# The Pursuit of Dippiness

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We search through the Evryscope database in order to find dippers, aperiodic stars with dips in flux on the order of 25% of their original magnitude. First, we query the Evryscope data to isolate young stars on the upper-main sequence or pre-main sequence and create an rms plot to determine variable stars. Then we use the Supersmoother and Lomb-Scargle periodograms to find stars that are aperiodic. Finally, we apply a filter to keep only stars with dips greater than 25%. We manually analyze the lightcurves and phase diagrams of the remaining stars and search for potential dippers. In the end, we find one definitive dipper, along with three other dipper candidates, and 37 other variable, periodic stars. Because our algorithm succeeds in identifying dippers, we suggest its use on larger databases in the future.

## I. INTRODUCTION

The data from the Kepler mission revealed a star, KIC 8462852, that underwent irregularly shaped, aperiodic dips in flux of up to $\approx 20\%$. In 2016, Boyajian, T.S. et. al. published a paper seeking to characterize the star. They conclude that the dips in flux are astrophysical in nature, rather than the result of instrumentation or environmental factors. Further, they suggest that the cause of the dips is an elliptical plane of comet or plantesimal fragments orbitting the star [2]. In a follow-up paper from 2018, they actually observe the first post-Kepler dips via a ground-based telescope. This allows them to further identify the dips as the result of elliptical panes of dust covering the star from view [1]. While a definitive explanation of KIC 8462852 still eludes us, the prospect of what a dipper is enticing. Following from the planetary debris explanation, dippers could be young stars in the early stages of solar system formation.

Our research aimed to discover more of these dippers. We were given access to UNC's Evryscope sky-survey telescopes, which are capable of imaging the entire observable sky every two minutes and producing hundreds of terabytes of data per year. The data from this survey has not previously been explored, and so the likelihood of discovery is fairly high.

## II. METHODS

### A. Young Stars

As mentioned in Sec. I, we are looking for young stars. To isolate these, we used the same query as Sari et. al [3] in order to filter the Evryscope data. We ended up with two different data sets: pre-main sequence stars and upper-main sequence stars.

### B. Variable Stars

Once we had our data sets, we analyzed them using Python multiprocessing. For each data set, we first determined which stars demonstrated significant variability. To do this, we created an rms plot on which we plotted each star's median magnitude versus the standard deviations of all of that star's recorded magnitudes. Variable stars showed higher standard deviations relative to other stars of similar magnitudes. To isolate these, we fitted a curve to the non-variable stars. Then we could keep only stars that were some distance $n\sigma$ away from that line, where $n$ is a multiplier $\sigma$ is the standard deviation of the standard deviations on the rms plot.

The pre-main sequence rms plot is shown in Fig. 1. Using a guess-and-check approach, we found that an appropriate curve to fit to the non-variable stars was $rms = 0.2(magnitude - 10)^2$. Similarly, we found that setting our multiplier to $n = 1$ allowed for a reasonable amount of variable stars while removing most of the non-variable stars.

The upper-main sequence rms plot is shown in Fig. 2. Similar to the pre-main sequence plot, we found that a good curve was $rms = 0.008(magnitude - 9.75)^2 + 0.04$ and that our sigma multiplier should be $n = 3$. The

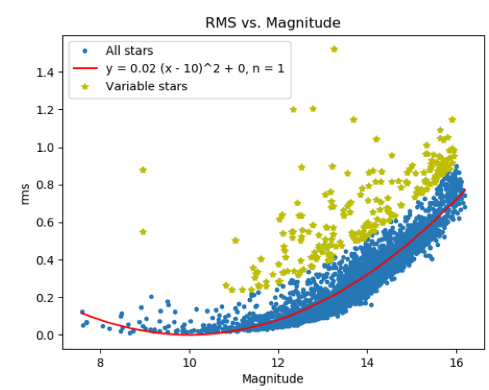


FIG. 1: RMS plot for pre-main sequence stars. All stars that were a distance of $d \geq \sigma$ away from the line $rms = 0.2(magnitude - 10)^2$ are considered variable.

