Star Formation in the Orion Nebula

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Orion Nebula is a well-known star-forming region and due to its close proximity can easily be observed. It is also extremely bright making it an excellent target for our research on stellar births and their star formation rate. We hypothesized that star formation is an inefficient process and in this report we will discuss the implications of our results. By discerning the observed colors of embedded stars in the Orion Nebula cluster and comparing them to their intrinsic colors we were able to infer the hydrogen column density and so an estimate of the mass of the interstellar gas. By gaging the rate at which this gas is converted into stars we calculated a value of the star formation rate, dM_*/dt, as $(8.3 \pm 0.008) \times 10^{-12}\ M_\odot/yr^{-1}$.

1. Introduction

Star formation is the process in which interstellar gas undergoes gravitational collapse. The gas becomes dense enough for its self-gravity to overcome the thermal pressure and prevent the gas from expanding. This causes the gas to form a protostar at its centre that accretes material from the surrounding cloud, and grows in mass and luminosity. When the temperature and density at the centre of the protostar become high enough to initiate nuclear fusion reactions, the protostar becomes a fully-fledged star.

Stellar birth remains to be an active area of research due to the lack of information behind the process it undergoes. This is because star formation occurs over very long timescales, on the order of millions of years, making it difficult to observe and study in real time. Another reason is that the early stages of star birth occur deep in the core of dense molecular clouds obscured by dust and gas. This complication causes difficultly in directly discerning the protostar. However, some observations have revealed that various physical and chemical processes can influence the evolution of the collapsing cloud and the formation of the protostar.

The Orion Complex contains the closest region of star formation to Earth at only 450 pc away [1]. The Trapezium cluster, named so because of its projected arrangement, is a segment of this complex. It is a well known hydrogen region ionized mainly by the θ^1 Ori stars. These are young O and B spectral type stars at the centre of the Trapezium. Scientists hypothesize that large scale contractions of the Orion Nebula Cluster cloud gave rise to star formation activity. This research focused on investigating these 4 stars using spectroscopic analysis to derive their stellar parameters.

The observations focused on the 4 brightest stars in the Trapezium, (θ^1 Ori A,B,C,D). θ^1 Ori A is an eclipsing binary with spectral type B0.5V and visible magnitude, m_V, as 6.29±0.004 (observed) . θ^1 Ori C is the main ionizing source of the Orion Nebula [2]. It has a spectral type of O7V and m_V observed 4.99±0.002. θ^1 Ori D has spectral type B0.5V and is the only star without a binary partner. It has a visible magnitude of 6.98 ± 0.005. The magnitudes of these stars were examined in order to calculate the colour excess. The colour excess is a measure of the amount of dust along the line of sight to the star, which causes the star's light to be reddened by the extinction of blue light more than red light. Colour excess is used to estimate the amount of interstellar dust and gas in the Orion Nebula Cluster (ONC). Star birth statistics show that most stars originate in OB associations, another reason why M42 was targeted for this research.

Maarten Schmidt introduced a star formation law which can be expressed in terms of gas surface densities and star formation:

$$\sum\nolimits_{SFR} = A \sum_{GAS} N \qquad (1)$$

It provides a parameterization that extends over a few orders of magnitude in SFR and gas density [3]. This power law was verified in several studies. A different interpretation of the law was used by Kennicutt, R. to model the " SFR in numerical simulations of galaxy formation and evolution" [3]. Another study conducted by Martin and Kennicutt uses CCD imaging of atomic hydrogen and carbon monoxide to quantify star formation performance in galaxies and to examine the star formation law. Our research utilized an estimate of the total mass of molecular hydrogen gas to calculate the star formation rate.

Atomic hydrogen and carbon monoxide are both particles used to study the interstellar medium which allows us to then investigate star formation. Although, at high densities we observe hydrogen to be molecular rather than atomic. It is extremely difficult to study directly therefore we search for proxies such as dust. These dust grains exist in the parent cloud of the Orion Nebula cluster and they absorb background starlight. This effect is called dust reddening A_V which is crucial in this study.

