

FAMILIES OF PLAUSIBLE SOLUTIONS TO THE PUZZLE OF BOYAJIAN'S STAR

JASON T. WRIGHT^{1,2} AND STEINN SIGURÐSSON

Department of Astronomy & Astrophysics and Center for Exoplanets and Habitable Worlds, The Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802, USA; astrowright@gmail.com

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ABSTRACT

Good explanations for the unusual light curve of Boyajian's Star have been hard to find. Recent results by Montet & Simon lend strength and plausibility to the conclusion of Schaefer that in addition to short-term dimmings, the star also experiences large, secular decreases in brightness on decadal timescales. This, combined with a lack of long-wavelength excess in the star's spectral energy distribution, strongly constrains scenarios involving circumstellar material, including hypotheses invoking a spherical cloud of artifacts. We show that the timings of the deepest dimmings appear consistent with being randomly distributed, and that the star's reddening and narrow sodium absorption is consistent with the total, long-term dimming observed. Following Montet & Simon's encouragement to generate alternative hypotheses, we attempt to circumscribe the space of possible explanations with a range of plausibilities, including: a cloud in the outer solar system, structure in the interstellar medium (ISM), natural and artificial material orbiting Boyajian's Star, an intervening object with a large disk, and variations in Boyajian's Star itself. We find the ISM and intervening disk models more plausible than the other natural models.

Key words: dust, extinction – extraterrestrial intelligence – ISM: structure – stars: individual (KIC 8462852, KIC 8462860) – stars: variables: general

1. INTRODUCTION

1.1. Discovery

Boyajian et al. (2016) announced the discovery of an extraordinary star, KIC 8462852, observed by *Kepler* (Borucki et al. 2010) during its prime mission. First noticed by citizen scientists as part of the Planet Hunters project³ to examine *Kepler* light curves by eye (Fischer et al. 2012), this star exhibited a series of aperiodic dimming events, with variable timescales on the order of days, amplitudes up to 22%, and a complex variety of shapes. Boyajian et al. established that the data are good and that this behavior is unique to KIC 8462852 among *Kepler* stars.

Extensive follow-up by Boyajian et al. allowed them to determine the star appears to be in all other ways an ordinary, main-sequence early F star, showing no signs of IR excess (that would be indicative of a disk or other close-in material responsible for absorption) or accretion. Indeed, the *Kepler* field was above the Galactic Plane and contains no known star-forming regions that might produce a star young enough to have significant circumstellar material. Using AO, Boyajian et al. (2016) did discover a 2" companion consistent with a bound M4V star at a projected distance of ~900 au, but this is not unusual, nor does it seem to provide any explanatory power for the star's *Kepler* light curve.

Boyajian et al. constructed "scenario-independent constraints" for the source of occulting material under the assumption that it is circumstellar, based on the duration and depths of the events, their gradients, the lack of IR excess, and other considerations. This allowed them to rule out many scenarios, and they offered a provisional explanation that *Kepler* had witnessed the passage of a swarm of giant comets. The hypothetical comets, which must be very large to block an appreciable amount of stellar flux, would only have produced a significant infrared excess during their periastron passage (presumably around the time of the *Kepler* mission), thus explaining the lack of IR excess at other times. Bodman & Quillen (2016) modeled this scenario, and found it would required hundreds to thousands of comets, perhaps tidally disrupted from a Ceres-massed progenitor, to explain the final 60 days of the *Kepler* light curve. Despite this success, that also found that they could not reproduce the long, slow, deep event observed during *Kepler* Quarter 8, casting doubt on the comet hypothesis.

Interest in KIC 8462852 (which we will refer to as "Boyajian's Star"⁴) increased significantly in response to popular media accounts of the work of Wright et al. (2016), who connected it to the speculation of Arnold (2005) that *Kepler* could discover large artificial structures orbiting other stars, if they exist. That is, rather than a swarm of comets, Wright et al. noted that a swarm of planet- or star-sized structures would produce numerous transit anomalies, including arbitrary ingress and egress shapes, anomalous transit bottom shapes, variable depths, and aperiodicity—all of which characterize Boyajian's Star's dimming events. Wright et al. recommended that, until Boyajian's Star's light curve had a more plausible natural explanation than had been offered to date, SETI⁵ researchers prioritize it in their searches for communication from extraterrestrial civilizations.

¹ Visiting Associate Professor, Breakthrough Listen Laboratory, Department of Astronomy, University of California, Berkeley, CA 94720, USA.

² PI, NASA Nexus for Exoplanet System Science.

³ http://planethunters.org

⁴ The star has picked up other popular monickers, including "WTF" (ostensibly for "Where's the Flux?," the subtitle to the Boyajian et al. (2016) paper), and "Tabby's Star" (with Dr. Tabetha Boyajian being its namesake). We agree that a more memorable name than KIC 8462852 seems warranted for this extraordinary object, and choose "Boyajian's Star" in keeping with the long astronomical tradition of similar eponyms, such as Barnard's Star, Kapteyn's Star, Teegarten's Star, etc.

⁵ The search for extraterrestrial intelligence, e.g., Tarter (2001).

1.2. Follow-up

Marengo et al. (2015) and Lisse et al. (2015) analyzed *Spitzer* and *IRTF* observations, respectively, taken after the *Kepler* observations, and showed that the lack of IR excess noted by Boyajian et al. (2016) (based on *WISE* data; Wright et al. 2010; taken before the *Kepler* observations) continued to later epochs. This ruled out many scenarios involving a cataclysmic, dust-generating event in a planetary system that occurred between the *WISE* and *Kepler* epochs. Boyajian et al. showed that the gradients of the dips were consistent with material on a circular orbit at ~10 au, where in equilibrium it would be quite cool and would escape detection at these wavelengths.

Thompson et al. (2016) found no significant millimeter or submillimeter emission and put an upper limit of 7.7 M_{\oplus} on the total circumstellar dust mass within 200 au. This upper limit rules out very massive debris disks orbiting KIC 8462852. Thompson et al. note that only $10^{-9} M_{\oplus}$ of dust is required to explain one of the deepest dimming events seen by *Kepler* and give an upper limit of $\sim 5 \times 10^{-3} M_{\oplus}$ for dust on elliptical orbits at the distances favored by the cometary hypothesis.

On the SETI front, Abeysekara et al. (2016) found no evidence of optical flashes using the VERITAS gamma-ray observatory. Harp et al. (2016) and Schuetz et al. (2016) found no evidence of narrowband radio communication or pulsed laser emission during a simultaneous viewing campaign with the Allen Telescope Array and the Boquete Optical SETI Observatory, respectively.

