A Search for Analogs of KIC 8462852 (Boyajian’s Star): A Second List of Candidates

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Abstract

In data from the Kepler mission, the normal F3V star KIC 8462852 (Boyajian’s star) was observed to exhibit infrequent dips in brightness that have not been satisfactorily explained. A previous paper reported the first results of a search for other similar stars in a limited region of the sky around the Kepler field. This paper expands on that search to cover the entire sky between declinations of +22° and +68°. Fifteen new candidates with low rates of dipping, referred to as “slow dippers” in Paper I, have been identified. The dippers occupy a limited region of the HR diagram and an apparent clustering in space is found. This latter feature suggests that these stars are attractive targets for SETI searches.

Unified Astronomy Thesaurus concepts: Peculiar variable stars (1202)

1. Introduction

Using photometry from the Kepler mission, citizen scientists of the Planet Hunters Project discovered several scattered groups of dips in the light curve of the otherwise constant F3V star KIC 8462858 (a.k.a. Boyajian’s star; Boyajian et al. 2016). Another episode of dipping was observed four years later (Bodman et al. 2018). Additionally, Schaefer (2016) showed that the star slowly dimmed over a century of Harvard archival plates. This variation was subsequently confirmed at wavelength from the near-ultraviolet to the mid-infrared (Montet & Simon 2016; Meng et al. 2017; Davenport et al. 2018; Hippe & Angerhausen 2018; Simon et al. 2018). Such behavior had not been previously observed in similar stars. Although a number of explanations have been proposed, none has been fully satisfactory (Wright & Sigurdsson 2016). For further discussions of this star, I refer the reader to Boyajian et al. (2018), Bodman et al. (2018), and to Pearce et al. (2021) for more recent references and a new hypothesis to explain the behavior.

Since it is difficult to gain an understanding of an astrophysical phenomenon with only a single example, I undertook a search for other objects similar to Boyajian’s star. Schmidt (2019; Paper I) described the method of the search and presented the first list of 21 candidates from a region of the sky spanning right ascensions from approximately 17°04′ to 23°12′ and declinations from +22° to +68°. The present paper extends the search to the remainder of the sky between those declinations for a total coverage of 11,400 square degrees, a little more that a quarter of the entire sky.

2. The Candidates

The identification of dipper candidates followed the procedures described in Paper I as clarified by Schmidt (2020). Briefly, the photometry from the Northern Sky Variable Survey (NSVS; Wozniak et al. 2004) was searched digitally for stars with dips that were at least 3σcont below the continuum level. In the present project, 485 stars were selected from among the 2.7 million stars with acceptable NSVS photometry. The NSVS light curves and sky images for these stars were examined manually and stars were rejected according to criteria 1 and 2 from Schmidt (2020), and criterion 3 from Paper I. Finally, light curves from the All Sky Automated Survey Survey for Supernovae (ASAS-SN; Shappee et al. 2014; Jayasinghe et al. 2019) were downloaded and examined to reject further stars (criterion 4 from Paper I). The ASAS-SN photometry used in Paper I was all obtained in the V band. Since then, the ASAS-SN project has switched to the g band. In the application of the ASAS-SN photometry here, the zero point of g observations has been adjusted to bring the continuum magnitudes of V and g into agreement.

Table 1 is the final list of the 15 slow dipper candidates that satisfied all of the criteria. Their NSVS light curves are plotted in Figure 1. As in Paper I, we do not show the ASAS-SN light curves since they are essentially constant with a few isolated dips.

In Paper I we identified six stars as rapid dippers. Since then, further information has appeared in the International Variable Star Index™ that casts doubt on this category. Additionally, no rapid dippers were found in the fields studied here. Thus, we will not consider them further at this time.

Column 1 of Table 1 gives the number of each star from the NSVS while the sexagessimal designation is given in column 2. Column 3 lists the number of dips more than 3σcont below the continuum in the NSVS light curve, NDips (including the dip that was used to identify the candidate), while column 4 gives the depth of the deepest one, Dmax. Columns 5 and 6 contain the same information from the ASAS-SN light curves. Column 7 lists the number of humps that rise at least 3σcont above the continuum in the ASAS-SN light curves, Nhumps, and column 8 gives the duration of coverage of the ASAS-SN data, Tobs. This

As in Paper I, we shall refer to the quiescent intervals between dips as the continuum. Its median magnitude will be denoted by mcont and the standard deviation of individual measurements about it, excluding the dips, by σcont.

For a star to be included in the initial computerized search for candidates its light curve was required to have at least 30 data points in the NSVS that met the criteria described by Wozniak et al. (2004) to be deemed “good.”

https://www.aavso.org/vsx
latter is essentially the total elapsed time of the observations minus the seasonal gaps. Column 9 contains the rate of dipping $R_{\text{dips}} = N_{\text{dips}}/T_{\text{obs}}$, expressed in dips per year.

