P4

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1 Introduction

With our main source of life and energy being the Sun, it is an important factor to understanding the evolution of our planetary lives. We must first grasp the concept of stellar evolution to map out the stages and possible future of our sun. After centuries of research, scientist have reach a common conclusion in the form of the stellar evolution theory. However, with the recent discover of blue straggler stars, we much now question our current beliefs and reevaluate our assumptions on the evolutionary stages of stars.

1.1 Blue Stragglers

A recently discovered stellar phenomena, blue straggler stars (BSS) are a rare occurrence throughout our known universe. Stumbled upon by Allen Sandage in 1953, BSSs have continued to stump astronomers due to its existence within clusters (Sandage (1953)). These stars are bluer, younger, more massive, and more luminous in comparison to its fellow cluster members on the main sequence. These contrasting attributes are what make BSS an anomaly and what make scientists pose the question of whether the commonly accepted stellar evolutionary theory is correct. The theory states that stars of this magnitude should have already surpassed the turnoff point on the Hertzsprung-Russell diagram and evolved into a different stage, however, they still persist and many are unquestionably members of the cluster which they are in.

Multiple theories have sprung up in the last several decades attempting to justify blue straggler stars' existence. However, only two theories have been commonly accepted as possible formation mechanisms. The first theory, binary merger/collision theory, states that stars within a closed binary system will collide and begin merging to form one star. The second theory, very similar to the previous one, is the mass transfer theory which occurs again in a closed binary system, however in this case, one of the stars would have grown so large that the other star would have passed within its Roche Lobe. The larger star would slowly begin absorbing the mass/material of the other star due to its stronger gravitational pull. Both of these formation theories would allow the star to seem younger, have more material and mass to burn while leaving the other star stripped bare of all but its core (Ahumada & Lapasset (2007)).

1.2 Open Clusters

The area which we are considering the existence of blue straggler candidates is the open cluster. An open cluster is a grouping of stars, held together by a loose gravitational attraction, making the shape of the cluster irregular. This weak pull allows other stellar gas clouds and clusters to easily disturb the cluster formation, causing the stars to disperse (Friel (1995)). This type of cluster is made up of roughly several hundred to a couple thousand stars. So far, around 1,110 open clusters have been identified in the Milky Way. Open clusters are the optimal cluster for studying stellar evolution due to their members being close in properties (Piskunov et al. (2006)).