Only one part of the analysis of Boyajian et al. (2016) showing Boyajian's Star to be an otherwise ordinary F3V star has been called into question: Schaefer (2016) used archival DASCH photographic plate photometry (Grindlay et al. 2012; Tang et al. 2013) to recover 100 years of brightness measurements for the field from 1890 to 1989. Schaefer's thorough analysis showed that Boyajian's Star "faded at an average rate of 0.164 ± 0.013 mag per century," which he claimed "is unprecedented for any F-type main sequence star" and "provides the first confirmation that KIC 8462852 has anything unusual" beyond the *Kepler* dips.

This claim, at least as extraordinary as the *Kepler* light curve itself, prompted multiple groups to attempt to confirm or refute it. Hippke et al. (2016) and Lund et al. (2016) found that the systematic errors in the DASCH photometry do not permit measurements at the accuracy claimed by Schaefer. In addition, Lund et al. (2016) found several *other* F stars that they claimed *do* show such long-term variations in brightness.

Montet & Simon (2016) performed an analysis of the fullframe images from the *Kepler* mission to determine if the secular dimming continued into the 21st century. They found that Boyajian's Star indeed shows irregular, monotonic fading at an average rate of ~0.7 mag per century (four times the Schaefer average) and was ~4% dimmer at the end of the mission than the beginning. They also show that many of the F stars that Lund et al. found to have secular photometric trends are revealed by *Kepler* to in fact be shorter-term variables and that the secular dimming of Boyajian's Star in the *Kepler* data is unique among the >200 stars they studied.

We agree with Montet & Simon's suggestion that the independent detection of an extraordinary, secular dimming of Boyajian's Star in the *Kepler* data makes Schaefer's result from the DASCH photometry more plausible, and with their

assessment that such dimming finds little or no explanation from the comet hypothesis.

We are thus left with no good explanation for the dimmings of Boyajian's Star—neither the complex, short-period events during the *Kepler* epoch, nor the similar amplitude, secular trends seen in both the DASCH photometry and the *Kepler* full-frame photometry.

1.3. Plan and Purpose of This Letter

Montet & Simon conclude their paper by stating that they "strongly encourage further refinements, alternative hypotheses, and new data in order to explain the full suite of observations of this very mysterious object." This Letter's purpose is to be responsive to their encouragement. In Section 2, we examine the periodicities of the deepest dips, and in Section 3, we examine the constraints on solutions imposed by the spectral energy distribution (SED) of Boyajian's Star. In Sections 4–11, we discuss several families of solutions with various degrees of plausibilities in light of these constraints.

In this work, we shall use the term "dimming" in a generic sense, to refer to the observed changes in the brightness of Boyajian's Star on all timescales. We adopt the term "dips" from Boyajian et al. for the days-long events seen in the *Kepler* light curve and "secular" or "long-term" dimming for the changes in brightness noted by Schaefer and Montet & Simon.

In our discussion below, we assume that the long-term dimming identified by Schaefer and Montet & Simon is real. The combined $\sim V$ -band dimming from the two works is 17% = 0.20 mag, which, according to the reddening law of Fitzpatrick (1999) for interstellar dust, would imply the total extinction across the spectrum of Boyajian's Star of 15%.

2. PERIODICITIES IN THE DEEPEST KEPLER DIPS

A potential constraint on the location of the cause of the dimming is periodicities in the patterns of dips in the *Kepler* light curve. Periods near 1 year might indicate obscurers in or near the solar system, with dimming modulated by the annual parallax. Other periods would presumably correspond with the orbital motion of material orbiting Boyajian's Star.

Indeed, the deepest points of the deepest dips (at *Kepler* days 793 and 1523) occur 2.000 years apart, a suspiciously precise interval. It should be noted, however, that *Kepler* is in an Earth-trailing orbit with an orbital period⁶ of 372.5 days. This means that the dips are separated by 1.96 *Kepler* years and that the dips' separation's coincidence with an Earth sidereal year is not important.

Further, taking the six deepest dips (at *Kepler* days 261, 793, 1206, 1496, 1523, and 1568), one finds that they all fall within a narrow range of phases when folded at a period near 24.2 days, suggesting a close-in orbital period. Boyajian et al. (2016) paid particular attention to the possibility of a 48.4 day orbital period with events occurring at both primary and secondary eclipse.

⁶ Mullally et al. (2016) and http://www.nasa.gov/mission_pages/kepler/ spacecraft/index-mission.html; retrieved 2016 July 27.

To check the significance of this period, we constructed a metric of clustering:

$$M = \left(\sum_{i} \sin \phi_{i}\right)^{2} + \left(\sum_{i} \cos \phi_{i}\right)^{2}$$

where $\phi_i = 2\pi t_i/P$ is the phase of dip *i* occurring at time t_i when folded at a given period *P*.

Indeed, a search of 2000 periods evenly sampled in frequency between 10 and 700 days reveals that M(P) is maximized with a value of 32.9 at P = 24.2 days. We then repeated this exercise for 10,000 mock sets of six dips with times randomly drawn from a uniform distribution with the same range as the *Kepler* time series. The corresponding set of 10,000 max(M) values has median 30.4, with 16.5% of all mock sets having a higher value (i.e., more significant clustering) than the actual *Kepler* dips. The median period P that maximized M in each of the 10,000 mock sets was 20.8 days.

From this we conclude that the apparent periods found among the deepest dips are unlikely to be significant, though we acknowledge that more robust statistical treatments are likely available.

3. CONSTRAINTS FROM OTHER DATA

3.1. Optical Constraints

The SED and spectra presented by Boyajian et al. and updated with longer-wavelength upper limits by Thompson et al. put two important constraints on the obscuring material.

Combining a spectroscopic temperature and metallicity with stellar models and the observed SED, Boyajian et al. found that Boyajian's Star suffered 0.11 ± 0.03 mag of E(B - V) color excess in 2014, ~1 year after the end of the *Kepler* data series.⁷ If this is due to standard interstellar reddening, this implies $A_V \sim 0.34$, or 37% V-band obscuration due to dust (corresponding to an optical depth $\tau_V \sim 1$).

The narrow sodium absorption features seen by Boyajian et al. in the spectrum have multiple components, implying multiple clouds of interstellar material contribute to this extinction. B. J. Fulton and Andrew Howard observed Boyajian's Star with Keck/HIRES (Vogt et al. 1994) on UT 2015 October 31. The D2 line is well modeled by a smoothed telluric spectrum (Wallace et al. 2007), a parabolic stellar line (which is not physical but is simple and describes the data well), and three Gaussian components (Figure 1) having equivalent widths 170, 200, and 50 mÅ, for a total of 420 mÅ.

The velocities of the sodium absorption features are offset from the center of the stellar line by $5-30 \text{ km s}^{-1}$. If the secular dimming persisted into 2015, then the lack of a component at the center of the stellar lines implies that there is not a persistent, circumstellar absorber with a neutral gas component, unless it somehow has significant radial motion (so not on a circular orbit).

