THE HIGH RATE OF THE BOYAJIAN’S STAR ANOMALY AS A PHENOMENON

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ABSTRACT

Boyajian’s Star (KIC 8462852) undergoes mysterious, irregular eclipses that aren’t yet explained. It also appears to have dimmed over a time of several years, possibly decades. I show that Kepler’s detection of a phenomenon with a duration of $t_{anom}$ is only expected if it occurs at a mean rate of $\gtrsim 30$ Gyr$^{-1}(t_{anom}/100 \text{ yr})^{-1}$ for each Kepler target and K2 star. If true, the phenomenon occurs hundreds of times during the lifespan of its host stars. Obscuration by the interstellar medium remains a plausible explanation, since it doesn’t actually affect the host star. An intervening cloud is consistent with the lack of an observed submillimeter excess but would be abnormally dilute.

Keywords: stars: individual (KIC 8462852) — ISM: extinction — stars: peculiar — stars: variable: general — extraterrestrial intelligence

1. INTRODUCTION

Boyajian’s Star (KIC 8462852, TYC 3162-665-1) is perhaps Kepler’s strangest discovery (Boyajian et al. 2016). Citizen scientists with the Planet Hunters project (Fischer et al. 2012) noticed a series of abnormal eclipses in the Kepler photometry of this F3 dwarf (Boyajian et al. 2016), which is located approximately 390 pc away (Hippke & Angerhausen 2016). The eclipses were diverse and irregular in shape, lasted for up to several days, and blotted out up to 20% of the star’s flux, too long and too deep for a planetary transit. While events with similar light curves do occur for young “dipper” stars with circumstellar disks, the disks usually glow with infrared radiation (Cody et al. 2014; Ansdell et al. 2016; Scaringi et al. 2016). Yet Boyajian’s Star has no infrared excess (Boyajian et al. 2016; Lisse et al. 2015; Marengo et al. 2015), nor any submillimeter excess (Thompson et al. 2016), and its kinematics suggest that it is not newly born (Boyajian et al. 2016).

The mystery deepened when Schaefer (2016) claimed that the star is dimming over century timescales, using a reconstructed light curve from Harvard archival plates accessed through the Digital Access to a Sky Century @ Harvard (DASCH) project (Grindlay et al. 2012; Tang et al. 2013). He found a mean flux decrease of $0.151\% \text{ yr}^{-1}$ from 1890 to 1989. This claim was disputed by Hippe et al. (2016a), who noted the potential for calibration issues as the Harvard data were taken with several different telescopes and suffer the “Menzel gap” in the data for the 1950s and 1960s. Further archival data at the Sonneberg Observatory appears to be consistent with a constant brightness (Hippke et al. 2016b). But Montet & Simon (2016) announced that the Kepler light curve for Boyajian’s Star showed an even faster dimming during its survey, $0.341\% \text{ yr}^{-1}$ for the first three years, followed by a rapid 2% flux drop. The star’s behavior on century timescales remains unclear.

Several hypotheses have been advanced to explain Boyajian’s Star, but none seem entirely satisfactory. It is hard to accommodate both the long-term dimming and the lack of infrared and submillimeter emission (Wright & Sigurdsson 2016). One hypothesis is that Boyajian’s Star is experiencing a shower of debris from the breakup of a large comet, and the occluders are clusters of comet fragments and their dust tails (Bodman & Quillen 2016). The number of disrupted giant comets to produce the long-term dimming would be exorbitant, however (Schaefer 2016). Intrinsic variability in the star is a possibility, but an atypical one for F dwarfs (Wright & Sigurdsson 2016; Montet & Simon 2016). It is also possible that the light of Boyajian’s star is being modulated by something between its system and us. The obscuring structure’s properties would be consistent with our current data on the interstellar medium (ISM) (Wright & Sigurdsson 2016). An ISM scenario might also explain the apparent astrometric motion of Boyajian’s star in Kepler data, as nearby blended stars experience variable extinction (Makarov & Goldin 2016).

The most unconventional hypothesis (so far) is that the phenomenon is artificial, the result of structures built by an alien intelligence (Wright et al. 2016). Before Kepler even launched, Arnold (2005) predicted that...
it might find “megastructures” as big as planets, which could easily signal distant societies. On an even larger scale, it’s possible that a society might shard their entire solar system in a Dyson sphere, a swarm of satellites that collects all of the optical light of the host sun (Dyson 1960; Kardashev 1964; Bradbury 2000). The long-term dimming might actually be the progress of a Dyson sphere’s construction (Lintott & Simmons 2016).

