KIC 8462852—Physical Modelling of its Occulting Objects and the Mystery of the Cyclic Fluctuations

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Abstract: KIC 8462862, an F-type main sequence star in the constellation of Cygnus, was found to be experiencing strange light fluctuations during the initial Kepler mission. Recorded data showed that the flux dropped by as much as 16 percent on one occasion in 2011 and 22 percent on another occasion in 2013. Various other major and minor light dipping episodes occurred across this same period, with an eclectic series of theories being offered to account for them. Experimental attempts are made to physically model the occulting objects behind the drops in flux to try and determine their line of sight profile, and through this their nature and appearance. The Kepler data for KIC 8462852 is re-examined to better understand the 0.88-day and 48.4-day periodicities noted in connection with the star (Boyajian et al, 2016). These reveal cyclic patterns suggesting that the prediction of future light dipping episodes might be possible, as well as recurring number sequences that warrant further investigation.

Key words: KIC 8462852, Tabby's Star, Boyajian's Star, Cygnus, Kepler, comets, asteroids, interstellar medium, planetary debris, rings, dust trails, cyclic periodicities, attention-grabbing signals, prime numbers.

Introduction

KIC 8462852, popularly known as Tabby's Star or Boyajian's Star after its discoverer astronomer Tabatha S. Boyajian of Louisiana State University, is an F-type main sequence star, 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 RA.: 20h 06m 15.457s Dec.: +44° 27′ 24.61″ (see fig. 1.1). It has been called the "weirdest star in our galaxy" (Andersen, 2015) due to the strange fluctuations in light it has displayed since it first came to the notice of the astronomical world following the completion of the Kepler space mission's initial phase in 2013.

Various theories have been proposed to explain KIC 8462852's curious light fluctuations. Tabatha Boyajian and her colleagues, following a detailed study of the Kepler data, concluded that they were caused by a swarm of exo-comets in a highly eccentric orbit following a single previous breakup event (Boyajian et al, 2016). A team led by Fernando J Ballesteros of the University of Valencia considers them the result of a giant ringed planet, five times the size of Jupiter, along with a swarm of Trojan asteroids (Ballesteros et al, 2017). Another team led by Brian Metzger of Columbia University has concluded that the star is recovering from a collision with an orbiting planet (Metzger et al, 2017), while Valeri V. Makarov of the United States Naval Observatory identifies the culprit as liberated planetary debris in the interstellar medium between here and the star (Makarov, 2016). And lastly, and most controversially, astronomer Jason Wright of Penn State University has suggested that the star's dimming episodes could be the result of alien megastructures in orbit around the star (Andersen, 2015; Wright and Sigurdsson, 2016. See also Heindl, 2016).

Figure. 1.1. *The Cygnus constellation showing the location of KIC 8462852 (Credit: Stellarium/Rodney Hale).*

1. Review of the Kepler Data for KIC 8462852

In an attempt to throw further light on the subject, one of the authors, Rodney Hale, examined the Kepler data for KIC 8462852 with the intention of physically modelling the transiting object or objects seen as responsible for the four biggest light dipping episodes. The first of these occurred on Kepler day 792 (henceforth D792), corresponding to March 5, 2011 (see fig. 1.2 for a listing of all the major dipping events recorded by Kepler between 2010 and 2013, and fig. 1.3 for their photometry). On this occasion the light dipped by a maximum of 16 percent. The second event took place on Kepler day 1519 (D1519), corresponding to February 28, 2013, when the light dipped by as much as 22 percent. The third occurred on Kepler day 1540 (D1540), corresponding to March 21, 2013, when a dip of 3.3 percent was recorded. The last major light dipping episode occurred on Kepler day 1568 (D1568), corresponding to April 17, 2013. On this occasion the resulting light curve showed that the star's flux had dipped by a maximum of 8 percent.

The D792 event would appear to have involved just one main occulting object. This passed in front of the star, causing a slow gradual dip before the flux dropped sharply by a maximum of 16 percent (see fig. 1.4 for the photometry of all four major dipping events). Thereafter it took the star a few days to return to its normal brightness. The other three events would all appear to be linked in some manner. They occurred across a period of approximately 40 days during which time the star's light fluctuated not only with the three major dips cited above but also with a succession of minor dips, suggesting a more complex series of events involving several occulting objects.

Kepler observations for KIC8462852 (Tabby's star) 2016

	Barycentric Julian Date	Kepler Day No.	Calendar date	Approx dip
Day 0	2454833	0	1 Jan 2009	
First data reading	2454953	120	1 May 2009	
Event 1	2455626	792	5 Mar 2011	16%
Event 2	2456353	1519	28 Feb 2013	22%
Event 3	2456373	1540	21 Mar 2013	3.3%
Event 4	2456401	1568	17 April 2013	8%
Final data reading	2456434	1591	11 May 2013	

Figure. 1.2. *List of the major dimming events recorded in the Kepler data for KIC 8462852 between 2009 and 2013.*