The velocities of the sodium absorption features are offset from each other by 25 km s^{-1} , which exceeds the escape velocity of the Sun at 5 au and is comparable to the escape velocity from Uranus. They are thus unlikely to be due to different parts of a single structure and very likely to be due to interstellar gas. It is perilous to extrapolate broadband extinction from sodium absorption features, which may be unresolved and saturated, and at any rate traces only neutral gas, not dust. But following Poznanski et al. (2012), who used high- and low-resolution QSO spectra to establish an empirical prescription, a D2 equivalent width of 420 mÅ corresponds to E(B - V) = 0.1, and so is consistent with the observed color excess.

Together, these observations are consistent, and require that Boyajian's Star be suffering roughly 35% extinction due to interstellar dust, and not significantly less or more.

3.2. IR and Millimeter Constraints

The *WISE W4* upper limit and the millimeter upper limits by Thompson et al. are difficult to reconcile with the amount of long-term dimming seen for scenarios invoking spherical clouds of circumstellar material.

The absorbing material must be cold enough not to produce significant 20 μ m emission and have a low enough surface area not to contribute significant 1 mm emission. Following the "AGENT" parameterization of Wright et al. (2014a), we quantify the total fraction of stellar flux reradiated at temperature *T* by circumstellar material with the parameter γ . As Figure 2 shows, the data require $\gamma < 0.2\%$ at T = 65 K. Other temperatures put even tighter restrictions on γ (since all of the longband flux must "fit between" the SCUBA and *WISE* upper limits, changing the temperature in either direction shifts the flux into one of those bands).

The WISE and Thompson et al. data thus argue that the longterm dimming seen by Schaefer and Montet & Simon cannot be isotropic. That is, if the Schaefer plus Montet & Simon dimming of $\sim 17\%$ occurs for observers along all lines of sight, then the absorbing material would easily be detectable at millimeter wavelengths, regardless of its temperature. Only circumstellar material intercepting less than 0.2% of the stellar flux—for instance, in a disk—is consistent with the data.

James Webb Space Telescope (JWST) photometry between 20 and 1000 μ m would further constrain such circumstellar scenarios.

3.3. Photometry of Nearby Stars

Classes of solutions that invoke solar system or interstellar material (Sections 6 and 7) would find support if stars near Boyajian's Star show similar photometric effects. Montet & Simon examined the brightnesses of stars in the *Kepler* field $\sim 1'-5'$ away. The lack of secular dimming or dips in these stars constrain such a hypothetical cloud to be smaller than this scale. To this end, Benjamin Montet (2016, private communication) examined KIC 8462860, a fainter star 25" NNW of Boyajian's star, in the same manner Montet & Simon produced their light curve of Boyajian's star. Figure 3 shows that this star shows no significant long-term dimming, showing that if such a cloud exists, it does not extend this far to the NNW from Boyajian's Star.

Of course, without distance information it is unclear whether KIC 8462860 would be in front of or behind any interstellar absorbers responsible for the dimming from Boyajian's Star. Nonetheless, we encourage ongoing and future studies of Boyajian's Star to similarly monitor neighboring stars for signs of dimming that might support such hypotheses.

⁷ The *BVRI* measurements reported in Boyajian et al. (2016) were made 2014 June 6–10 (K. Vida & T. Boyajian 2016, private communication).



Figure 1. Top: Keck/HIRES spectrum of the D2 line of Boyajian's Star, with a smoothed Wallace et al. (2007) telluric spectrum overlain. Middle: a telluricsubtracted spectrum with a simple paraboloidal model to the rotationally broadened D2 line. Bottom: detail of the narrow absorption features, modeled with three components. HIRES spectrum courtesy of B. J. Fulton and Andrew Howard. Plots and analysis courtesy of Jason Curtis.



Figure 2. NEXTGEN spectrum (Hauschildt et al. 1999) of Boyajian's Star ($T_{\rm eff}$ 6750 K, $\log(g) = 4.0$ [cgs], [Fe/H] = 0), reddened by E(B - V) = 0.11 following Fitzpatrick (1999). Two cases are shown, with 15% and 0.2% of the stellar flux reprocessed at T = 65 K (parameterized here using the AGENT formalism of Wright et al. 2014a where γ is the fraction of stellar flux reprocessed). The measurements and (1 σ) upper limits are taken from Boyajian et al. (2016) and Thompson et al. (2016). In both cases, the SEDs are scaled to the optical photometry. The upper limits show that less than 0.2% of the stellar flux is reprocessed as thermal emission. Thompson et al. showed this is equivalent to $\langle 7.7M_{\rm fl} \rangle$ of dust within 200 au.

4. POSSIBILITIES

The fact that Boyajian's Star is rare—LaCourse (2016) finds no similar star among the ~150,000 *Kepler* prime mission stars or any of ~165,000 *K2* targets—suggests that the correct solution is an inherently unlikely one. This unlikelihood may help explain why few or no plausible solutions to the puzzle have yet been offered in the literature. We will therefore attempt a "clean-sheet" survey of possible solutions, employing a higher threshold for dismissal than one might normally use.

Occum's Razor points toward a single explanation for both the secular dimming and the dips. Of course, in principle they may be unrelated, in which case Boyajian's Star is extraordinary for two independent reasons. The possibilities we explore below will for the most part be general enough that they could explain either effect, but we will favor explanations that could plausibly cause both and in each case discuss how this could happen.

There are four possible locations for the dimmings: in the solar system, in interstellar space, orbiting Boyajian's Star, and Boyajian's Star itself. These lead to six broad categories of solutions: instrumental effects, material orbiting the Sun, an interstellar cloud or disk, circumstellar dust, other circumstellar material such as artifacts, and a rare form of stellar variability.



Figure 3. Figure kindly provided by Benjamin Montet, showing the photometric time series for KIC 8462860, 25" NNW of Boyajian's Star, analyzed in the same manner as Boyajian's Star in Montet & Simon (2016). This star shows no significant secular dimming, constraining the size of any cloud of material in this direction.

In the following sections, we discuss families of solutions in each of these categories. Since our purpose is to circumscribe the space of plausible solutions, and since Boyajian's Star may be an example of a new astrophysical phenomenon for which no good precedent exists, we will usually avoid committing ourselves to a particular model, preferring to consider families of solutions generally, even at the cost of being somewhat vague.

5. INSTRUMENTAL EFFECTS

Boyajian et al. (2016) carefully ruled out instrumental effects in the *Kepler* camera or data pipeline. The significant public attention to the star created a renewed interest in the data, and other groups, such as Montet & Simon, have independently reproduced the signal from the public *Kepler* data. All pixels with significant flux from Boyajian's Star show similar features, ruling out a problem with any individual pixel. Dips were observed when the star was being monitored by four separate modules as the spacecraft rotated, ruling out a problem with any particular module.

The long-term dimming in the DASCH data may be more easily explained as instrumental—indeed Hippke et al. and Lund et al. argue this dimming is entirely instrumental—but the care of Schaefer's analysis and the confirmation of secular dimming by Montet & Simon suggest it is real.