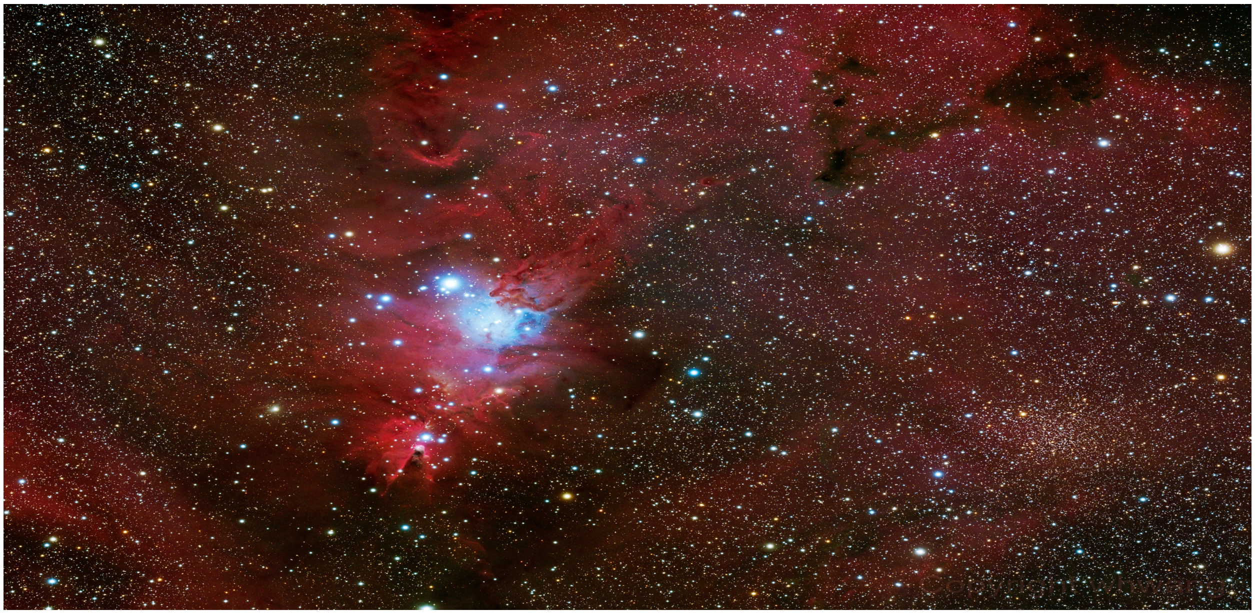


Figure 1: NGC 2264 (the Christmas Tree) and Open Cluster Trumpler 5 (103 blue straggler candidates.) Credit - https://www.astrobin.com/326897/?nc=all

2 Research Question

Through our research, we want to explore how a cluster's unique parameters impact the number of blue stragglers the cluster contains. To conduct this investigation, we compare the age, radial velocity, radius, and metallicity of various open clusters to their number of blue stragglers. Blue stragglers' unique relationship with stellar evolution creates a new opportunity to better understand our universe by understanding what leads to the creation of such stars. Stellar evolution, a general assumption about the universe in order to study astronomy, states that all stars within a cluster should share the same characteristics such as mass, age, velocity, and so on. However, as previously stated, stellar objects like blue stragglers exist that defy this fundamental theory. By better understanding how a cluster's conditions foster blue stragglers, astronomers can better understand the minute, inner workings of our universe. In the field, there is greater acknowledgement to study this aspect of formation, thus outlining its importance. As such, the parameters we have chosen to explore are based directly on theories of blue straggler formation, as to provide greater insight into a cluster's parameters effect on formation of stragglers leading to a higher number of blue stragglers.

3 Sources and Tools

Our focus on open clusters in our research led to much of our information being derived from literature or databases to keep cluster measurements as consistent as possible. The nature of open clusters creates conflicting data depending on different observations, modes of driving data, and so on. For our research, we were able to derive the number of blue stragglers, age, proper motion, the distance, and parallax of 408 open clusters from Rain et al.'s 2021 blue straggler catalogue (Rain et al. (2021)). The contributors to this catalogue have been periodically cataloguing blue straggler candidates since 1995, and their studies appear in a variety of published works from this point on. As such, the catalogue is a reputable source to begin research as the contributors are well-established in the blue straggler field. To find the radial velocity of our chosen clusters, we queried said clusters on SIMBAD, a french astronomical database as it was the greatest, comprehensible resource for radial velocity. SIMBAD is run by CDS, the Strasbourg Astronomical Data Centre, and thus is affiliated with NASA, ADS, and other well-known astronomical organizations, adding to its credibility. For radii, we gathered angular radii from Sanchez et al.'s catalogue of open cluster radii (Sánchez et al. (2020)). We transformed angular radii to actual radii of a cluster. Finally, for metallicity, we used values from Paunzen et al.'s study on metallicity in open clusters. The values they calculated were validated by comparing them to two previous extreme values from literature, placing Paunzen et al.'s metallicity as a safe middle ground.

Our research was conducted on Jupyter Notebooks. To transform, analyze, and plot our data we used various Python libraries like Pandas, Numpy, Scipy, and Matplotlib. To analyze our data, we used both a Pearson coefficient and a distance coefficient. As Pearson measures for linear correlation, inconclusive parameters utilize a distance coefficient as well as the distance coefficient is more sensitive to non-linear correlation.