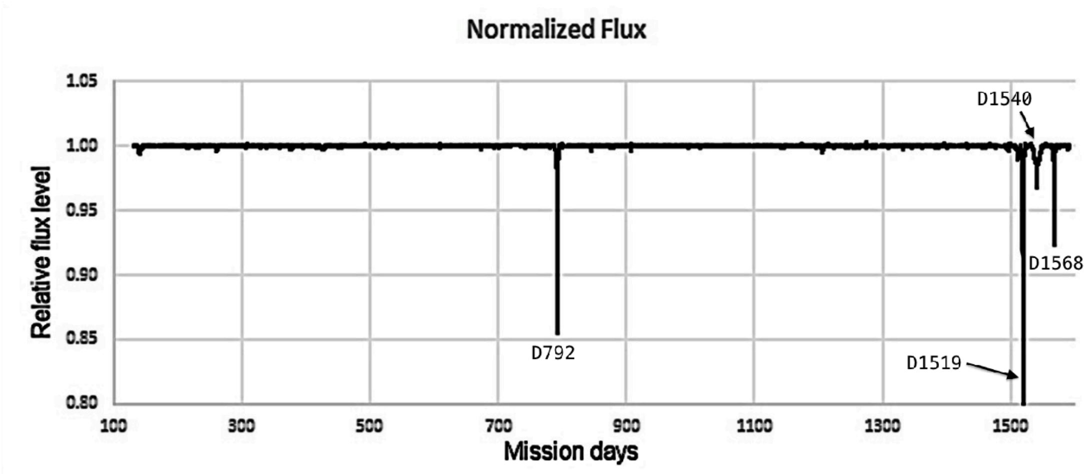

Figure 1.3. *The photometry from the Kepler data for KIC 8462852 from May 1, 2009, through till May 11, 2013. The D792, D1519, D1540 and D1568 dates are all marked.*

2.1. Cyclic Fluctuations

Before any physical modelling of the objects could begin it was essential to establish whether or not the cause of the light dimming events existed independently of the star. For this Hale focused his attentions on the 0.88-day fluctuations first reported in connection with KIC 8462852 by Tabatha Boyajian and her colleagues (Boyajian et al, 2016). The existence of these fluctuations does not seem in doubt, although Valeri Makarov suggests that this 0.88-day cycle is most likely interference from a nearby star (Makarov et al, 2016), a theory unsubstantiated at this time. More likely is that these 0.88-day fluctuations define KIC 8462852's rotational pattern (Boyajian et al, 2016).

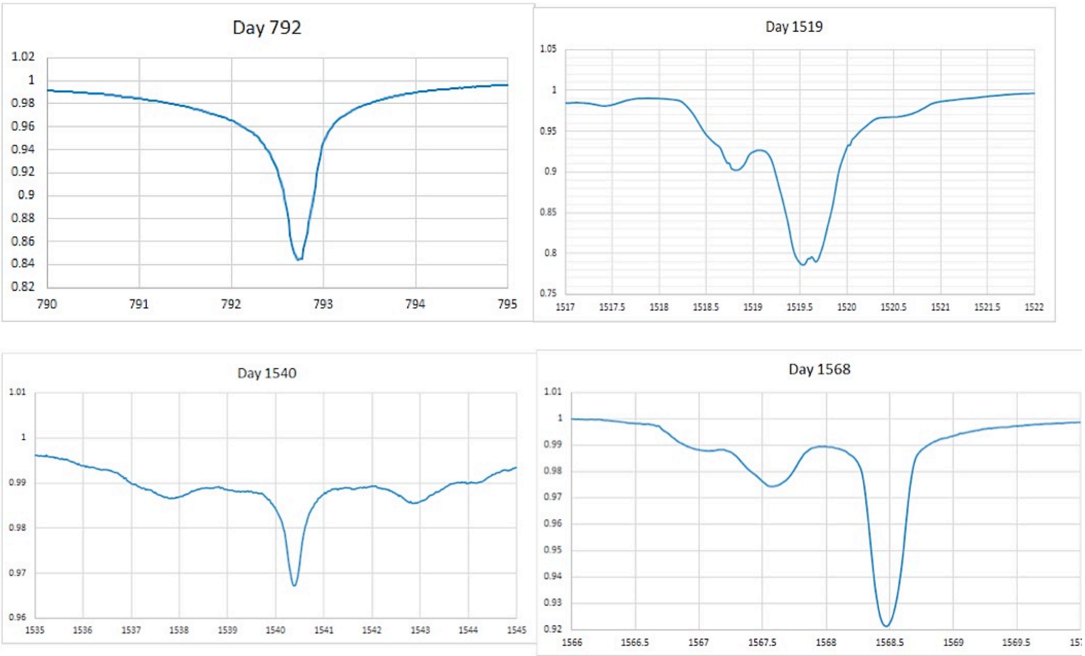

Figure. 1.4. *Photometry of all four major dimming episodes for KIC 8462852 as recorded in the Kepler data.*

With all this in mind, Hale was able to use the Kepler data[1] to show how regularly occurring changes of light levels across the entire four-year period of observation of the star can be shown as a spectrogram (see fig. 2.1). Its base line covers the entire period of observation of KIC 8462852, while its vertical scale indicates the cyclic frequency of light level changes. The random light grey peppering of the area of the plot comes from a general background of noisy signals. Persistent signals with a regular repeating pattern show up as darker horizontal bands, while short-term, larger changes show as narrow vertical bands.

The spectrogram's lowest horizontal band indicates KIC 8462852's 0.88-day fluctuation, which is equivalent to a rate of about 1.14 cycles per day. The two bands above it are second and third harmonics of this fluctuation. The significant fact gleaned from this exercise is that the lowest band representing the 0.88-day fluctuation continues without interruption throughout the entire duration of Kepler's observation of the star, *even through the major dip events.* This important realisation provides two possible scenarios. Either the 0.88-day periodicity is unconnected with KIC 8462852 and is, as Valeri Makarov has concluded, simply interference from a nearby star, or the 0.88-day fluctuation does indeed show the orbital periodicity of the star. If it does record the rotation of the star, this raises the question of what exactly is causing this 0.88-day fluctuation in the visible light reaching us from the star. It cannot be sunspots as these occur randomly, and not in the same position time after time. The only logical explanation is that it represents some kind of permanent light dimming on the star's surface, or, alternately, it is caused by something in low orbit around the star.