6. SOLAR SYSTEM OBSCURATION

Material in orbit around the Sun suffers significant parallactic motion: at a distance of 10,000 au, the annual motion of the Earth (or *Kepler*) corresponds to a parallax of 20". In order to persistently dim Boyajian's star and explain the secular dimming, the material must span this angle, and so be

~1 au across at that distance. The material's own orbital velocity is smaller by $\sim 1/\sqrt{a}$ or ~100 at that distance, consistent with the effects being observable for 100 years. Material closer than this distance must span a proportionally larger space to persist on annual and century timescales. Material much farther than 100,000 au should be considered interstellar (see Section 7).

If obscuring material in the solar system, then the variations in the brightness of Boyajian's Star would be due to a varying optical depth along our line of sight through the cloud as the Earth and *Kepler* orbit the Sun. The dips would thus probe the structure of the cloud on scales of hundredths of an au, while the secular dimming described variations in its optical depth on au scales. In this scenario, the dips in the *Kepler* data are not strictly periodic, as might be expected for parallactic motion, because the cloud itself has orbital motion, so each *Kepler* year probes a slightly different part of the cloud.

This scenario finds weak support in the fact that the two deepest dips occur 1.96 *Kepler* years apart, potentially reflecting time for return of the line of sight to a dense part of the cloud, with a $\sim 2\%$ correction for the cloud's orbital motion. The absence of significant dips of 0.98 *Kepler* year before and after the day 793 dip would then be difficult to explain.

If such clouds were abundant, we would have expected other examples of Boyajian's Star to have been discovered in the past, so if this solution is correct they must be rather rare, but there is no obvious physical reason that such a cloud could not persist if it were cold. The mass required to hold such material within a Hill sphere is not large—a small asteroid would suffice. The surface brightness in reflected sunlight would be extremely low at such a distance, especially if the dust albedo were low, and at any rate obscured in low-resolution images by Boyajian's Star itself.

The primary difficulty with this picture is that we have no reason to expect that there exist ~1 au sized, $\tau \sim 1$ clouds of dust in the far reaches of the solar system, especially clouds containing 10^{-2} au, $\tau \sim 1$ clumps. This difficulty is only enhanced by the high ecliptic latitude of Boyajian's Star (+62°). The origin and persistence of such clouds are uncertain to say the least, but might be created by material being gently ejected by a geyser on a geologically active Kuiper Belt object or Oort cloud member, or a slow collision between comets. If the resulting material was sufficiently cold (30 K), then the thermal velocity of ~100 m s⁻¹ is consistent with the orbital speeds at these distance. A 1 au diameter cloud then lasts for 10^9 s (i.e., centuries).

This possibility perhaps should be explored further, especially if neighboring stars are observed to exhibit similar dimmings.

7. OBSCURATION BY INTERSTELLAR DUST

7.1. Obscuration by Dense Regions of the ISM

The modest Galactic latitude of Boyajian's Star (b = +6) allows for significant extinction along the line of sight. Schlafly & Finkbeiner (2011) estimate the total E(B - V) in this direction is 0.95 mag, significantly above the measured value of 0.11 mag, indicating that most of the dust (and structure in their extinction map) lies behind the star.

Green et al. (2015) provide a three-dimensional dust map in this direction, but it is unreliable at the distance of Boyajian's Star (~450 pc; their Figure 8 and Web interface⁸ shows that results are only meaningful beyond ~500 pc). That said, their "best-fit" reddening at a distance of 450 pc is E(B - V) = 0.09, consistent with the observed reddening in 2014.

The fact that other stars suffering from significant interstellar absorption have never been observed to exhibit behavior similar to Boyajian's Star would suggest that the interstellar medium (ISM) is not responsible. Nonetheless, we should explore how such obscuration could explain the observed data.

The space velocity of Boyajian's Star is $\sim 30 \text{ km s}^{-1}$ (Boyajian et al. 2016). Our line of sight to the star thus traverses intervening structure at similar rates, on the order of au yr⁻¹. The dips in the *Kepler* data would thus imply significant sub-au structure in the ISM.

Small neutral structure in the ISM exists. Heiles (1997) describes how observations of "tiny-scale atomic structure" (TSAS)—exhibited in angular and temporal variations in hydrogen absorption features in pulsar and quasar spectra—are best explained by the alignment of filaments and sheets of cold (15 K) neutral material along the line of sight. Heiles (2007) summarized the canonical values for TSASs, including a neutral HI column of $\sim 10^{18}$ cm⁻² and length scale of 30 au. Such TSAS should be overpressurized with respect to the surrounding ISM, and so evolve dynamically on a timescale of 10^3 years.

These values for the dynamical timescale and physical size are broadly consistent with the secular dimming exhibited by Boyajian's star, but these canonical column densities are too low to generate the optical depths seen in the dimmings of Boyajian's Star by a factor of $\sim 10^2$ (e.g., Güver & Özel 2009, who find $A_V = 2.2 \pm 0.09 \times 10^{21} N_{\rm H}$), and these sizes are too large to provide a satisfactory explanation for the dips.

However, sub-au-scale structure would be quite difficult to detect without the cadence and sensitivity afforded by *Kepler*, and so would probably not have been noticed before. It is not unreasonable to conjecture that the phenomenon extends to even smaller scales and higher densities, in which case it should occasionally lead to the behavior exhibited by Boyajian's star. Indeed, Stanimirović et al. (2003) argued that such TSAS could be "a quite rare phenomenon," which may explain why Boyajian's Star is the first to show its most dramatic effects on broadband optical extinction.

7.2. An Intervening Molecular Cloud

Alternatively, there might be a chance alignment with a localized molecular cloud (as opposed to an overdense filament or sheet).

The Clemens & Barvainis (1988) catalog of small molecular clouds was selected optically based on examination of the POSS plates, and was sensitive to clouds smaller than 10', typically down to ~1'. Clemens et al. (1991) found that the mean radius of these clouds was 0.35 pc. The clouds in this catalog cluster near the Galactic plane presumably both because clouds are intrinsically more common there and because they are easier to identify in silhouette against the large number of stars there.

A quiescent Bok globule 0.1 pc $\approx 20,000$ au across and midway between Earth and Boyajian's Star would have almost certainly escaped detection. It would have a radius of 40", and examination of the POSS plates for Boyajian's Star confirms that the star counts are too low in this region to clearly reveal such a small object, especially if some of the stars in the image were foreground to it and the globule were not spherical. Such high-latitude clouds exist: Getman et al. (2008) describe the "mysterious" high Galactic latitude cloud CG12, which sits 200 pc above the plane at a distance of 550 pc (about the same distance as Boyajian's Star).

