Young Stellar Objects in the Orion Nebula Cluster

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January 26, 2023

Abstract

M42, also known as the Orion Nebula, is a star-forming region located within the Orion Constellation at a distance of 412pc from Earth. Using a 13"x13" image of M42 centred at 05:25:17, -05°23'28" taken in three wavelength filters from the Pico dos Dias Observatory, we were able to identify approximately 250 astronomical objects. Data from the Gaia DR3 release led to 31 stars being identified within the Orion Nebula Cluster. These stars were verified to be young stellar objects using a 353GHz Planck map to locate them within a region of high star formation activity, and a Hertzsprung-Russel diagram with overlaid generic age isochrones. Stellar ages ranging from 1-2Myr to $\geq$ *10Myr were identified in agreement with contemporary literature on star forming regions in M42.*

1. Introduction

M42 is a nebula in the Orion Constellation (central coordinates 05:25:17, -05°23'28") best observed during winter months in the Northern Hemisphere. It is located 412pc from Earth, is believed to contain around 3500 young stars, and has a high rate of star formation [Sahan, 2017]. These factors make it a prime candidate for studies into young stellar objects (YSOs) and star formation. The formation of a stellar cluster begins when large amounts of cold gas and dust begin to collapse under gravity. As such, areas of active star formation can often be traced to areas with high emission in the microwave region as a result of this dust. For local clusters such as M42, direct imaging can allow us to identify their individual stars which can then be cross-referenced against existing spectrophotometric sky surveys.

The primary goal of this project was to produce an image of the Orion Nebula Cluster (ONC) worthy of scientific publication. This image would then be used to identify YSOs within the cluster using data from the Gaia and Planck surveys.

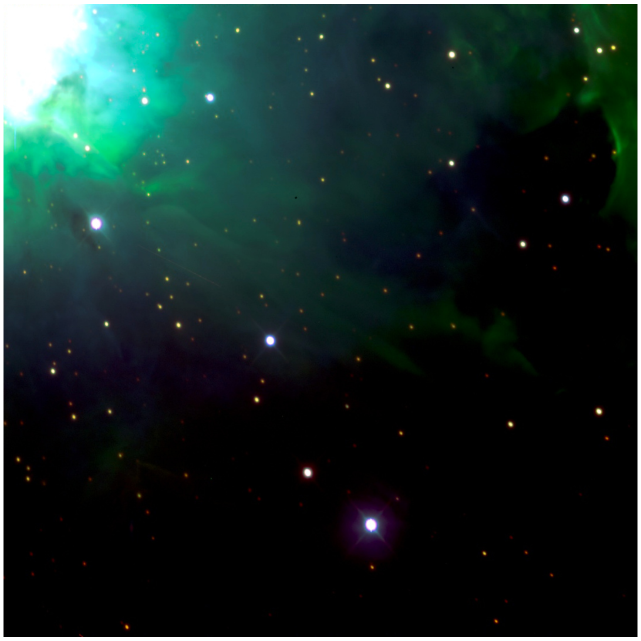
The Orion Nebula has been the subject of countless surveys across a wide range of wavelengths in the past due to it being the nearest known region of high-mass star formation [Siebert, 2009]. In recent years, significant work has been conducted on the formation of high mass stars in this region using observations to model the effects of molecular cloud collision [Fukui, 2018]. Research has also been conducted into the influence of surrounding gas density on stellar density in the M42 cluster, which suggested that tidal effects in dense gas could eject young stars and disperse embedded clusters [Stutz, 2017]