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

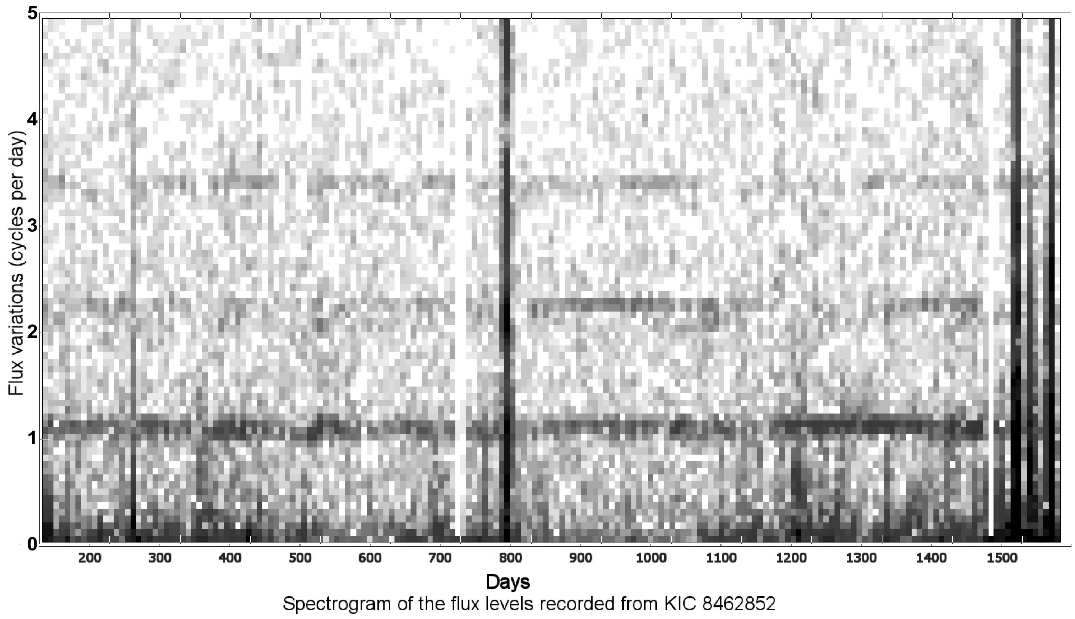

Figure. 2.1. *Spectrogram showing the cyclic fluctuations and dimming events recorded in the Kepler data for KIC 8462852. The 0.88-day fluctuation represented by the thick horizontal line at the base continues unabated during all the major dimming events represented by the vertical lines.*

Whatever the cause of the 0.88-day fluctuation seen in connection with KIC 8462852, the fact that it continues unabated during the light dipping episodes means that the occulting objects responsible for the star's major light fluctuations are most likely independent of the star itself. If they *were* a product of the star then there is a strong likelihood that the cycle would be interrupted in some way. Thus either the occulting objects causing the light dimming episodes belong to liberated planetary material existing in our line of sight between here and KIC 8462852, the conclusion of Valeri Makarov (2016), or they are in orbit around the star.

2.2. A Second Periodicity

Of these two alternatives, the second can be shown to be more plausible. Tabatha Boyajian and her colleagues noted a second possible periodicity in the Kepler data for KIC 8462852 based on the timing between several major and minor dimming events. They seemed separated by periods of 48.8 days, refined to 48.4 days, with the presence also of a possible half cycle amounting to 24.2 days (Boyajian et al, 2016). A connection exists between this second periodicity and the star's 0.88-day fluctuation in that there are exactly 55 cycles of 0.88 days during a period of 48.4 days. This implies an interrelationship between the two periodicities, almost as if one is a faster version of the other by a factor of 55.

3.1. Physical Modelling

So under the assumption that the objects creating KIC 8462852's major light fluctuations are indeed in orbit around the star, what exactly might they look like? The likelihood that they are planetary debris seems ruled out by the fact that Tabby's Star is a mature, main sequence star, where such debris will already have either coalesced into planets, been absorbed by the star itself, or banished to the edge of the star system to form planetoids, comets, etc. Only young, immature stars possess such planetary debris. What is more, planetary debris orbiting a young star is invariably hot, its excess heat released in an isotropic manner, i.e., in every direction. This is registered by telescopes in the form of infra-red (IR) radiation. However, no noticeable IR excess has been detected coming from KIC 8462852 (Boyajian et al, 2016). The same might be said for the idea that the objects are artificial megastructures, such as a Dyson sphere or Dyson series after the physicist Freeman Dyson (1923-). If such structures were in orbit around the star collecting stellar energy, the law of entropy implies that even if an efficient means of energy storage were in place, a small percentage of heat would still be lost as IR radiation. It was this lack of IR excess coming from KIC 8462852 that convinced Tabatha Boyajian and her colleagues that the occulting objects causing the star's strange light fluctuations were perhaps a swarm of exo-comets in a highly eccentric orbit.