There are multiple problems with this explanation for Boyajian’s Star. First, Dyson spheres should re-radiate the host star’s emission in infrared to submillimeter wavelengths (Sagan & Walker 1966), but the lack of such emission from Boyajian’s Star strongly constrains megastructure scenarios (Wright & Sigurdsson 2016). Second, both optical and radio studies report no artificial signals from the star (Abeysekara et al. 2016; Schuetz et al. 2016; Harp et al. 2016), despite communication being a primary motivation in Arnold (2005).

But on a more foundational level is the Fermi Paradox and its corollary, the Great Silence (Brin 1983; Ćirković 2009). If aliens can build megastructures that big, they are probably easily capable of launching interstellar voyages. And Kepler found Boyajian’s Star among a few hundred thousand stars, implying that there are tens of thousands of similar systems in the Galaxy, presumably all hosting high tech societies right now, and perhaps many more over the past 4.5 billion years. Yet the Solar System shows no evidence of artificial tampering over all that time, despite the presence of many thousands of societies of cosmic engineers. That is the Fermi Paradox (Hart 1975; Tipler 1980). While it’s possible that actual aliens are too restrained to alter the Solar System visibly (Freitas 1985; Schaefer 1994; Haqq-Misra & Baum 2009), the audacity of the required structures suggests that the putative Boyajian’s Star inhabitants would have few such qualms.

Furthermore, all surveys for Dyson spheres have come up negative, including one examining millions of stars (Slysh 1985; Timofeev et al. 2000; Jugaku & Nishimura 2004; Carrigan 2009). More worryingly, there are no signs of galaxy-scale engineering among thousands to millions of galaxies (Annis 1999; Griffith et al. 2015; Garrett 2015; Zackrisson et al. 2015; Lacki 2016). Even if the inhabitants of Boyajian’s Star had no interest in it, the reaches of current surveys would include billions of such societies, each probably capable of galactic engineering. Cosmic engineering seems to be an all or nothing thing, and our current surveys lean strongly towards nothing (whether because it’s infeasible or because nobody else is around).\footnote{On the subject of unconventional explanations, nobody has suggested that the phenomenon is biological to my knowledge — Motivated by the strangeness of the anomaly, there have been a few attempts to find analogous stars. LaCourse (2016) reports that there are no similar stars among the 165,000 studied during the K2 campaign. As far as long-term dimming goes, Villarroel et al. (2016) find that at most 1 star among $10^7$ appears to have disappeared from the United State Naval Observatory B1.0 catalog over the past few decades. Meanwhile, Davenport & Ruan (2016) advocate looking for analogs with Sloan photometry among the stars of Stripe 82. Kochanek et al. (2008) describe a survey for disappearing massive stars in nearby galaxies on decade timescales, with one apparent discovery (Gerke et al. 2015), but it would only be sensitive to large secular fluctuations of the brightest stars.

This paper proceeds under the assumption that the anomalies of Boyajian’s Star represent a single astronomical phenomenon. I focus on the long-term dimming observed by Kepler (and possibly other surveys), since it is one of the most baffling aspects of the anomaly and it has a characteristic lifetime. I then calculate how commonly the anomaly has to occur around stars in order to have been found by Kepler. The anomaly turns out to be something that must happen multiple times during a typical star’s lifespan.

2. THE FREQUENCY OF THE ANOMALY

2.1. The discovery rate with Kepler

Let $\Gamma_{\text{Kepler}}$ be the mean rate at which a survey like Kepler would observe a given anomaly in one star. It may be that only a fraction $f$ of the stars observed by Kepler ever display the anomaly. Then the true rate that anomalies occur around these host stars is $\Gamma_{\text{host}} = \Gamma_{\text{Kepler}}/f$. Note also that $f$ does not necessarily equal the host stars’ true fraction $f_{\text{true}}$ among a volume-selected sample of stars. Kepler is biased towards Solar-type stars a few hundred parsecs away and observed Cygnus, a part of the Milky Way’s disk with star-forming regions (Koch et al. 2010).

