KIC 8462852—Windows of Opportunity: Cyclic Periodicities, Light Dimming Episodes and the Star's 0.88-day Rotational Period

Andrew Collins[1] and Rodney Hale[2]

1 Independent researcher. Email: andrewcollinsweb@btinternet.com

2 C Eng MIET. Email: rhale@canopia.demon.co.uk

Abstract: KIC 8462862, an F-type main sequence star in the constellation of Cygnus, experienced strange light dimming episodes during the initial Kepler mission between 2009 and 2013. These continue with further events in 2017. The authors use Kepler and post-Kepler data to create folding plots to examine the relationship between the star's reported 0.88-day rotational period and suspected periodicities noted in connection with the light dimming episodes. This reveals a new possible periodicity of 9.68 days (11 stellar rotations). Confirmation of a mathematical relationship between suspected periodicities and the star's rotational period would begin to eliminate some of the proposed explanations for the star's strange fluctuations in light, while at the same time bringing to the fore other possible theories to account for both the short term and long term dimming events.

Key words: KIC 8462852, Tabby's Star, Boyajian's Star, Cygnus, Kepler, periodicities, stellar rotation, circumstellar environments, intrinsic variability, AGB stars.

Introduction

KIC 8462852 (otherwise known as Boyajian's Star or Tabby's Star) is an F-type main sequence star, approximately one and a half times larger than the Sun. It lies around 1,280 light years (390 pc) away in the constellation of Cygnus, the swan, at coordinates RA: 20h 06m 15.457s Dec: +44° 27" 24.61'. Across the initial Kepler mission between May 1, 2009 to May 11, 2013, a total period of 1,591 days, the star was found to be experiencing strange drops in flux. These dips in light varied from one half a degree to 16 percent on one occasion (March 5, 2011, Kepler day 793, henceforth D793) and 22 percent on another (February 28, 2013, Kepler day 1519 or D1519).

Long term secular dimming has also been noted in connection with KIC 8462852. Dr Bradley Schaefer determined from a detailed eyeball examination of photographic plates forming part of the DASCH-Harvard collection that between 1890 and 1989 the star faded by as much as 20 percent (Schaefer, 2016). Two separate teams of astronomers failed to find the same trend (Hippke et al, 2016; Lund et al, 2016), although an examination of the Kepler data for KIC 8462852 (Montet and Simon, 2016) showed that Boyajian's Star faded by around 3 percent across the initial Kepler mission. A similar "non linear fade" is reported by Bruce Gary, an astronomer who has monitored the star since October 2015. He has noted a fading rate of approximately 1.4 percent per year.[1] Finally, the American Association of Variable Star Observers (AAVSO) also reports a clear dimming trend across 638 days of

[1] See Bruce L. Gary's webpage: "Kepler Star KIC 8462852 Amateur Photometry Monitoring Project," http://www.brucegary.net/KIC846/#Yearly_Timescale_Fade_Observations/

monitoring the star. In the V band this amounts to a rate of almost 3% per year (0.028 magnitudes/year) and in B about 2% per year.[2] This secular fading is most likely linked with the periodic dimming events.

1.1. Cyclic Fluctuations

One matter that could help resolve the problem of KIC 8462852's strange light emissions is a better understanding of its minor fluctuations in light that occur every 0.88 days, something first noted by Tabatha Boyajian and her colleagues in their initial study of the star, and interpreted as representative of stellar rotation (2016).

A Fourier analysis of the Kepler data[3] for KIC 8462852 conducted by one of the authors, Rodney Hale, reveals the 0.88-day fluctuations with the second and third harmonics across the period of the initial Kepler mission (see fig. 1.1).

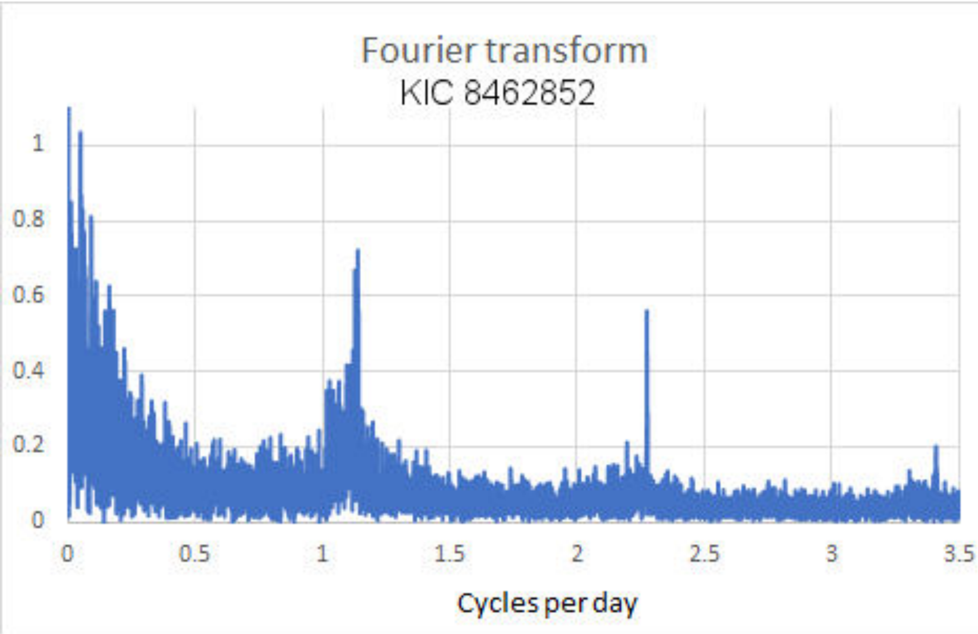

Figure 1.1. *Fourier analysis of KIC 8462852's 0.88-day cycle.*

2.1. The Probability of Recurring Cycles

Tabatha Boyajian and her colleagues also reported a separate periodicity in the Kepler data for KIC 8462852 based on the time occurrence between several major and minor dimming events. This was 48.4 days (see table 2.1), with a suspected half cycle of 24.2 days (2016). It was noted, for example, that the gap between the D800 and D1520 events (elsewhere in this article D793 and D1519) was 726 days, the equivalent of 13 x 48.4 day cycles, or 26 x 24.2 days, while that between the D1520 episode and the D1568 event was approximately 48.4 days or 2 x 24.2 days (Boyajian et al, 2016).

---

[2] Carr, Paul, Dream of the Open Channel, June 29, 2017, https://disownedsky.blogspot.co.uk/2017/06/more-on-aavso-trends-for-boyajians-star.html?m=1.

[3] Flux data from www.wheresmyflux,com/public. Spectrogram using Excel and associated maths software Octave.