Having established that the occulting objects responsible for the strange fluctuations in light on KIC 8462852 were almost certainly in orbit around the star, Hale looked at how solid objects of different shapes affect the appearance of resulting light curves. To achieve this he created a computer simulation showing a dark shape transiting a white disk representing the star. The output from a photocell monitoring the light level from the computer screen was recorded and plotted by a second computer, thus comparisons between light curves arising from different shapes were readily made. The transits may be equatorial (as viewed from Earth) or at higher latitudes (see Hale, 2016).

What Hale found was that transiting objects with regular shapes of appropriate sizes, including spheres, squares, triangles, etc., produce a characteristic light curve with a flat base (see fig. 3.1). This was completely unlike the sharp dips produced in connection with KIC 8462852. To create a light curve with a pointed tip the object has to have a diameter matching the star's width at the particular latitude of the crossing, as well as a thickness to produce the relevant light drop.

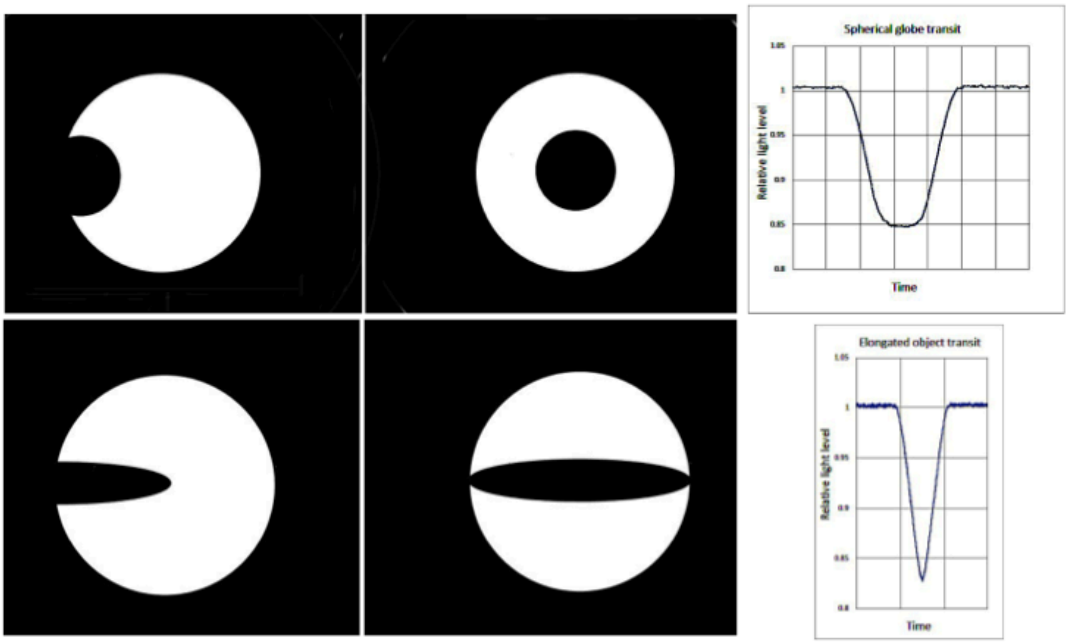

Figure 3.1. *Transiting objects with regular shapes, such as spheres, squares, triangles, etc., produce a characteristic light curve with a flat base when they pass in front of a star (appropriate to the amount of dimming observed), while those with elliptical profiles create light curves with characteristic narrow tips.*

Recognizing the similarity between the four major dips reported in connection with KIC 8462852, Hale superimposed all four together, keeping their scale yet synchronizing them in a manner corresponding to their lowest point. The resemblance in sharpness and form of all four is remarkable and is unlikely to be without meaning (see fig. 3.2). 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. 3.3). Not one of these dips, whether major or minor, display a characteristic flattened base.

Hale determined that one basic shape profile corresponded closely with the resulting light curves seen in the Kepler data for KIC 8462852. This was either an ellipse with a flat base and top or a slim disk seen edge on. A similar profile could also be created by an irregular shard, which if rotating along the line of sight as it transited across the face of the star would average out its profile to create the impression of an ellipse or disk. Hale was able to apply this information to Kepler event D1519 to show that it could have been caused by three elongated ellipses, disks or rotating shards of irregular shape (see fig. 3.4). Similar objects could be seen to be behind the D1540 and D1568 events (see below for more on the physical modelling of the D1540 event).