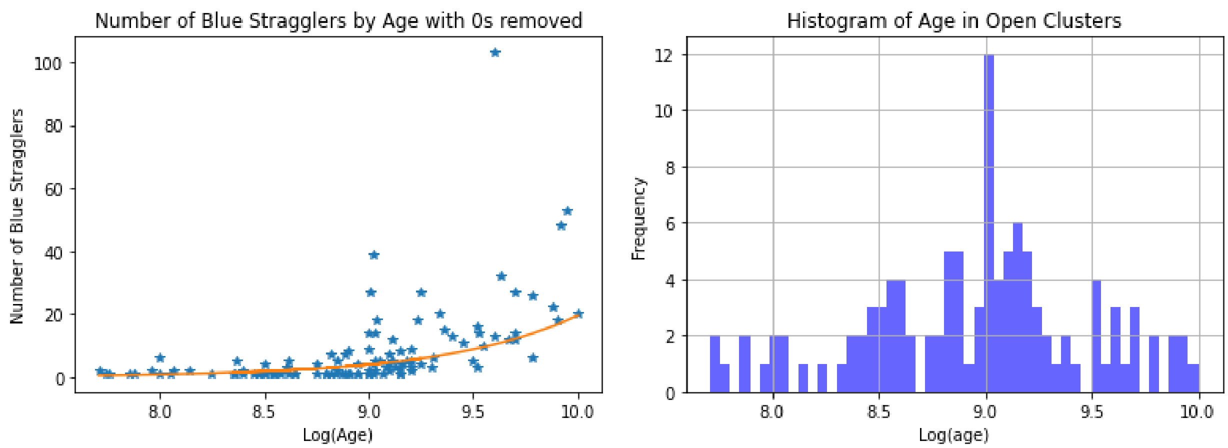
4 Results

4.1 Age vs. Blue Straggler Star Frequency

	Cluster	Log(Age)	NBSS
0	Berkeley 17	10.00	20
1	Collinder 261	9.95	53
...	...	...	...
108	Waterloo 7	7.76	1
109	NGC 7790	7.74	1
110	IC 361	7.71	2

Table 1: Table of 110 open clusters, their log(age), and number of blue stragglers.

For our analysis, we took advantage of the information compiled in Rain et al.'s 2021 blue straggler catalogue (Rain et al. (2021)). From this catalogue, we picked up the 110 open clusters containing blue straggler candidates (*Table 1*). The average log(age) in our dataset of 110 clusters was about 8.94. Through *Fig. 2b*, age is concentrated primarily between 8.5 and 9.5 log(age) as the frequency of ages below and above begin to taper off on the sides. Once plotted, it is clear to see an exponential relationship between number of blue stragglers and the age of open clusters *Fig. 2a*.



(a) Scatterplot: NBSS vs Log(Age)

(b) Histogram: NBSS vs Log(Age)

Figure 2: Age and Blue Stragglers

By logging the number of blue stragglers, thus creating a linear relationship, the Pearson correlation coefficient is .682, showing a strong correlation between the two. This relationship lines up with literature over blue stragglers, as it is hypothesized that older clusters have more time for binary systems to form, and thus merge (Ahumada & Lapasset (2007)). However, because an older cluster also grows in mass, it is unclear if it truly is age creating this relationship with the number of blue stragglers or if it is age's relationship with mass. Regardless, it is clear that age is in some way exponentially correlated with the number of blue stragglers.

4.2 Radial Velocity vs. Blue Straggler Star Frequency

	Cluster	Radial Velocity	NBSS
0	Berkeley 17	-73.34	20
1	Collinder 261	-24.67	53
...	...	...	...
104	Waterloo 7	65.91	1
103	NGC 7790	-80.20	1
104	IC 361	-37.90	2

Table 2: Table of 104 open clusters, their radial velocity in km/s, and number of blue stragglers.