The expected number of times Kepler finds an anomalous star is

$$N_{\text{anom}} = \Gamma_{\text{Kepler}} N_{\text{Kepler}} t_{\text{eff}},$$

where $N_{\text{Kepler}}$ is the number of stars observed by Kepler. During its original survey, Kepler had 150,000 high priority target stars (Batalha et al. 2010). The extended K2 survey, studied an additional 165,000 stars scattered space trees of some sort. Without knowledge of other stars and dependent on sunlight, space trees wouldn’t spread beyond Boyajian’s Star. Nor would they send us narrowband radio signals or optical laser pulses. Arnold (2005) mentions this possibility for non-artificial, irregular transits, citing the hypothetical Kuiper Belt life of Dyson (2003).
over several fields along the ecliptic at a wide range of galactic latitudes (Howell et al. 2014; LaCourse 2016). Boyajian’s Star was unique among them (expected if \(N_{\text{anom}} = 1\)). The effective exposure \(t_{\text{eff}}\) is the sum of the lifetime of the anomaly, \(t_{\text{anom}}\), and the duration of the survey, \(t_{\text{Kepler}}\). \(Kepler\)’s original survey accumulated photometry of Boyajian’s Star for \(t_{\text{Kepler}} = 4\) yr (Boyajian et al. 2016).

Thus, the frequency of the anomaly is

\[
\Gamma_{\text{host}} = \frac{N_{\text{anom}}}{N_{\text{Kepler}}t_{\text{eff}}},
\]

(2)

2.2. The duration of the long term decline

The long-term decline observed by \(Kepler\) is probably related to the occultations. The eclipses by themselves already appear to be a unique trait of stars in the \(Kepler\) and K2 fields (Boyajian et al. 2016; Davenport & Ruan 2016). But the secular trend is also quite rare, present in \(\lesssim 1\)% of F dwarfs in the field, so the odds that it would coincidentally affect Boyajian’s Star are small (Lund et al. 2016; Montet & Simon 2016). This suggests that both would be observed together when observing the star.

A key feature of the secular dimming is that it has a very short timescale compared to stellar evolution. The slowest reported decline is that of Schaefer (2016), in which the e-fold time is 660 yr. If the trend were continuing for much longer than that, its current rate, then Boyajian’s Star would have been implausibly bright. It would have been a sixth magnitude star around 3,500 years ago and visible to the naked eye, which would have been before the construction of star catalogs that deep. Around 9,400 years ago, Boyajian’s Star would have been a million times brighter than it is now, among the brightest stars in the Galaxy. I therefore assign a conservative upper limit of \(t_{\text{anom}} = 10,000\) yr to the anomalous dimming’s lifetime. I am assuming that the secular dimming is in fact secular, and not just a small slice of a very long period oscillation.

\(Kepler\)’s photometry indicates an even faster dimming in recent years, with an e-folding time of 290 yr. At this rate, it would have had \(V = 2.45\) around 2,500 years ago, and its disappearance would be a glaring discrepancy with ancient star catalogs. Yet it is unlikely that Boyajian’s Star has faded anywhere near this much. Boyajian et al. (2016) are able to model the star’s spectrum as a typical F dwarf at a distance of 450 pc. \(Gaia\) has made a preliminary measurement of its distance of 390 pc (Hippke & Angerhausen 2016); the agreement between the distance modulus and the parallax distance implies that the apparent luminosity of Boyajian’s Star is not greatly affected by the dimming. The small discrepancy could be explained by a fading of \(\sim 33\)%, which would take 84 years at \(Kepler\)’s measured rate. The difference could be entirely due to interstellar extinction, since the measured reddening \(E(B-V) = 0.11\) implies \(A_V \approx 0.33\) (Boyajian et al. 2016). Thus, a medium value for the decline’s lifetime is \(t_{\text{anom}} = 100\) yr.

Finally, the \(Kepler\) light curve indicates that the decline is unsteady and accelerated rapidly towards the end of the survey (Montet & Simon 2016). According to Montet & Simon (2016), Boyajian’s Star dimmed by 2.5% in a mere 200 days. While this precipitous fall ended afterwards, the star showed no sign of starting to recover its flux by the end of its survey. The anomalous transits were observed over a span of about 1,500 days during \(Kepler\)’s survey, however, or about 4 years (Boyajian et al. 2016). I will use a compromise value of \(t_{\text{anom}} = 1\) yr for a lower limit to the anomaly’s lifespan. The effective exposure is then \(t_{\text{eff}} = 5\) yr.