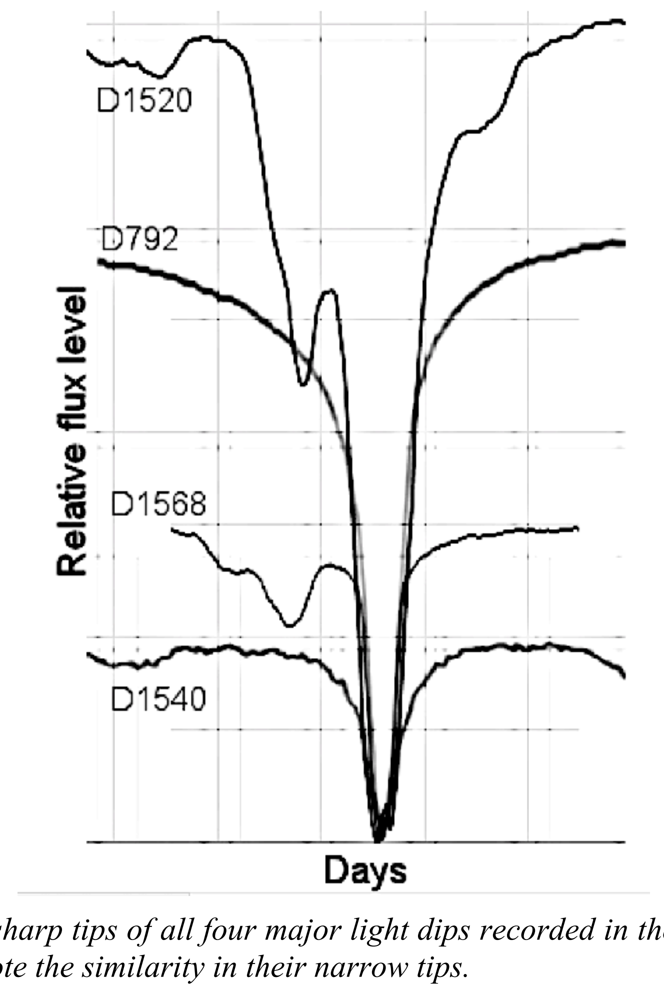

Figure 3.2. *The sharp tips of all four major light dips recorded in the Kepler data for KIC 8462852. Note the similarity in their narrow tips.*

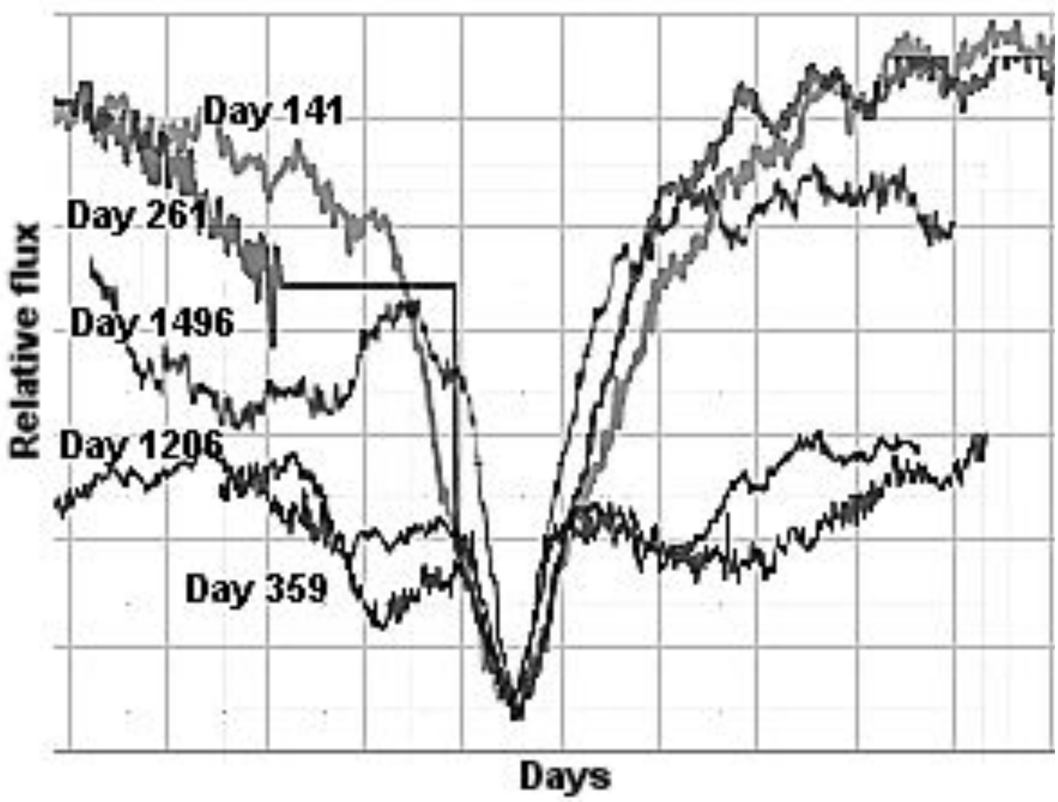

Figure 3.3. *The sharp dips of five minor events as extracted from the Kepler data for KIC 8462852. The day 261 event has some missing data.*

3.2. Modelling the D792 Event

Reconstructing the obscuring object that created the D792 light curve was more difficult in that it had to include the long, slow gradual dips that occurred before and after the sharp dip of 16 percent. These can only be explained by something extremely long and thin crossing in front of the star's face both before and after the appearance of the main object. Arguably they are dust trails. Whether or not they extend behind and in front of the main occulting object, showing they are in fact rings, is unclear from the data.

Some indication of a ring around an ellipse or disk-like profile is shown in two events, D1540 and another minor dip on Kepler day 1206 (D1206). Rodney Hale placed these two events together to show their close relationship (see fig. 3.5). Each can be seen to have a shallow depression either side of the main object, suggesting the presence of dust rings. This tells us that the extremely long trail seen during the D792 object's ingress and egress is either an incredibly large ring seen virtually along the line of sight, or it is some kind of twin trail, one a dust tail and the other an ion tail. The only argument against the identification of these anomalies as either rings, trails, or tails is that they would most likely re-radiate heat and so should be visible within the IR frequency range, something that has not so far been the case.