2. Target Selection and Observation

M42 was selected for its proximity to Earth, high apparent magnitude, and large quantity of available spectroscopic data. Observation of the ONC was conducted remotely on 23/09/2022 from the Pico dos Dias Observatory (OPD) in Brazil. While this date fell before the optimum observation period, it was the most suitable within the time constraints of this project. Images were taken in SDSS i', g', and r' filters with central wavelengths of 4770, 6215, and 7545 Angstroms [Brown, 2013] corresponding to blue, green/yellow, and red respectively. Processing of the images was done via a Python script provided by Juan Santisteban of the University of St Andrews. Bias and flat frames for each filter were combined to produce two master frames which were then artificially subtracted from the respective exposure. Finally, the three corrected exposure frames were combined with colour maps suitable for their central wavelengths. The result was an image (Figure 1.) containing multiple well-defined stars and a saturated core that was identified as NGC1976 (the combination of M42 and M43) by the Nova Astrometry service [Lang, 2010]. Desaturation of this region was attempted by varying parameters in the combination of the three corrected exposure images, and although the final version does represent a substantial improvement on the original a high degree of saturation remains.

When generating a list of all identifiable stellar objects in the field of our image, the corrected exposure frame in the i-band, corresponding to 7545 Angstroms, was used for its greatest apparent depth of field. This corresponds with our understanding that dust extinction is more significant at lower wavelengths, and so we would expect fainter stars

Figure 1: *Three-colour image of M42 taken from the Pico dos Dias Observatory oriented such that North is upwards. HII region visible in top right.*



in this region to be more visible using this filter. The Nova Astrometry service provided a fits file with coordinates for the identified stars which could then be cross-referenced with data from other surveys via the TOPCAT program [Taylor, 2005].

3. Gaia and Plank Data

The two sources of comparative data used in this analysis came from the Gaia DR3 and Planck PR3 releases. Gaia is an ongoing mission to create a catalogue of stars within the Milky way via photometric and spectroscopic observations across different wavelength bands. The most recent data release, DR3, includes improved measurements for roughly 1.8 billion stars [Brown, 2021]. The Planck satellite was an ESA project to provide the most accurate map of the Cosmic Microwave Background to date. Its extended mission involved mapping the sky in other wavelengths in the microwave region. Due to the high emissivity in the microwave region of dust particles, this data proved particularly useful in mapping areas of young star formation [Kim, 2017].

Of the approx. 250 astronomical sources identified using the Nova Astrometry service, only around 120 could be matched to existing Gaia DR3 data. There are a number of potential explanations for this discrepancy. Firstly, Gaia has to date mapped only around 2% of stars in the Milky Way, so it is possible that many of the sources detected in the astrometry process simply have not yet been mapped by Gaia. Furthermore, many of those sources may have been distant galaxies rather than nearby stars, and some may not have been observed due to high dust extinction in that region.

4. Analysis

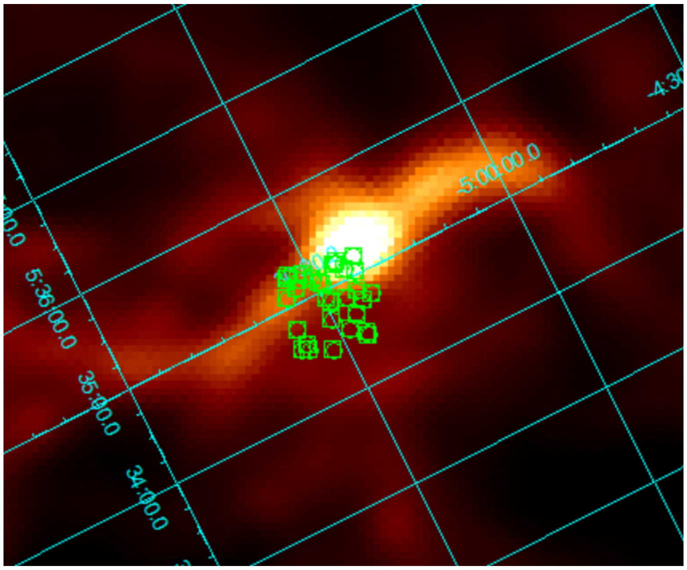
Identifying YSOs within the cluster was dependent on five key criterion:

1. The must share a similar distance from Earth
2. They must have a similar proper motion
3. They should appear above and redder than the main sequence of a CM diagram
4. Some should show a colour excess in the IR region
5. They should lie near regions of high emission in the Planck map

Justification of the first two criterion is self-explanatory - if the stars were distant from each other and did not appear to be moving in the same direction it is unlikely that they would be members of the same cluster. The second criterion appears as a result of the unlikeliness that younger stars will have reached the main sequence yet. Pre-main sequence stars lie at greater apparent magnitudes with redder colours than their main sequence counterparts. The fourth and fifth criterion are explained in the next paragraph and next subsection respectively.

