"How fast do Molecular Clouds grow?"

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# Abstract

Molecular clouds are extremely important regions in space where star formation occurs. This report summarises the processes that occur within a molecular cloud and outlines the conditions required for star formation. With the goal of simulating the growth of a molecular cloud, preliminary efforts have been made to model the motions of particles in a wrapped box and are described here. The two methods of molecular cloud growth that will be investigated are: Bondi-Hoyle accretion and coalescing collisions. Their methods and future implementation are explained and possible ways of analysing the results are briefly detailed.

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# 1. Background

## 1.1 Molecular Clouds

-Context, literature review and required theory (attempt segue to aims)

Molecular clouds, Star formation, Jeans mass & SFE/Freefall times, high mass star formation, IMF, Supernovas, Accretion, GMC, Cloud collisions

The interstellar medium (ISM) is a collection of gaseous, solid particles and cosmic rays that exist throughout space. The gaseous portion takes up of the mass in the ISM meanwhile the solid particles known as dust take the remaining . The composition of the gases consists of hydrogen and helium with the remaining being heavier elements . The density and chemical composition of the ISM tends to vary however, but can be broadly split into five categories: hot ionised, warm ionised, warm atomic, cold atomic and cold molecular mediums. The cold molecular medium otherwise known as molecular clouds is of particular importance.

Molecular clouds are well known for being the main sites of star formation. The cold nature of the molecular cloud results in a minimal amount of thermal pressure, which decreases the requirements for gravitational collapse. The temperatures required for this to occur is in the range of K. This is substantially lower than the cold atomic medium which has temperatures in the ranges of K. While this may seem to suggest the molecules of the cloud possess a efficient means of cooling, this is not necessarily true. The primary constituent of the molecular cloud, H2, has an relatively high energy requirement for its first excited state of J K] . Unsurprisingly, the emissions from H2 within the molecular cloud is negligible. On the other hand, CO is another molecule commonly found in the molecular clouds with a much lower energy requirement of J [K] for the emission line. Due to the high density of H2, CO can be easily excited through collisions with H2 . This gives a method of tracing the density of H2 in the cloud using the observed intensity of CO. Cooling through CO radiation is significant but is not required to reach range of K. Simulations using cooling from C+ (C II) fine-structure lines with sufficient dust extinction also show they can reach similar temperatures. In fact, simulations also show the presence of molecular gas has little effect on the ability to form stars and appear to be a by-product of the conditions required for star formation .

## 1.2 Star Formation

If a isothermal molecular cloud of uniform density is sufficiently large enough, it will become gravitationally unstable and collapse. For a spherical model of the cloud this radius is known as the Jean's length . The mass associated with this length is known as the Jean's mass given as:

|  |  |  |
| --- | --- | --- |
|  |  | [1] |

where is the mass density and is the sound speed which has dependence. In the case where the cloud has no outward support mechanism, the time it takes to collapse is given by the free-fall time:

|  |  |  |
| --- | --- | --- |
|  |  | [2] |

which represents the minimum timescale a cloud can collapse in . There are multiple support mechanisms for a cloud however. In reality it is found that only of a cloud is converted into stars for a single free-fall time. This parameter is known as the star formation efficiency and is given by:

|  |  |  |
| --- | --- | --- |
|  |  | [2] |

where is the mass of the molecular cloud excluding , the star mass within the cloud. While the cloud is in freefall collapse, density increases rapidly. It can be shown from equation 1, that the Jean's length will decrease in response from the increased density. As a result, it is common to find multiple points of a collapsing cloud to also collapse locally. This can result in multiple stars being formed during cloud collapse and this process is referred to as fragmentation.