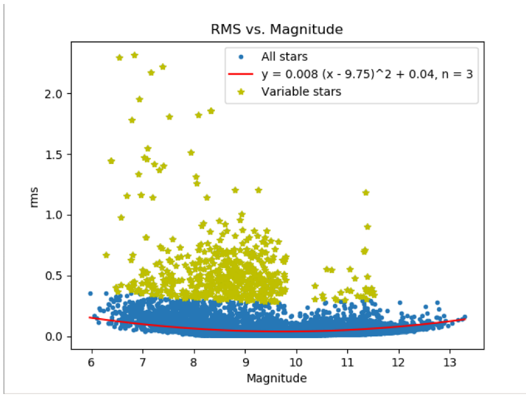


FIG. 2: RMS plot for upper-main sequence stars. All stars that were a distance of $d \geq 3\sigma$ away from the line $rms = 0.008(magnitude - 9.75)^2 + 0.04$ are considered variable.

selection of our sigma multipliers was largely arbitrary. While we wanted to include as many variable stars as possible, we also knew that the dippers we wanted would have very large variability, and therefore occupy the higher portions of the rms plot.

### C. Aperiodic Stars

Once we had selected the variable stars, we wanted to isolate only those which were aperiodic. To do this, we ran both data sets through two different periodograms: Supersmoother and Lomb-Scargle.

The algorithm for the Supersmoother measures the smoothness of a lightcurve at a variety of periods. For each star, we tested periods between 0.2 and 2 days, since the most common periodic stars fall within this range. By taking the modulus of each epoch with respect to the selected period, we convert the time measurements to phase. Then we sort the datapoints by their phase. To do this, we used the numpy.argsort function to obtain the indices of all the phase points from least to greatest. Then we could pass this index array through the magnitude array to sort the magnitudes. Then we simply subtract adjacent datapoints and find the average displacement. This average displacement is a single point on the periodogram. A larger average displacement means that the light curve is not very smooth at the selected period. A smaller average displacement means that it is smooth. Therefore, to find aperiodic stars, we wanted stars with Supersmoother periodograms that had, on average, larger values. To do this, we made an array with the minimum value of each star's Supersmoother plot (the period at which the lightcurve is most smooth). Then we simply sigma clipped the array. We only kept stars with Supersmoother powers greater than $4\sigma$ away from the median. Our sigma multiplier of 4 was chosen so as to remove any clearly periodic stars. However, we did not want to cut out any dippers so it is purposely lenient–many periodic stars slipped through the filter.

The other periodogram we used was Lomb-Scargle. In this algorithm, we select a variety of sinusoidal graphs, since these are the form of common periodic lightcurves. Assuming a star is periodic, if the algorithm selects the correct sine curve then multiplying the actual lightcurve by the sine curve will yield a large number. On the contrary, an incorrect sinusoid multiplied by the lightcurve will yield a small number. We chose the same test periods as for Supersmoother, such that we would test sinusoids with periods between 0.2 and 2 days. Contrary to the Supersmoother, periodic stars are now indicated by large values, and aperiodic stars are small. Thus, we used the same process as before, only now we formed an array with all of the maximum Lomb-Scargle powers, and sigma clipped them accordingly. As before, we used a sigma multiplier of $n = 4$, and only kept data less than $4\sigma$ away from the median.

### D. Dippers

We now had isolated young, variable, aperiodic stars. The last step was to examine the depth of a star's dip, and only keep stars that dip more than 25% of their original magnitude. To do this, we found the maximum and minimum magnitude of each star and subtracted them. If the difference was greater than 25% of the minimum, then we kept it.

### E. Plots

With a final array of potential dippers, we then plotted the standard lightcurves (magnitude vs. epochs) as well as the phase diagrams (magnitude vs. phase) for each star. The phase diagrams were found with the periodograms. We used the period that yielded the lowest Supersmoother value and the largest Lomb-Scargle value to calculate the phase. Once these plots were created and saved to our computer, we could analyze them manually to search for dippers or other interesting astrophysical activity.