Verification of the first four criterion was achievable using data from the Gaia DR3 release. Plotting a histogram of distances allowed a large number of the candidate stars to be ruled out, leaving only stars within 50pc of the expected distance of the ONC to account for errors. The proper motions in right ascension and declination for the remaining stars were then plotted, revealing a distinctly independent grouping with similar values. At this point it was considered highly likely that those stars were members of the ONC, which was confirmed by their adherence to the third criterion upon plotting a colour-magnitude diagram. Around fifteen of these stars also showed an excess (compared to solar values) in the IR region, implying the potential existence of proto-planetary discs [Clarke, 2000].

Figure 2: *Planck map portraying emission in the microwave region (353GHz) with locations of identified YSOs in green. DS9 coordinate system shown with RA (hours) on the vertical and Dec (degrees) on the horizontal.*



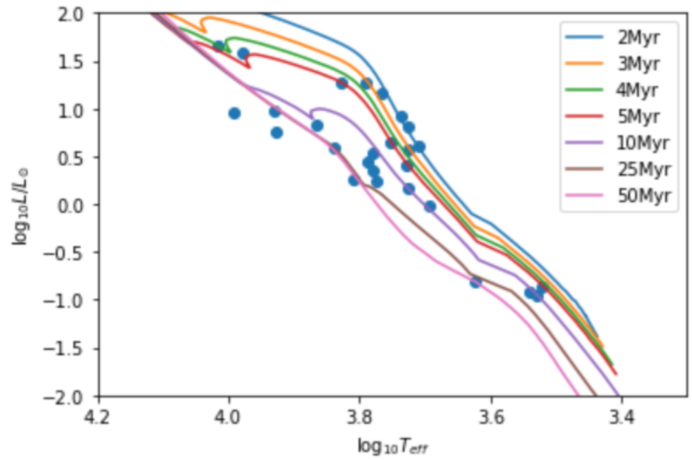
4.1. Planck Map

At 353GHz the Planck survey maps the distribution of interstellar dust [Ade, 2016]. From this we can identify cold regions on the brink of collapsing into hot young stars. By generating a Planck map (Figure 2.) with the same central coordinates as our image and plotting the positions of the YSO candidates on top of it, we were able to verify that the they coincided with one of these cold, compact regions. This adds further weight to the likelihood that all thirty one objects are indeed young stars. Visible in the Planck map are two spiral arms, most likely due to infalling gas from the surrounding filamentary structure. Not visible is the lack of cold gas directly above and below the core region. The existence of these spiral arms may merit followup analysis, but this is considered outwith the scope of this project.

4.2. Hertzsprung-Russel Diagram

Another method by which we analysed the stars within the cluster was to plot them on a Hertzsprung-Russel diagram (Figure 3.) overlaid with age isochrones - lines that trace the positions of stars of varying mass that share the same age. Generic isochrone data was generated using the online service created by Marigo et al. [Marigo, 2017] available as of 25/11/2022 from http://stev.oapd.inaf.it/cgi-

Figure 3: *HR diagram of YSOs (blue dots) within M42 cluster with overlaid age isochrones*