Observations of the ISM show large amounts of polarisation in the starlight received. This effect has been accredited to the dust aligning on a large scale to polarise the light for a particular axis. In order to produce such a effect there must be a large magnetic field. This can be measured from the polarised light using the Zeeman effect . The compression of the ISM into molecular clouds and later into pre-stellar cores also causes the magnetic field lines to compress as well. This increases the magnetic field strength which also increases magnetic pressure, that opposes gravitational collapse. The magnetic field also aids in gravitational collapse by removing angular momentum from pre-stellar cores through magnetic braking. This reduces the angular speed of the outer parts of the envelope, allowing it to collapse inwards towards the core.

Observations of a molecular cloud's spectral lines usually possesses some degree of additional line broadening caused by Doppler shifts. A significant amount of this can be explained by the thermal velocity dispersion of the gas in the cloud however there is still a large amount that cannot be explained by other broadening methods. This non-thermal velocity dispersion is caused by turbulence . Turbulence can arise from multiple sources such as stellar winds, protostellar outflows or supernovas . Each one of these sources creates some degree of shock front. These shock fronts sweep up material and compress the cloud, producing regions of decreased and increased density. If the shock is sufficiently large enough, the regions of decreased density will lose their gravitational support and disperse. On the flip side, the regions of increased density may become gravitationally unstable and begin to collapse .

The initial mass that a star starts hydrogen fusion with will determine the lifetime of the star and as well as its luminosity and temperature. It is found that the mass distribution of a population of stars commonly takes the form of a power law known as the initial mass function. Very little is known about the IMF. The exact form and cause of the is of heavy debate . Though IMF appears roughly constant throughout space this feature has also been questioned.

While the formation process for low mass stars is reasonably well understood, the formation of extreme cases of high mass stars and brown dwarfs are much less known. Using the same assumptions during formation as with low mass stars, it can be calculated that there is a maximum mass limit due radiation pressure. This is limit can be calculated to be in the range of M⊙ indicating that the assumptions made are incorrect or that there are different mechanisms for high mass star formation(2). One assumption made is that accretion of material is spherically symmetric. It is already known that infalling material tends to form a disc round a protostar due to angular momentum. Consequently a large amount of accretion would occur from the disc and the total amount of radiation pressure felt by the accreting material will be drastically lower. This alone cannot enable the formation of high mass stars, as this requires the majority of the material to be held within the disc before the protostar starts emitting large amounts of radiation pressure. However gravitational torque will prevent the disc mass exceeding the core mass which limits the effectiveness for this method of accretion (13).

There are other theories for high mass star formation. The "competitive accretion" model suggests that stars at the centre of a stellar cluster will naturally accrete more mass as a result of gravitational focusing. As a result it is possible for such a star to rapidly accrete mass into a massive accretion disk to overcome more radiation pressure (15). This model is limited to stellar clusters and suggests lone high mass star formation cannot occur. Another suggested formation method is through collisions of lower mass stars. Accretion of material in a stellar cluster will increase the mass and gravitational attraction of the stars within it. This will subsequently decrease the size of the stellar cluster and increase the chance of collisions between stars. This process effectively produces accretion-induced collisions (13). Eventually the collisions will dominate over accretion for mass gain, allowing this method to completely bypass the problems associated with radiation pressure. This method is also limited to stellar clusters and also suggests a decrease in number of the intermediate mass stars ( M⊙) used in the collisions (13).

## 1.3 Giant Molecular Clouds

As star formation highly depends on molecular clouds, it is clear that the lifetime of those clouds govern the total number of stars that may form. The time-scales of formation and dispersion for the largest molecular clouds, known as giant molecular clouds (GMCs) are particularly important for understanding star formation rates across the galaxy.

There are multiple theories for the formation of molecular clouds. It has been thought that GMCs arise from large-scale instabilities, such as gravitational or magneto-Jeans instabilities in the ISM. It has also been theorised to arise from converging flows from expanding HII regions, though this method cannot produce sufficiently large GMCs to match observations. Rather than immediately forming a GMC from the ISM, it has been suggested that smaller molecular clouds may collide with each other and coalesce to form a large cloud. While cloud-cloud collisions were originally dismissed due to the extremely long time-scales required to form a GMC, the conditions within the spiral arms would drastically increase the rate of collisions and hence decrease formation time. Additionally, there has been some claims that cloud collisions are one of the primary driving factors in high mass star formation. REFERENCE - add numbers?

