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The *GALEX* View of “Boyajian’s Star” (KIC 8462852)

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Abstract

The enigmatic star KIC 8462852, informally known as “Boyajian’s Star,” has exhibited unexplained variability from both short timescale (days) dimming events, and years-long fading in the *Kepler* mission. No single physical mechanism has successfully explained these observations to date. Here we investigate the ultraviolet variability of KIC 8462852 on a range of timescales using data from the *GALEX* mission that occurred contemporaneously with the *Kepler* mission. The wide wavelength baseline between the *Kepler* and *GALEX* data provides a unique constraint on the nature of the variability. Using 1600 s of photon-counting data from four *GALEX* visits spread over 70 days in 2011, we find no coherent NUV variability in the system on 10–100 s or month timescales. Comparing the integrated flux from these 2011 visits to the 2012 NUV flux published in the *GALEX*-CAUSE *Kepler* survey, we find a 3% decrease in brightness for KIC 8462852. We find that this level of variability is significant, but not necessarily unusual for stars of similar spectral type in the *GALEX* data. This decrease coincides with the secular optical fading reported by Montet & Simon. We find that the multi-wavelength variability is somewhat inconsistent with typical interstellar dust absorption, but instead favors a $R_V = 5.0 \pm 0.9$ reddening law potentially from circumstellar dust.

Key words: stars: individual (KIC 8462852) – ultraviolet: stars

Supporting material: data behind figure

1. Introduction

KIC 8462852, also known as “Boyajian’s Star,” is an unusual F3 dwarf in the *Kepler* field that has exhibited unexplained optical variability on a variety of timescales. The initial discovery was of several dramatic, short timescale (days) dimming events with amplitudes of up to 20% in the Kepler 30-minute cadence data (Boyajian et al. 2015). Though the *Kepler* mission (Borucki et al. 2010) obtained data at a 30-minute cadence for ~4 years on this star, no definitive pattern or cycle was found, nor has any single explanation for this variability been accepted by the community (Wright & Sigurdsson 2016).

An analysis of archival optical photographic plates has found that KIC 8462852 may have additionally faded nearly 16% over the past century (Schaefer 2016). Such a precise measurement for a single star is difficult, and the result has been debated (Hippke et al. 2016). However, using the 53 “Full Frame Images” (FFIs) spread over the 4-year *Kepler* mission, Montet & Simon (2016) were able to trace the brightness of KIC 8462852 using an independent flux calibration. The resulting flux-calibrated FFI light curve showed definitively that KIC 8462852 faded by more than 3% over 4 years. A years-long timescale variability, with possible periodicity, has recently been confirmed with an analysis of archival ground-based optical photometry (Simon et al. 2017).

The short (days) and long (years) timescale variability discovered for KIC 8462852 has presented a unique set of observational constraints for any single model used to describe the system. For example, if variable dust extinction is responsible for both temporal features, then the dust must have a wildly variable density distribution on small spatial scales, and a small density gradient over large spatial scales. Searches for an infrared flux excess consistent with a foreground or circumstellar dust shell have found no strong detection (e.g., Marengo et al. 2015), further complicating attempts to attribute the variability to dust structures.

Since optical variability and infrared follow-up has not produced a robust explanation for KIC 8462852, further multi-wavelength studies are needed to constrain the nature of the long timescale fading and short timescale dimming. Multi-band photometric and spectroscopic campaigns are underway,[13] which will provide an improved understanding of any future “dips.” However, no multi-wavelength measurement of the

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[13] http://www.wherestheflux.com

