natural in the animations.

2.2.1 Gravity of background gas

Another force acting on the clumps is the gravitational force of the background gas. For this force I made use of the shell theorem which says that a gas clump within a spherically symmetric shell experiences no gravitational force by the shell regardless of the clumps position within the shell. And the theory also states that a spherically symmetric body affects a gas clumps gravitational as if it were a point source of equal mass in its center. The gravitational pull of this virtual point source is calculated using Newton's law of universal gravitation.

$$F = G\frac{m_1 m_2}{r^2} \tag{2.2}$$

With F the force acting on the clump and the virtual point source, G the gravitational constant, m_1 the mass of the clump, m_2 the mass of the virtual point source and r the distance between them.

2.2.2 Gravity of the gas clumps and the central star

The next force is the gravitational force due to the clumps and the central star. Each clump exerts a gravitational force on the other clumps and on the star. However for simplicity the star is kept fixed in the center of the cloud. The gravitational pull is again calculated using Newton's law of universal gravitation (eq. 2.2).

2.2.3 Drag

The clumps move through the background gas, this creates a force in the opposite direction of the clumps movement due to drag. For simplicity the background gas is assumed to be stationary.

This force is calculated using the next formula:

$$F = \frac{1}{2} \rho v^2 C_D A \tag{2.3}$$

With ρ the mass density of the background gas, v the absolute velocity of the clump, C_D the drag coefficient and A the cross sectional area. The drag coefficient is a factor which depends on the shape of the clump. All clumps are assumed to be spherical, thus the corresponding drag coefficient is 0.47.

2.2.4 Clump evaporation

The last force acting upon the clumps in this program is the force caused by the photoevaporation of the clumps (see section 1.2). All formulas needed to calculate the mass loss and rocket acceleration were taken from [Bertoldi and McKee, 1990]. For simplicity we assumed there are no shadows cast by the clumps, meaning when one clump is behind another clump, this clump will still receive the same amount of radiation as if there is no clump in front of it.

First of all we need to find the photoevaporation parameter ψ. This dimensionless parameter is calculated with the following formula,

$$\psi = 5.15 \times 10^4 \frac{S_{49}\ r_{c,pc}}{R_{pc}^2} \tag{2.4}$$

With S_{49} the amount of photons reaching the clump each second divided by 10^{49} s^{-1}, $r_{c,pc}$ the radius of the clump in parsec and R_{pc} the distance of the clump to the radiation source in parsec. The amount of photons reaching the clumps is dependent on the background gas the photons have to travel through. This data is obtained from the 1D hydrodynamic program.

The mass loss of the clump due to clump evaporation is determined with the following formula,

$$\frac{dm}{dt} = 1.49 \times 10^{-3} \frac{\phi_{ml}\phi_{mr}}{\phi_m} \left(\frac{S_{49}}{R_{pc}^2}\right)^{1/2} r_{c,pc}^{3/2}\ M_\odot\ yr^{-1} \tag{2.5}$$

With ϕ_{ml} the mass loss factor, ϕ_{mr} mass radius factor, ϕ_m mass factor. The logarithmic value

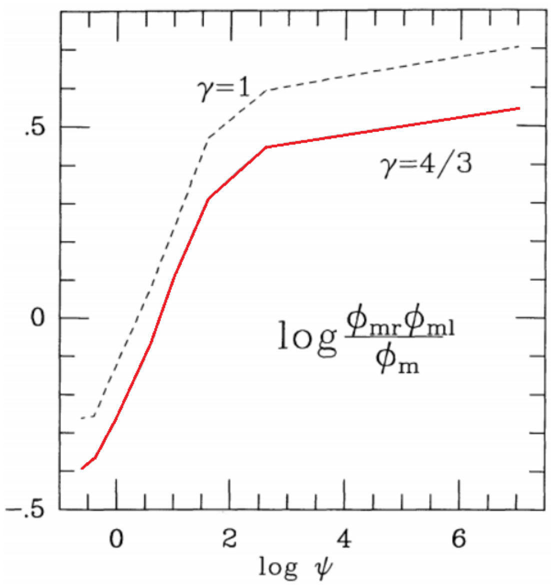


Figure 2.2: Dimensionless factor for the mass loss function described in eq. 2.5. This factor is dependent on the photoevaporation parameter ψ (formula 2.4) on the x-axis. The red line is used since the adiabatic index $\gamma = 5/3$, this is the value for monatomic gas. This figure is taken from [Bertoldi and McKee, 1990].

of the three factors are plotted in figure 2.2. $M_\odot$ is the solar mass in kg and yr is the amount of seconds in a year.