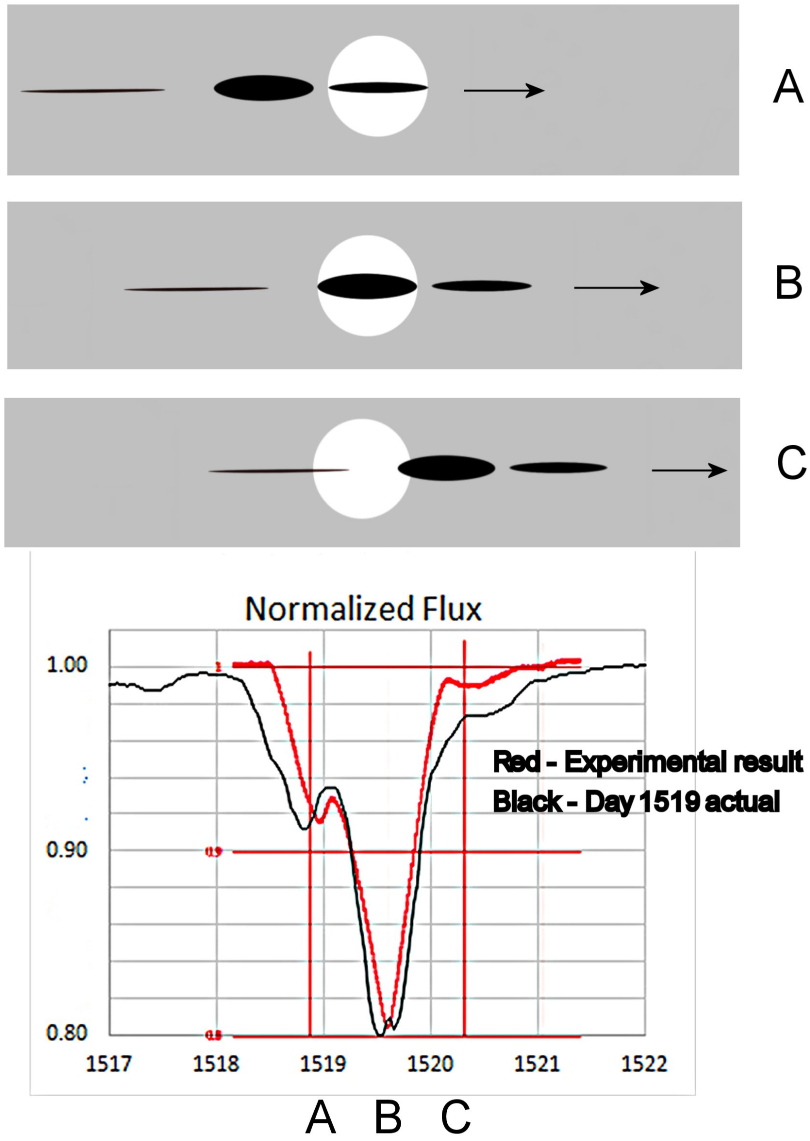

Figure 3.4. *The profiles of the D1519 event as determined from the physical modelling of the Kepler data for KIC 8462852. It shows that at least three occulting objects were responsible for this light curve, all of them ideally either elongated ellipses, disks in profile, or rotating irregular shards.*

The profile of the occulting object behind the D792 episode indicates that, like those of the D1519 event, it too bore a profile consistent with an ellipse showing a flat top and bottom. Equally, it could have been a disk viewed edge on, or, once again, an irregular shard rotating along the line of sight. Hale has provided a black and white image showing the profile of the D792 object complete with its "wings" (see fig. 3.6), while also accompanying this paper is an artist's impression of what the D792 object might have looked like as it transited the star during its ingress and egress (see fig. 3.7).

Very clearly the elliptical or discoid appearance of these objects almost rules out the likelihood that the main occulter in the D792 event is itself a giant-sized planet. As we have seen, a round object like a planet would create a light curve with a characteristic flat bottom, and that is certainly not what we see in the case of D792. It remains possible that the object is in fact a large planet surrounded by dense rings, which we see at a slightly up-tilted angle to give the impression that the rings possess a strong elliptical profile (the actual planet itself not being seen due to the profile of the rings). However, the idea that three such planets, all with rings tilted at an angle, passed in front of the star, one after the other, during the D1519 event stretches the imagination indeed. The possibility of the occulting objects being either swarms of exo-comets or Trojan asteroids also still exists. Yet accurately modelling such hypothetical swarms or clusters of objects from the Kepler data alone seems impossible without knowing more about their exact nature and appearance.