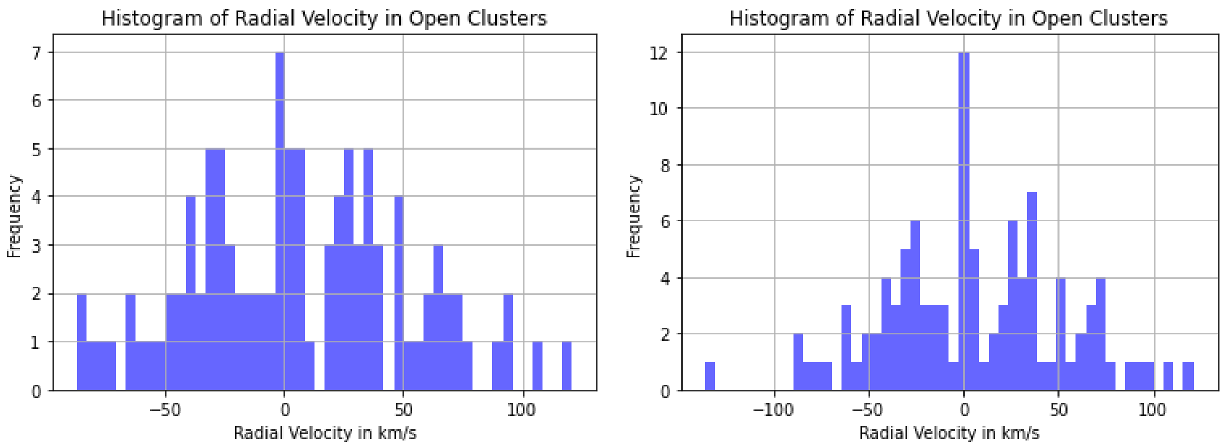
As binary merger/collisions was the primary focus of our study, we sought to understand how radial velocity affects the number of blue stragglers as faster cluster members would imply more collisions. We compiled the number of blue straggler in previously chosen 110 clusters with the available radial velocity values from SIMBAD (*Table 2*). Before analyzing the frequency of blue stragglers to radial velocity, we noted that radial velocity was dispersed similarly to age, with a substantial peak at roughly 0 (*Fig. 3b*).

The mean radial velocity among our clusters was 6.15 km/s. When the radial velocity was compared to the number of blue stragglers, no correlation was found. This is evident through the visualization of the two features, as the data is clustered around 0 (*Fig. 4*)

Pearson Coeff	Distance coeff
0.056	0.985

Table 3: Table of calculated correlation coefficients for radial velocity vs. number of blue stragglers.

The Pearson coefficient, without any clusters removed, was .02, and with outliers removed it was .06; the distance correlation was .98 (*Table 3*). Both coefficients display the lack of correlation between radial velocity and the number of blue stragglers, both linearly and non-linearly.



(a) Without Outliars (b) With Outliars

Figure 3: Histogram - Frequency of Blue Stragglers vs Radial Velocity

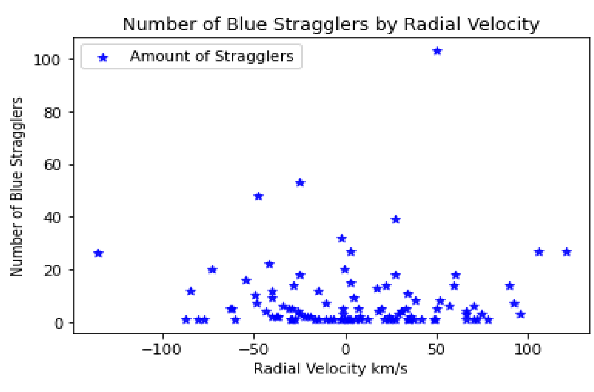


Figure 4: Scatter Plot - Frequency of Blue Stragglers vs Radial Velocity of OCs

4.3 Radii vs. Blue Straggler Star Frequency

As previously mentioned, open clusters have conflicting radii because of how loosely bound they are. Regardless, we hypothesized that a smaller cluster would be denser, thus implying greater collisions. To keep all data uniform, we picked up as many clusters from Sanchez et al.'s catalogue (Sánchez et al. (2020)) and transformed angular radii to actual radii (*Table 4*). The clusters sampled had an average radius of 8.06 pcs, a higher average than the mean found among all open clusters. However the data skewed right, emphasizing that most sampled clusters fall in the expected radii category (*Fig. 5a*). The scatter plot of radii to number of blue stragglers visually displays a lack of frequency, with the data points clusters around 0 to 10 pcs *Fig 5a*.

	Cluster	Radius	NBSS
0	Berkeley 17	6.44	20
1	Collinder 261	9.12	53
...	...	...	...
40	Waterloo 7	1.40	1
41	NGC 7790	2.77	1
42	IC 361	8.44	2

Table 4: Table of 42 open clusters, their radius in pcs, and number of blue stragglers.