GMCs are rather short lived, existing for a few years before dispersion. While there are many processes which could occur that can disrupt molecular clouds, there are few that can do so in sufficient scale to completely disperse them. It has been shown through numerical simulation that photoionization is capable of dispersing GMCs up to solar masses [Dale et al. (2012, 2013) and Col´ın et al. (2013)]. This may not be the case for higher mass clouds however, as the increased escape speed may prevent effective mass loss. Another prominent dispersion method is through supernovae within the clouds. Supernovae are expected to be capable of dispersing clouds of all sizes and is also theorised to create additional molecular clouds from the dispersed gas [https://arxiv.org/pdf/1701.03781.pdf].

The formation of molecular clouds is generally thought to be due to supersonic compression caused by gravitational, thermal or magnetic instability [(e.g., Goldreich and Lynden-Bell 1965a, (Field 1965, (Parker 1966; Mouschovias 1974].

-ask results/analysis direction

-talk about development process? or major issues? (follow on from stablitly)

converging flows driven by stellar feedback or turbulence 10^4 (§ 3.1), agglomeration of smaller clouds (dismissed in [http://www.astro.yale.edu/larson/papers/Ringberg93.pdf ] - but greater in spiral arms(§ 3.2), gravitational instability (§ 3.3) and magnetogravitational instability (§ 3.4), and instability involving differential buoyancy

(relate to GMCs and add bit on accretion? could include in method as a modelling part)

(consider tie in with supernovas and MC lifetime)

JUST START WRITING SHIT ABOUT MCS YOU DAMN FOOL

>>>>Check average particle mass?

Project aims

The

# 2. Project Outline

This project seeks to develop a realistic simulation of the evolution of molecular clouds over time and to attempt to determine the viability of cloud-cloud collisions as a means of producing GMCs. However in order to provide a simulation that is reasonably fast, many approximations must be made to simplify otherwise complex physical processes.

Rather than simulating all gas molecules within a cloud, we approximate the entire cloud to be a single spherical particle of uniform density. Additionally, instead of simulating clouds over the entire galaxy, only a small x parsec box is used. The molecular clouds are then allowed to accrete mass from the background ISM and collide with each other before eventually dispersing via supernova.

# 3. Project Design

## 3.1 Numerical Integration

When the simulation begins, the gravitational accelerations of every particle is calculated at each timestep and the next timestep positions and velocities are calculated numerically and this process repeats.

The numerical integration method used in this project is the 'Velocity Verlet' method. Unlike the basic Verlet method, this method explicitly calculates the velocities at the same time as position. This method takes the form of:

|  |  |  |
| --- | --- | --- |
|  |  | [3] |

for position and

|  |  |  |
| --- | --- | --- |
|  |  | [4] |

for velocity . This method makes a assumption that accelerations only depend on position, but this is correct for this project.

The gravitational acceleration for a particle due to particle in the -direction is calculated using

|  |  |  |
| --- | --- | --- |
|  |  | [6] |

where is the distance between the two particles and is the difference in -coordinates. This difference can be calculated from

|  |  |  |
| --- | --- | --- |
|  |  | [7] |

and the difference in and can be found by substituting their respective coordinates. The total acceleration for particle is then summation of all the acceleration contributions from other particles. Acceleration in and coordinates can be found replacing with their respective differences. The softening factor is used to more accurately model the effect of close approaches between clouds. This factor corresponds the radius of the molecular cloud and will change as the particles gain mass. As the clouds are spherical, it simply takes the form:

|  |  |  |
| --- | --- | --- |
|  |  | [7] |

where is the density of the molecular cloud. The terms 'cloud radius' and 'softening parameter' will be used interchangeably in this report.