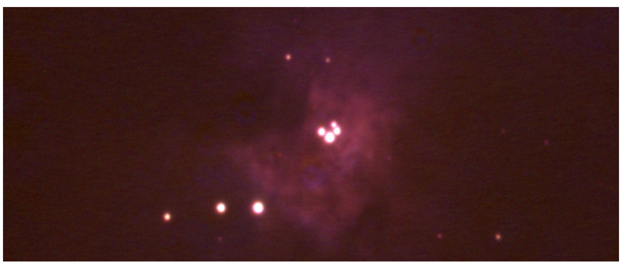

Fig. 1: Colour composite image of the Trapezium cluster created using DS9 in the V, B and R bands.

2. Method

A telescope with diameter 33.18 cm and efficiency of 37.1% was used. For star θ^1 Ori C with visible magnitude of ≈ 8 in the V-band and exposure time of 0.1 seconds: the total number of counts was 9519 and a total signal to noise ratio of 16.6.

Using this telescope, images of the ONC were taken in the B,V and R filters. Seventy five images with seeing greater than 2 were taken per filter and layered on top of each other in a mosaic. This allows us to obtain mages of large areas of the sky with high spatial resolution and sensitivity. A corresponding “flat” was then layered over the mosaics to correct for any abnormalities or dust on the lens of the telescope. Another way to limit systematic errors was to calculate the zero point of each image using an installed program. Zero point is a reference value or baseline used to define the measurement scale for astronomical observations. It is often used in photometry, which is the measurement of the amount of light coming from an astronomical object. The brightness of the reference star is used to calibrate the photometric measurements obtained from the object being studied. Creating an aperture around the target star allowed us to analyse this object and its magnitudes. This measurement was repeated on the four Trapezium stars in the three bands. From there the color excess, *E(B-V)*, was calculated by finding the difference between the observed and intrinsic colors of each star using their spectral types to identify which of the 4 stars we were analysing [1].

$$E(B-V) = M(B-V)_{OBS} - M(B-V)_{INT} \quad (2)$$

The total dust reddening was calculated using colour excess and its respective coefficient R, reddening [4]. By measuring the amount of dust reddening for a particular star, we can estimate the amount of interstellar material between us and the star. This can then be used to estimate the column density of hydrogen gas (in units cm^{-2}) along that line of sight. Estimating the hydrogen column density using a calibration of the dust reddening, A_v , and *N(H)* by:

$$N(H) = (2.21 \pm 0.09) \times 10^{21} \text{ x } A_V \text{ [5].} \quad (3)$$

The spatial extent of the ONC is 4’ by 6’ which allows us to calculate the area as $4.63\text{x}10^{36}$ cm^2, taking into consideration the distance from Earth to the Trapezium Cluster. [6]. Assuming the area is entirely dominated by hydrogen we can integrate the total mass between zero and the total area to derive the total mass of the gas cloud. The total hydrogen mass was found by multiplying the total number of atoms in the cloud by the mass of one hydrogen atom, 1.67×10^{-27} . The total flux, *F*, passing through the Orion nebula in the 4’x6’ frame is 4×10^{-12} W/cm^2 [6]. Using the flux and luminosity, *L*, relation:

$$F = \frac{L}{4\pi D^2} \quad (4)$$

we were able to calculate the total luminosity passing through that area.

Assuming that all the gas in the cloud will be converted into stars we can use the following relation to calculate a constant rate of star formation:

$$SFR\left(\frac{M_\odot}{\text{yr}^{-1}}\right) = 4.5 \times 10^{-37} \text{ x } L \text{ [7].} \quad (5)$$

During our calculations we assumed the solar mass to be $(1.99 \pm 0.0002) \times 10^{30}$ [8]. Dust reddening varied between the four stars. Due to this discrepancy our calibration of the hydrogen column density therefore differed as well. Therefore we plotted a graph of total hydrogen mass against gas depletion time.
Using linear regression it was possible to find a constant star formation rate along with its uncertainty.

3. Results

By the flux equation we were able to derive a value of the total luminosity of the ONC as 2×10^{25} W [6]. Using the calibration provided in equation (2) we calculated the star formation rate, SFR, $(8.3 \pm 0.008) \times 10^{-12}$ $M_\odot/yr^{-1}$ .The error on the SFR was established using the least square fit method on Fig.2. It shows the relationship between the derived hydrogen mass according to the dust reddening of the stellar gas surrounding each of the four stars and the gas depletion time.