Pearson Coeff	Distance coeff
0.222	0.777

Table 5: Table of calculated correlation coefficients for radii vs. number of blue stragglers.

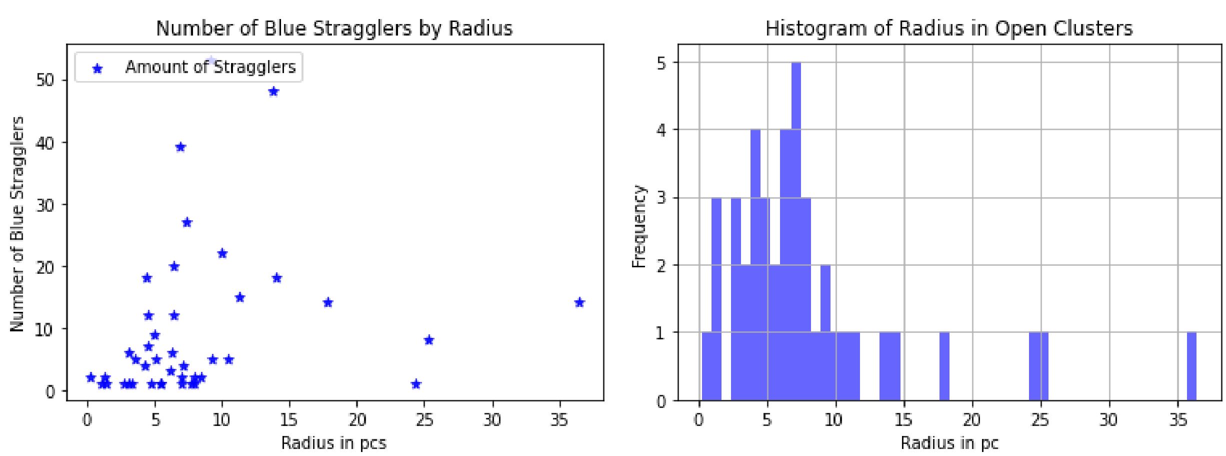


Figure 5: Frequency of Blue Stragglers vs Radius of OC

The Pearson coefficient was .22, alluding to the non-linear shape of the two features and displaying evidence of the loose correlation of the graph (*Table 5*). Noting the non-linear shape, we also calculated the distance correlation calculation to be .78 (*Table 5*). Once again, while both numbers display a higher correlation than radial velocity vs number of blue stragglers, the correlation coefficients are too low to draw any strong conclusions from this area of study. However, we recognize that by acquiring more data to analyze, as our dataset was cut to 42 clusters for this parameter, this relationship may become clearer.

4.4 Metallicity vs. Blue Straggler Star Frequency

Pearson Coeff	Distance coeff
-0.211	1.189

Table 6: Table of calculated correlation coefficients for metallicity vs. number of blue stragglers.

	Cluster	Metallicity	NBSS
0	NGC 6791	0.23	48
1	Berkeley 39	-0.33	18
...	...	...	...
56	NGC 6025	0.19	1
57	NGC 2422	0.11	1
58	NGC$_7$790	-0.22	1

Table 7: Table of 58 open clusters, their metallicity in [Fe/H], and number of blue stragglers.