To calculate the rocket acceleration V_R we also need to know the speed of sound in the ionized hydrogen gas. This is value is calculated using a formula derived from the ideal gas law,

$$c_i = \sqrt{\frac{2\gamma \; k_B \; T_i \; X}{m_H}} \tag{2.6}$$

With c_i the speed of sound in ionized hydrogen gas, γ the adiabatic index of monatomic gas with a value of $5/3$, k_B the Boltzmann constant, T_i the temperature of ionized hydrogen gas with a value of 8400 K [Geen et al., 2015], X the hydrogen mass fraction of the gas with a value of 0.74 (same value of the sun [Asplund et al., 2009]) and m_H the mass of hydrogen. The rocket velocity is then obtained from a graph taken from [Bertoldi and McKee, 1990]. See figure 2.3.

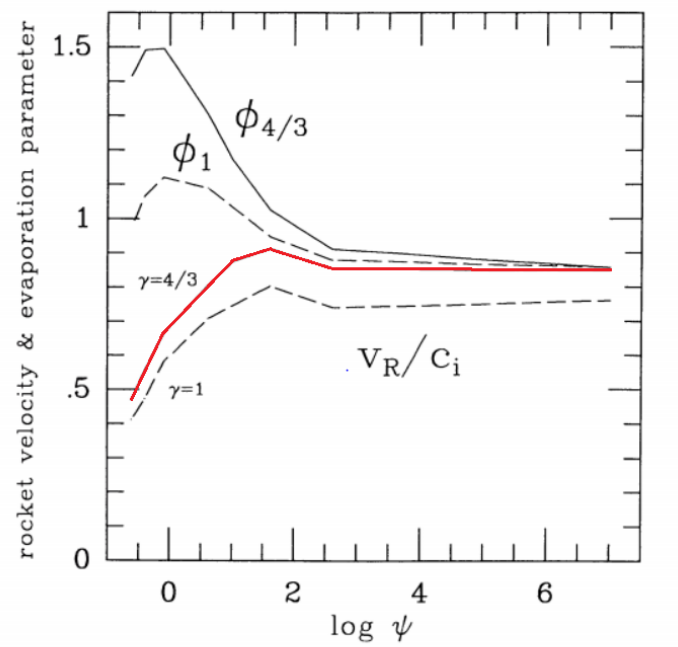


Figure 2.3: This figure shows the rocket velocity of clumps V_R. This value is divided by the speed of sound of the ionized gas (formula 2.6). The rocket velocity is dependent on the photoevaporation parameter ψ (formula 2.4) on the x-axis. The red line is used since the adiabatic index $\gamma = 5/3$, this is the value for monatomic gas. This figure is taken from [Bertoldi and McKee, 1990]

The acceleration the clumps experience due to clump evaporation is described using the formula,

$$g = -\frac{V_R}{m} \frac{dm}{dt} \tag{2.7}$$

With g the acceleration of the clumps away from the radiation source, V_R the rocket velocity, m the mass of the clump and dm/dt the mass loss due to clump evaporation (eq. 2.5).

2.2.5 Initial conditions

With the forces now defined, the motion of the clumps can be calculated using the Euler method. However for reliable results we needed realistic initial conditions. For the clump masses, size of the clumps, amount of clumps and the size of the cloud I made use of two graphs dr. Sam Geen provided me with (figure 2.4 and 2.5). These graphs were sampled from full three dimensional hydrodynamic simulations [Geen et al., 2015]. Each point in the graphs represent a gas clump. The clump furthest away from the radiation source had a distance of 6.3 pc, we therefore decided that the radius of the cloud should be 6.5 pc. The mass of the clump would depend on the distance it was from the star. This was done using the formula,

$$M = 1.10 \times 10^3 R_{pc}^{-3.43} M_\odot \alpha_m \tag{2.8}$$

This is the formula of the fitted red line in figure 2.4 with an additional factor α_m, more on this

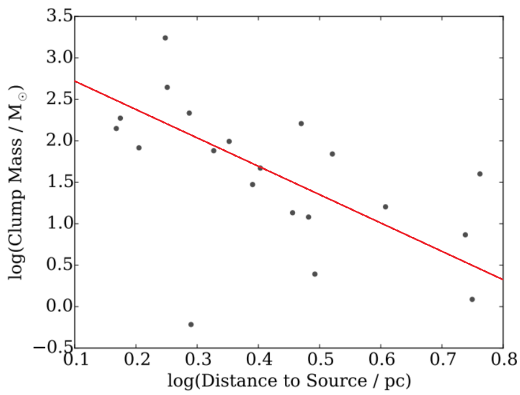


Figure 2.4: Data about the correlation between the distance of the clumps to the radiation source and the clumps mass. The formula of the fit is $M = 1.10 \times 10^3 R_{pc}^{-3.43} M_\odot$, with M the mass of the clump, R_{pc} the distance of the clump to the star and $M_\odot$ the mass of the sun. This data is from [Geen et al., 2015].