### 3. Discussion

Table 2 presents other properties of the dipper candidates. The slow dippers from Paper I and Boyajian’s star are also included with some updated information. The first column contains the NSVS number of each star. Columns 2 and 3 list the parallaxes and their standard errors from the Gaia Early Data Release 3 (Gaia Collaboration 2016, DR2). The effective temperatures and the luminosities from the Second Gaia Data Release (Gaia Collaboration 2016, DR2) are listed in columns 4 and 5. The last three columns are explained below.

#### 3.1. Photometric Properties

The ASAS-SN light curves have dipping rates, $R_{\text{dips}}$, that range from 0.0 to 0.8 yr$^{-1}$ with an average of 0.4. A Kolmogorov–Smirnov test failed to demonstrate a statistically significant difference in the distributions of $R_{\text{dips}}$ between the slow dippers of Paper I and those of the present sample. Boyajian’s star also falls within the same range. This is

| NSVS Number | Sexegessimal Designation | $N_{\text{dips}}$ | $D_{\text{max}}$ | $N_{\text{max}}$ | $N_{\text{humps}}$ | $T_{\text{obs}}$ | $R_{\text{dips}}$ |
|-------------|--------------------------|-------------------|------------------|-----------------|-----------------|----------------|---------------|
| 1933490     | J025354.50+534120.6       | 7                 | 0.97             |                | 2               | 0.16           | 1210          | 0.6           |
| 2354429     | J070824.21+621319.0       | 3                 | 0.33             |                | 2               | 0.00           | 2010          | 0.4           |
| 2506699     | J085215.37+561839.1       | 1                 | 0.13             |                | 2               | 1.00           | 1910          | 0.8           |
| 2506138     | J103205.21+605508.0       | 1                 | 0.41             |                | 3               | 0.07           | 1930          | 0.6           |
| 3781455     | J003653.98+422830.2       | 4                 | 0.33             |                | 0               | ...            | 1950          | 0.0           |
| 4754014     | J01549.13+511104.3        | 1                 | 0.34             |                | 2               | 0.22           | 1260          | 0.6           |
| 4989822     | J113625.37+465332.6       | 6                 | 0.14             |                | 2               | 0.08           | 1260          | 0.3           |
| 5190574     | J153957.90+465805.5       | 3                 | 0.34             |                | 3               | 0.06           | 1860          | 0.6           |
| 6757658     | J041338.18+253803.9       | 2                 | 0.14             |                | 2               | 0.10           | 1680          | 0.4           |
| 6804071     | J043123.31+320313.9       | 1                 | 0.43             |                | 3               | 0.11           | 1400          | 0.8           |
| 6814519     | J044212.48+343245.9       | 1                 | 0.20             |                | 1               | 0.09           | 1243          | 0.3           |
| 7255468     | J070817.94+267155.5       | 6                 | 0.22             |                | 0               | ...            | 1726          | 0.0           |
| 7575062     | J111332.38+334009.6       | 3                 | 0.24             |                | 1               | 0.10           | 1928          | 0.2           |
| 7642696     | J123442.46+355031.2       | 3                 | 0.07             |                | 1               | 0.10           | 1467          | 0.2           |

Figure 1. The NSVS light curves for the stars classified as slow dippers. The upper horizontal line is the continuum level and the lower line is three standard deviations below it.
consistent with the slow dippers from both papers and Boyajian’s star all being the same type of star.

### 3.2. Location in the HR Diagram

Figure 2 shows a portion of the HR diagram containing the slow dipper candidates from Paper I (large squares) and the dipper candidates from this paper (large circles). The small dots are the statistical sample from Gaia as described in Paper I. The two quadrilaterals delineated by light lines are the boxes defined in Paper I to encompass the dipper candidates.

Six of the dippers from the present sample fall outside of the boxes from Paper I. To reassess the significance of the grouping of these stars in the HR diagram, we have defined a larger rectangular box, delineated by bold lines, that encompasses all of the dippers; it is bounded by effective temperatures from 4000 to 7050 K and logarithmic luminosities from -0.65 to 1.88. 29 of the 30 slow dippers from both studies pass all of the dippers; it is bounded by effective temperatures from 4000 to 7050 K and logarithmic luminosities from -0.65 to 1.88. 29 of the 30 slow dippers from both studies

The locations of the dipper candidates on the sky are plotted in Figure 3(a). The region enclosed by dashed lines is the area studied in Paper I while the stars outside of it are from the present paper. There is an apparent clump of 12 dippers (plus Boyajian’s star) between 254° and 303° of R.A. while the density of stars elsewhere is much sparser. We will consider the NSVS tiles\(^5\) to the west of the central dividing line in the Paper I region to encompass this clump (NSVS tile numbers 23, 24, 41, 42, 43, 62, 63, 64, 65). There are 1,337,101 stars with acceptable photometry in the NSVS in this region.