## III. RESULTS

We found 39 stars of note in the survey. These are included in Table I. Of these, only one can be confidently considered a dipper, although a few others may be dipper candidates. This star is EVRJ71.7759+16.9785, and its lightcurve and phase diagram, are included in Figs. 3 and 4. According to the SIMBAD database, this is a variable star of Orion type.

Another star that appears to be a promising dipper candidate is EVRJ299.9573+29.162. Its lightcurve is shown in Fig. 7.

We ran this star through the ASAS-SN database and found the lightcurve shown in Fig. 6. It appears to show strong evidence of being a dipper.

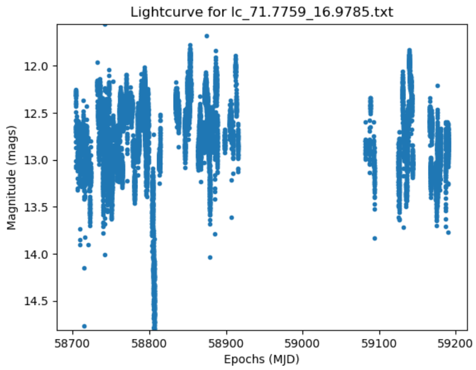


FIG. 3: Lightcurve for EVRJ71.7759+16.9785, a variable star of Orion type.

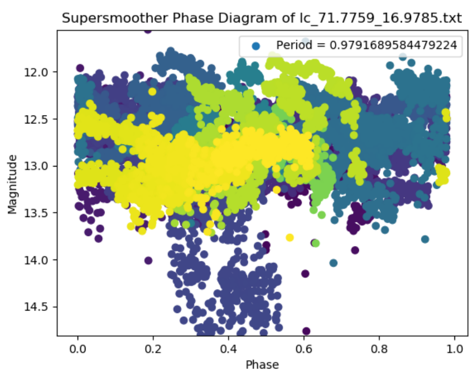


FIG. 4: Phase diagram for EVRJ71.7759+16.9785 at a period of 0.9792d, found using the Supersmoother algorithm.

We found some other stars that showed some signs of being dippers, but could not be confirmed with confidence. They are EVRJ60.1048+17.2617 and EVRJ155.9212+78.3517, and their lightcurves are below in Figs. 8 and 9, respectively. Other less-likely dipper candidates are included in Table I.

Another interesting star was a semi-regular variable star EVRJ310.0015+67.5951. This star's period is so long (on the order of 100 MJD, as seen in the lightcurve) that the periodograms only picked up periodicity from the day/night cycle. The lightcurve and phase diagrams and featured in Figs. 10 and 11.

We also found a variety of pulsating stars with very similar periods. One of these, EVRJ60.678+61.0384, is featured in Figs. 12, 13, and 14. It has a period of 1.0329 days, found using the Supersmoother periodogram.

Finally, another periodic star, EVRJ84.0855+9.872, was found to have rotational variability with a period of 1.0324 days, from the Lomb-Scargle periodogram. Its lightcurve and phase diagrams are in Figs. 15, 16, and 17.

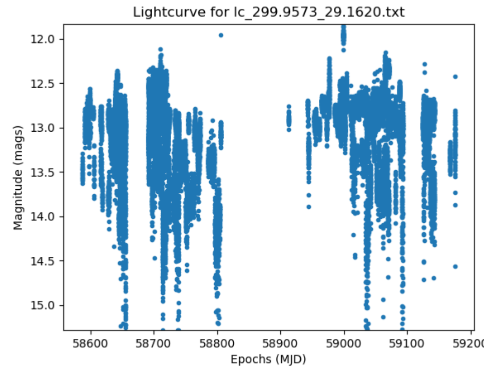


FIG. 5: Lightcurve for EVRJ299.9573+29.162, a potential dipper.