In this case, the secular dimming would be naturally explained by the changing line of sight to Boyajian's Star through the cloud's slowly varying radial column density profile, and the dips would then be explained by small-scale (sub-au) structure within the cloud.

7.3. Implications of the ISM Possibilities

In both of the above scenarios, the space motion of Boyajian's Star and the Sun (and, presumably, the cloud itself) changes our line of sight through the cloud, revealing its structure on sub-au scales, a potentially interesting development for studies of turbulence in molecular clouds and pressure in the cold ISM. Indeed, Boyajian's star would not be unique in probing an intervening molecular cloud, as many dark clouds have background stars that could serve this purpose, and the K2 mission has explored many of them in its survey of star-forming regions in the ecliptic.

As with the possibility of a solar system cloud, these scenarios could be confirmed if the much fainter stars near Boyajian's Star could be confirmed to show similar dimming behaviors, or extreme reddening from darker parts of the cloud. Indeed, the 2" stellar companion identified by Boyajian et al. (2016) as likely to be a bound M4 dwarf with projected separation 900 au might be such a star, since it has no published color, proper motion, or spectral information.

The cloud or ISM sheet or filament might also be revealed via its molecular emission, such as CO lines, with an instrument with sufficient angular resolution, such as ALMA. At the very least, single-dish observations may reveal an overdensity of atomic or molecular material in the direction of Boyajian's Star.

8. THE DISK OF AN INTERVENING OBJECT

8.1. Consistency with Existing Observations

The intervening material may be even more compact than a Bok globule: it might be a disk. Given the duration of the long-term dimming, explanations involving a disk must invoke one that is $\sim 10^2$ au across. The central object must be at least on the order of a solar mass (to support such a large disk) and nonluminous (or it would appear in the AO imaging of Boyajian et al. and it would heat the disk, producing long-wavelength emission; see Section 3.2). The disk must be non-accreting, or else the central object would be detectable.

One piece of parameter space left in this hypothesis is then a chance alignment with the disk of a dim stellar remnant, such as a black hole, quiet neutron star, or old white dwarf. The pulsar planets (Wolszczan & Frail 1992; Ford et al. 2000) provide evidence for disks of various sizes around neutron stars, and Perna et al. (2014) provide theoretical arguments for long-lived black hole fallback disks, so this possibility warrants further thought.

We note that the Einstein radius of such a black hole between Earth and Boyajian's Star is ~ 4 mas, or $\sim 10^3$ times smaller than the angular size of the disk itself, and too small to

http://argonaut.skymap.info

provide any reasonable likelihood of generating a microlensing event.

8.2. Number Density Required

We can estimate the number density of such objects in the Galaxy required for such an alignment to have a reasonable chance of one detection among 100,000 stars. Given that the timescale of the obscuration is of the order of or longer than the life of the *Kepler* mission, the volume of the Galaxy probed by a single star in the *Kepler* field is of the order of

$$V \approx D^3 (r/d)^2$$

where *D* is the distance to the star, $r \sim (30 \text{ km s}^{-1} \times 100 \text{ years}) \sim 600 \text{ au}$ is the physical size of the intervening object, and $d \sim D/2$ is its distance. If we estimate that N = 100,000 stars at typical distances of $D \sim 500$ pc were tested for similar sorts of dips, then we have 1 such detection in a search volume *NV*, so

$$n \sim (NV)^{-1} \sim 10^{-3} \,\mathrm{pc}^{-3}.$$

This is a rather reasonable number density, being an order of magnitude smaller than the number stars at the Galactic midplane ($\sim 10^{-2} \text{ pc}^{-3}$; e.g., Holmberg & Flynn 2000) and perhaps not inconsistent with the estimated $\sim 10^9$ black holes and neutron stars in the Milky Way (Timmes et al. 1996; Corral-Santana et al. 2016). This scenario thus deserves further study, especially if it is found that these sorts of cold, large disks are quite common and long-lived around such remnants, or if stellar remnants are more common than the Timmes et al. estimate.

8.3. Plausibility of Black Hole disks

Following Perna et al. (2014), we consider a fallback disk around a canonical 10 M_{\odot} black hole in the field (Cameron 1971). For a compact object, the timescales go as $M^{\frac{1}{2}}$. The initial fallback consists of a large amount of mass, 1 M_{\odot} or more for a black hole, which falls back with some finite angular momentum and stalls at the circularization radius, generally of the order of $10^2 R_{\odot}$.

The initial fallback material accretes very rapidly onto the central object, powering a bright X-ray source. This bright X-ray phase ends after $\leq 10^7$ years as the inner disk is depleted and internal angular momentum evolution drives a small amount of material outward from $100R_{\odot}$ to ~100 au. The outer disk is cold, evolving slowly on viscous timescales and internal secular evolution timescales.

The viscous timescale, $t_0 \sim 10^3 \alpha_{0.1}^{-1} M_{10}^{-1/2} R_{100}^{3/2} (R/H)^2$ years, where $\alpha_{0.1}$ is the Shakura–Sunyaev viscosity parameter (written in units of $\alpha_{0.1} = \alpha/0.1$), $M_{10} = M/(10 M_{\odot})$ is the mass of the central object, $R_{100} = R/100$ au is the radial distance, and H is the disk scale height, assumed for simplicity to be constant and $\sim R/100$.

The remnant disk mass is $\leq 10^{-2} M_{\odot}$. The disk is Toomre stable for masses less than about $10^{-3} M_{\odot}$. For disk masses above $10 M_{\oplus}$, for solar metallicities, the disk opacity is of order unity at 100 au.

At 100 au, the viscous timescale exceeds 10^8 years, and the disk evolves slowly, expanding toward 10^3 au over the lifetime of the object, the (metal-rich) fallback material will have created dust that will presumably evolve similarly to the outer solar system disk, but slowly. Planetesimal growth and secular

disk instabilities will lead to au-scale substructure in the disk, consistent in principle with the observed dips. Slower variation in surface density with radial distance would then explain the secular dimming.

Since the central illumination is near zero by hypothesis, and since the viscous timescale is long, the heating of the disk is minimal and it will quickly cool to very low temperatures, well below the upper limit set by Thompson et al.

Since some fraction of black holes formed by supernovae should have such fallback disks and since angular momentum conservation demands an extended remnant disk, the primary remaining question with this suggestion is their overall frequency and the detailed probability of having seen one occult a star in the *Kepler* field.

8.4. Intervening Disk of a Binary Companion

A disk similar to the sort discussed in above might also be found in orbit around Boyajian's Star, instead of in the field. It could then be smaller than in the interstellar case, having a minimum physical size $r \sim \tau/v$ set by the $\tau \sim 100$ -year duration of the Schaefer dimming and its orbital velocity v. However, in this case, the angular extent leads to a very unlikely alignment. If a fraction *f* stars have companions of this sort, spanning angular size r/a as seen from the star, then the probability of an alignment (obscuration) is

$$p \sim f(r/a)^2/(4\pi)$$

However, by (Johannes) Kepler's Laws, $v^2 \sim 1/a$, and from (the observatory) *Kepler*, we have $p \sim 10^{-5}$, yielding

 $f \sim 10^{-8} a^3$

with a in units of au. For wide companions at $a \sim 10^3$ au, this yields $f \sim 10$, meaning that even if every star had a companion capable of producing the dips in Boyajian's Star, we would only have a 10% chance of having seen it in the entire *Kepler* data set.