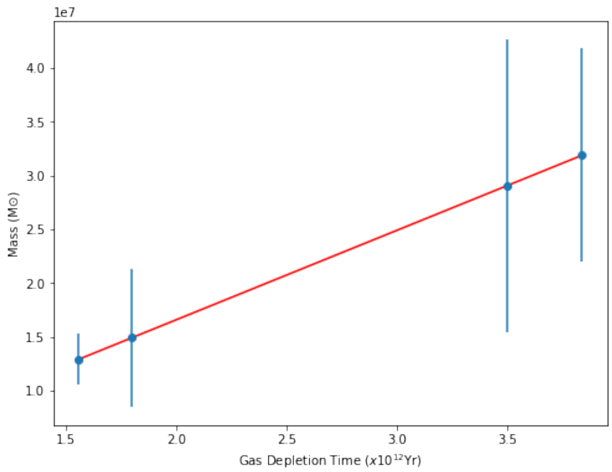

Fig.2: Plot of Total Hydrogen Mass against Gas Depletion Time with a line of best fit.

Star	Color Excess	Dust Reddening
θ^1 Ori A	0.328 ± 0.02	3.38 ± 1.12
θ^1 Ori B	0.432 ± 0.02	3.72 ± 1.12
θ^1 Ori C	0.266 ± 0.02	1.51 ± 0.271
θ^1 Ori D	0.038 ± 0.02	1.74 ± 0.746

Table 1: Results of the calculated colour excess and dust reddening with their respective stars.

4. Discussion

Initially, it was postulated that star formation is an inefficient process. Analysing our value of the star formation rate informs us that 8.3×10^{-12} $M_\odot$ of stellar gas is converted into stars per year. However we are looking at gas clouds between 13 – 32 $M_\odot$. This means that a very small portion of the existing gas is translated into new stars over a very large period of time. Using this statement we confirm the validity of the hypothesis. However, there are several flaws in this hypothesis that need to be discussed. Several studies have shown that the rate of star formation Is not constant, but rather it has been observed to accelerate at large timescales [2]. In this research the star formation rate is taken to be spatially uniform through the Trapezium Cluster as well as constant through time when that may not be the case.

The largest source of systematic error in our method to derive the SFR is the dust reddening. This is because it holds significant effect on the observed brightness and colors of the studied stars. The amount of scattering and absorption depends on the wavelength of the light, with shorter wavelengths (blue light) being more strongly affected than longer wavelengths (red light). This preferential extinction is known as the extinction curve. The effect of dust reddening also depends on the distance between us and the star. As can be seen from Table 1 the dust reddening varied between the four stars depending on the calculated colour excess. This explains why we calculated different values of the hydrogen column density. Dust reddening is also treated as a parameter that is estimated from the data collected. This estimate is open to large uncertainties and assumptions which then lead to uncertainties in the inferred physical properties (such as SFR).

Special care of nebular contamination has to be taken in future observations [1]. This is because in regions of stellar births the gas clouds in these regions are highly ionized by the surrounding stars and they exist inside molecular hydrogen regions. This ionized gas leads to the contamination of light coming from the observed object by the emission or scattering of light from that gas. This contamination is especially sensitive when observing point sources such as stars.

When integrating the hydrogen column density to find the total mass of the hydrogen gas cloud several assumptions were made that affect the quality of our results. We supposed that the hydrogen gas is uniformly distributed in the area and that the density is constant throughout. We also assumed that the hydrogen gas is optically thin, therefore it does not absorb or scatter any of the emitted light. This is a crucial postulation since if we assumed the gas to be optically thick then the hydrogen column density will not accurately reflect the total mass of the gas. It is unlikely that the gas cloud is composed entirely of hydrogen or for it to have a uniform abundance of it .Nevertheless, other molecules and elements were neglected in our calculations. We also neglected to account for the irregularities in the spatial area which we were integrating over. We assumed a perfect shape when in the real world that is hardly ever the case. However, this allowed us to simplify our calculations.