\(^5\) The NSVS was organized into 206 16° X 16° tiles covering the entire sky. See Figure 1 of Akerlof et al. (2000) for the locations of the tiles.

### Table 2

| NSVS (1) | \(\pi\) (2) | \(\sigma_\pi\) (3) | \(T_{\text{eff}}\) (4) | Log\((L/L_\odot)\) (5) | \(x'\) (6) | \(y'\) (7) | \(z'\) (8) |
|----------|------------|-------------------|---------------------|-------------------|--------|--------|--------|
| **Stars from this paper** |
| 1933490  | 1.446      | 1.2\%             | 3999                | 1.15              | 183    | 650    | -151   |
| 2354429  | 1.182      | 4.4\%             | 6980                | 0.59              | 228    | 758    | 299    |
| 2506699  | 2.425      | 0.6\%             | 5371                | 0.07              | 105    | 321    | 237    |
| 2560138  | 0.962      | 1.2\%             | 5451                | 0.62              | 461    | 668    | 650    |
| 3781455  | 1.011      | 1.8\%             | 4932                | 1.46              | 394    | 711    | -563   |
| 4111136  | 0.629      | 2.5\%             | 5010                | 1.08              | 314    | 1527   | -314   |
| 4754014  | 2.527      | 0.6\%             | 5428                | 0.38              | 46     | 341    | 196    |
| 4989822  | 2.902      | 1.2\%             | 5835                | 0.15              | 144    | 143    | 278    |
| 5190574  | 1.276      | 0.9\%             | 5803                | 0.27              | 699    | 46     | 352    |
| 6757658  | 1.249      | 1.2\%             | 4110                | 0.68              | -226   | 749    | -171   |
| 6804071  | 0.511      | 4.0\%             | 4250                | 1.62              | -398   | 1902   | -225   |
| 6814519  | 1.469      | 1.0\%             | 4454                | 0.35              | -119   | 669    | -45    |
| 7255468  | 1.274      | 1.2\%             | 6265                | 0.70              | -265   | 651    | 349    |
| 7575062  | 3.304      | 1.7\%             | 4942                | -0.51             | 68     | 99     | 278    |
| 7642696  | 6.374      | 0.3\%             | 5502                | -0.18             | 72     | 25     | 137    |

**Clump stars from Paper I**

| 2913753  | 4.510      | 0.2\%             | 4590                | -0.65             | 210    | 56     | 39     |
| 3037513  | 1.688      | 0.6\%             | 5259                | 0.88              | 579    | 125    | -10    |
| 3093586  | 3.002      | 0.3\%             | 5861                | 0.02              | 313    | 101    | -55    |
| 5334181  | 1.716      | 0.8\%             | 6322                | 0.30              | 574    | -31    | 98     |
| 5436225  | 3.810      | 0.7\%             | 5232                | -0.17             | 262    | 16     | -3     |
| 5482005  | 1.602      | 0.6\%             | 6580                | 0.38              | 623    | -1     | -33    |
| 7971210  | 1.608      | 0.6\%             | 5868                | 0.56              | 580    | -182   | 130    |
| 8046240  | 2.510      | 0.4\%             | 5702                | 0.11              | 394    | -49    | 36     |

**Non-clump stars from Paper I**

| 2958269  | 0.424      | 2.8\%             | 4588                | 1.82              | 2180   | 836    | 332    |
| 8128754  | 0.639      | 2.1\%             | 4126                | 1.82              | 1507   | -418   | -56    |
| 8233191  | 0.128      | 7.7\%             | 4216                | -1                | 7658   | -876   | -1142  |
| 8491743  | 0.875      | 2.2\%             | 4104                | 1.48              | 1025   | 21     | -508   |
| 8935719  | 0.522      | 2.8\%             | 4708                | 1.70              | 1154   | 507    | -1444  |
| 8942941  | 0.865      | 1.5\%             | 5807                | 1.03              | 687    | 344    | -863   |
| 8987978  | 0.527      | 2.5\%             | 4888                | 1.70              | 829    | 757    | -1530  |

**Boyajian’s Star**

| 5711291  | 2.255      | 0.4\%             | 5899                | 0.47              | 415    | 77     | -137   |

\[\text{Figures and tables are placeholders for actual data.}\]
4.9 candidates per million stars, respectively. Thus, the
appearance of a clump is not the result of the higher star
density near the galactic plane.