2.3. The anomaly is common

From the anomaly’s lifespan and the number of stars observed during the \(Kepler\) survey and K2, I calculate that the rate the phenomenon occurs is

\[
\Gamma_{\text{host}} = 0.32 \left(0.0080–1.8\right) \text{Gyr}^{-1} f^{-1} \times \left(\frac{N_{\text{Kepler}}}{315,000}\right)^{-1} \left(\frac{t_{\text{eff}}}{10 \text{ kyr}}\right)^{-1},
\]

(3)

from equation 2. The range in the parentheses is the two-sided 95% confidence interval (one-sided 97.5% confidence limits) (Gehrels 1986). I’ve used the longest possible timespan allowed by Section 2.2. Using a shorter duration for \(t_{\text{eff}}\) causes \(\Gamma_{\text{host}}\) to rise proportionally: it would be 32 \((0.80–180)\) \(f^{-1}\) \(\text{Gyr}^{-1}\) for \(t_{\text{eff}} = 100\) yr and 620 \((16–3,500)\) \(f^{-1}\) \(\text{Gyr}^{-1}\) for \(t_{\text{eff}} = 5\) yr.

This is actually quite high when compared to the lifetime of a main sequence star. The majority of the \(Kepler\) target stars are dwarfs with effective temperatures near \(10000\) K — they’re G dwarfs like the Sun (Batalha et al. 2010; Ciardi et al. 2011). Their lifetimes on the main sequence should be around \(t_{\text{MS}} \approx 10\) Gyr. Thus if every star is a potential host, it should display the phenomenon roughly \(N_{\text{life}} = \Gamma_{\text{host}} t_{\text{MS}}\) times:

\[
N_{\text{life}} = 3.2 \left(0.080–18\right) \text{f}^{-1} \times \left(\frac{t_{\text{MS}}}{10 \text{ Gyr}}\right) \left(\frac{N_{\text{Kepler}}}{315,000}\right)^{-1} \left(\frac{t_{\text{eff}}}{10 \text{ kyr}}\right)^{-1}.
\]

(4)

Again, this is the most conservative possible estimate, which allows Boyajian’s Star to have been a million times brighter than it is now. A more realistic value is

\[
N_{\text{life}} = 320 \left(8.0–1800\right) \text{f}^{-1} \times \left(\frac{t_{\text{MS}}}{10 \text{ Gyr}}\right) \left(\frac{N_{\text{Kepler}}}{315,000}\right)^{-1} \left(\frac{t_{\text{eff}}}{100 \text{ yr}}\right)^{-1}.
\]

(5)
For the shortest $t_{\text{eff}}$, the fiducial $N_{\text{life}}$ is 6,300 (160–35,000) $f^{-1}$. It is clear that the anomaly is probably something that we would observe multiple times during a host star’s lifetime, probably hundreds of times.

If only a small fraction of stars can display the phenomenon, then in general the number of times it happens to these stars is even larger. Boyajian’s Star, with an effective temperature of 6,750 K is relatively hot for a Kepler candidate star, so perhaps the anomaly only occurs around early type stars. Then $f$ is fairly small, although not as small as in a volume-limited population. Batygin et al. (2010) estimate that there are 24,806 dwarf stars with effective temperatures around 6,500 K among the Kepler target stars, indicating that $f \approx 1/6$ (in fact, the great majority of these are late F dwarfs cooler than 6,500 K, suggesting an even smaller fraction; see Ciardi et al. 2011; Pinsonneault et al. 2012). Against this, Boyajian’s Star is expected to last shorter than a G dwarf. With an estimated mass of 1.43 M$_\odot$ and a luminosity of 4.68 L$_\odot$ (Boyajian et al. 2016), its time on the main sequence is $\sim$ 3 Gyr. Thus,

$$N_{\text{life}} = \left(\frac{t_{\text{MS}}}{3 \text{ Gyr}}\right) \left(\frac{f}{1/6}\right)^{-1} \left(\frac{N_{\text{Kepler}}}{315,000}\right)^{-1} \times$$

$$\begin{cases}
5.7 \ (0.14–32) \left(\frac{t_{\text{eff}}}{10 \text{ kyr}}\right)^{-1} \\
570 \ (14–3,200) \left(\frac{t_{\text{eff}}}{100 \text{ yr}}\right)^{-1} \\
11,000 \ (290–64,000) \left(\frac{t_{\text{eff}}}{5 \text{ yr}}\right)^{-1}
\end{cases}$$

Restricting the host population increases $N_{\text{life}}$ further. The minimum reasonable $f$ is $\sim N_{\text{anom}}/N_{\text{Kepler}} = 3 \times 10^{-6}$, for which $\Gamma_{\text{host}} \approx 1/t_{\text{eff}}$. This is the case when the dimming is actually a periodic variation, or an aperiodic fluctuation with a duty cycle near 1.