Dip No.	name	depth	BJD (-2454 833)	Cycles (from dip 5)	|residual| (from integer)
1	D140	0.5%	140.49	-13	0.52
2	D260	0.5%	261.00	-11	0.01
3	D360	0.2%	359.11	-9	0.04
4	D425	0.2%	426.62	-7	0.44
5	D800	16%	792.74	0	0.00
6	D1200	0.4%	1205.96	8	0.54
7	D1500	0.3%	1495.97	14	0.53
8	D1520	21%	1519.60	15	0.02
9	D1540	3%	1540.40	15	0.45
10	D1568	8%	1568.49	16	0.03

Table 2.1. *Principal Dip Times of KIC 8462852 vs. 48.4-day Period (after Boyajian et al, 2016).*

2.2. Testing the 24.2-day half cycle

To test the validity of the 24.2-day and 48.4-day cycles Hale used the Kepler data for KIC 8462852 starting on day O (MJD 54952, May 1, 2009) and with all subsequent data from the initial mission through till its final date, day 1591 (MJD 56423.5), segmented into periods of 24.2 days and overlaid to create a folding plot. Bruce Gary's data since May 2nd 2017 UT (MJD 57875) was then added to the Kepler spread sheet by translating the screen image of his published graphs into flux data and then incorporating this into the Kepler spread sheet and time data commensurate with the Kepler data, creating an extended "Kepler" start date of day 3042.5. This enables graphs of the whole timescale of around eight years to be produced, acknowledging, of course, that a gap of 1451.5 days exists between the Kepler data and the start of the Gary data (see fig. 2.1).

Fourteen significant dips were then highlighted in the results—twelve from the Kepler data and two from the Gary data (see fig. 2.2 & table 2.2). These were the "Elsie" dip, which took place across several days in May 2017, with a maximum drop of approximately two percent on May 18, and "Celeste," which reached a near two percent drop in flux on June 16 (a third dip that occurred in August 2017 is dealt with separately in Section 4.1). The dips from the Kepler data retain their Kepler identifications, while those from the post-Kepler era are given their names as allotted by Tabatha Boyajian and the Where's the Flux team.[4]

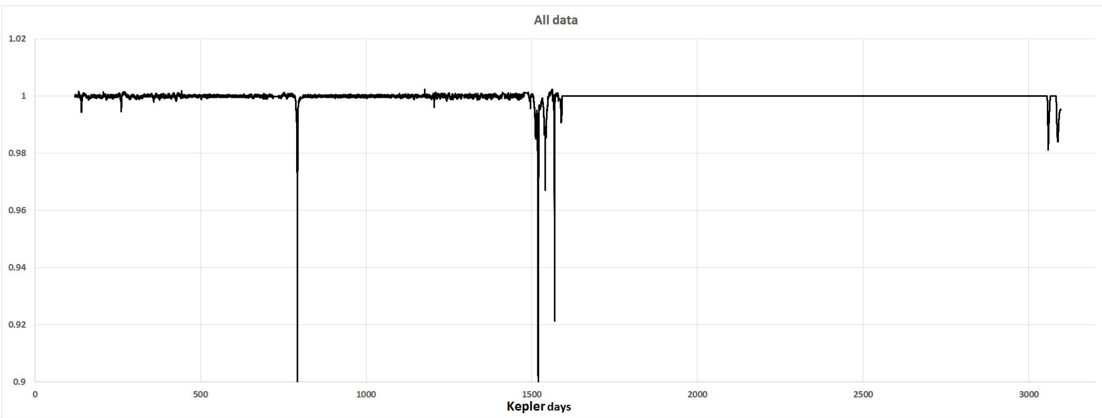

Figure 2.1. *All Kepler and Gary flux data for KIC 8462852 up to June 2017.*

[4] See http://www.wherestheflux.com.

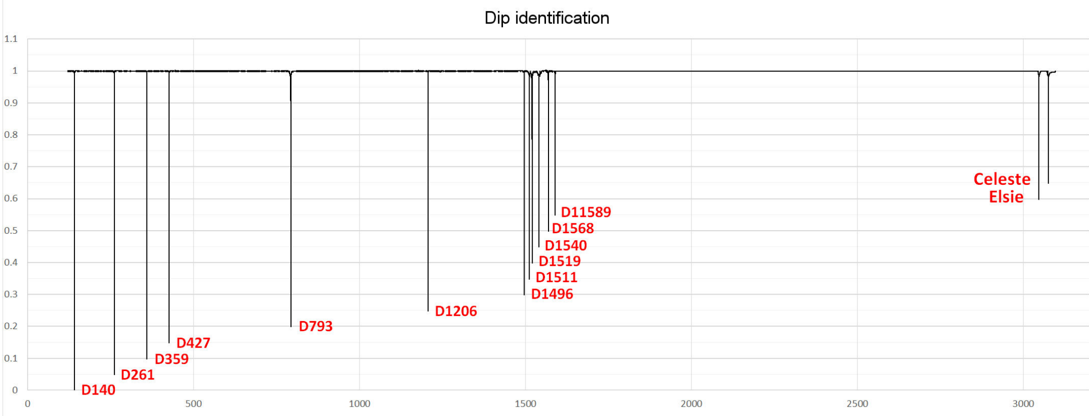

Figure 2.2. *The Kepler and post-Kepler dips for KIC 8462852 chosen for closer examination in the resulting rolling plots. Please note that the extended lines do not reflect the actual depth of recorded dips.*

	Selected Dip minima of KC8462852 from May 2009 to July 2017			
	General name	Exact Kepler Day Time	Normalised Flux level	Flux level % below unity
1	D140	140.502	0.9962	0.38
2	D261	260.899	0.9947	0.53
3	D359	359.119	0.9976	0.24
4	D427	426.693	0.9985	0.15
5	D793	792.761	0.8452	15.48
6	D1206	1205.888	0.9962	0.38
7	D1496	1495.902	0.9958	0.42
8	D1511	1511.513	0.9851	1.49
9	D1519	1519.543	0.7862	21.38
10	D1540	1540.386	0.9672	3.28
11	D1568	1568.482	0.9214	7.86
12	D1589	1588.937	0.9908	0.92
13	Elsie	3058.91	0.9812	1.88
14	Celeste	3071.98	0.9841	1.59

Table 2.2. *The fourteen selected dip minima of KIC 8462852 from May 2009 through to June 2017.*

2.3. Observations on the 24.2-day and 48.4-day folding plots

Of the two resulting plots for 24.2 days and 48.4 days, we shall examine the former first (see fig. 2.3). This shows that the dip minima of twelve of the fourteen events took place across just five and half days of the 24.2-day period from days 15 to 21, or around 25 percent of the potential 24.2-day period. This leaves the rest of the 24.2-day period free of all but two events, D1511 and Elsie.