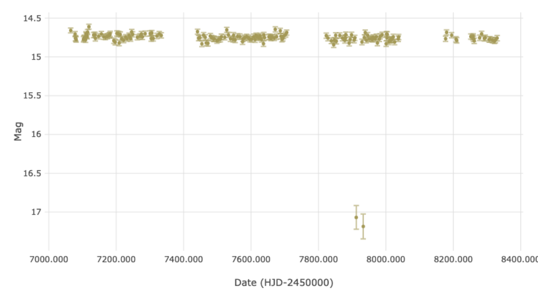


FIG. 6: ASAS-SN lightcurve for EVRJ299.9573+29.162, a strong dipper candidate.

## IV. DISCUSSION

We started with 36,858 stars between both both data sets. Our algorithms narrowed this down to 250 targets. From these candidates, we found 39 objects of note, and of these objects, only EVRJ71.7759+16.9785 was definitively a dipper. Unfortunately, this is not the kind of dipper we want. This star is dipping because it is so young and volatile that it is constantly morphing and changing in aperiodic and unpredictable ways. It is well documented in literature, and thus we can say with confidence that it is not dipping because of an elliptical plane of dust crossing in front of it. While this was the only definite dipper, we also found a promising candidate in EVRJ299.9573+29.162. This star is not documented at all, with only one reference in the SIMBAD database. The ASAS-SN plot of the star, Fig. 6, appears promising as well, showing a prominent dip despite an otherwise steady lightcurve. This appears to be the best candidate for the type of dippers we are looking for, but further research is needed to confirm it. We did find a few other potential dippers, such as EVRJ155.9212+78.3517 and EVRJ60.1048+17.2617, but both stars showed signs of instrument error (evidenced by the very bright spots recorded at the same moment as dimmer spots). Overall, finding only a handful of potential dippers out 36,858 stars emphasizes the rarity of these objects.

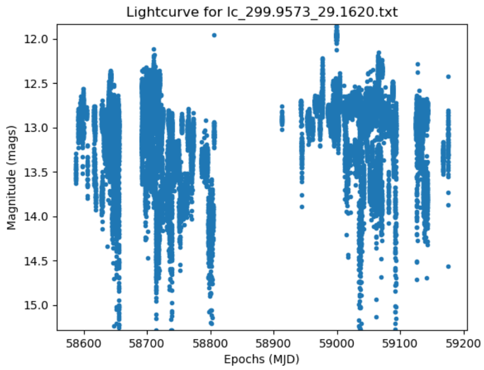


FIG. 7: Lightcurve for EVRJ299.9573+29.162, a potential dipper.

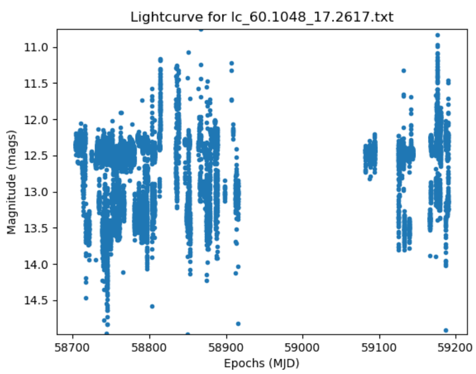


FIG. 8: Lightcurve for EVRJ60.1048+17.2617, a potential dipper.

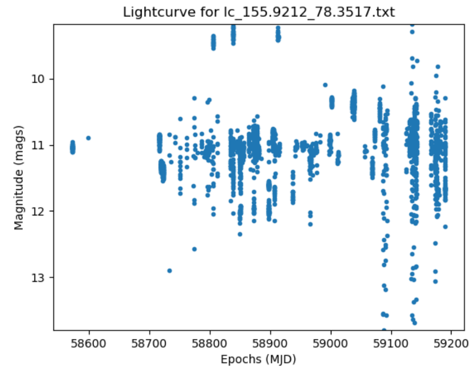


FIG. 9: Lightcurve for EVRJ155.9212+78.3517, a potential dipper.