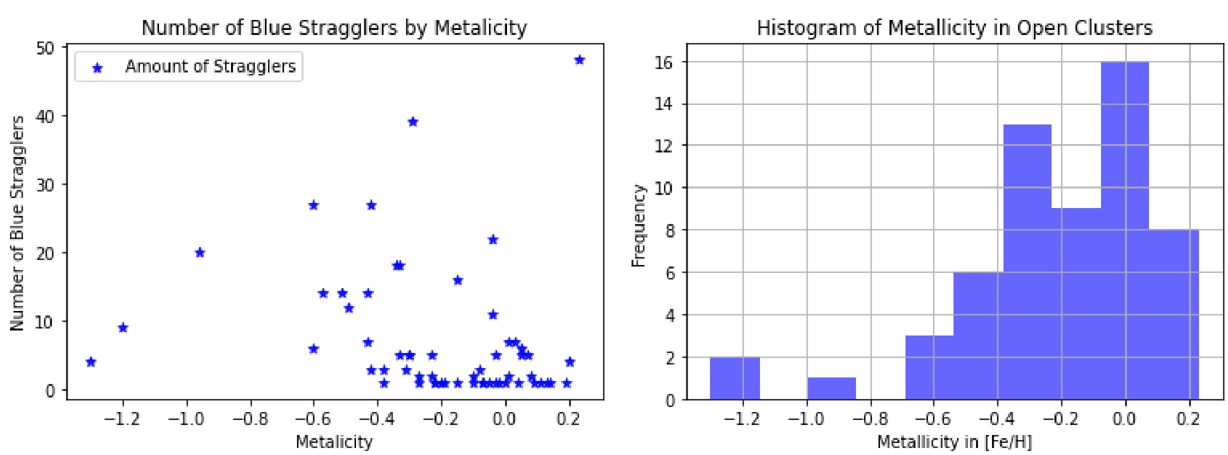


Figure 6: Frequency of Blue Stragglers vs Metallicity

When regarding metallicity, we took into account formation theories for blue stragglers once again. As it is estimated that low metallicity within a gas cloud has an inverse relationship with the binary systems that emerge within a cluster (Machida et al. (2009)). We investigated how lower metallicity impacted the number of blue stragglers within a cluster via binary system formations. We created our dataframe (*Table 7*) comparing the number of blue stragglers with their associated metallicity from Paunzen et al.'s catalogue

(Paunzen et al. (2010)). Our preliminary analysis on the data finds the average metallicity from our sample was -.21 [Fe/H], with the data skewed right (*Fig. 6b*).

Once compared, the Pearson coefficient between metallicity and number of blue stragglers -.21, and the distance correlation was equal to 1.19 (*Table 6*). While both numbers are too small to reach a definitive conclusion, both correlation coefficients reveal a present anti-correlation. As such, perhaps with greater analysis, a greater relationship can be found between low metallicity, the formation of binary systems, and the number of blue stragglers in an open cluster.

5 Comparison to Other Literature

Utilizing the most comprehensive data so far on blue straggler candidates and open cluster parameters, our study was able to analyze data from Rain et al. (2020) catalogue of 889 blue straggler candidate stars and 408 open clusters. Within the study associated with the catalogue, the authors found that the blue straggler candidates were lacking in younger open clusters and were unable to include open clusters that were younger than log(t) 8.7 because of their lack of candidates(Rain et al. (2021)). Therefore, along with the lack of younger open clusters in our data, our research also showed a strong correlation between the age and frequency of blue straggler stars.

This conclusion is again supported by Jadhav and Subramaniam (2021) in their research done analyzing the relationship between mass, density, and age parameters, and created observational constraints of BSSs formation mechanisms. Consisting of 670 open clusters that were all older than 300 Myr, with 228 of those open clusters consisting of blue straggler candidates, the study concluded that almost all of the clusters older than 3 Gyr had candidates and found a correlation for the age and mass of the open cluster with the frequency of blue straggler candidates. The paper also stated that there is not a relationship between radius and the frequency of blue straggler stars (Jadhav & Subramaniam (2021)). This conclusion confirms our own results and assertions of this relationship.