Decreasing *a* to 100 au brings this down to $f \sim 1\%$, which is better but still very implausible and begins to conflict with the constraints from the lack of infrared excess, and the considerations presented in Boyajian et al. (2016). While these probabilities seem too low to make this scenario plausible, objects such as EE Cep (Gałan et al. 2010; Graczyk et al. 2003) and ϵ Aur (Kloppenborg et al. 2010) exist, so it perhaps should not be entirely dismissed.

Another possibility is that the disk material is associated with the 2" companion identified by Boyajian et al. This appears to be a found M4 dwarf at projected separation 900 au, and so would need to have a disk at least 900 au in radius to be responsible for the dimming in this scenario, and yet contributes no long-wavelength excess to the SED of Boyajian's Star, which seems unrealistic. Boyajian's Star (and so too, presumably, the M4 companion) shows no signs of youth or accretion, so an optically thick disk would not be expected around either.

9. CIRCUMSTELLAR MATERIAL

Boyajian et al. (2016) discussed circumstellar scenarios extensively and concluded that material such as comets on eccentric orbits could be responsible for the short-term dips. Before the long-term dimming of Boyajian's Star was discovered, other possibilities invoking ephemeral close-in

material were possible, for instance, material ejected by a closein planet, similar to KIC 12557548 (Rappaport et al. 2012).

We will not repeat the discussion of Boyajian et al. here, except to note that explanations invoking any stellar-mass close-in orbital companions (such as stars or stellar remnants) are ruled out by the lack of radial velocity variation seen by Boyajian et al. (2016). Atomic circumstellar material at small orbital velocity being responsible for the secular dimming is also inconsistent with the lack of sodium absorption at zero velocity (Section 3.1).

While the asymmetric light curves of some of the dips are reminiscent of the transit profiles of gravity darkened stars, their depth and lack of periodicity preclude such transits, and the star's rotation period (which Boyajian et al. 2016 measured from the photometry and spectral broadening) precludes significant gravity darkening.

It is worthy of note that light curves with some qualitative similarities to Boyajian's Star have been observed for the central stars of planetary nebulae (e.g., Mendez et al. 1982; Miszalski et al. 2011). These events are thought to involve the formation of dust in the planetary nebula and modulated by the binary orbital motion of the central star. The lack of any signs of a planetary nebula or similar source of dust toward Boyajian's Star (such as significant W4 emission from WISE) would seem to rule out a similar explanation for it. This explanation does bear qualitative similarity, however, with the interstellar dust explanations proposed in Section 7. Similarly, a class of young stars with disks known as "dippers" have asymmetric and variable-depth dips, similar to those seen in Boyajian's star (Ansdell et al. 2016; Scaringi et al. 2016). However, whereas dippers are observed to have strong IR excesses from their disks, Boyajian's Star shows no IR excess belying close-in dust, and so must have a different explanation.

The possibility of a cloud in the outer solar system from Section 6 has a counterpart in this section in the form of a large cloud with large orbital period orbiting Boyajian's Star. The constraints on its size then come only from its orbital motion, with the effects of parallax being negligible.

10. ARTIFICIAL STRUCTURES

10.1. Fleshing Out the Hypothesis

Because we have no way beyond fundamental physics to constrain or parameterize the likelihood or nature of artificial structures that may be orbiting Boyajian's Star, it is a sufficiently flexible model to fit almost any data. As such, it should be an "explanation of last resort" (Wright et al. 2016). Nonetheless, until the mystery is solved it is worthwhile to at least outline a straw-man version of the hypothesis.

Lintott & Simmons (2016) suggested, apparently tongue-incheek, that the secular dimming of Boyajian's Star might be representative of the pace of construction of a "Dyson sphere" orbiting Boyajian's Star (Dyson 1960). A similar possibility is skeptically mentioned by Villarroel et al. (2016) with respect to the object USNO-B1.0 1084-0241525, which seems to have disappeared in the past few decades. A simpler hypothesis than such rapid construction rates exists, however.

For the sake of concreteness, assume the artificial structures to be thin panels used for stellar energy collection to be used on-the-spot to power "factories" performing some task (Wright et al. 2014b). The panels might have a range of sizes, from $\sim 1 \text{ m} - 1 R_{\odot}$. Their shapes, too, might be arbitrary, or they may

orbit in formations. Finally, they might span a range of orbital distances, and so have a range of orbital velocities. They would thus form a "swarm," with the smallest panels effectively acting as an opaque screen, larger panels causing the star to flicker as they transit, and the largest ones causing the dips seen in the *Kepler* data. (Wright et al. 2016)

If the circumstellar volume is filled with such panels, closein panels would shadow panels farther out, reducing their efficiency. An optimization balancing total energy collection against total mass or construction costs might thus result in a typical optical depth of order unity. The optical depth along our line of sight would be modulated by the orbital motions and clustering of the panels. Indeed, if a very large opaque structure orbited into view the star might entirely disappear while it occulted the star (Wright et al. 2016).

The timescale of the variations thus reflect the size scale and orbital velocity of the absorbers: the years- or decades-long dimming seen by Schaefer and Montet & Simon would be due to au-scale overdensities of panels in the swarm orbiting into view. The days-long events noted by Boyajian et al. would be due to star-sized individual objects (or tight formations of smaller objects) transiting the disk.

10.2. Tests of the Hypothesis

This hypothesis might find support in at least three ways.

First, as Wright et al. (2016) noted, the panels might be expected to be geometric absorbers, and so produce achromatic dimmings. This could be checked once the total extinction of the star (perhaps as established by stellar models and a GAIA parallax) can be compared to that expected from the observed color excess. If the GAIA parallax is significantly larger than the spectroscopic parallax after accounting for reddening, this would imply that geometric absorbers, not dust, are responsible for a significant fraction of the absorption.

Conversely, if GAIA finds that Boyajian's Star's brightness is consistent with its distance and reddening, this implies that the secular dimming observed by Schaefer and Montet & Simon is entirely due to dust. Increased reddening during a future dip with be a further blow against the megastructure hypothesis.

Second, if there is a spectrum of sizes of panels (f(r)) and orbital velocities (f(v)), the star should "flicker" at timescales corresponding to r/v and R_*/v with higher amplitudes than typical F stars.

Finally, of course, communications SETI efforts could confirm the existence of an extraterrestrial civilization in the direction of Boyajian's Star, which would strongly support this interpretation of the data.