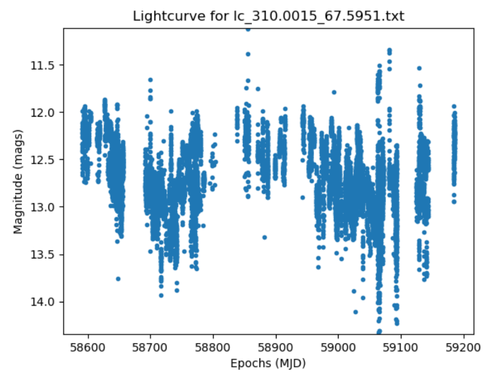


FIG. 10: Lightcurve for EVRJ310.0015+67.5951, a semi-regular variable star.

The other variable stars we found were largely periodic. Perhaps the most interesting non-dipper is the semi-regular variable star, EVRJ310.0015+67.5951. This has only one reference in the SIMBAD database and is listed simply as a "young star candidate". We also found a fair amount of pulsating stars in the datasets, but this is largely because of the nature of our search. By isolating stars with dips greater than 25% of the original magnitude, we restrict any periodic stars to those which demonstrate more variability. For example, the plots of a pulsating star and a star that is variable due to rotational effects can look similar, but the pulsating star will have greater variability. This is why there are more pulsating stars in our discoveries

Our process of finding dippers relied heavily on sigma clipping. In other words, we cut out a lot of data. At any point in our procedure, a larger sigma multiplier could have allowed for one more dipper to get through the filters. Similarly, we only accepted stars that dipped more than 25%. However, the dipper found in the Boyajian, T.S. et. al. paper [2] only dipped 22%. We chose a larger percentage so that any real dippers would be more obvious, and so that we could have fewer stars to analyze manually. However, because of this, we could have easily left out a star that dipped slightly less. In this way, we cannot claim to have found everything within the data set. Out of $36,000$ stars, we have only scratched the surface.

## V. CONCLUSIONS

We analyzed $36,858$ young stars in the Evryscope database to search for potential dippers. After isolating the variable, aperiodic stars with dips greater than 25% of their original magnitude, we analyzed the lightcurves and phase diagrams manually to identify interesting astrophysical phenomena. Because the Evryscope data has not been analyzed yet, we were able to discover variable stars of different kinds. Only one can be classified as a definite dipper: EVRJ71.7759+16.9785, a variable star of Orion type. This is not the type of dipper we were originally looking for, but it is encouraging to know that our algorithm can pick out dippers from a large dataset.

Our survey was a good start at identifying dippers, but could be improved in a variety of ways. First, with more time, we could loosen some of the requirements for candidacy. Lowering the dip size cutoff would allow dippers

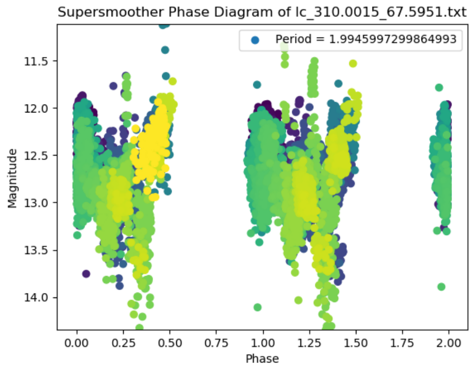


FIG. 11: Phase diagram for EVRJ310.0015+67.5951 at a period of 1.9946d, found using the Supersmoother algorithm.

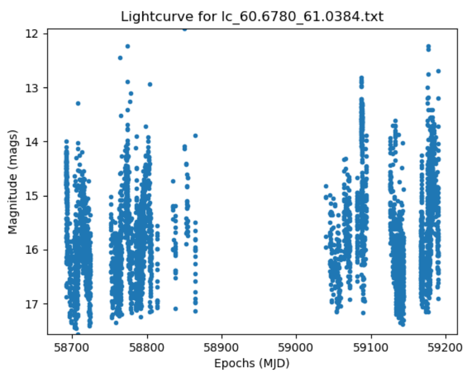


FIG. 12: Lightcurve for EVRJ60.678+61.0384, a pulsating star.

with smaller dips to be identified. Similarly, lowering some of our sigma multipliers could allow for more potential dippers to get through to the final plotting stage.