Many factors affect the rate of star formation which we neglected to take into account when conducting this research. Taking these values into consideration would allow us to calculate a value of the SFR with more accuracy since we would be able to describe in our values any acceleration or turbulence in the rate. The abundance of heavy elements such as oxygen and nitrogen affect the cooling rate of the gas, which in turn affects the rate at which it can collapse and form stars. Lower metallicities can lead to low cooling efficiency, which can restrain star formation [7]. Another factor is the turbulence in the gas, however it can have both advantages and disadvantages. While it can help dissipate the energy and expedite the collapse of the gas cloud into protostars, too much turbulence has the opposite effect and inhibits star formation. Support against gravitational collapse can be given by a magnetic field. However, magnetic fields can also help to regulate the flow of gas and trigger star formation in some cases. Due to its dual effect, magnetic field of the observed area also needs to be taken into account.

In order to minimize the sources of systematic errors mentioned above there are several methods we can use in future studies. For dust reddening we could obtain more accurate calculations by correcting for the effects of interstellar extinction using the extinction law [8]. Selecting the proper photometric bands that are least affected by the dust reddening such as infrared and radio are also a viable correction to our methods. Because we used photometric analysis of mosaic images to retrieve values of the magnitude, we can minimize the error on nebular contamination by choosing the right aperture size. It should be large enough to capture all of the flux from the star but small enough to minimize impurity from the surrounding environment. The background subtraction method is where the flux from a nearby region free of both of the sources is measured and is subtracted from the flux in the aperture around the star. This method also minimizes the effect of the contamination.

Relating hydrogen column density and optical extinction to infer the star formation rates of different galaxies in nebulas has been reviewed for years using several methods. In 1975 Gorenstein used measurements of optical extinction and column density for 7 supernova remnants which yielded *N(H),* (2.22 ±0.14) × 10^{21} A_{V}. Another example is Predehl and Schmitt who analysed 25 bright X-ray point sources and 4 supernova remnants using ROSAT observations. They studied the soft X-ray halos around these sources to determine their shape and intensity. They combined this information with dust halo models to estimate the dust column density. They also discovered a correlation between the hydrogen column density derived from X-ray data and the optical extinction [5].

Due to the difficulty of studying and observing stell births and calculating their formation rates there was a difficulty in finding literature values of the SFR to compare our values to. Another issue arose when we used literature values of the total flux passing through a spatial extent of 4' x 6' that were quoted without their errors or uncertainty. There was not enough information in the research for us to conduct our own error analysis. Therefore the error on gas depletion time was the standard error on the four values calculated.

For future endeavours there are other suitable targets to study stellar birth such as the Rosette Nebula. It is approximately 5000 light years away and has "petals" that are known to contain a lot of stellar births. Its shape is illuminated by the cluster of O-type stars.

5. Conclusions

To conclude, our study found that only a small amount of gas is converted into new stars over a long period of time. With a SFR of (8.3 ± 0.008) x10^{-12} $M_{\odot}$/yr $^{-1}$. Therefore proving our hypothesis that star formation is an inefficient process. However, there are flaws in our methodology, including the fact that star formation rate is not constant and can accelerate over time. The largest source of error is dust reddening, which affects the observed brightness and colours of stars. In future studies nebular contamination and other factors such as metallicity need to be taken into consideration. The assumptions made in the our calculations of the total hydrogen mass, such as uniform distribution and constant density of gas, also affected the accuracy of the results. Other factors affecting the rate of star formation, such as heavy elements and turbulence, were not taken into account. To minimize errors in future studies, methods such as correcting for dust reddening and using proper photometric bands can be used.