3. INTERPRETATION

3.1. Boyajian’s Star and the lesson of Drake’s Equation

The fundamental reason why the anomalous dimming must be a common phenomenon is familiar in the Search for Extraterrestrial Intelligence (SETI). Equation 2 can be seen as a version of Drake’s Equation, estimating the number of alien societies in the Galaxy, applied to anomalies: the number observed is the number of host stars times the fraction that are active at any given moment.

As is well known in SETI, if a phenomenon happens only once for each star and lasts for a few decades, one would need to search millions of stars to have a reasonable chance of finding it. Humanity has been broadcasting radio waves for that long (Sullivan et al. 1978) — the same sorts of timescales found in the secular dimming of Boyajian’s Star. Since we are the only technological society we know of, and since we do not know how much longer we’ll be broadcasting, we can’t be sure that alien societies will last longer. If that’s the case, then there may only be a few dozen societies in the Milky Way at any moment, separated by thousands of parsecs, even if every Solar-type star gives rise to one (Sagan 1973). The trouble is that we are barely capable of detecting our own radio broadcasts, at their typical levels, around the nearest stars (Loeb & Zaldarriaga 2007). Even using something as powerful as the Square Kilometer Array, with a potential reach of millions of stars, one would not expect to see a short-lived analog of humanity (Forgan & Nichol 2011).

With Boyajian’s Star, we have the same problem. Kepler observes a measly few hundred thousand stars, not enough to catch one in a single decades-long phase (Villarroel et al. 2016 reach the same conclusion for their own anomaly search). This means that the total amount of time a star would be observed to be anomalous must be much greater than a few decades. Since the anomalous dimming can only be sustained for a few decades per episode, there must be several such episodes. At least in the case of Boyajian’s Star, this is allowed; for SETI, it is unlikely that a typical solar system independently generates much more than one technological society.

SETI deals with this problem by extrapolating from humanity: it can work if alien societies last for many thousands of years, or if they produce a signal that is far more noticeable than our normal radio broadcasts, possibly something deliberately designed to grab our attention (Tarter 2001). It was this very need for an easily detectable signal that prompted Arnold (2005) to suggest looking for artificial transits. In this sense, whatever is responsible for the anomaly, it is deeply linked from our point of view with the issues of SETI.

3.2. Implications for scenarios

If we accept the $\Gamma_{\text{host}}$ calculated in Section 2.3, it challenges many scenarios for Boyajian’s Star. It cannot be the result of a merger with a companion star (Wright & Sigurdsson 2016), since stars do not even have dozens of companions, much less devour them. Planetary collisions might generate the required obscuration. In our own Solar System, there were probably several large collisions (including the one responsible for the formation of the Moon) during its first 100 Myr (e.g., Jackson & Wyatt 2012). The space motion of Boyajian’s Star is unlike typical $\lesssim$ 100 Myr old stars, though (Boyajian et al. 2016). Planetary collisions can happen throughout the main sequence phase of a sun if dynamical instabilities are triggered (Ford et al. 2001;
The Nice model of the Solar System’s evolution conjectures there was a chaotic phase about 4 billion years ago, for example (Tsiganis et al. 2005): it may have ejected a giant planet (Nesvorný 2011), but in other systems collisions might be the result. While planetary collisions are consistent with the most conservative limits on $\Gamma_{\text{host}}$, the most reasonable $\Gamma_{\text{host}}$ values with hundreds of events are implausibly high.

Comet showers might happen repeatedly during a planetary system’s history. Whitmire & Jackson (1984) and Davis et al. (1984) suggested that a distant Solar companion perturbs the Oort Cloud every 26 Myr, leading to a burst of comets in the inner Solar System and extinction events on Earth. Occasional showers might also occur during encounters with passing, unbound stars (Hills 1981). The moderate value of $\Gamma_{\text{host}}$ associated with $t_{\text{anom}} = 100$ yr is actually once per 30 Myr, and Boyajian’s Star appears to have a red dwarf companion that could act as a “Nemesis” (Boyajian et al. 2016; Bodman & Quillen 2016). The comet shower hypothesis is hard to reconcile with the secular dimming trend used to derive $t_{\text{anom}}$, though, since roughly 0.4 M$_\odot$ of comets would have to be disrupted to fuel the obscuration for decades (Schaefer 2016). There are only 40 M$_\odot$ of comets in our own Oort Cloud, suggesting the entire cloud would be depleted in showers by these events (Weissman 1996). The sheer scale of the showers may be incompatible with the continued existence of complex life on Earth as well, if our Solar System is typical.