10.3. Waste Heat Constraints

The WISE and Thompson et al. (2016) constraints on longwavelength excess of Boyajian's Star put constraints on the collecting area, temperature, and energy efficiency of the factories. In the AGENT parameterization of Wright et al. (2014a), these are α (the fraction of stellar luminosity absorbed), T (the typical waste heat disposal temperature, characteristic of the operating temperature of the factories), and γ (the fraction of stellar luminosity radiated as waste heat).

Wright et al. (2014a) argued that values of T much below 150 K would be surprising, since there is little thermodynamic efficiency to be gained by going to such low temperatures, but

a huge increase in the amount of collecting/radiating area necessary to collect/dispose of energy at those temperatures. Wright et al. further noted that most work done by humanity results in $\alpha = \gamma$; that is, little of the energy we generate or collect ends up stored or emitted as low-entropy radiation, and virtually all of it is reradiated as waste heat after it is used. Of course, neither of these observations are physical limits on an advanced civilization, but it is interesting to see whether they are consistent with the data for Boyajian's Star.

In Section 3.2, we saw that the *WISE* and Thompson et al. upper limits implied $\gamma < 0.2\%$. This is inconsistent with a spherical swarm of collectors being responsible for the observed secular dimming (which would imply $\alpha \gtrsim 15\%$) unless $\alpha \gg \gamma$. If we assume that some sort of non-dissipative work is being performed with the energy, such as the emission of low-entropy emission (lasers or radio beacons, for instance) or energy-to-mass conversion, the efficiency of this work is limited by the thermodynamic (Carnot) efficiency η set by the factories' radiation temperature. For T = 65 K and $T_* = 6750$ this is $\eta \sim 99\%$, and so if the factories operate at this limit, we have

$$\gamma = (1 - \eta)\alpha \sim 0.15\%,$$

which is just barely consistent with observations. That is, a spherical swarm of megastructures can produce the Schaefer dimming only if they emit around T = 65 K and operate near the maximum efficiency allowed by thermodynamics. More sensitive measurements between $20-10^3 \mu m$ would rule out this hypotheses completely.

The data are still consistent, however, with structures whose collection or re-radiation strongly anisotropic: either we are seeing obscuration from a ring-like structure of collectors (allowing $\alpha = \gamma$ to be 100 times smaller) or they preferentially re-radiate away from our line of sight (which seems unlikely unless paired with a ring explanation, where the plane of the ring establishes a preferred radiation direction away from Earth).

11. INTRINSIC VARIATIONS

11.1. Timescales

Except for stars undergoing pulsations significantly large enough to alter their internal structure to the point that their core pressure changes, main-sequence stars' interior luminosities are constant on timescales shorter than the nuclear timescale. Their surface luminosities can vary by small amounts about this constant value-the Sun's luminosity changes by $\sim 0.1\%$ throughout the solar cycle—but any decrease in surface luminosity must eventually be balanced by a later increase. The timescales for these variations are a sound-crossing time (on the order of minutes, as with asteroseismic variations), that of a driving mechanism (in the case of the solar cycle or pulsating stars), or a thermal timescale (i.e., a Kelvin–Helmholtz timescale, $\sim 10^6$ years for an early F star.) The presence of dimmings in Boyajian's Star on timescales from days to decades is hard to reconcile with any of these mechanisms.

Montet & Simon's demonstration that Boyajian's Star has significant secular dimming on decadal timescales—and the corollary that Schaefer's century-long dimming is therefore likely to be real—would therefore seem to rule out any explanations that involve the star itself. Further, their demonstration that the *Kepler* light curve shows only shortterm *dimmings*, and that previously reported *brightenings* were artifacts of data processing removing low-frequency power, argues against the source of the dimmings being changes in the surface luminosity of the star itself.

11.2. Polar Spots

One possible way out is to invoke surface inhomogeneities: very large starspots could create temporary dimmings balanced not by later brightenings, but by bright regions elsewhere on the stellar disk. This explanation finds difficulty in the clear, 0.88 day rotation period of the star (from both the photometry and consistency with the observed line broadening; Boyajian et al. 2016), which is much shorter than most of the dips' durations.

Slow growth of large polar spots, as suggested by Montet & Simon (2016), might explain the long-term dimming (which would be seen as a brightening from an edge-on orientation), but would—as Montet & Simon point out—be an unexpected and extraordinary feature for an early F star. This explanation also is not obviously consistent with the multiple timescales for the dimmings.

11.3. A Post-brightening Return to Normal?

An alternative to the star being *dimmer* than it should be is that it is actually too *bright* and is returning to an equilibrium state after some event injected significant energy into its envelope or temporarily increased its core luminosity. For instance, perhaps Boyajian's Star recently merged with a brown dwarf or another star and is still processing the absorbed orbital energy. Residual material from the merger might transit the star occasionally, producing the dips, or the star might still be undergoing internal changes on a hydrodynamic or thermal timescale as it adjusts to its new state.

The primary problem with this scenario is the timescales of the brightness changes. Since the thermal timescale for an early F star is $\sim 10^6$ years, a change of 15% in only 100 years (or 4% in 4 years) is about four orders of magnitude too fast. It is possible that a detailed hydrodynamical or other stellar structure simulation might reveal changes on faster timescales, however, saving the hypothesis and suggesting an origin of the dips.

This possibility finds some support in the consistency of the depth of the sodium features, the measured reddening, and the Schla & Finkbeiner estimate of the reddening of Boyajian's Star. Together, these argue that the total interstellar extinction currently exhibited by Boyajian's Star is not especially higher than expected for stars at this distance in this part of the *Kepler* field. Since the star was apparently ~17% brighter in 1890, this implies that it was indeed overluminous then.

12. SUMMARY OF POSSIBILITIES AND FUTURE WORK

Above, we have discussed several possible solutions to the problem of Boyajian's Star. Here, we list them in rough order of our qualitative assessment of their plausibility, along with a summary of how they might explain the dips and the secular dimming and how future studies that could help bolster them or rule them out.

Small-scale ISM Structure (Section 7.1)—plausible: Dense regions of the ISM that vary on scales of au are known to exist and cause phenomena similar to that seen in Boyajian's Star,

though never before noticed on these physical or column density scales. This possibility would find support if neighboring stars could be found to exhibit similar behavior to Boyajian's Star, or if small-scale structure in the ISM in this direction could be found. Similarly, this hypothesis would be strengthened if future dimmings are accompanied by variations in reddening and absorption features associated with interstellar dust.

An Intervening Dark Cloud (Section 7.2)—plausible: Bok Globules exist, and there are clouds at higher Galactic latitude than Boyajian's Star. Their relatively smooth density profiles would naturally explain the secular dimming, and if they have significant sub-au structure, this would explain the dips. This possibility would find support is similar ways to the small-scale ISM structure possibility, but additionally if the column of neutral or molecular gas were significantly higher in the direction of Boyajian's Star.