## 3.2 Bondi-Hoyle Accretion

The model of accretion that is used for this project is the Bondi-Hoyle accretion model. This model assumes that the accreting mass can be approximated as a point mass that moves through a infinite stationary background ISM. As it does so, sufficiently close background mass is pulled towards the point mass into a accretion column wake behind the direction of motion which is then accreted. The accretion rate for a column wake is:

|  |  |  |
| --- | --- | --- |
|  |  | [11] |
|  |  |  |

where refers to density of the background ISM, refers to the sound speed of the ISM and is a accretion column parameter. is expected to be in the range of - REFERENCE BONDI PAPER. The radius that determines whether the background material is accreted is referred to as the Bondi-Hoyle radius and takes the form of:

|  |  |  |
| --- | --- | --- |
|  |  | [12] |

where refers to the relative velocity of the gas to the point mass. This model assumes the background has no self-gravity and ignores radiative feedback in the wake. The latter effect is negligible in highly supersonic flows however .

The main assumption that may give inaccurate results is the assumption of a point mass. Molecular clouds, while much denser than the background ISM are still very diffuse. It is possible in some cases that the Bondi-Hoyle radius may be lower than the actual size of the cloud. For this project, the larger of the two radii will be used to calculate accretion for any given timestep.

The numerical method used for accretion is the first order Euler method, given by:

|  |  |  |
| --- | --- | --- |
|  |  | [12] |
|  |  |  |

in this case would be the larger radius between Bondi-Hoyle and cloud radius. While this method is rather notorious for its relatively high errors, high accuracy is not required in this case.

## 3.3 Timestep Control

Due to the large accelerations produced from close approaches between particles, a very small timestep is required to retain accuracy. However consistently small timesteps will result in a very slow simulation. As a result, a timestep control method is required to maximise efficiency. By arranging equation NUMBER for time, it is possible to require:

|  |  |  |
| --- | --- | --- |
|  |  | [5] |

where is simply . A limit can then be placed on to prevent particles moving too far in a single timestep. This is usually given in terms of cloud radii which results in the final position-based timestep control formula of:

|  |  |  |
| --- | --- | --- |
|  |  | [5] |

where is the tolerance parameter for position. A second timestep control formula is used to restrict mass gain via accretion. This is derived in a similar manner to the previous timestep control formula, except with equation NUMBER. This takes the form:

|  |  |  |
| --- | --- | --- |
|  |  | [5] |

specifically noting the Bondi-Hoyle radius is used. This is because the other form of accretion, via cloud radius is directly proportional to the velocity of the accreting particle. As a result, it would already be limited by the position-based timestep control so further limitation is unnecessary.

The timestep is calculated across all particles and the minimum timestep is used.

## 3.4 Collision (maybe arange with 3.3)

The alternative form of mass growth that will be investigated is through cloud-cloud collisions. FINISH THIS - consider where to place initial conditions and whether to add values around. (front and yes)

segue into supernovas? + add IMF, separate SFE section?

Given a set of pre-existing molecular clouds in a cold atomic medium (much like spiral arm -https://arxiv.org/abs/astro-ph/0701822)

-Aims/objectives, approach, activities undertaken

Collision vs Accretion -> Solely collision for high mass stars?

Acquire a stable and well reasoned simulation.

## 3. Results

-Information acquired (graph spam), brief analysis

have placed cloud lifetimes at around 20– 30 Myr (Bash et al. 1977; Blitz and Shu 1980; Fukui et al. 1999; Kawamura et al. 2009; Miura et al. 2012), although there have been longer estimates for molecule rich galaxies (Tomisaka 1986; Koda et al. 2009) and shorter estimates for smaller, nearby clouds (Elmegreen 2000; Hartmann et al. 2001).

## 4. Discussion

Full analysis, comparing with real evidence. Important findings and implications

Because GMCs are clumpy, this interaction will differ from the standard solutions in a uniform medium (e.g., Cioffi et al. 1988; Blondin et al. 1998) supernova

## 5. Conclusion

Summarise.

# 6. References

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