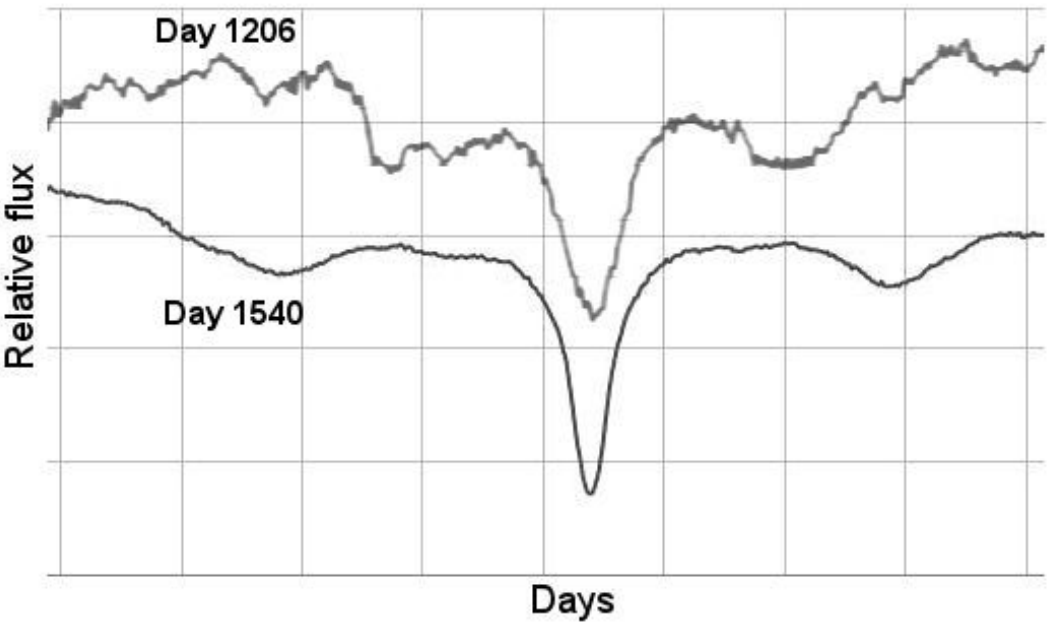

Figure 3.5. *Photometric comparison between two light dipping events in the Kepler data for KIC 8462852, one a major event, D1540, and the other a minor event, D1206. Note that both have shallow depressions on either side of the main dip, suggesting the presence of a ring surrounding an ellipse or disk-like object.*

Figure 3.6. *The profiles of the D792 event as determined from the physical modelling of the Kepler data for KIC 8462852. The extending "wings" have been severely shortened to better show the object's profile.*

Having said this, the elliptical or perhaps discoid appearance of the occulting objects certainly does not rule out a more exotic explanation. Ellipses or slim disks (although not irregular shards) might well conform to the appearance of alien megastructures.

What is more, a disk would only absorb some of the heat coming from the star. Since we only see part of a disk it might re-radiate its waste heat in a non-isotropic fashion. In other words, it could be directed, whether purposely or otherwise, away from our line of sight, a possibility acknowledged by Jason Wright.[2] This could explain why no significant IR excess has been detected in connection with Tabby's Star's light dimming episodes.

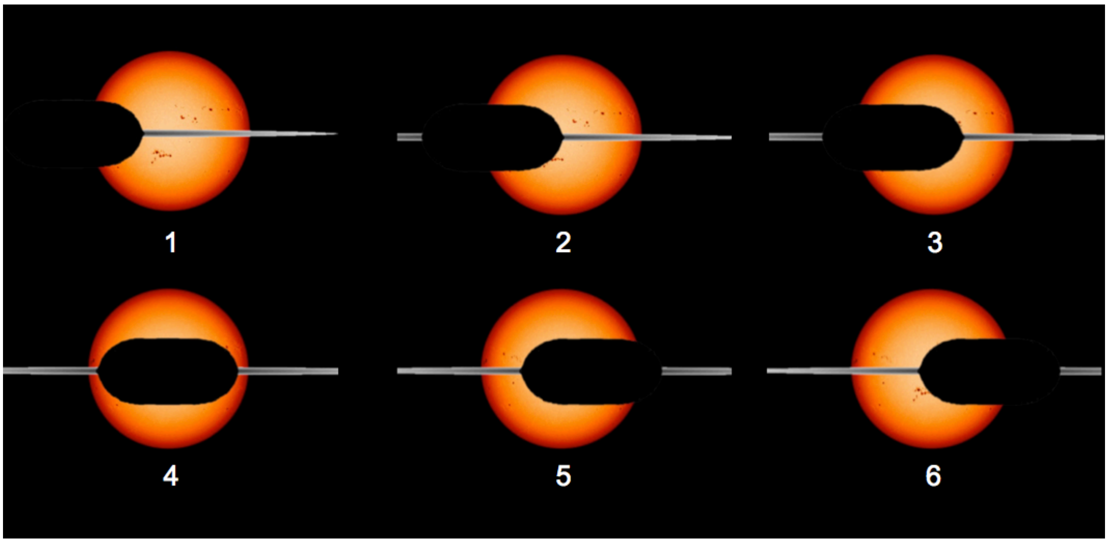

Figure 3.7. *Ingress and egress of the D792 event's occulting object against the background of a star. Not to scale.*

4.1. Recurring Cycles

A better understanding of the nature of the occulting objects passing in front of KIC 8462852 might be forthcoming from a deeper examination of the cyclic fluctuations recorded in connection with the star. As previously noted, periods of 48.4 days, and possibly a half cycle of 24.2 days, separate certain major and minor dipping events. For example, the time between the D792 and D1519 events was 726/7 days, the approximate equivalent of 13 x 48.4 day cycles, while the time between the D1519 episode and the D1568 event was approximately 48.4 days (Boyajian et al, 2016). We have also noted how this 48.4-day periodicity corresponds to precisely 55 cycles of its suspected 0.88-day rotational pattern. It is, however, possible to speculate further on this matter.

4.2. Multiples of Eleven

Tabby Star's orbital periodicity of 0.88 days coincides with the earth's own solar cycle every 22 days. What is more, the star's suspected 48.4-day cycle coincides with the earth's solar calendar every 242 days, while its suspected half cycle of 24.2 days synchronizes with the Earth's solar cycle every 121 days. Curiously, these synchronizations between Tabby's Star and the Earth's own solar cycle are all multiples of 11 (2 x 11 = 22, 11 x 11 = 121, and 22 x 11 = 242), as is the relationship between the star's 0.88-day periodicity and its 48.4-day cycle (5 x 11 = 55).