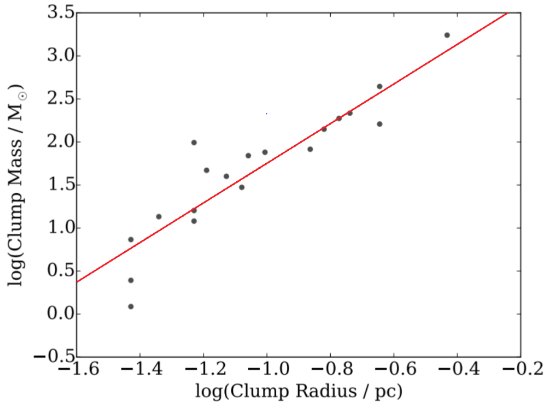


Figure 2.5: Data about the correlation between the radius and the mass of the clumps. The formula of the fit is $r_{c,pc} = 1.80 \times 10^{-2}\ (M/M_\odot)^{0.43}$, with $r_{c,pc}$ the radius of the clump divided by one parsec, M the mass of the clump and $M_\odot$ the mass of the sun. This data is from [Geen et al., 2015].

factor later. The program would place clumps in a random position by picking a random distance and a random angle of orientation. It would then calculate the mass of the clump depending on its distance to middle of the cloud using formula 2.8. It would keep on placing gas clumps until the total mass of all clumps exceeded a certain maximum value. This maximum value is the total mass of all clumps of figure 2.4 or figure 2.5 (both figures are about the same gas clumps). This value is about 3400 solar masses. When using this method of placing clumps only 13 clumps would be placed until the maximum of 3400 solar masses was reached. This was too few clumps since we also wanted to do research on clump collisions. One clump practically in the center of the cloud would consist of more than 90% of the total clump mass. To solve this we added two things to the program. The first thing was a restriction from clumps being placed within a radius of 0.2 times the cloud radius, this prevented too massive clumps from forming. And the second thing was an additional factor α_m to the formula 2.8, the clumps would still have a nice balance between mass and distance but there would be more clumps since the average mass of each clump was lowered. When this factor was set to 0.20 the total amount of clumps in the initial state was 363, this was enough. The radii of the clumps were calculated using the formula,

$$r_{c,pc} = 0.018 \left(\frac{M}{M_\odot}\right)^{0.43} \tag{2.9}$$

This formula is derived from the data in figure 2.5.

The clumps were given an initial velocity of two kinds, a random velocity and a rotational velocity. The direction of the rotational velocity was in the direction which gives the whole system of clumps a counter-clockwise spin around the z-axis going through the center of the cloud. When determining the speed of the orbital velocity we again applied the shell theorem. The velocity of a clump was determined by looking at the gravity of all other clumps closer to the center of the cloud and considering all those clumps to be a point source in the center. All clumps further away from the center were ignored. The velocity of the clumps were orbital velocities calculated using the formula,

$$V_{orbital} = \alpha \sqrt{\frac{GM_{closer}}{R}} \tag{2.10}$$

With M_{closer} the summation of all clump masses closer to the center of the cloud. R is the distance of the clump to the center and α a factor to adjust the velocity by hand to create a more stable orbit of clumps.

Everything described in this section was done to create realistic initial conditions for the cloud. A last measurement to make the initial condition of the cloud even more realistic was to let the cloud evolve for 10 Myr before placing the star in the middle, this is about 2-3 times the free-fall time of the cloud.

2.2.6 Different cloud configurations

In this project I ran simulations for eight different cloud configurations. All configurations would be different from the standard configuration in one field. The standard configuration was:

- $t_{tot} = 60$ Myr
- $t_{delay} = 10$ Myr
- $dt = 3 \times 10^{-3}$ Myr
- $R_{cloud} = 6.5$ pc
- $M_{star} = 21.2\ M_{\odot}$
- $Q_H = 10^{48}\ s^{-1}$
- $M_{clumps}\ \approx 3400\ M_{\odot}$
- $n_0 = 100\ cm^{-3}$
- $T_0 = 10$ K
- $T_{ion} = 8400$ K

with t_{tot} the total time frame of the simulation, t_{delay} the time after which the star was placed in the center of the cloud, dt the time step, R_{cloud} the radius of the cloud, M_{star} the initial mass of the star (which increased when clumps collided with it), Q_H the rate of hydrogen ionizing photons emitted by the star (which was kept constant), n_0 the particle density of the background gas, T_0 the temperature of neutral gas and T_{ion} the temperature of ionized gas. The values Q_H=10^{48} s^{-1} and M_{star}=21.2 $M_{\odot}$ were obtained by using a star with spectral type B0 from table 1 of [Sternberg et al., 2003]. The value of $T_{ion} = 8400$ K was obtained from [Geen et al., 2015].