Perhaps the best way to improve upon this research is to simply obtain more data. Because dippers are so rare, this is the most clear-cut way to increase the number of dippers found. A new telescope system in development under Dr. Nicholas Law at UNC Chapel Hill, known as the Argus Array, will allow for more data to be taken. Because our methodology allowed us to identify dippers, we believe that the more stars we can look at, the more likely we are to find dippers.

In addition to finding more dippers, a natural next step to this research is following up on the dippers that have been identified. While EVRJ71.7759+16.9785 has already been documented well, EVRJ299.9573+29.162 has only one reference and no existing research suggests that it is a dipper. Therefore, we think efforts should be focused on identifying it fully by observing it regularly to see if more dips occur.

[1] Boyajian, T.S. et al. 2016, MNRAS, 457, 3988B.
[2] Boyajian, T.S. et al. 2018. ApJL, 853(1), L8.
[3] Sari et. al. 2018. AA 620, A172.

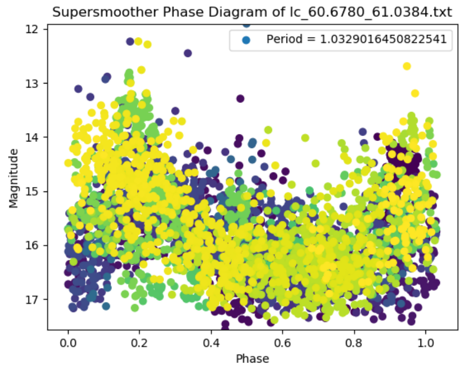


FIG. 13: Phase diagram for EVRJ60.678+61.0384 at a period of 1.0329d, found using the Supersmoother algorithm.

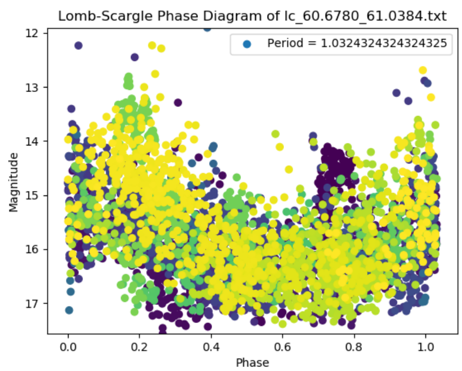


FIG. 14: Phase diagram for EVRJ60.678+61.0384 at a period of 1.0324d, found using the Lomb-Scargle algorithm.

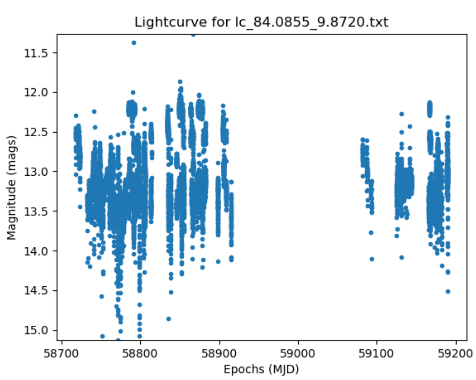


FIG. 15: Lightcurve for EVRJ84.0855+9.872, a variable star due to rotational effects.

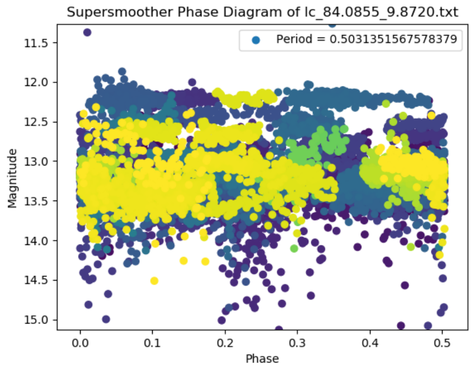


FIG. 16: Phase diagram for EVRJ84.0855+9.872 at a period of 0.5031d, found using the Supersmoother algorithm.