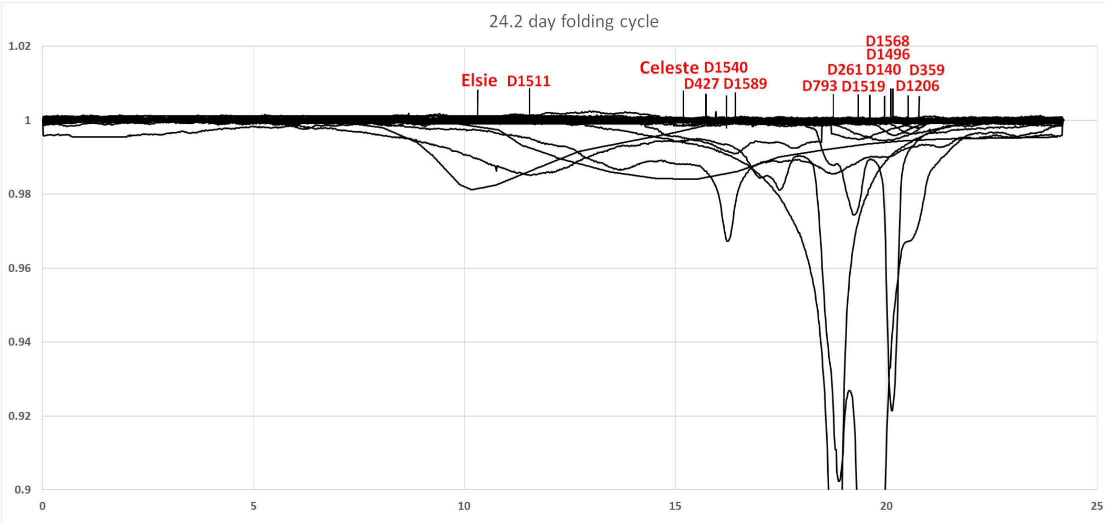

Figure 2.3. *The Kepler and Gary data for KIC 8462852 up until June 2017 overlaid in plots of 24.2 days with the selected dips highlighted in red.*

The rolling plot for sequences of 48.4-day periods (see fig. 2.4) reveals that the dip minima of seven selected dips occurred across a window of six days, between days 15 to 21, while the dip minima of another five events occurred across a window of just two days between days 43 and 45. Only two dips fell outside of these windows with these being the same pair as in the 24.2-day rolling cycle—D1511 and Elsie.

Both the 24.2-day and 48.4-day rolling periods seem to display groupings that are unlikely to be random. The Celeste event of June 2017 seems to conform to these clustering trends, unlike the Elsie event of May 2017, which does not. In summary, this exercise suggests that the rolling cycle of 24.2 days seems to better express a trending pattern than that of 48.4 days.

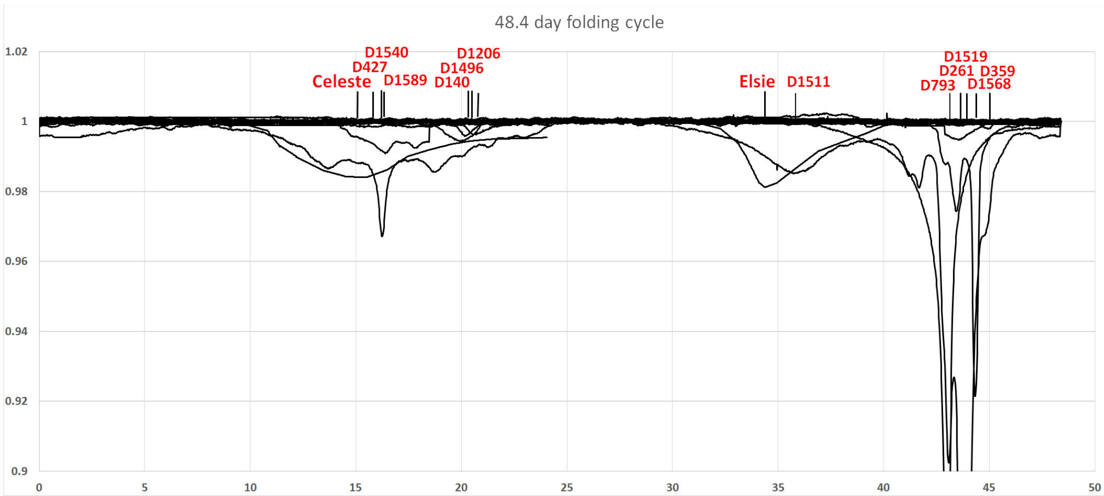

Figure 2.4. *The Kepler and Gary data for KIC 8462852 up until June 2017 overlaid in plots of 48.4 days with the selected dips highlighted in red.*

3.1 Exploring a potential 9.68-day periodicity

Hale looked next at finding whether any further periodicities might exist in connection with the star's dipping events. After a careful examination of the data, one additional potential periodicity did reveal itself. This was 9.68 days in length corresponding to 11 stellar rotations of 0.88 days, as well as $1/5^{th}$ of a 48.4-day cycle or 55 stellar rotations.

Once again, both the Kepler data and Gary data were used to create a folding plot featuring rolling blocks of 9.68 days (see fig. 3.1). This shows that the dip minima of eleven out of fourteen of the selected dimming events occur within a window of approximately two and a half days between days 4 and 7 of the cycle. The remaining three dips—D140, D1206 and D1496—occur across a period of around fifteen hours across days 1 and 2, the average gap between the two clusterings being approximately 4.65 days, close to a half cycle of 4.84 days. In summary, the distinct clustering of dips in the 9.68-day rolling plots strongly indicates the existence of a hitherto unrecognised periodicity of this length.

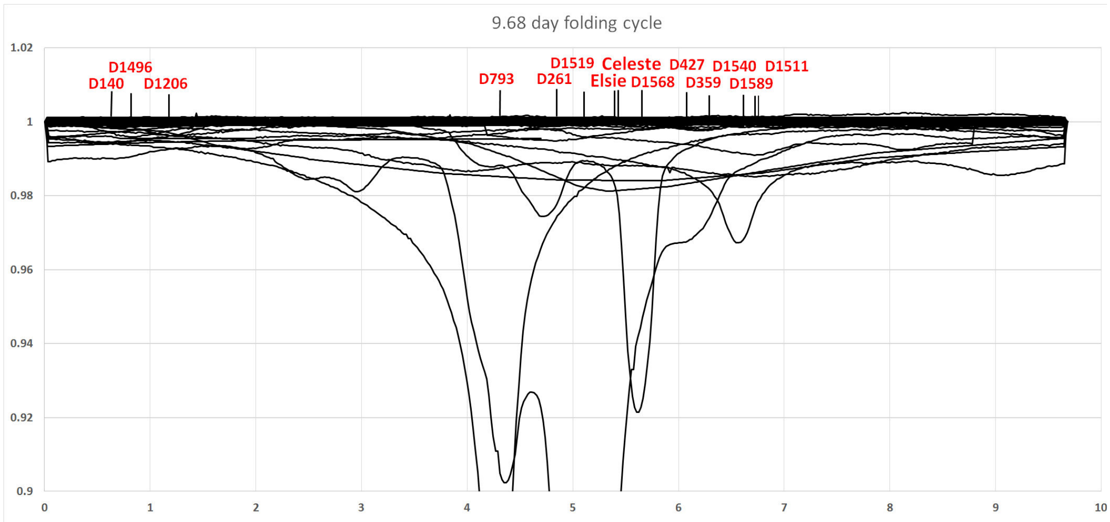

Figure 3.1. *The Kepler and Gary data for KIC 8462852 up until June 2017 overlaid in plots of 9.68 days with the selected dips highlighted in red.*

3.2. Periodic division of dips

In an attempt to further check the proposed 9.68- and 24.2-day periodicities in connection with the star Hale next examined the gaps in time existing between the dip minima of the fourteen selected flux drops. As previously pointed out (see section 2.1), it was this same exercise that alerted Tabatha Boyajian and her team to the existence of a 48.4-day gap between dips with an additional potential half cycle of 24.2 days (Boyajian, 2016).[5] Starting with the proposed 9.68-day periodicity, Hale realised that a number of dips seemed to reflect multiples of 9.68 days, the most recent example being the gap between Elsie and Celeste, which was 29.065 days. This was almost exactly three cycles of 9.68 days or 33 stellar rotations (the actual amount of three 9.68-day cycles is 29.04 days). So a useful table was created to show the distance in time between all fourteen selected dips (see table 3.1).