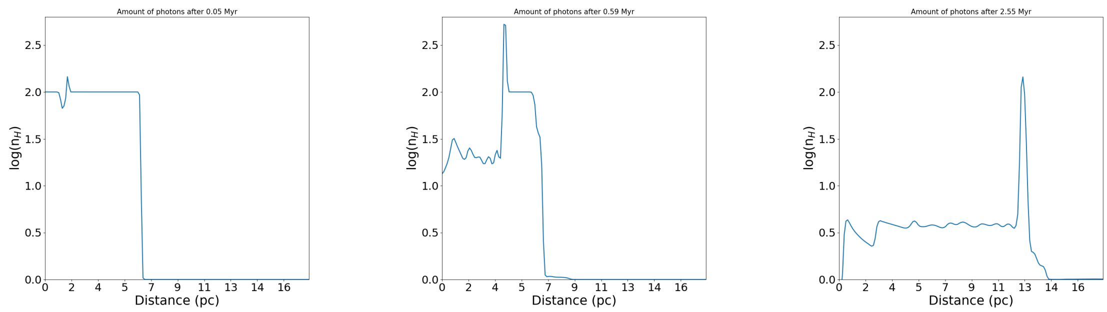
All other configurations were different from the standard configuration in only one aspect. All the eight different configurations were:

- Standard
- Standard with no star present
- Standard with 10x more n_0
- Standard with 10x more Q_H
- Standard with 10x less Q_H
- Standard with 10x larger R_{cloud}
- Standard with 10x heavier M_{clumps}
- Standard with 10x lighter M_{clumps}

Chapter 3

Results

In figure 3.1 we can see the evolution of the particle density of the background gas as it is pushed away by the radiation of the star. The first frame (figure 3.1a) is 0.05 Myr after the initial state. In this frame it can be seen that the background gas has a constant particle density of 100 particles per cm^{-3} and a radius of 6.5 pc. A small wave front can be seen forming around 1 pc of the cloud. In the second frame (figure 3.1b) we can see a peak in particle density at about a radius of 4 pc, this is the ionization front as discussed in section 2.1. The gas within this front is hot, ionized, less dense gas, almost entirely transparent for radiation. The outer edge of the cloud is still at 6.5 pc and untouched since the ionization front hasn't reached it yet. The last frame (figure 3.1c) shows the cloud expanding in size, the ionization front has reached the outer edge of the cloud and has swept up all the gas. The cloud (or we can call it a shell at this point) has a radius of about 12 pc at that moment in time.



(a) The particle density of the background gas after 0.05 Myr

(b) The particle density of the background gas after 0.59 Myr

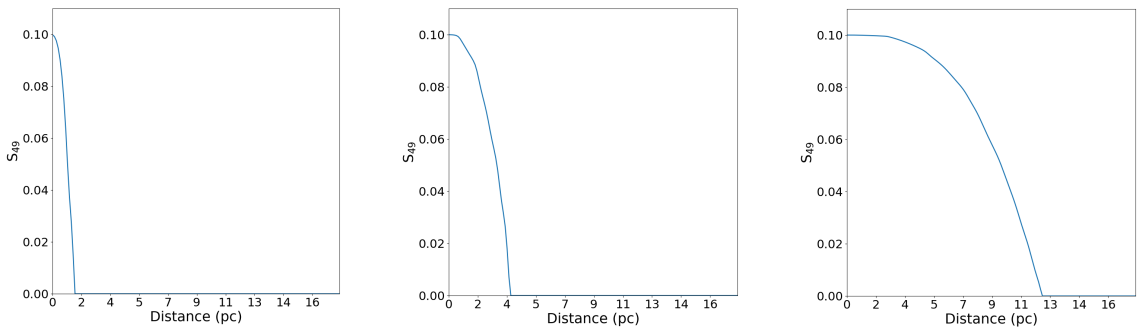
(c) The particle density of the background gas after 2.55 Myr

Figure 3.1: Three frames of the particle density for each radius of the background gas in the "Standard" configuration. This data is produced by the 1D hydrodynamics code made by dr. Sam Geen as I described in section 2.1. The time mentioned is the amount of time after the star has been initialized. The radiation source is on the left of the plot, pushing the wave front to the right.

Besides the particle density profile of the background gas, the 1D hydrodynamic program (section 2.1) also provided data about the rate of hydrogen ionizing photons reaching each radius of the cloud. Divided by 10^{49} s^{-1} this gives the value of S_{49} (eq. 2.4), this is shown in figure 3.2. As the ionization front grows in size (figure 3.1) more ionizing photons reach further distances, increasing the distance at which clump evaporation can take place.