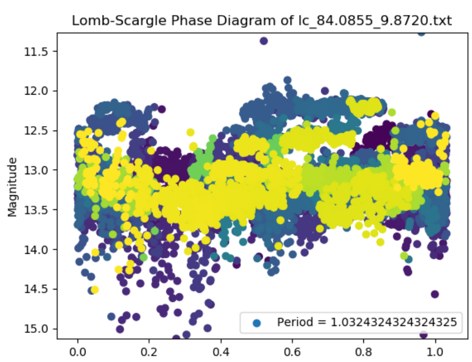


FIG. 17: Phase diagram for EVRJ84.0855+9.872 at a period of 1.0324d, found using the Lomb-Scargle algorithm.

TABLE I: Star Discoveries

| RA | Dec | Discovery Type | SIMBAD References |
|---|---|---|---|
| 71.7759 | 16.9785 | Dipper | 489 |
| 299.9573 | 29.162 | Dipper | 1 |
| 321.678 | 44.7588 | Dipper | 1 |
| 105.8735 | 16.2759 | Dipper | 1 |
| 115.8461 | 42.9931 | Dipper | 1 |
| 306.3408 | 35.9049 | Dipper | 1 |
| 323.6217 | 50.7351 | Dipper | 1 |
| 341.37 | 41.8791 | Dipper | 1 |
| 272.3638 | 6.1653 | Dipper | 1 |
| 291.0679 | 10.7035 | Dipper | 1 |
| 283.406 | 36.8465 | Dipper | 1 |
| 278.08 | 11.26 | Dipper | 1 |
| 322.8964 | 48.626 | Dipper | 1 |
| 337.238 | 56.3263 | Dipper | 1 |
| 338.76 | 51.5164 | Dipper | 1 |
| 331.2487 | 61.3833 | Dipper | 1 |
| 306.544 | 42.9202 | Dipper | 1 |
| 353.973 | 61.1792 | Dipper | 1 |
| 65.1175 | 78.0758 | Dipper | 1 |
| 60.1048 | 17.2617 | Dipper | 1 |
| 310.0015 | 67.5951 | Semi-Regular | 1 |
| 61.4741 | 34.2739 | Pulsating | 2 |
| 76.0599 | 21.2423 | Pulsating | 3 |
| 31.0949 | 76.1145 | Pulsating | 1 |
| 358.1858 | 33.7296 | Pulsating | 1 |
| 357.4663 | 39.5865 | Pulsating | 1 |
| 357.2139 | 6.7186 | Pulsating | 1 |
| 60.678 | 61.0384 | Pulsating | 1 |
| 82.5546 | 41.2825 | Pulsating | 11 |
| 83.6601 | 6.1267 | Pulsating | 16 |
| 46.9633 | 30.7054 | Pulsating | 1 |
| 54.3998 | 46.4891 | Pulsating | 1 |
| 60.678 | 61.0384 | Pulsating | 1 |
| 285.1726 | 7.6143 | Pulsating | 1 |
| 2.2447 | 54.894 | Pulsating | 1 |
| 294.4592 | 39.504 | Pulsating | 1 |
| 342.0386 | 63.3576 | Pulsating | 1 |
| 66.6392 | 64.1971 | Rotational | 1 |
| 312.322 | 77.8291 | Rotational | 1 |
| 78.8661 | 9.4155 | Rotational | 2 |
| 84.0855 | 9.872 | Rotational | 16 |
| 5.7386 | 31.1256 | Rotational | 1 |
| 29.0829 | 19.8675 | Rotational | 1 |
| 342.529 | 66.6131 | Rotational | 1 |
| 347.334 | 61.6563 | Rotational | 14 |