[5] The authors acknowledge also the work done on the proposed 24.2-day cycle by gdsacco, a member of the [Reddit group for KIC 8462852.]() See, for example, the following thread: https://www.reddit.com/r/KIC8462852/comments/6ins5x/significance_of_the_242_day_cycle_and_does_that/.

	140.502	260.899	359.119	426.693	792.761	1205.888	1495.902	1511.513	1519.543	1540.386	1568.482	1588.937	3058.91	3087.98
140.502	0	120.397	218.617	286.191	652.259	1065.386	1355.4	1371.011	1379.041	1399.884	1427.98	1448.435	2918.408	2947.478
260.899	120.397	0	98.22	165.794	531.862	944.989	1235.003	1250.614	1258.644	1279.487	1307.583	1328.038	2798.011	2827.081
359.119	218.617	98.22	0	67.574	433.642	846.769	1136.783	1152.394	1160.424	1181.267	1209.363	1229.818	2699.791	2728.861
426.693	286.191	165.794	67.574	0	366.068	779.195	1069.209	1084.82	1092.85	1113.693	1141.789	1162.244	2632.217	2661.287
792.761	652.259	531.862	433.642	366.068	0	413.127	703.141	718.752	726.782	747.625	775.721	796.176	2266.149	2295.219
1205.89	1065.386	944.989	846.769	779.195	413.127	0	290.014	305.625	313.655	334.498	362.594	383.049	1853.022	1882.092
1495.9	1355.4	1235.003	1136.783	1069.209	703.141	290.014	0	15.611	23.641	44.484	72.58	93.035	1563.008	1592.078
1511.51	1371.011	1250.614	1152.394	1084.82	718.752	305.625	15.611	0	8.03	28.873	56.969	77.424	1547.397	1576.467
1519.54	1379.041	1258.644	1160.424	1092.85	726.782	313.655	23.641	8.03	0	20.843	48.939	69.394	1539.367	1568.437
1540.39	1399.884	1279.487	1181.267	1113.693	747.625	334.498	44.484	28.873	20.843	0	28.096	48.551	1518.524	1547.594
1568.48	1427.98	1307.583	1209.363	1141.789	775.721	362.594	72.58	56.969	48.939	28.096	0	20.455	1490.428	1519.498
1588.94	1448.435	1328.038	1229.818	1162.244	796.176	383.049	93.035	77.424	69.394	48.551	20.455	0	1469.973	1499.043
3058.91	2918.408	2798.011	2699.791	2632.217	2266.149	1853.022	1563.008	1547.397	1539.367	1518.524	1490.428	1469.973	0	29.07
3087.98	2947.478	2827.081	2728.861	2661.287	2295.219	1882.092	1592.078	1576.467	1568.437	1547.594	1519.498	1499.043	29.07	0

Table 3.1. *Time differences between the fourteen selected dips from the Kepler and Gary data for KIC 8462852.*

Hale then calculated the number of 9.68-day periods between the dip minima of the fourteen events and found that in eighteen instances the gap was a multiple of 9.68 days to within an error of less than half a day (see table 3.2). What this suggests is that in addition to the star's rotational period of 0.88 days the dimming events can reflect gaps between dips that are multiples of 9.68 days, something already indicated by the folding plots. As previously indicated, 9.68 days is 11 stellar rotations, making it clear that this is the intended length of the periodicity.

DIFFERENCE BETWEEN CALCULATED and ACTUAL DIP TIMES (days) **CYCLE PERIOD (Days)** **9.68** **DIFFERENCES SHOWN ARE THOSE** **LESS THAN** **0.50** **DAY**

Dip day	140.502	260.899	359.119	426.693	792.761	1205.888	1495.902	1511.513	1519.543	1540.386	1568.482	1588.937	3058.91	3087.98
140.502							0.20							
260.899									0.24				0.49	
359.119				0.19				0.47		0.31		0.46		
426.693										0.49	0.45			
792.761														
1205.89							0.39							
1495.9														
1511.51										0.17		0.02		
1519.54													0.25	0.28
1540.39												0.15		
1568.48													0.29	0.26
1588.94														
3058.91														0.03
3087.98														

Table 3.2. *Difference between calculated and actual dips based on a 9.68-day cycle with an error of less than 0.5 days.*

Hale looked next at the number of 24.2-day periods between the dip minima of the different dips and found that in twenty-four instances the gap was a multiple of 24.2 days to within an error of a single day (see table 3.3).

DIFFERENCE BETWEEN CALCULATED and ACTUAL DIP TIMES (days) **CYCLE PERIOD (Days)** **24.20** **DIFFERENCES SHOWN ARE THOSE** **LESS THAN** **1.00** **DAY**

Dip day	140.502	260.899	359.119	426.693	792.761	1205.888	1495.902	1511.513	1519.543	1540.386	1568.482	1588.937	3058.91	3087.98
140.502		0.60	0.82			0.59	0.20		0.36		0.18			
260.899					0.54		0.80		0.24		0.78			
359.119						0.23	0.62				0.64			
426.693										0.49		0.64		0.71
792.761									0.78					
1205.89							0.39		0.95		0.41			
1495.9									0.56		0.02			
1511.51														
1519.54											0.54			
1540.39												0.15		
1568.48														
1588.94														
3058.91														
3087.98														

Table 3.3. *Difference between calculated and actual dips based on a 24.2-day cycle with an error of less than one day.*

In order to test the significance of this finding, Hale made a small change in the cycle period from 24.2 days to 24.0 days. This showed just seven instances where the dipping events were multiples of 24 days with an error rate of less than 0.5 days. A cycle of 24.4 days was also tested in a similar manner, and this also showed just seven matches. All this suggests that a cycle of 24.2 days is indeed important to the timing and occurrence of dimming events.