Figure 3.3 shows three frames of the cloud evolution in the "Standard" configuration. Full animations of all configurations can be found at dr. Sam Geen's website[1]. Figure 3.3a shows the cloud state just before the star gets initialized. There is a wide spectrum of different clump sizes with the largest and heaviest clumps more centered in the middle and the small, lighter clumps

[1]http://samgeen.com/hwilkes/



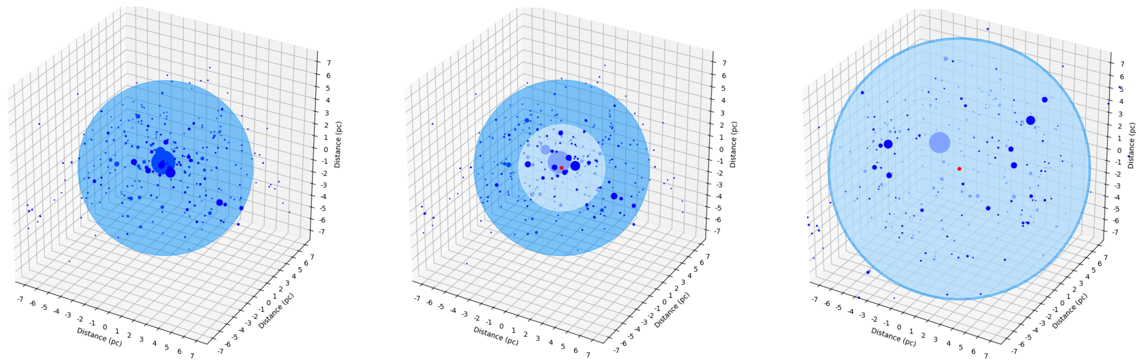
(a) The photon transparency of the background gas 0.05 Myr

(b) The photon transparency of the background gas 0.59 Myr

(c) The photon transparency of the background gas 2.55 Myr

Figure 3.2: Three frames showing how many photons reach each radius of the cloud. These figures show the value of S_{49} from eq. 2.4 for each distance from the star. This illustrates the evolution of the photon transparency of the background gas of the "Standard" configuration. This data is produced by the 1D hydrodynamics code made by dr. Sam Geen as I described in section 2.1. The time mentioned is the amount of time after the star has been initialized and are the same moments in time as in figure 3.1. The radiation source is at zero distance.

more present in the outer regions of the cloud. Figure 3.3b shows the cloud's state a short moment after the star is initialized, the ionization front (see figure 1.2) expands rapidly outwards, all the clumps inside the "bubble" experience photoevaporation and the clumps outside the "bubble" barely or don't experience photoevaporation, this is because the background gas absorbs all the ionizing photons. Figure 3.3c shows the HII region growing in size, the background gas has been concentrated into a thin, dense shell. All clumps within this shell (which is most of them) get accelerated outwards and are losing mass.



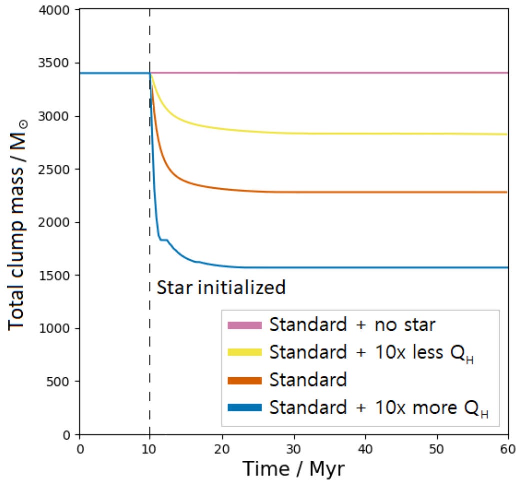
(a) The cloud after 9.99 Myr

(b) The cloud after 10.32 Myr

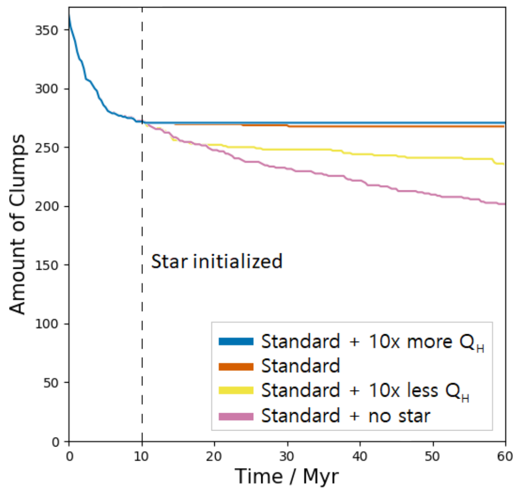
(c) The cloud after 12.06 Myr

Figure 3.3: Three frames of the cloud state in the "Standard" configuration right after the star gets initialized. The red dot is the star, the dark blue spheres are the gas clumps, the medium blue is the background gas and the light blue is the bubble filled with hot, less dense, ionized gas. The clumps and background gas get pushed away by the radiation of the star. The background gas forms a thin, high density shell which can be seen in figure (c).