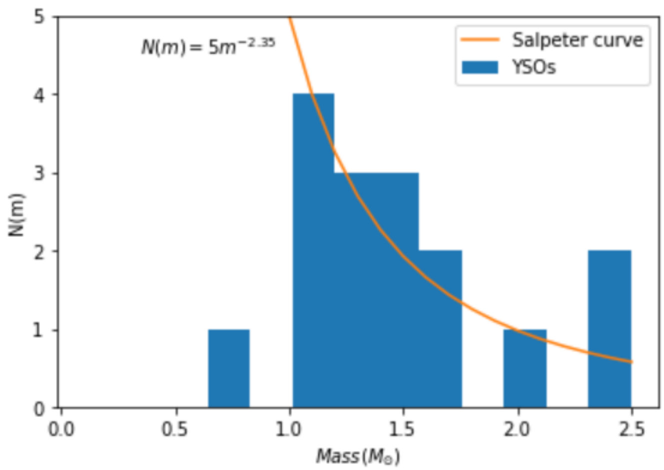


bin/cmd. Due to the limited information on individual stars in the M42 cluster, default parameters were used to generate isochrones from 2-50Myr. These approximations were deemed suitable as the YSOs identified were of roughly solar mass (0.5-2$M_{\odot}$). Through this method, we found that many of the stars within our list of YSO candidates followed these isochrones with a high degree of accuracy. The youngest of these stars lay along the two million year old isochrone, and the oldest were found to be above 50Myr. This implied that the stars within this cluster were particularly young in terms of stellar evolution.

4.3. Mass Distribution Function

For stars in a defined environment, we expect the mass distribution function to follow a function known as the Salpeter slope [Oey, 2014]. If this were the case for our candidate YSOs it would greatly support the argument that they were indeed members of the same cluster. A histogram of masses for our candidate stars is shown in Figure 4. The immediate issue with this line of analysis was that Gaia data included masses for only seventeen of the identified YSO candidates. With such a low sample size, any inferences made from a mass distribution plot will be relatively weak. Despite this, the profile of the distribution function does appear to match the expected Salpeter slope well in the range of masses for which we do have sufficient data. An attempt was made to calculate rough masses for those stars without Gaia masses using the mass-luminosity relation, but the high uncertainty of this method rendered the resulting mass distribution

Figure 4: *Mass distribution of YSOs with overlaid expected Salpeter slope*



plot unusable; with any adherence to the Salpeter slope being negated by a deficit of low mass stars. For this method to hold a greater weight in verifying the nature of the cluster, a much larger sample size of stars would be required. This analysis does however still merit a place in this paper if only to highlight the importance of sample size in astronomical data.

5. Conclusion

The underlying aim of this project was to identify young stellar objects in the known star-forming nebula M42 via observation in the optical range. To determine which stars were members of the Orion Nebula Cluster we utilised spectrophotometric data from the Gaia satellite, analysing distance, proper motion, and colour. To determine which of these stars were young, emission data in the microwave region from the Planck satellite was used to verify that they coincided with regions of cold, dense gas - conditions ripe for star formation. The candidate YSOs were also plotted on a Hertzsprung-Russel diagram with overlaid generic age isochrones. Analysis revealed a close fit to the 2-50Myr isochrones. This result matched with contemporary literature suggesting that M42 would contain a large number of stars around 1-2Myr old [Jeffries, 2007] and some older than 10Myr [O'Dell, 2015]. In total, 31 stars were found with a high likelihood of being YSOs.

The distance of the YSOs from the brightest region in the Planck map could be evidence of the displacing tidal effects of dense gas discussed by A. Stutz [Stutz, 2017]. Although our image did not cover that region of the sky, it would appear upon visual inspection that the density of YSOs decreases with distance from that core region. From age isochrone analysis we found that these displaced stars are on average older than the others, which is an expected result of velocity dispersion in young clusters.

The results of this analysis would be more definitive with a larger sample of stars. The most obvious improvement to make would be to analyse a wider region of the M42 nebula. As was evident from the Planck map of the region, the ONC is heavily obscured in the optical band by dust and so an observation at longer wavelengths may lead to the detection of a greater number of stars within the cluster. In the case of high mass stars, the UV flux may be sufficiently high as to be observable even with dust extinction.

The suggested followup to this project would be to repeat the process for several neighbouring regions across the centre of M42. This would allow for a more precise spread in ages for stars within the ONC, insight into stellar density around the core of the Planck map, and a truer representation of the mass distribution function.

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