DIFFERENCE BETWEEN CALCULATED and ACTUAL DIP TIMES (days)					CYCLE PERIOD (Days)		48.40		DIFFERENCES SHOWN ARE THOSE		LESS THAN	1.00	DAY
Dip day	140.502	260.899	359.119	426.693	792.761	1205.888	1495.902	1511.513	1519.543	1540.386	1568.482	1588.937	3058.91	3087.98
140.502						0.59	0.20							
260.899					0.54				0.24		0.78			
359.119											0.64			
426.693										0.49		0.64		0.71
792.761									0.78					
1205.89							0.39							
1495.9														
1511.51														
1519.54											0.54			
1540.39												0.15		
1568.48														
1588.94														
3058.91														
3087.98														

Table 3.4. *Difference between calculated and actual dips based on a 48.4-day cycle with an error of less than a day.*

Finally, and to complete the series, Hale looked at the number of 48.4-day periods between the dip minima of all the different dips and found that in thirteen instances the gap was a multiple of 48.4 days to within an error of a day (see table 3.4). Tabatha Boyajian and her team, in their own study of the periods in time between dipping events, found ten examples from the Kepler data where the gaps were multiples of 48.4 days within an error of less than one day (see table 2.1).

3.3. Periodicity relationships

It is only when a cycle of 48.4 days is introduced that periodicities of 9.68 days and 24.2 days synchronize, since the former is 1/5th of 48.4 days, or 55 stellar rotations, while 24.2 days is one half a cycle of 48.4 days (see table 3.5 and fig. 3.2). This suggests that 48.4 days, or 55 stellar rotations, is the intended value of a full cycle, with one half and 1/5th of 48.4 days not only defining the value of two clear periodicities connected with the star, but also the manner in which the dip minima of the dimming events seem to match multiples of these periodicities. The fact that not all the dips conform to these periodicities, or that they are misaligned from them too much to be included within these results, could suggest either a slow, gradual drift in the occurrence of dips or, alternately, the existence of periodicities yet to be determined.

Cycle in days	Stellar rotations	Divisions
0.88 days	1	
9.68 days	11	11 x 1 rotations
48.4 days	55	5 x 11 rotations
Half cycles		
4.84 days (half of 9.68 days)	5.5	½ of 11 rotations
24.2 (half of 48.4 days)	27.5	½ of 55 rotations

Table 3.5. *The various cycles and half cycles noted in connection with KIC 8462852 complete with their divisions and value in stellar rotations.*

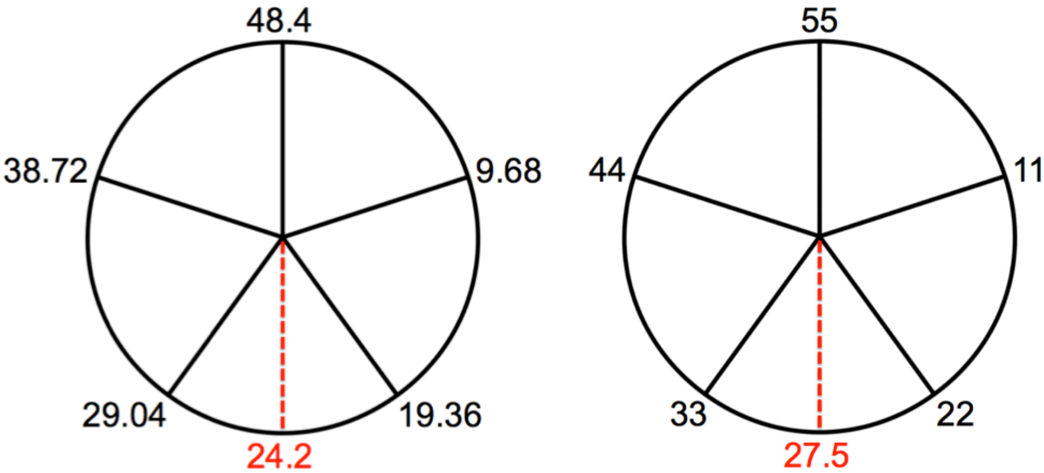

Figure 3.2. *Relationship between the 9.68- and 24.2-day periodicities and a full cycle of 48.4 days. On the left we see the values in days and on the right the values in stellar rotations.*

4.1. The Skara Brae dip of August 2017

Toward the completion of this study, KIC 8462852 was once again experiencing a notable dimming event, the first since Celeste in June 2017. It started on August 1, 2017 and was given the name Skara Brae by Tabatha Boyajian and the Where's the Flux team.

As this dimming event progressed the authors watched closely to see whether it might conform to the proposed 9.68-day periodicity outlined in section 3.1. This seemed a particularly interesting exercise in the knowledge that the gap between the dip minima of Elsie and Celeste was almost exactly 3 x 9.68 days, i.e. 29.04 days or 33 stellar rotations. The authors realised there was a possibility that Skara Brae's dip minima might occur on or around 6 x 9.68 days, i.e., 58.08 days, on from Celeste's own dip minima on June 16 2017. This provided a possible synchronization date of August 13, 2017.

Photometric data from Tabatha Boyajian and the Where's the Flux team shows that Skara Brae reached its dip minima at 0.986 percent of normalised flux on August 10, recovering quickly afterwards.[6] The Bruce Gary data for Skara Brae produces a light curve showing a dip minima of approximately one percent away from normalised flux on August 12 with the same rapid recovery afterwards. Gary's dip minima is a little under one day away from the anticipated synchronization point of the 9.68-day periodicity on August 13 (see fig. 4.1). This means that the gap between Celeste and Skara Brae is ideally 6 x 9.68-day cycles or 2 x 29.04-day cycles, a total of 58.08 days or 66 stellar rotations.

4.2. Cyclic expansions of the stellar rotational period

The introduction of a possible 29.04-day periodicity with the occurrence of the star's dimming events allows for a new review of the potential relationship between all the proposed cycles noted so far, viz. 0.88, 9.68, 24.2, 29.04 and 48.4 days (see table 4.1) corresponding, respectively, to 1, 11, 27.5, 33 and 55 stellar rotations. This reveals that whereas the 9.68- and 24.2-day cycles synchronize with a full cycle of 48.4 days

[6] See the Where's the Flux website blog http://www.wherestheflux.com/blog.

or 55 stellar rotations, the first time that the 9.68-, 24.2-, 29.04- and 48.4-day cycles all synchronize is after 145.2 days, the equivalent of 165 stellar rotations.

If such an exercise is valid it suggests that mathematical expansions of the stellar rotational period of 11, 55 and 165 could be important to the mechanism responsible for the generation of the periodicities. This same numerical sequence—11, 55, 165—appears in row 11 of Pascal's Triangle, a triangular array of binomial coefficients. As in all the rows of Pascal's Triangle the eleventh defines the numeric expansion of polytopes or simplexes, in this instance the 10-simplex known as the hendecaxennon or hendeca-10-tope, an 11-faceted polytope in 10-dimensions.[7] This has 11 vertices, 55 edges, 165 faces, 330 tetrahedral cells and a series of higher dimensional faces.