In figure 3.4 we can see the influence of different photon emissions rates by the central star on the evolution of the cloud. Figure 3.4a shows that the higher the luminosity of the stars the higher percentage of mass loss of the clumps. In "Standard + no star" there is no clump mass loss since there is no radiation causing photoevaporation, while in "Standard + 10x more Q_H" with $Q_H = 10^{49}\ s^{-1}$ the total clump mass drops by 55%. Figure 3.4b shows the amount of clumps over time and indirectly shows the amount of collisions happening. The amount of clumps of the blue configuration "Standard + 10x more Q_H" is stable as soon as the star gets initialized, implying there are no collisions happening after 10 Myr. This is due to the clumps being accelerated away by the radiation of the star. The increase in distance between the clumps results in no more collisions. Here it can be seen that the more photons are emitted by the star, the less collisions are happening.



(a) The total mass of all clumps over time.



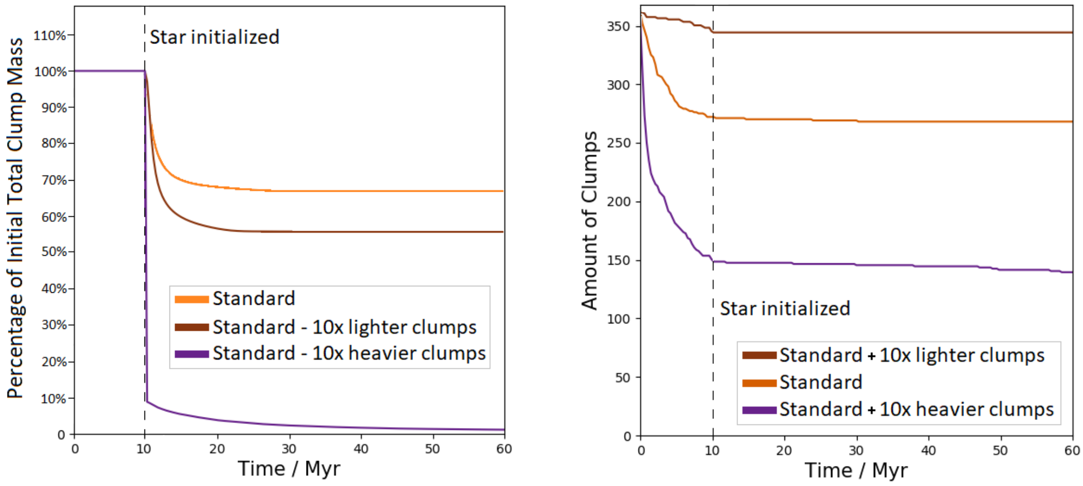
(b) The amount of clumps over time.

Figure 3.4: The influence of different amounts of photon emissions rates of the central star on the evolution of the cloud. The "Standard + 10x less Q_H" configuration has a star which emits 10^{47} hydrogen ionizing photons each second, "Standard" has a star which emits 10^{48} photons each second and "Standard + 10x more Q_H" has a star that emits 10^{49} photons each second.

In figure 3.5 we can see the influence of different clump masses on the evolution of the cloud. Figure 3.5a shows that the "Standard" clumps lose the least amount of mass relative to its initial mass, about 30%. The "10x lighter" clumps, with about 45% mass loss, lose a bit more mass than the "Standard" ones. And the "10x heavier" clumps lose the most mass, almost all of their mass gets evaporated. The "Standard + 10x heavier clumps" configuration has a steep drop in mass after 10 Myr and then a sharp curve, opposed to the other two configurations which have smooth curves. The sharp angle in the line is due to the star being instantly placed at 10 Myr, all clumps which happened to be in that same area will instantly be absorbed by the star. Since this configuration has ten times heavier clumps, the clumps are about 2.7 times larger (see clump radius eq. 2.9) and thus more likely to be in the same area as where the star will be placed.

The order of the three configurations by looking at the total mass of the clumps is not the same order as the order of relative mass loss of each configuration. The "Standard + 10x lighter clumps" configuration losses a higher percentage mass than the "Standard" configurations and the "Standard + 10x heavier clumps" losses the highest percentage mass. Figure 3.5b shows in all three configurations a almost complete stop in collisions after 10 Myr when the star gets initialized. The amount of collisions before 10 Myr is different for each configuration, This is due to the different sizes of the clumps in each configurations, bigger clumps means less space between the clumps and thus more collisions.

