**Interim Report**

**November 2016**

**Abstract**

**1. Introduction**

N-body simulations of physical systems are a key factor to solving and understanding problems in science, they can be used to help the understanding of interactions between molecules and to help visualize the Brownian motion in molecular dynamics and are widely used in astrophysics. Astrophysical simulations are used to help predict the effects of dark matter on astronomical bodies, and can also help to understand and theorize the theoretical models of phenomena’s such as star formation.

**1.1 Star formation**

Perturbations such as shock waves from nearby supernovae and collisions between two giant molecular clouds (GMC) can lead to contractions on the clouds, if the contraction of these clouds surpasses a certain radius called the Jeans radius, gravity overcomes turbulences and thermal pressure and becomes the dominant force and produces a dynamical collapse which is uncontrollable. This is process sparks the beginning of star formation. (Appenzeller, et al., 1980)

During this collapsing phase of the molecular cloud, the original molecular cloud breaks up into smaller clouds through fragmentation. This collapsing process increases the opacity of the clouds and leads to an increase in temperature and therefore using the ideal gas laws the pressure built up inside the clouds increases. The fragmentation process is halted when hydrostatic equilibrium is reached, this results in the formation of a protostar.

An envelope of gas and dust surrounds the protostar which due to gravity accretes onto the protostar which increases the mass and temperature of the protostar, the lack of an envelope leads to a pre-main-sequence star (PMS star). A PMS star is a star that has yet to start hydrogen burning through nuclear fusion. Once the protostar’s opacity increases to the point that the gravitational contraction causes the temperature to increase to a point that hydrogen burning can start, the star is then said to be a main-sequence star (MS star). This is a generally accepted overview of star formation.

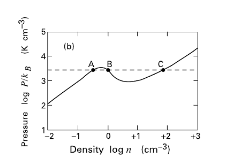
**1.2 Main stages of star formation**

To delve deeper into the details of star formation requires a combination of accepted and disputed peer reviewed papers. This section will go deeper into star formation by discussing each of the main stages of star formation. [add further info]

**1.2.1 Giant molecular clouds and the Interstellar medium**

The interstellar medium (ISM) is defined as the “stuff” that occupies the space between stars. This “stuff” is predominantly made up of matter and electromagnetic radiation. The ISM can be split up into five different thermal phases (Ryden & Pogge, 2016).The first phase is the hot ionized medium (HIM); this phase occupies of the ISM, in it includes low density gas that is heated up to temperatures of over K due to supernovas, powerful winds from the largest progenitor stars and UV radiation, the gas in the HIM can be detected by X-ray emission and absorption lines in the UV region of the spectrum.

The second phase is the warm ionized medium (WIM); Using results provided by Ferrière (2001), it is thought that this phase occupies of the ISM and is made up of ionized hydrogen atoms (H+ or HⅡ). It is thought that most HII arises from the photoionization with strong UV radiation from O and B stars, which creates regions of HII around most O and B stars. The temperatures of the WIM range between 6000 to 10,000 K and is regulated by the heating of the photoionization of the hydrogen atoms and the cooling from Lyman alpha line emission (Lyα). The gas in the WIM can be traced using the Hα emission observed at a wavelength of 656.3nm.



**Figure 1** Theoretical prediction of equilibrium pressure as a function of number density which was provided by Wolfire, et al. (1995)

The third and four phases are the warm neutral medium (WNM) and cold neutral medium (CNM); both phases together occupy of the ISM and have number densities of and cm-3 for the WNM and CNM respectively, it is mostly made up of neutral hydrogen (HI) and is heated to K in the WNM and K in the CNM. Both phases are heated by various ways; such as photoelectrons ejected from dust grains and cosmic rays ionizing atoms through collisions. It was first suggested by Field, et al. (1969) that the two phases are in thermal pressure equilibrium since , where n is the density and T is the temperature. This agrees with the theoretical prediction for the equilibrium pressure as a function of density (as seen in Figure 1), where the WNM matches the stable point A and the CNM matches the stable point C, the point B represents an unstable point at which a perturbation causes the gas to fall into one of the stable points depending on the conditions of the perturbation. The CNM is cooled through the de-excitations of collisionally excited fine-structure lines of C+ and other metals. The CNMcan be traced using the C+emission line observed at a wavelength of 158μm (Bennett, et al., 1994). The WNM on the other hand has a very similar cooling mechanism to the WIM, where the Lyα emission is again the main cooling mechanism. The WNM can be traced using the 21cm emission line of HI formed due the spin-flip transition between two hyperfine energy levels, which was first discovered by Ewen & Purcell (1951).