Nor does it seem likely that we are witnessing the construction of a complete Dyson sphere. Since repeated events are needed, a megastructure hypothesis requires that a partial shell is assembled and then disassembled, hundreds of times. Another possibility is that the sphere is destroyed by a collisional cascade (Carrigan 2009; Lacki 2016) and the inhabitants keep rebuilding it in a failure-prone state. Moreover, this behavior needs to happen in technological societies around every Solar-like star — or else, it happens many thousands of times around a subset of stars. Maybe we’re in no position to question the wisdom of such powerful entities, but it strikes me as a bizarrely specific behavior for something so universal.

A further problem with many of these scenarios is that they should leave traces that last for much longer than the anomaly itself. These traces should then be commonly found around stars. Planetary collisions could heat the remnant worlds for thousands of years, during which they shine brightly in the infrared (Zhang & Sigurdsson 2003). While the initial debris clouds from a collision of terrestrial planets might survive for only a few years (Boyajian et al. 2016), a residual disk could persist for $10^3$–$10^7$ yr afterwards as it is regenerated by collisional grinding of the fragments (e.g., Jackson & Wyatt 2012). During this time it would be visible as an infrared excess (if not already in tension with the infrared limits for Boyajian’s Star itself). Dense, warm debris disks are rare around older stars, however. According to Trilling et al. (2008), about 4% of mature F, G, and K dwarfs (7% of mature F and A dwarfs) have 24 $\mu$m excesses, although $\sim 20\%$ have 70 $\mu$m excesses characteristic of exo-Kuiper Belts. These disks reprocess $\sim 10^{-5}$–$10^{-4}$ of the sun’s light, indicating a few hundred times more dust than our asteroid belt. A Nemesis-like comet shower is expected to last for 0.1–1 Myr (Hills 1981; Davis et al. 1984; Whitmire & Jackson 1984), and would have to be going on around $\sim 0.3$–3% of stars. While a giant comet disintegration may be a rare episode during these showers, a shower of the required intensity could release gas and appear as time-varying absorption in the host star’s spectrum (e.g., Welsh & Montgomery 2013). For the megastructure hypothesis, one might expect a completed Dyson sphere as a result, but Carrigan (2009) rules out completed Dyson spheres around even 1 Solar-like star in $10^6$.

Two broad classes of hypotheses are unaffected by the $\Gamma_{\text{host}}$ constraints. First, it is possible that the anomalous light curve is solely due to intrinsic variability in Boyajian’s Star. The observed variability, which seems to be happening over decades, is not expected with our current understanding of stars (Wright & Sigurdsson 2016). Very large amplitude dimmings lasting centuries would probably have dramatically disturbed the Earth’s climate if they occurred in the Sun. For comparison, pollution and cloud cover changes caused a few percent dimming of the amount of sunlight reaching Earth’s surface happened in the 1950s to 1980s, which probably slowed down global warming in the mid 20th century (Wild 2009). Still, occasional bursts of variability every $\sim 10$ Myr in F dwarfs would be hard to rule out observationally without something like Kepler.

Second, it is possible that the anomaly has nothing to do with Boyajian’s Star itself, but is due to obscuration by unassociated intervening material. Wright & Sigurdsson (2016) list several possible ISM structures that could affect the star’s brightness, including tiny-scale atomic structure, Bok globules, and disks around stellar remnants. The advantage of this scenario is that it would leave no trace in the host star since nothing is actually happening there. If this scenario is true, then no doubt the Sun displays a similar anomaly to other stars in the Galaxy without our knowing it.

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2 WISE later showed that the Sun has no distant stellar or brown dwarf companions (Luhman 2014).
Makarov & Goldin (2016) argue that astrometric fitting of Boyajian’s Star in Kepler data also supports an ISM obscurer, because it appears to be blended with other sources that also are variable.

If the obscuration is due to the ISM, the anomaly should appear more often in stars that are distant from us and located behind large columns of gas, perhaps the molecular gas associated with star-forming regions like those in Cygnus. A volume-limited sample of nearby stars would find disproportionately few examples of the phenomenon. Maybe that’s why K2 hasn’t found anything like Boyajian’s Star: it mostly observes fields away from the Galactic Plane (Howell et al. 2014). Likewise, there may be no Boyajian’s Star analog among the 200,000 stars to be examined by the Transiting Exoplanet Survey Satellite (TESS): these are nearer than the Kepler targets and at a diverse range of galactic latitudes (Ricker et al. 2014).