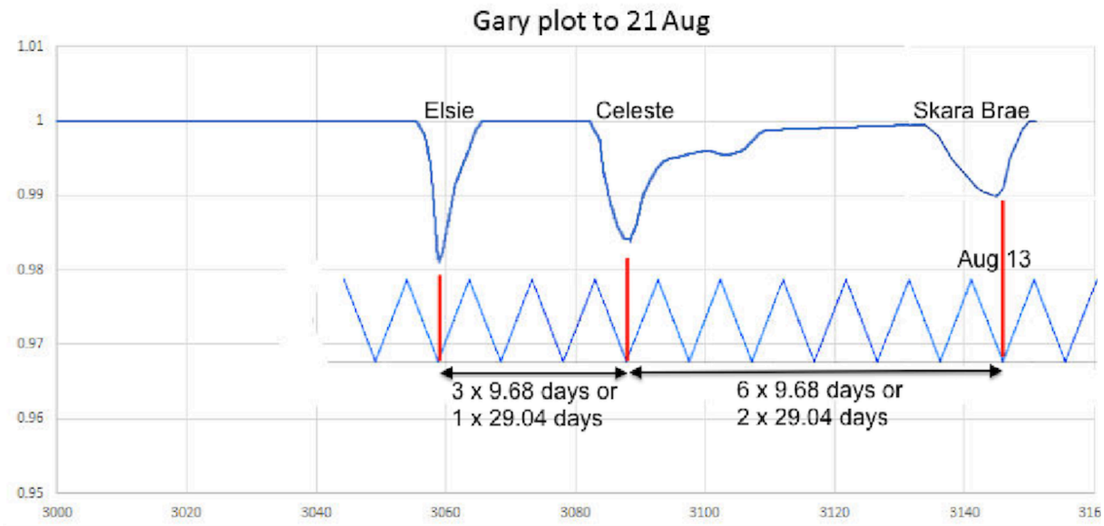

Figure 4.1. *Light curve derived from photometric data between May 02, 2017 and August 17, 2017 courtesy of Bruce Gary. The Elsie, Celeste and Skara Brae events are marked, with the proposed 9.68-day cycle shown as a series of interlinked triangles. The red vertical line denotes the multiples of 9.68 days between the three highlighted dimming events.*

0.88 days (1 stellar rotation)	9.68 days (11 stellar rotations)	48.4 days (55 stellar rotations)	145.2 days (165 stellar rotations)
1 x 0.88 days	11 x 0.88 days	55 x 0.88 days	165 x 0.88 days
	1 x 9.68 days	2 x 24.2 days	6 x 24.2 days
		1 x 48.4 days	5 x 29.04 days
			3 x 48.4 days

Table 4.1. *Relationship between the various periodicities explored in connection with KIC 8462852's light dimming events.*

5.1. Discussion

Accepting that the drops in flux, and in particular their dip minima, conform to periodicities that are themselves expansions of the star's rotational period is crucial to understanding the cause of these short-term dimming events. It would mean reviewing all the current theories proposed in connection not just with these flux drops, but also

[7] Ten dimensions of space and one of time defines eleven-dimensional supergravity used to determine the low-energy limit of M-theory in theoretical physics.

any possible causes proposed to explain secular dimming (see the Introduction). Theories that would suffer if rotation-linked periodic expansions were to be accepted include the proposal that the drops in flux are caused by either the observation of circumstellar material at the edge of our own solar system (Katz, 2017) or the presence of liberated dust and debris in the interstellar medium (Makarov & Goldin, 2016).

In addition to this, proposed solutions involving orbiting circumstellar objects or materials such as swarms of comets (Boyajian et al, 2016) or trojan asteroids moving in conjunction with a large, ringed planet (Ballesteros et al, 2017; Solorzano, 2017; Sucerquia et al, 2017) would also struggle if stellar rotation-linked periodicities really are connected with dimming episodes. In this knowledge, any remaining theories would have to focus either on the intrinsic variability of the star (Boyajian et al, 2016; Metzger et al, 2017), or on the occultations of circumstellar objects synchronized with the star's proposed periodicities.

5.2. Intrinsic variability

Stellar rotation-linked periodicities connected with the appearance of light dips lends support to the recent proposal by Peter Foukal that flux changes occur in the star when the light becomes blocked and is thus unable to reach the surface, being instead constrained within a shallow convective zone (Foukal, 2017). In his opinion, magnetic activity, differential rotation, sporadic changes in photospheric abundances, or random variation in convective efficiency could all be responsible for drops in flux. If correct, then there seems every likelihood that such events would conform to the star's stellar rotational period and any cyclic periodicities associated with it.

5.3. Characteristic shape of dips

One possible clue to the dimming events being produced by the blocking of flux is the characteristic shape of dips, something highlighted by the authors in a previous study (Collins and Hale, 2017). In fig. 5.1 we see four major events—D793, D1519, D1540 and D1568—all superimposed, yet with their scale kept and synchronizing them in a manner corresponding to their greatest depth.

Their resemblance in sharpness and form is remarkable and unlikely to be without meaning. In addition to this, when five minor dipping events found in the Kepler data for KIC 8462852 were synchronised these too displayed a similar width and sharpness (see fig. 5.2). Not one of these dips, whether major or minor, shows a flattened base, which would indicate the transit of a regular object such as an orbiting planet (although one or more planets with Saturn-like rings does remain plausible). All of this indicates that, whether large or small, the dips have a strong relationship in appearance, which could argue for them all being simply the product of the star's intrinsic variability.

This explanation can also help explain the long-term secular dimming. According to Foukal, sporadic flux-blocking events would cause KIC 8462852 to be constantly relaxing from a post-blockage enhanced luminosity (2017).

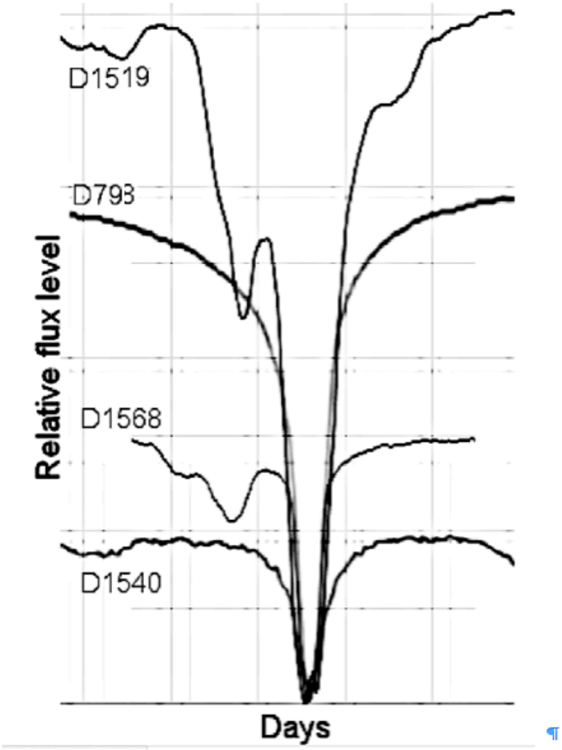

Figure 5.1. *The sharp tips of all four major light dips recorded in the Kepler data for KIC 8462852. Note the similarity in their narrow tips.*