During the process of winnowing the initial lists of
candidates, somewhat subjective judgments had to be made
as to which stars to retain and which to delete. All of the clump
stars are from Paper I and most of the stars elsewhere are from
the present paper. Although an effort was made to be consistent
between the two studies, the possibility that the clump resulted
from a shift in the criteria can not be ruled out. To address this,
we will take advantage of the fact that the clump is confined to
the western portion of the region studied in Paper I while the
eastern portion, with only three candidates, is typical of the
sparser regions. Since the tiles were analyzed from west to east
one decl. strip at a time, there should be no systematic shift in
the criteria between the two sides of the Paper I field.

The 1,337,101 stars in the clump region represent 0.581 of
the 2,302,237 stars with acceptable photometry in the entire
Paper I field. Using this as the probability of randomly drawing
a star in the clump area, the binomial distribution yields a
probability of randomly drawing at least 12 stars in the clump
out of 15 in the Paper I field of 0.07. While a probability at this
level is not generally considered to be highly significant, it does
suggest that the clump is real.

3.4. Spatial Distribution

Using the EDR3 parallaxes we calculated the Cartesian
coordinates of all the dipper candidates in a frame where the
direction to the origin is at the Sun, the x' axis is in the direction of the center
of the clump, α = 280°, δ = 45°, y' is toward the west and z'
toward the north. These coordinates are listed in columns 6, 7
and 8 of Table 2. Figure 3(b) is a plot of the stars in the x'-z'
plane, a "side" view of the clump, and Figure 3(c) displays the
stars in the x' - y' plane, a "top" view.

Four of the 12 clump stars are more than 1000 pc distant
from the Sun and are clearly separated from the others. The
remaining eight stars in the clump as well as Boyajian’s star form
a structure that is about 50% longer in the x' direction
than in the y' or z' directions. This is, of course, a very rough
estimate since it is based on very few objects. When a structure
appears to be elongated in the radial direction, it is often be
attributed to errors in the distances. However, in this case, none
of the the uncertainties in the parallaxes are larger than 0.8%,
much too small to explain the elongation of the clump.

We note that the nine stars in the clump are all in the lower
quarter of the the uncertainties in the parallaxes are larger than 0.8%,
much too small to explain the elongation of the clump.

We note that the nine stars in the clump are all in the lower
quadrangle defined in Paper I, referred to there as the “main
sequence region.” This is consistent with these stars forming a
physically significant group.

Since no fully satisfactory explanation for the behavior of
Boyajian’s star, and by extension the dipper candidates, has
been found, it is premature to try to explain the existence of the
clump. However, the possibility that extraterrestrial civilizations
might have developed interstellar travel and expanded
beyond their original planetary systems has been widely
discussed in connection with the search for extraterrestrial
intelligence (for example, in connection with the Fermi paradox). If this is actually possible, it could lead to a clump
of stars with inhabited planets over an extended region of space.

Figure 2. The HR diagram of the dipper candidates. Squares, circles, and a star
represent slow dippers from Paper I, dipper candidates from the present paper,
and Boyajian’s star, respectively. The small dots represent the statistical sample
from Paper I. The two irregular quadrilateral areas delineated by light lines are
the two regions defined in Paper I and the large rectangle defined by bold solid
lines is the modified region defined here.

Figure 3. (a) The distribution of the dipper candidates on the sky. The slow
dippers are represented by circles, and Boyajian’s star by a star. The solid curve
shows the location of the galactic plane. The dashed box delineates the area of
the sky studied in Paper I and the dashed line through it separates the tiles of the
clump from those of the comparison region. (b) and (c) The distribution of the slow dippers in the x'z' and x’y' planes, respectively. Filled circles denote
stars between α = 254° and 303° and open circles represent stars outside this
region. Boyajian’s star is represented by a star and the Sun by the usual symbol.

remainder of the band of the sky we have studied, there are
3,675,728 stars with acceptable photometry. With 12 and 18
candidates in the two regions, we find that there are 11.2 and
“hot spot” may deserve some extra attention (with regard to SETI).” In a subsequent paper, Villarroel et al. (2021) discussed a group of nine apparent transients scattered over a region about ten arc minutes across on a plate from the Palomar Observatory Sky Survey. With these considerations in mind, I suggest that the dippers in the clump and other stars in the same region would be appropriate targets for SETI searches.

4. Conclusions
1. We have finished searching the region between \( \delta = +22^\circ \) and \( +68^\circ \) for analogs to Boyajian’s star. This has yielded 15 more slow dippers.
2. No new rapid dippers were found in the present study.
3. With the addition of the new candidates, the dippers still occupy a restricted region of the HR diagram.
4. There is an overdensity of slow dippers in a region of the sky centered on \( \alpha = 280^\circ, \delta = 45^\circ \) that is also restricted in distance. Although the reality of this clump of stars is somewhat uncertain, it would be a worthwhile target for SETI programs.

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