An Intervening Disk (Section 8)—less plausible: A chance alignment with the large disk of a dark object—such as a black hole—could explain the observations. Complex ring structure in the annular disk sculpted by bodies within it could explain the dips, while an overall diffuse component would explain the secular dimming. This solution is similar to the case of 1SWASP J140747.93-394542.6 (Mamajek et al. 2012; Kenworthy & Mamajek 2015, an apparent ringed protoplanet around a pre-main-sequence star), although we find it more likely that the disk would be in the field than in orbit around Boyajian's Star (Section 8.4). This hypothesis would find support if a pattern to the dips and secular dimmings show symmetries consistent with a disk (as Kenworthy & Mamajek found for J1407) or if more detailed studies of black hole frequencies and disks support our rough calculation that such an alignment is not terribly unlikely in the Kepler field.

Artificial Structures (Section 10)—spherical swarm not likely; other geometries' plausibility unclear: The millimeter upper limits put tight constraints on any circumstellar solution invoking a spherical cloud responsible for the observed ~17% secular dimming. A spherical swarm of artificial structures is not quite excluded if they operate near the Carnot limit at $T \sim 65$ K, but more sensitive FIR–millimeter work will be able to rule this possibility out. Other geometries would find support if future dips and secular dimmings prove to be achromatic, or if the GAIA distance indicates Boyajian's Star already suffers significant achromatic extinction. If future dips are accompanied by reddening or absorption features consistent with ordinary astrophysical extinction, this possibility would be very unlikely.

A Solar System Cloud (Section 6)—unclear: A cold cloud of material at large distance from the Sun, perhaps from a slow cometary collision or a geyser from a large body, could cause obscuration but be otherwise very difficult to detect. The primary difficulty here is that the plausibility of such a cloud existing at all is unclear. If it existed, it could explain the dips if it were clumpy and the secular dimming if it had a more diffuse component. Such a cloud might also orbit around Boyajian's Star, where it could cause similar effects. The hypothesis that such a cloud orbits the Sun could find support if stars near Boyajian's Star could be found to suffer similar effects. In either case, the absorption spectrum of the material (presumably containing ices) might distinguish it from interstellar dust or other materials.

Post-merger Return to Normal (Section 11.3)—unclear: If Boyajian's Star suffered a brightening, we may be seeing a return to normal brightness, rather than a secular "dimming." In this scenario, the dips might be due to internal restructuring of the star on a hydrodynamical timescale or leftover material from a merger, while the secular "dimming" occurs on a thermal timescale for perhaps only the outer layers of the star. It is unclear what the mechanism could be, but it is possible that a merger event with a close companion could result in such a brightening. While we do not find this hypothesis sufficiently concrete to be classified as "plausible" or otherwise, we find the it to be worth considering further. On the theory side, this possibility would find support if a brightening mechanism could be identified, and if the dimming could be explained by that mechanism. On the observational side, this hypothesis would find support if future dimming events were not accompanied by the reddening or absorption features expected from dust, or if they were accompanied by changes in the effective temperature or other properties of Boyajian's Star. A larger-than-expected GAIA distance would also indicate that the star is overluminous.

Circumstellar Material, such as Cometary Swarms (Section 9)—plausible for some of the dips, very unlikely for the secular dimming: Boyajian et al. discussed the difficulties with most such hypotheses, and the comet swarm hypothesis may explain some of the dips. Invoking circumstellar material to explain the secular dimming seems less fruitful, especially given the millimeter flux upper limits.

Pulsations and Other Structural Variability (Section 11.1) not likely: The variety of timescales of dimmings observed and lack of mechanism for such pulsations make this possibility unlikely. This possibility would find support if mechanisms to generate such variability are found and if future dimmings are accompanied by changes in stellar parameters but not reddening or absorption features.

Polar Spots (Section 11.2)—not likely: Polar spots are neither expected nor seen around F stars such as Boyajian's Star. The variety of timescales of the dimmings also seems inconsistent with spots. While this possibility seems unlikely, we also find it difficult to rule out entirely. This possibility would find support if spectra during future dips revealed the spots through, for instance, Doppler imaging (e.g., Vogt et al. 1987) or variations in effective temperature or other spectral features.

Instrumental Effects (Section 5)—very unlikely: We agree with Boyajian et al. that instrumental effects are very unlikely to be the cause of the dips and find Montet & Simon (2016) persuasive that at least some secular dimming occurs, meaning it would be an unlikely coincidence for the similar effects seen by Schaefer to be instrumental. Independent confirmation of the long-term dimming seen by Montet & Simon (2016) would further rule out this scenario.

13. CONCLUSIONS

In response to Montet & Simon's strong encouragement to generate alternative hypotheses for the extraordinary light curve of Boyajian's Star, we have examined new and existing data and attempted to survey the landscape of potential solutions for plausibility.

We have shown that the timings of the deepest dips exhibited by Boyajian's Star appear consistent with being randomly distributed in time, and so potential explanations should not be constrained by any perceived periodicities in the Kepler data. We argue that the star's secular dimming combined with a lack of long-wavelength excess in the star's SED strongly constrains scenarios involving circumstellar material. In particular, we find that no more than 0.2% of Boyajian's Star's flux is being intercepted by the absorbing material, despite what appears to be at least a 15% decrease in total flux toward Earth.

We find that scenarios involving a spherical swarm of artificial structures absorbing the material are only just barely consistent with the data if they involve non-dissipative work done at the maximum (Carnot) efficiency at 65 K-other temperatures and lower efficiencies are ruled out, although other swarm geometries are not.

We have briefly surveyed a range of explanations that do not invoke circumstellar material, and find two broad categories worthy of further consideration: an intervening Bok globule or other ISM overdensity, and an intervening stellar remnant with a large disk. We have shown that the star's color excess, absorption lines due to interstellar sodium, and predicted extinction due to interstellar dust are all consistent with $A_V \sim 0.34$, or about twice the total amount of secular dimming observed to date.

Less compelling, but difficult to rule out, are intrinsic variations due to spots, a "return to normal" from a temporary brightening (due to, perhaps, a stellar merger) and a cloud of material in the outer solar system. We find instrumental effects, other intrinsic variation in Boyajian's Star, and obscuration by a disk around an orbital companion to Boyajian's Star very unlikely to be responsible.

We have identified several additional lines of research that may help explain Boyajian's Star's light curve, including JWST MIR-FIR observations; optical broadband and spectroscopic observations during future dips; a study of the ISM toward Boyajian's Star; a hunt for similar variations in stars near on the sky to Boyajian's Star; and careful consideration of its GAIA parallax.

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Many of the other ideas and possible solutions in this work are not original to us; in many cases, a particular solution has been suggested multiple times independently in private communication, at public talks, and/or in social media.

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