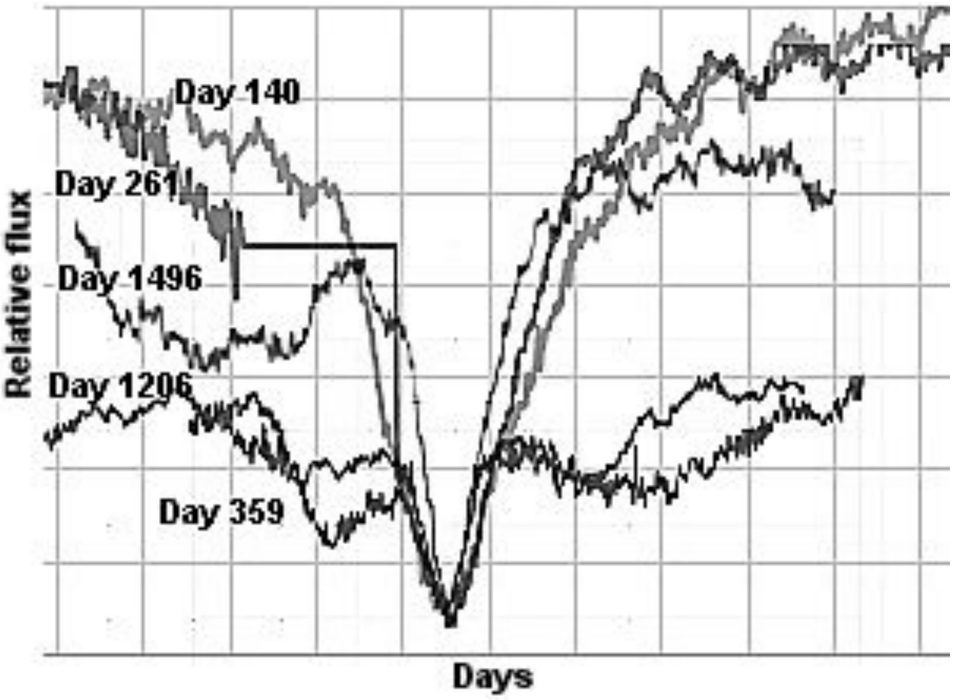

Figure 5.2. *The sharp dips of five minor events as extracted from the Kepler data for KIC 8462852. The day 261 event has some missing data.*

One major drawback with this theory, however, is that to produce sustained light dimming episodes any shallow convective zones of the type proposed by Foukal would have to remain constantly in the line of sight between here and the star. If these were to occur on or close to the equator and within line of sight of the earth then the drops in flux would tend to display a sinusoidal pattern reflecting the 0.88-day rotational period.

This is something that was noted by Fernando Martnez Isla (2016). Examining the changes in brightness around dimming events on Kepler days 1519 and 1568 he observed that the dip minima of primary and secondary curves appeared to reflect gaps matching the duration of the star's 0.88-day rotational period. For instance, the gap between dips on days 1567 and 1568 were exactly 0.88 days apart, while that between a minor dip on day 1518 and a major double dip on day 1519 were in one instance 0.70 days part and 0.84 days apart in the second instance (see table 5.1). This led him to conclude that the cause of the flux variations was consistent with intrinsic variability, and not the result of occultations by external objects (Isla, 2016).

Time main peak	Time small peak	Time span	Rotation period %
1568.461	1567.582	0.879	99.9 %
1519.522	1518.822	0.700	79.5 %
1519.665	1518.822	0.843	95.7 %

Table 5.1. *Gaps between major and minor dip minima and their relationship to the star's 0.88-day rotational period (after Isla, 2017).*

5.4. Relationship to the 0.88-day rotational period

Against the idea that intrinsic variability of the star is the cause of the drops in flux is the fact that the Kepler data shows the star's 0.88-day rotational period continuing unaffected during major and minor dimming episodes. Using the Kepler data Hale was able to demonstrate how regularly occurring changes of light levels for KIC 8462852 across the four-year Kepler mission can be shown as a spectrogram, with its base line covering the entire period of observation of the star and the vertical scale indicating the cyclic frequency of light level changes (see fig. 5.3). What this shows is that the lowest band representing the 0.88-day fluctuation continues across the entire duration of Kepler's observation of the star, even during major dimming events.

So either the 0.88-day periodicity is unconnected with KIC 8462852 and is simply interference from a nearby stellar source (Makarov & Goldin, 2016), or the 0.88-day fluctuations in light are indeed reflective of the star's rotational period and continue to occur independently to any major short term drops in flux. Yet if these dimming events are truly the product of intrinsic variability, the chances are the 0.88-day flux variations would be either interrupted or cancelled out during such events. This, however, does not appear to be the case.

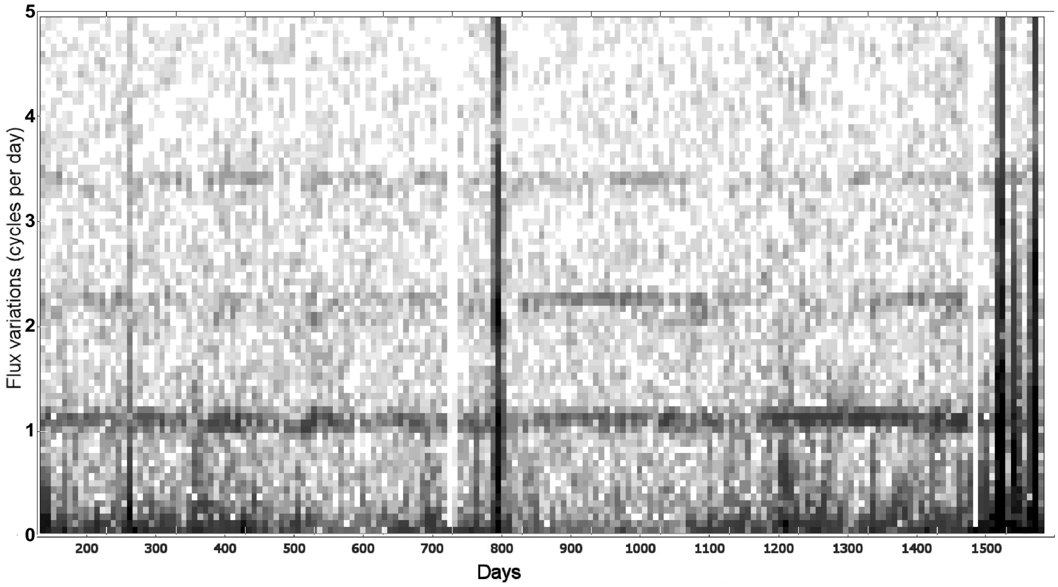

Figure 5.3. *Cyclic fluctuations and dimming events recorded in the Kepler data for KIC 8462852. Its lowest horizontal band indicates the 0.88-day fluctuation, equivalent to a rate of approximately 1.14 cycles per day. The two bands above it are second and third harmonics of this fluctuation. Persistent signals with a regular repeating pattern show up as darker horizontal bands, while short-term, larger changes show as narrow vertical bands.*

5.5. Hybrid theory involving both the star and circumstellar objects.

Attempting to find a solution to KIC 8462852's light dimming episodes beyond the star itself becomes almost impossible if periodic expansions reflecting the star's rotational period are connected with their timing and occurrence. Theories involving comets, dust, asteroids, large ringed planets and even alien megastructures (Wright and Sigurdsson, 2016) will all struggle in this respect. If intrinsic variability is not solely responsible for the short-term dimming events, then a hybrid theory might be proposed involving both the internal mechanism of the star and the allied appearance of occulting objects able to achieve manifestation in accordance with the star's noted periodicities.