The last configurations we compared were the "Standard + 10x larger R_{cloud}" and the "Standard + 10x more n_0" configurations. These results can be seen in figure 3.6. In figure 3.6a we can see the total clump mass over time, the "10x larger R_{cloud}" configuration is losing mass at a slower rate than the "Standard" and "Standard + 10x more n_0" configurations, however the larger cloud could possibly lose more mass than the standard and the 10x more dense background gas configuration since the mass loss hasn't stopped yet after 60 Myr opposed to the other two configurations. In figure 3.6b we can see the amount of clumps over time. Noticeable is the clump count of the 10x larger cloud, not a single collision has occurred in this configuration. This is probably due to the increase in size of the cloud and thus the increase in distance between clumps, lowering the change of collisions. Also when comparing the standard and 10x more dense background gas

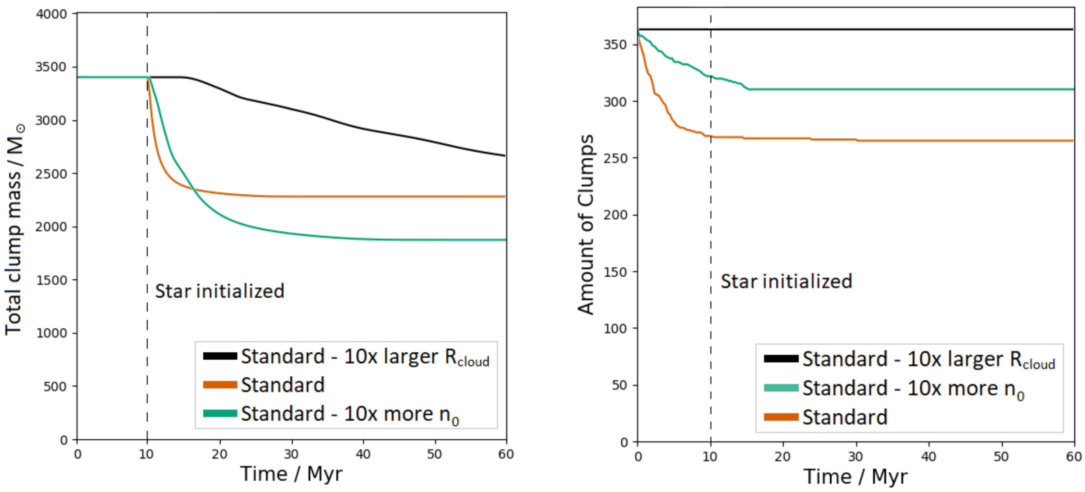


(a) The total mass of all clumps over time.

(b) The amount of clumps over time.

Figure 3.5: The influence of different clump weights on the evolution of the cloud. The "Standard" configuration has a total clump mass of 3,400 $M_\odot$, "Standard + 10x lighter clumps" has a total clump mass of 340 $M_\odot$ and "Standard + 10x heavier clumps" has a total clump mass of 34,000 $M_\odot$. In figure (a) the total clump mass in given in percentages to be able to compare the different configurations to each other.

configurations we can see a significant difference in the amount of clump collisions. This can only be due to the gravity caused by the background gas or the drag, these are the only two forces different in these configurations.



(a) The total mass of all clumps over time.

(b) The amount of clumps over time.

Figure 3.6: The influence of a different background gas particle density and a different cloud size on the evolution of the cloud. "Standard + 10x larger R_{cloud}" has a cloud radius of 65 pc. "Standard + 10x more n_0" has background gas with an initial particle density of 1000 particles cm^{-3}. "Standard" has a cloud radius of 6.5 pc and a particle density of 100 particles cm^{-3}.

Chapter 4

Discussion

The dynamics of molecular clouds are incredibly complicated. A lot of assumptions and simplifications had to be made in this project. The results of this project are not exact, however they give a good intuition for subject. I'll discuss the assumptions or simplifications made, which can be improved in further research.

The first one was the simplification of the project limiting itself to only one star. This star was placed in the center of the cloud and kept fixed. The gas clumps all had the potential to form stars but star formation was not included in this project. This project showed that clumps lose more mass when a central star get more powerful, however the exact fractions of mass loss are not realistic since only one star was present while in reality a lot of stars would form in a molecular cloud.

Further, gas clumps were always considered regions of gas which had the potential to form stars no matter how much mass they lost. Gas clumps could lose 99% of their mass and still be considered star forming regions. The properties describing the gas clumps were taken from data produced by dr. Sam Geen and in the initial state of the cloud every clump had the realistic criteria to form stars. However after the gas clumps lost some mass due to photoevaporation the conditions of the gas clumps might have changed and they might have not matched the star formation criteria anymore. This could mean for instance that a gas clump which would only have lost 20% of its mass, no longer has the ability to form stars and thus should be removed entirely since it can't be considered a gas clump anymore. Implementing a continuous checking of the gas clumps if they fit star formation criteria will probably decrease the amount of star forming gas even more.