3.3. Is an intervening cloud compatible with submillimeter data?

Obscuration by a dusty cloud in the ISM is compatible with $\Gamma_{\text{host}}$, and Wright & Sigurdsson (2016) note that small enough clouds would go unnoticed in optical light. Dusty clouds glow at submillimeter wavelengths, however, as they are heated to $\sim 20$ K by background starlight (Draine 2011). One test of the intervening cloud test is submillimeter observations.

The thermal flux at a frequency $\nu$ from a cloud with a temperature $T$ is

$$F_\nu = \frac{2h^3\Omega}{c^2} \frac{1 - e^{-\tau_\nu}}{e^{-h\nu/(kB T)} - 1} \approx \frac{2h^3\Omega}{c^2} \frac{\tau_\nu}{e^{-h\nu/(kB T)} - 1},$$

for a cloud covering a solid angle $\Omega$ of the sky with an absorption optical depth at $\nu$ of $\tau_\nu$. The other constants are $c$, the speed of light; $h$, Planck’s constant; and $kB$, Boltzmann’s constant.

We can estimate the minimum size of the cloud from the proper motion of Boyajian’s Star, $\mu = 0.0153''$ yr$^{-1}$ (Zacharias et al. 2013), as long as the motions of the cloud and Boyajian’s Star are uncorrelated. Then the angular width of the cloud is $\theta \geq \mu t_{\text{anom}}$, and the solid angle covered is $\Omega \approx \theta^2 \geq (\mu t_{\text{anom}})^2$. Assuming $t_{\text{anom}} \approx 100$ yr, $\theta \geq 1.5''$, and $\Omega \geq 2.3''^2$. A minimal cloud would be unresolved by the Submillimeter Array, which observed the star with a beam size of $4'' \times 3''$ (Thompson et al. 2016). The cloud must be smaller than $\sim 1'$ in diameter, since there are non-anomalous stars at that angular distance (Wright & Sigurdsson 2016).

The optical depth of the cloud at visible wavelengths is approximately the observed fractional dimming of the star’s brightness. To extrapolate this optical depth to submillimeter wavelengths, I use the extinction curves given in Fitzpatrick & Massa (2007). At an infrared wavelength $\lambda$, these curves can be described with a function

$$k(\lambda - V) = (0.63R_V - 0.83) \left( \frac{\lambda}{\mu \text{m}} \right)^{-1.84} - R_V, \quad (7)$$

using a reddening coefficient of $R_V = 3.001$ (Fitzpatrick & Massa 2007). The ratio of $\tau_\nu$ to $\tau_V$ in $V$-band is then

$$\frac{\tau_\nu}{\tau_V} = 1 - \omega_\nu \frac{k(\lambda - V) + R_V}{R_V}, \quad (8)$$

where $\omega_\nu = 0.5$ is the albedo of interstellar dust in $V$-band and $\omega_\nu = 0$ is the albedo at submillimeter wavelengths (Draine 2011). For reference, I also consider the case of black dust with equal opacity at all frequencies.

Table 1. Expected submillimeter flux from a minimal obscuring cloud

| $\lambda$ (µm) | $\tau_\nu/\tau_V$ | $F_\nu$ (mJy) | $F_\nu^{\text{black}}$ (mJy) | $F_\text{max}$ (mJy) |
|---------------|------------------|--------------|------------------|------------------|
| 1100         | $1.8 \times 10^{-6}$ | 6.2 $\times 10^{-5}$ | 35                | 32.1             |
| 850          | $2.9 \times 10^{-6}$ | 1.5 $\times 10^{-4}$ | 51                | 2.55             |
| 450          | $9.3 \times 10^{-6}$ | 7.1 $\times 10^{-4}$ | 77                | 2.19             |

Note—I assume $T = 20$ K, $\Omega = (1.5'')^2$, and $\tau_V = 0.03$. $F_\nu$ is the predicted submillimeter flux using the Fitzpatrick & Massa (2007) extinction law. $F_\nu^{\text{black}}$ is the submillimeter flux if $\tau_\nu = \tau_V$. The observed flux limits from Thompson et al. (2016) are listed under $F_\text{max}$.

As seen in Table 1, the predicted submillimeter fluxes of a 20 K cloud with $\tau_V = 0.03$ (as required for the Kepler dimming) is easily consistent with the submillimeter flux limits (Thompson et al. 2016). If the cloud has the minimum required size and density, it is $\sim 3,000$ times too faint to detect. If I use $t_{\text{anom}} = 10,000$ yr to calculate $\theta$, then the cloud is about 3 times the flux limits. An unphysical black cloud should have been detected by the Submillimeter Array.