The final phase is the molecular cloud; this phase is cold enough to give rise to interstellar molecular gas such as CN and CH (Swings & Rosenfeld, 1937), and were found through absorption lines produced in stellar spectra. The temperatures inside molecular clouds range between – K with densities of over 103 cm-3 and occupy of the ISM. Although the molecular clouds only occupy a very small percentage of the ISM, the contribution of the fractional ISM mass from molecular clouds is much greater than the volume of the ISM it occupies, due to the much heavier elements that are present in the molecular clouds compared to the other phases. The most abundant molecules in the molecular clouds are molecular hydrogen (H2)and carbon monoxide (CO). Relative to the overall number of hydrogen nuclei, the abundance of H2 is given by and relative to hydrogen, the abundance of COis given by (Clark, et al., 2012). Carbon monoxide arises in molecular clouds through a series of reactions between C+, H2 and neutral oxygen (OI). Although molecular hydrogen is the most abundant molecule in these molecular clouds, it is in fact the CO that is main cooling mechanism in the molecular clouds. It is suggested by Glover & Clark (2012) that H2 provides a particularly inefficient cooling, due to widely spaced energy levels of ~ 170 J K, it is therefore particularly difficult to excite molecular hydrogen at low temperatures [contrasting to old theories]. The temperatures of the molecular cloud can reach as low as 10 K due to the rotational excitation of CO which has very low energy levels compared to that of hydrogen, and therefore can be exited at lower temperatures, resulting in cooling through the emitted photons that have been released from the rotational transition. The emission line of CO is the primary tracer of molecular clouds due to the high abundance of CO in molecular clouds. The C+ fine structure excitation also plays a key role in cooling the molecular cloud, it was shown by Glover & Mac Low (2007) that C+ could cool the molecular gas down to ~20 K and was also suggested by Glover & Clark (2012) that molecular gas wasn’t necessary due to C+ cooling, however this is still heavily debated throughout the scientific community. Observations of these molecular clouds are often very difficult to obvserve due to the obscuration of starlight from interstellar dust as a result of absorption and scattering. Dust grains are solid materials composed mainly of carbon, silicon and oxygen and vary in size from a few microns down to the size of a few atoms (Draine, 2003). Dust provides another way of keeping the molecular clouds cool, through gas-grain collisions, the excited gas can release their energy to the dust grains in the form of collisions, which is then re-radiated away. When a molecular cloud contracts it behaves isothermally due to the mean free path of the photons realesed being very large and can be freely radiated away from the cloud (Ward-Thompson & Whitworth, 2011).

The largest of these molecular clouds are called Giant molecular clouds (GMC). Typically, they have masses greater than with similar properties to that of molecular clouds. It is generally agreed that most stars form within the GMC [reference] through external forces acting on GMCs and through turbulences. Turbulences can be described as an unstable flow of gas and are still a highly debated topic due to the very complicated physics involved. Usually the GMC will not have a uniform density throughout, instead most will have locally dense regions and tend to have a dense core. These cores are usually called ‘starless cores’ or ‘pre-stellar cores’ dependant on whether the core is gravitationally bound or not.