One imagined scenario would be the creation of giant plumes of gas that in turn produce clouds of dust in the circumstellar environment. In time these trails, which might become ring-like in appearance, would dissipate, the dust collecting to form a thin shell around the star. The dust's continued existence might result in the reported secular dimming of the star (see the Introduction).

Such plumes are generally polar in nature, and are usually associated with AGB (asymptotic giant branch) stars, a phase of stellar evolution late on in the life of evolved cool luminous stars of between 0.6–10 solar masses (Wooden, 2012). Even though there are no indications that KIC 8462852 has entered such a late phase of evolution, the production of polar plumes and dust trails could well be a realistic solution to its dipping episodes. It might also explain why both major and minor flux drops seem to retain a consistent shape as outlined in section 4.3. Such events involving both the star and the circumstellar environment could well adhere to cyclic patterns reflecting mathematical expansions of the stellar rotational period.

The main problem with the polar plume theory is that dust trails and dust rings would create an infra-red excess, which has not been reported in connection with the star

(Boyajian et al, 2016). This then brings us back to the more likely explanation that the cause of the short-term dimming events are the result of the star's intrinsic variability.

6.1. Windows of opportunity

If KIC 8462852's light dimming episodes are indeed tied into cyclic expansions of the star's rotational period of 0.88 days then it brings extra complications to this already fascinating mystery. It would mean that only theories directly relating to either the star's intrinsic variability or hybrid theories involving both the star's internal mechanism and allied occultations of circumstellar objects can even start to explain what is causing the short-term light reductions.

The adherence of the drops in flux to cyclic periodicities should not, however, be seen as in any way responsible for *causing* the dimming episodes. Instead, it is suggested that the presence of these periodicities and their synchronization with the star's rotational period offer windows of opportunity when dimming events either become visible to us or are permitted manifestation through some unknown mechanism.

A suitable analogy to this situation is the automaton clock. Its internal cog mechanisms turning at different speeds can be compared to the star's proposed periodicities and the manner in which they seem to reflect mathematical expansions of the star's rotational period. With the synchronization of certain cogs a door or window opens and a cuckoo appears. In other words, a dip occurs. At other times different figures emerge, indicating the varying shapes and depths of individual dips. However, on other occasions the door opens and nothing appears, even though the correct synchronization between the different cogs has been achieved, so what has happened? The answer is most likely twofold. Firstly, we clearly do not know all the factors determining why dips occur when they do and, secondly, an element of uncertainty must play a role in these events just as it does in any type of occurrence in the natural world. Think, for instance, of the sun, which adheres to sunspot cycles of eleven years in length. Even though these cycles are known to exist, it remains impossible to accurately predict the frequency of sunspots, and so we should assume something similar in connection with short-term dimming events in connection with KIC 8462852.

The analogy of the automaton clock tells us that although the periodic time gaps noted in connection with KIC 8462952 might provide synchronization times for reductions in flux, it does not always follow that an event will occur or, if it does, what the depth and duration of the dip might be. However, an understanding of the relationship between the star's periodicities, along with their relationship to stellar rotation and the various light dimming episodes, could well prove crucial in determining what exactly is able to take advantage of these windows of opportunity and produce the drops in flux seen in connection with the star. The authors welcome correspondence on any of the topics featured in this study.

References

Ballesteros (2017), Fernando J., Pablo Arnalte-Mur, Alberto Fernandez-Soto and Vicent J. Martınez, "KIC 8462852: Will the Trojans return in 2021?" *MNRAS* 000, 1–5, https://arxiv.org/pdf/1705.08427.pdf.

Boyajian (2016), T. S., et al. "Planet Hunters IX. KIC 8462852 – where's the flux?" *MNRAS* 457: 4, 3988-4004. https://arxiv.org/abs/1509.03622.

Collins, Andrew (2017), and Rodney Hale, "KIC 8462852—Physical Modelling of its Occulting Objects and the Growing Mystery Surrounding its Cyclic Fluctuations: A New Assessment," http://vixra.org/abs/1706.0093.

Eiroa (2012), C., et al, *Infrared Space Interferometry: Astrophysics & the Study of Earth-Like Planets: Proceedings of a Workshop held in Toledo, Spain, March 11–14, 1996. Astrophysics and Space Science Library book series (ASSL, volume 215).* New York, NY: Springer, 2012.

Foukal, Peter (2017), "An explanation of the missing flux from Boyajian's mysterious star," arXiv:1704.00070v3, https://arxiv.org/abs/1704.00070.

Isla (2016), Fernando Martinez, "KIC 8462852 Intrinsic variability," http://vixra.org/pdf/1608.0101v1.pdf.

Katz, I. I (2017). "Can Dips of Boyajian's Star be Explained by Circumsolar Rings?" ArXiv #: 1705.08377, http://harvard.voxcharta.org/tag/quot-boyajians-star-quot-kic-8462852/.

Makarov (2016), Valeri V., and Alexey Goldin, PHOTOMETRIC AND ASTROMETRIC VAGARIES OF THE ENIGMA STAR KIC 8462852, The Astrophysical Journal 833:78 (December 10, 2016), 1-13, http://iopscience.iop.org/article/10.3847/1538-4357/833/1/78/pdf.

Metzger (2017), Brian D., Ken J. Shen, and Nicholas C. Stone, "Secular Dimming of KIC 8462852 Following its Consumption of a Planet," https://arxiv.org/abs/1612.07332.

Montet (2016), Benjamin T., and Joshua D. Simon, "KIC 8462852 Faded Throughout the Kepler Mission," https://arxiv.org/abs/1608.01316.

Sucerquia (2017), Mario, et al, "Anomalous lightcurves of young tilted exorings," https://arxiv.org/abs/1708.04600.

Schaefer (2016), Bradley E., "KIC 8462852 Faded at an Average Rate of 0.164+-0.013 Magnitudes Per Century From 1890 To 1989," *AJL* 822: 2, article id. L34, 6 pp. https://arxiv.org/abs/1601.03256.

Solorzano (2017), Jose, "KIC 8462852: Modeling D792 as a Ringed Planet With sim-transit-lc," http://www.science20.com/jose_solorzano/kic_8462852_modeling_d792_as_a_ringed_planet_with_simtransitlc-225246.

Wooden (2012), D.H., "Stellar Death: Ejecta and Circumstellar Matter: IR Inferomtry of Dusty AGB Stars, Expanding Novae, & Explosive Supernovae." In Eiroa, et al, 133-145.

Wright (2016), Jason T. and Steinn Sigurdsson, "Families of Plausible Solutions to the Puzzle of Boyajian's Star," *AJL* 829: 1, 1-12. http://iopscience.iop.org/article/10.3847/2041-8205/829/1/L3/pdf.

Acknowledgments

The authors wish to thank Catherine Hale, Greg Little, Richard Ward, and Russell M. Hossain for their help in the preparation of this paper.