The importance of the number 242 is further emphasised by the fact that the 726/7 days between Kepler events D792 and D1519 mark three cycles of 242 days (i.e. 242

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[2] Jason Wright during a presentation for the SETI Institute: Science Colloquium: "Frontiers in Artifact SETI: Waste Heat, Alien Megastructures & Tabbys Star - Jason Wright (ST 2016)", uploaded August 12, 2016. https://www.youtube.com/watch?v=XEDR-G2EDRM

x 3 = 726), that is three 242-day synchronizations between the star's 48.4-day cyclic periodicity and the Earth's solar cycle.

No logical explanation seems forthcoming as to why periods of 242 earth days should create a unit of length for cycles defining major light fluctuations on a star approximately 1,300 light years away. If all this is not some bizarre coincidence, or a fault generated within the Kepler data, should we not be considering the possibility that these cyclic fluctuations are being manipulated or generated by an intelligent source?

4.3. Attention-grabbing Signals

In 2005 French astronomer Luc Arnold proposed that the launch of space telescopes like the future Kepler mission would provide extraterrestrial civilizations with an ideal opportunity to communicate information using what he referred to as "attention-grabbing signals" (Arnold, 2005). In his opinion, this could be achieved by deploying massive solar panels with the express purpose of transiting stars. The resulting light curves could then be used to convey mathematical patterns such as prime number sequences, binary code, and even more complicated formulas. As Jason Wright realised when he first saw the Kepler data regarding KIC 8462852, this was exactly what Luc Arnold predicted we should look for in light curves produced by occulting objects transiting stars.[3]

5. New Light Dip—May 2017

In May 2017, KIC 8462852 displayed its first noticeable light dimming event since the end of the first Kepler's mission in 2013. Over the course of several days the star's light dipped by just over two percent before regaining its original brightness. The lowest point reached during the dip occurred on May 19. If it had peaked on May 26, a time span of 2,274 days since the D792 event of March 5, 2011, this would have been significant, as it would have equalled 9 x 242-day cycles plus an additional 2 x 48.4-day cycles (or, alternately, 47 x 48.4-day cycles), making a total of 2274.8 days. Using the Kepler data Tabatha Boyajian and her colleagues have predicted a recurring cycle amounting to around 750 days (Boyajian et al, 2016), which if taken from the date of the D1568 event (2 x 750 days) brings us to May 26, 2017, the same date achieved using a combination of the 242-day and 48.4-day cycles mentioned above.

Even though this potential synchronization between the 242-day cycle linking Tabby's Star's 48.4-day periodicity with the Earth's own solar cycle, as well as the star's own 48.4-day cycle, was out by around seven days it does suggest that such patterns be noted and tested against future light dimming episodes.

6.1. Summary

A number of solutions have been put forward by a host of authors to explain the strange fluctuations in light experienced by KIC 8462852. Some of these rely on the assumption that the source of the fluctuations can be found on the star itself (Metzger et al, 2017). Others rely on the surmise that they are caused by liberated planetary material in the interstellar medium (Makarov, 2016), or that the culprits are occulting objects orbiting the star (e.g. Boyajian et al, 2016; Ballesteros et al, 2017). Of all

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[3] Ibid.

these possible solutions the physical modelling of the light curves from the Kepler data leans toward the conclusion that the true source of the light dimming events will be found to be extremely large objects, natural or otherwise, orbiting the star. This seems confirmed by the strange relationship between the cyclic fluctuations recorded in the Kepler data and the possible synchronizations with three out of four of the major light-dimming episodes recorded to date.

6.2. Ellipses

The Kepler data suggests also that the occulting objects, which all display light curves with sharp tips, are profiles of ellipses with flat bottoms and tops. If correct, this indicates that the occulters are themselves ellipses, and if not ellipses then slim disks or irregular shards rotating along the line of sight. Indeed, if the obscuring objects can be shown to be slim disks then a disk's non-isotropic manner of distribution of its waste heat could help explain why no IR excess has been noted in connection with the star.

6.3. Physical modelling

Although physical modelling does not tell us what these objects are, the one idea it can rule out is that the D792 occulter is a giant-sized planet (Ballesteros et al, 2017). Being round, a planet of any size would provide a distinctive light curve with a characteristic flat-bottomed profile, which is not seen in the Kepler light curve. The possibility that the obscuring objects are in fact the dense rings of planets tilted so that they assume an elliptical profile (and thus hiding with their shape the actual profile of the planet) remains on the table. However, the fact that three slim ellipses in a line appear to have created the D1519 event alone makes the ringed-planet idea inadequate to explain the sheer quantity of objects involved. Such a theory cannot also explain the overall shape of the D792 event. This, as we have seen, showed the presence of incredibly long "wings" or trails visible during the ingress and egress of the star, while the main object itself would appear to have been an ellipse with a flat bottom and top. Together these two quite separate elements do not add up to a giant-sized planet with dense rings tilted so as to create an elliptical profile.

With all these considerations in mind several other explanations remain possible, including swarms of comets, clusters of Trojan asteroids, and even alien megastructures.

6.4. Cyclic fluctuations

Lastly, and most controversially, the slim relationship between the cyclic fluctuations found in the Kepler data for KIC 8462852 and the Earth's own solar cycle remains an enigma. There is every likelihood this is a bizarre coincidence. Yet the fact that these periodicities and their synchronizations with the Earth's solar cycle reflect multiples of 11—a prime number—should be noted. As bold as such an assertion might seem, we should not rule out the possibility that encoded within the Kepler data for KIC 8462852 is mathematical information derived from an intelligent source. It is a proposition that if proved correct would vindicate the predictions made in this respect by Luc Arnold who as long ago as 2005 had one eye on the greater potential of future space missions, including that of Kepler.

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