**1.2.2 Pre-stellar cores and their gravitational collapse**

A pre-stellar core is defined as a dense core in a molecular cloud that is gravitationally bound with similar properties to that of molecular clouds due to the isothermal nature of molecular clouds

* Mention turbulences and magnetic field, perturbations on clouds and starless core/prestellar core leading to collapse, jeans mass and radius and also critical density, freefall time, and how the cloud keeps cool during contraction, mention fragmentation mention bondi hoyle accretion on protostar.
* Binary stars and multiplicity.
* IMF
* Elliptical orbits

**2. Outline**

* Write the important bits of code used…. Acceleration and verlet method and adaptive time steps also mention GADGET2

The outline of the project is to understand the interactions between protostars and how the initial conditions applied to the protostars can lead to various systems such as binary systems, and to see whether there is a strict constraint needed on the initial conditions to create such systems or if these systems can materialize with a wide array of initial conditions. [needs redoing]

Through the use of N-body simulations, several simulations of multiple protostars will be made using a programming language called Python/C, each simulation will have various initial conditions and hopefully different outcomes.

* Results from Earth moon sun and eccentric orbit, and how it show a working simulation
* Goal for next semester (Discussion)
* CHECK YOUR REFERENCES…..

# **References**

Appenzeller, I., Lequeux, J. & Silk, J., 1980. *Star Formation.* 10th ed. : Swiss Society of Astronomy and Astrophysics.

Bennett, C. et al., 1994. Morphology of the interstellar cooling lines detected by COBE. *Astrophysical Journal,* Volume 434, pp. 587-598.

Clark, P., Glover, S., Klessen, R. & Bonnell, I., 2012. How long does it take to form a molecular cloud. *Monthly Notices of the Royal Astronomical Society,* Volume 424, pp. 2599-2613.

Draine, B. T., 2003. Interstellar Dust Grains. *Annual Review of Astronomy &Astrophysics,* Volume 41, pp. 241-289.

Ewen, H. I. & Purcell, E. M., 1951. Observation of a Line in the Galactic Radio Spectrum: Radiation from Galactic Hydrogen at 1,420 Mc./sec.. *Nature,* Volume 168, p. 356.

Ferrière, K., 2001. The interstellar environment of our galaxy. *Reviews of Modern Physics,* Volume 73, pp. 1031-1066.

Field, G. B., Goldsmith, D. W. & Habing, H. J., 1969. Cosmic-Ray Heating of the Interstellar Gas. *Astrophysical Journal,* Volume 155, p. 149.

Glover, S. & Clark, P., 2012. Is molecular gas necessary for star formation?. *Monthly Notices of the Royal Astronomical Society,* Volume 421, pp. 9-19.

Glover, S. O. & Mac Low, M.-M., 2007. Simulating the Formation of Molecular Clouds. II. Rapid Formation from Turbulent Initial Conditions. *The Astrophysical Journal,* Volume 659, pp. 1317-1337.

Ryden, B. & Pogge, R., 2016. *Interstellar and Intergalactic Medium.* 2nd ed. : The Ohio State University.

Stahler, S. & Palla, F., 2008. *The formation of stars.* : Wiley-VCH.

Swings, P. & Rosenfeld, L., 1937. Considerations Regarding Interstellar Molecules. *Astrophysical Journal,* Volume 86, pp. 483-486.

Ward-Thompson, D. & Whitworth, A., 2011. *An Introduction to Star Formation.* : Cambridge University Press.

Wolfire, M. et al., 1995. The neutral atomic phases of the interstellar medium. *Astrophysical Journal,* Volume 443, pp. 152-168.

**[N-body simulations of young protostellar systems]**

**Introduction**

* [Class systems in great detail]
* [Multiplicity of stellar systems]
* [IMF and what it can show and do]

**Outline of my project**

* [The problem we don’t understand]
* How protostars interact with one another and how stars form binaries and other system, what initial conditions do they need… etc.
* [What I’m going to be doing]
* Numerical simulation of multiple protostars inside a potential which arises from filaments
* [How the project will work]
* By creating and calculating initial conditions for protostellar systems, look at how the protostars interact due to gravity and the presence of the potential.
* [Computational setup]
* Using python, how to speed the process up etc.
* [results/tests or preliminary results]
* Earth – sun – moon.
* [goal and strategy for next semester]
* [make it a story whilst being **formal**]
* What integration methods and main equations I used.