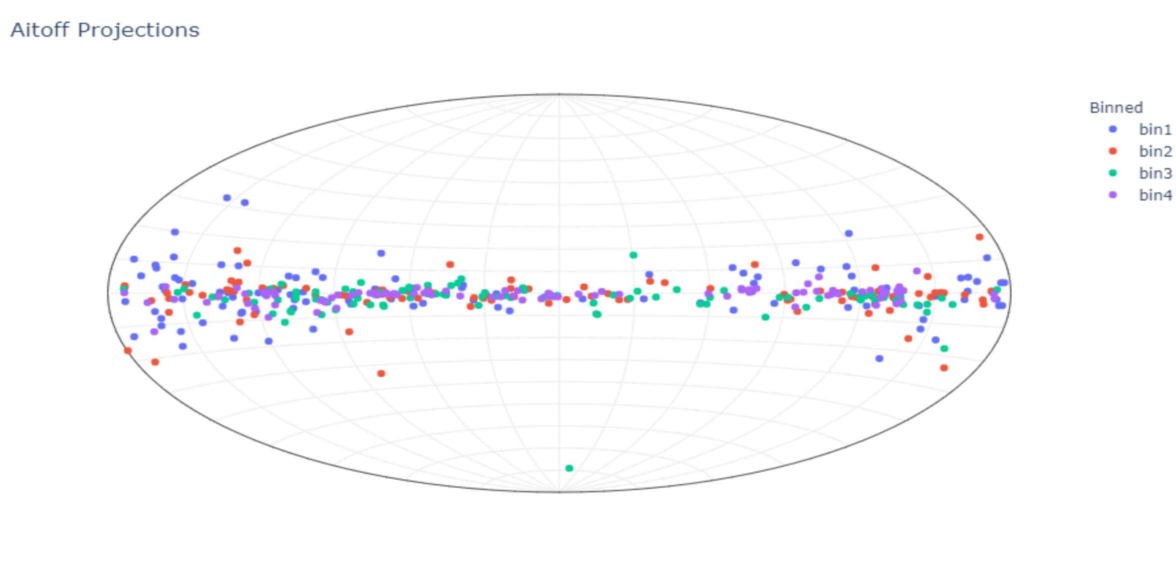


Figure 7: Aitoff Projection of all 408 Open Clusters in the catalogue

In another study done by Rain et al.(2020) on Collinder 261, an older, metal-rich open cluster, the researchers utilized data on said cluster to identify the blue straggler star candidates and their radial distribution within the cluster itself. Although it is not directly related to the conclusions done on our study, the results of their numerical data can be compared to the results which we were able to find/calculate on Collinder 261. This provides us important insight on our data collection and calculator process. For example, the radial velocity given in the Collinder 261 study is -25.44 $\pm$ 0.93 km s-1, which means our value of -24.67 km s-1 is within their margin of error (Rain et al. (2020)).

With the proven methods for value calculation and the matching correlation coefficient derived from the Pearson method through Pandas, we are able to conclude that our data will be accurate as long as the parameters which we derive from literature or catalogues are correct.

6 Conclusion

Utilizing our data sets derived from multiple catalogues and literature, we were able to reach several conclusions about open cluster's parameters effects on blue straggler candidates frequency within said cluster. Through statistical analysis, we are able to conclude that there seems to be a correlation between age of open clusters and an increased frequency of BSSs. However, through the same techniques, we are unable to conclude that radius, radial velocity, and metallicity of open clusters have any strong correlation on BSSs frequency. Regardless, metallicity seems to trend towards the expected negative correlation, displaying possible proof for our hypothesis.

6.1 Further Additional Work

To expand our current research, there are a couple things we would like to address. The major roadblocks we encountered during our calculation phase was a lack of open cluster data. Specifically, there was a lack of spectroscopic data, membership values, and solid size definitions. This absence of substantial data made it more difficult to be able to build up a large enough sample size to reach stronger conclusions. To later build up a larger catalogue of accurate data points and expend research into different parameters, we would like to utilize a convex hull in order to calculate open cluster radii. Dr. Gebhardt also suggested that the age of an open cluster may show a correlation due to the mass of the star allowing it to persist longer, thus having high density/materials to generate blue straggler stars. In order to breach this line of thought, we would like to also find the mass of open clusters with the radial velocities which we have obtained using the virial theorem. Lastly, to further solidify the formation theories of blue straggler stars, we would like to find the frequency of binary star systems within these open clusters to compare with the frequency of blue straggler stars in order to find a correlation between the two.

6.2 New Sciences and Contributions

Our study's conclusion has contributed new found knowledge to humanity's encyclopedia on blue straggler star candidates and how the parameters of open clusters have affected their frequency. As we uncover the possible causes of their formation, we can begin to further the definition of stellar evolution so it encompasses more than just our current understanding. Attempting to dissect the progression of stellar members is important to fully comprehending the conceivable time within this universe and other stars around us. The sun which powers our earth is not an exception to the stages of stellar evolution or the effects of other stars around it, so being able to grasp its timeline is an important part of looking out for humanity and its future.

7 Acknowledgement

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