The initial orbital velocity given to the clumps was to create an as stable cloud as possible. This was done manually by adjusting a factor α (eq. 2.10). This didn't work as well for all cloud configurations and can be done better in a follow-up research.

In this project we assumed all clumps would stay intact and maintain their spherical shape when experiencing photoevaporation. However there are more scenarios possible. Photoevaporation of large gas clump which are close to the radiation source ($r_c > R_c$) leads to a "champagne flow" and destroys the clumps [Tenorio-Tagle, 1979]. Adding this feature in future research will interesting and it will decrease the total clump mass even more.

In this project we made the assumption that clumps merge 100% of the time when colliding. In reality this is not always the case. When clumps scrape each other rather than a head on collision they might not merge but instead exchange some of their mass and then go separate ways. Including new criteria for the merging of clumps will alter the motion of the clumps and might change some results. This will be a nice addition for future research.

We assumed the background gas to be stationary when looking at the relative motion of gas clumps moving through the gas. This is contradictory to our other assumption we made in the 1D hydrodynamics program. There we assumed that the gravity would cancel out partly due to the centripetal force cause by the rotation of the background gas. But even if the last assumption wasn't made, the first assumption would be illogical since the movement of clumps through the background gas would create flow in the background gas. Yet I expect this to be of minor influence since the acceleration due to drag turned out to be negligible compared to other forces.

When combining the formula 2.5 and formula 2.9

$$\frac{dm}{dt}\,\frac{1}{M} = 3.60 \times 10^{-6}\,\frac{\phi_{ml}\phi_{mr}}{\phi_m}\left(\frac{S_{49}}{R_{pc}^2}\right)^{1/2}\,\left(\frac{M}{M\odot}\right)^{-0.35}\,yr^{-1} \tag{4.1}$$

we can see the fractional mass loss rate is proportional to $M^{-0.35}$, meaning heavier clumps lose a smaller fraction of their mass compared to the fractional mass loss of lighter clumps. This is not the case when looking at the "Standard + 10x heavier clumps" configuration in figure 3.5a. Here the heavier clumps lose the highest percentage of their mass. This is due to a clump collision with the central star. Before the star got initialized a huge gas clump formed by collisions with other clumps. This huge gas clump contained about 90% of the mass of all clumps and was located in the middle of the cloud. When the star got initialized in the middle of the cloud it instantly destroyed the huge gas clump and absorbed all the gas. In future research this should be given more thought. For instance the star should not instantly absorb the gas clump entirely but only a part of it. And perhaps divide the rest of the huge clump up into multiple smaller clumps which get blown away again using the same dynamics of photoevaporation.

Chapter 5

Conclusions

In this project we did research to the behavior of gas clumps in a molecular cloud under the influence of a young massive star in the center of the cloud. The behavior of the background gas was described by a 1D hydrodynamic program[1] written by dr. Sam Geen. The motion of the clumps were described by a program made by me during the project. We looked at the mass loss of gas clumps due to photoevaporation. We also looked at the collisions between clumps.

The presence of a young massive star in a molecular cloud has a large impact on the molecular cloud and the gas clumps within it. Where the cloud had a somewhat stable radius before the presence of the star, the radius of the cloud drastically increased as soon as the star was initialized. The background gas gets compressed into a dense shell which was pushed away form the star.

As soon as the ionization front of the background gas passed the gas clumps, the gas clumps experienced a mass loss and acceleration away from the star due to photoevaporation. The amount of mass loss is dependent on many factors. When looking at different amounts of luminosity of the configurations it is clear that a higher photon emission rate by the star results in a higher mass loss of the gas clumps. Our standard configuration star of Q_H=10^{48} s^{-1} caused an average mass loss of around 30% amongst the gas clumps. This shows that the amount of gas which can form stars decreases when a young massive star is present.

Further there is a strong drop in the amount of collisions between gas clumps whenever a young massive star is present. All configurations except for the "Standard + 10x less Q_H" configuration sees the amount of clump collisions practically drop to zero as soon as the star gets initialized. But even the "Standard + 10x less Q_H" configuration experiences a reduction in clump collisions compared to the configuration with no star present. In summary we can make the conclusion that the presence of a young massive star within a molecular gas cloud will decrease the amount of mass which has the potential to form stars and it will also decrease the amount of collisions between gas clumps which may trigger star formation.

A lot of assumptions and simplifications were made during this project, thus a lot can be added to the program to make the simulations more realistic. A couple examples of improvements are having the background gas being influenced by the gas clumps, letting the gas clumps cast shadows and allowing the central star to move. However the most prominent improvement will be adding star formation to the program. Having stars form from the gas clumps will give a whole new dynamic to this research and probably will result in a even higher mass loss of the clumps. It would be interesting to see an addition of star formation in future research.

[1] https://github.com/samgeen/weltgeist

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