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Error Appendix

To find the error on the colour excess, *E(B-V)*, we used literature values of the intrinsic colors along with their uncertainty as well the error on observed colors and their values obtained by photometric analysis. The total uncertainty of *E(B-V)* :

$$\alpha_{E(B-V)} = \sqrt{(\alpha_{M(B-V)_{OBS}})^2 + (\alpha_{M(B-V)_{INT}})^2} \quad (6)$$

Error on A_v was calculated by literature values of the coefficient R quoted with its error. The same propagation was used for the uncertainty on the calculation of *N(H)* as well as the error on the total mass of the gas cloud:

$$\alpha_A = A\sqrt{(\frac{\alpha_B}{B})^2 + (\frac{\alpha_C}{C})^2} \quad (7)$$

The error on the mass of one hydrogen atom is taken to be negligible. Therefore, the error present in the total hydrogen mass given in units of solar mass must take the uncertainty of the total mass of the sun into account [11]:

$$\alpha_M = \mathrm{M}\sqrt{(\frac{\alpha_{\mathrm{M}\odot}}{\mathrm{M}\odot})^2} \quad (8)$$

The best estimate of the error is the mean, therefore the standard error on the gas depletion time was calculated by:

$$SE = \frac{\sigma}{\sqrt{N}} \quad (9)$$

Where σ is the standard deviation and *N* is the number of samples.

There is no error quoted on the literature values utilized to calculate the total luminosity (flux, area) so error on SFR was found by method of linear regression and least squares fit.
The derived properties are dominated by systematic errors.

During the chi-squared analysis we obtained a reduced chi squared value of 5.37 and the probability, P(chi2min, DoF), as 0.005. The value of the reduced chi-squared tells us that the theoretical model provides a poor fit compared to our observed data. This is because its value is greater than 1. P(chi2min, DoF) represents the probability of obtaining a chi-squared value at least as high as the minimum value found in our analysis, judging by the degrees of freedom. In this case, the probability is 0.005, which is extremely low. This indicates that the observed data is unlikely to be consistent with the theoretical model, given the degrees of freedom.

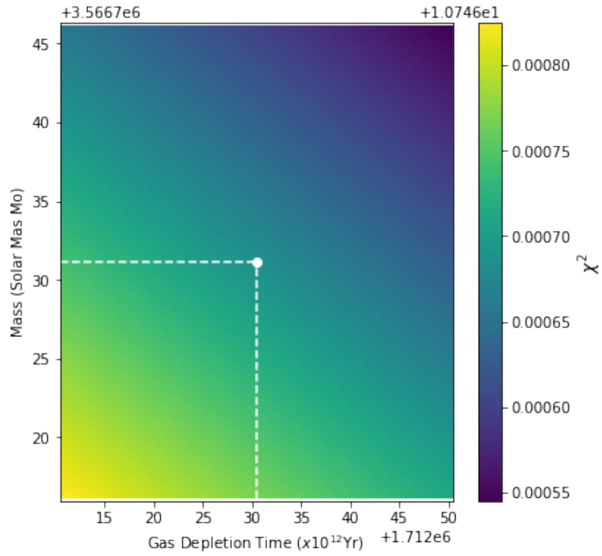

Fig.3: Chi-squared contour plot.

The minimum point on the plot represents the best-fit values for the parameters of the theoretical model. The coordinates of the minimum point correspond to the values of the parameters that minimize the chi-squared value. In our case the parameters would be at approximately 31 M⊙ and 30 × 10^{12} yrs. We can tell the data is a poor fit by the skewness of the contours from the minimum point of the plot. The contours on the right hand side tell us the confidence level in percentages. The 68% confidence level contour contains the parameter values, that are within one standard deviation of the best-fit values, (30 × 10^{12},30).

Scientific Summary for a General Audience

The process of star formation involves the collapse of gas in space until it is sufficiently dense to form a protostar. The protostar increases in mass and brightness until it transforms into a star. Yet, star formation takes millions of years and takes place deep beneath clouds of gas and dust, making it challenging to observe. The Orion Complex, which is the area of star formation nearest to Earth, contains the Trapezium cluster, which is the subject of this research. To learn more about the stars' characteristics, we concentrated on four of the cluster's stars. We calculated the amount of gas and dust in the region by analysing the hues of the stars. We determined the overall luminosity of the trapezium stars in a given region by applying the flux and luminosity relation. Where flux is the amount of energy passing through a certain area at a certain time. We discovered a steady star formation rate (SFR) of 8.3×10^{-12} by calibration of the star formation rate and total brightness.