If molecular, the mass of a minimal cloud would be abnormally small compared to known structures. An extinction-to-gas ratio of $A_V/N_H = 5.3 \times 10^{-22}$ cm$^{-2}$ H$^{-1}$ implies a gas mass of $2 \times 10^{27}$ g $\approx 0.3$ M$_{\odot}$ for $A_V \approx 0.03$, assuming a distance of 200 pc (Draine 2011). A cloud that dilute could not be gravitationally bound. The maximum mass allowed by the submillimeter data for an unresolved cloud is $\sim 6 \times 10^{30}$ g $\approx 0.003$ M$_{\odot}$.

Transient clumps of gas are generated in molecular clouds by supersonic turbulence (Mac Low & Klessen...
but most such clumps follow the Larson (1981) relation between velocity dispersion and length scale. With a diameter of \( \sim 0.0015 \) pc, an extrapolation of Larson’s relations for a self-gravitating clump gives a mass of \( \sim 0.002 \, M_\odot \), requiring the cloud to be almost detectable (Draine 2011). Put another way, the characteristic surface density of Galactic molecular clumps is \( \sim 200 \, M_\odot \, \text{pc}^{-2} \) (Solomon et al. 1987), whereas a minimal cloud has \( 0.5 \, M_\odot \, \text{pc}^{-2} \). A typical density cloud is allowed by the submillimeter data, but the mass must be hidden in sub-clumps to avoid obscuring Boyajian’s Star too much. Perhaps sub-clumps are responsible for the larger eclipses, although they would have to be extremely small and themselves would be dilute. In a Kolmogorov turbulence cascade, density contrasts are expected to be negligible on small scales (Elmegreen & Scalo 2004; this is also the case for plasma turbulence, as in Armstrong et al. 1995). Supersonic turbulence can generate sharp features like shocks, though (Elmegreen & Scalo 2004).

An intervening disk explanation may better explain the size of the cloud (Wright & Sigurdsson 2016).

3.4. Alternatives to a common anomaly

There are a couple of caveats to my calculation of \( \Gamma_{\text{host}} \) and its favoring of ISM obscuration.

The main loophole is if \( t_{\text{anom}} \) is actually much longer than 10,000 yr. In order to be true, the apparently secular dimming must actually be an oscillation on century (or longer) timescales, which only appears to be monotonic because we only have data over a century. I assumed that the dimming trend is non-repeating because the light curve appears to be roughly constant for the early 20th century (as in Hippke et al. 2016b). Most of the dimming is concentrated in the last few years, as observed with Kepler (Montet & Simon 2016). But a long period of constant flux punctuated by drops would be the expected light curve if Boyajian’s Star is eclipsed by a distant companion’s disk (although an improbable case according to Wright & Sigurdsson 2016). If it is shown that Boyajian’s Star was brightening decades ago, this would be evidence that the dimming is actually an oscillation. Then the relevant timescale would be the duration the star is variable, which could be millions of years.

The anomaly might be observed as a fluke even if the actual value of \( \Gamma_{\text{host}} \) is much smaller than calculated. If the true value is \( p \ll 1 \) times the derived value, then the probability that the anomaly would be observed in the Kepler field is \( \sim p \). For example, the anomaly is consistent with being a singular event in main sequence stars (\( N_{\text{life}} = 1 \)) at \( p = 1/300 \). This is a 3 \( \sigma \) deviation — very unlikely, but not unheard of.

The other possibility for a fluke is that the secular dimming is unrelated to the eclipses of Boyajian’s Star. Then, the derived \( \Gamma_{\text{host}} \) would still apply to the dimming but not to the eclipses, which could have been happening for millions of years. Of 644 F dwarfs with good photometry in the DASCH Harvard data, Lund et al. (2016) found that 11 of them (1.7\%) of them have significant variability on century timescales. Boyajian’s Star is not one of these 11, so the number of stars with enough anomalous variability may be greater. Montet & Simon (2016) found that the level of variability in Boyajian’s Star over the Kepler mission is very rare. The rapid trend in the brightness for the first three years is found in 0.7\% of F stars, and the sharp fall-off of the last year is unique in the several hundred F stars they examine (Montet & Simon 2016). Again, it is unlikely but not unheard of that the dimming is an effect expected 0.1–1\% of the time and is unrelated to the unexplained eclipses. More information about the variability of F dwarfs on long timescales would be helpful in this regard.

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