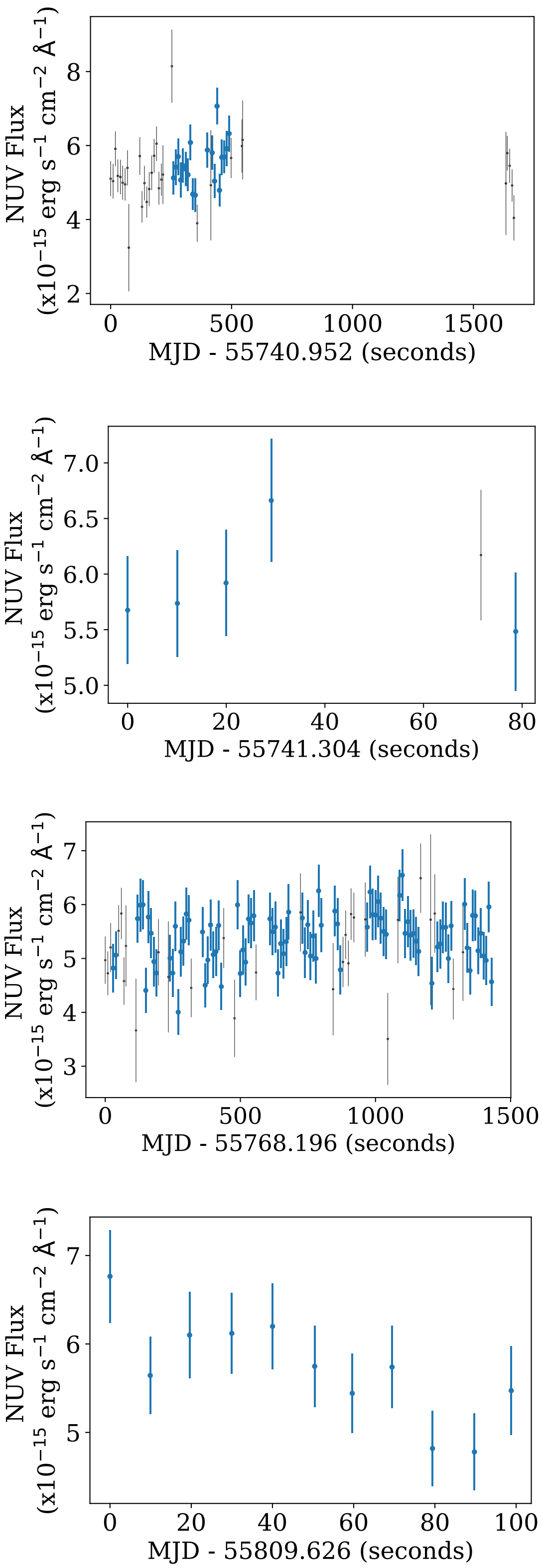

Figure 1. Light curves from `gPhoton` sampled at a 10 s cadence for the four visits in 2012. All epochs are shown (gray), while those having no photometric warning flags set are highlighted (blue). Error bars shown are the photometric errors for each point computed by `gPhoton`. The data used to create this figure are available.

mysterious variability for KIC 8462852 contemporaneous with the *Kepler* observations has been analyzed.

Archival photometry at ultraviolet wavelengths from the *GALEX* mission (Martin et al. 2005) spanning a range of timescales from seconds to more than a year is now available. This unique set of observations occurred during the *Kepler* mission, providing an independent constraint on the variability discovered in the *Kepler* photometry for KIC 8462852. The wide wavelength range probed by *GALEX* and *Kepler* also allows us to explore models of the variability based on dust extinction and thermal cooling.

The various *GALEX* data products used in our analysis are introduced in Section 2. In Section 3, we analyze the NUV data over 10–100 s timescales. In Section 4, we explore the long timescale evolution of KIC 8462852 between the 2011 and 2012 visits, and compare directly to the observed fading by Montet & Simon (2016). In Section 5, we discuss possible interpretations for the nature of KIC 8462852 that the combined *Kepler* and *GALEX* observations provide, including an estimate of the dust extinction properties necessary to reproduce the long timescale NUV observations. Finally, in Section 6, we summarize this work, and discuss the potential utility of *GALEX* in the study of other rare and unusual variable *Kepler* objects.

2. *GALEX* Observations

Time-tagged photon data has recently become available for *GALEX* (Million et al. 2016a), including a Python toolkit to search for and interact with this high-cadence data product called `gPhoton` (Million et al. 2016b). This allows us to resample the *GALEX* main survey data into any desired cadence. In the case of KIC 8462852, the primary *GALEX* survey obtained ∼1600 s of data during four separate visits spread across a ∼70-day baseline in 2011. These high-cadence data from 2011 are also coadded as part of the *GALEX* "GR6" data release (Bianchi et al. 2014). In this work, we analyze only the NUV data ($\lambda_{\mathrm{eff}} = 2315.7$ Å), as KIC 8462852 is too faint in the *GALEX* FUV band. Note that the *GALEX* NUV band is similar in wavelength coverage to the Swift *uvm*2-band analyzed for KIC 8462852 by Meng et al. (2017).

As part of the *GALEX* Complete All-sky UV Survey Extension (CAUSE) program, 104 square degrees within the *Kepler* field were reobserved in the NUV, creating the *GALEX*-CAUSE *Kepler* survey (hereafter GCK). This survey occurred in 2012, and overlapped a portion of the Quarter 14 operations from the original *Kepler* mission. The GCK data was obtained using scan-mode observing that differed from the standard *GALEX* survey. A catalog of the integrated fluxes and uncertainties for 475, 164 *Kepler* targets observed in GCK, including for KIC 8462852, was made available by Olmedo et al. (2015). In the case of KIC 8462852, the GCK catalog utilizes 1413.8 s of integration in 2012. Unfortunately, since the observing mode differed from the standard *GALEX* survey, GCK data is not available for time-series analysis with `gPhoton` presently.

3. Short Timescale Variability

Within each of the four primary mission *GALEX* visits available for KIC 8462852, we searched for short timescale variability using `gPhoton`.[14] While nanosecond optical variability has been investigated for this target (Abeysekara et al. 2016), few other

[14] Using `gPhoton` version 1.28.2.

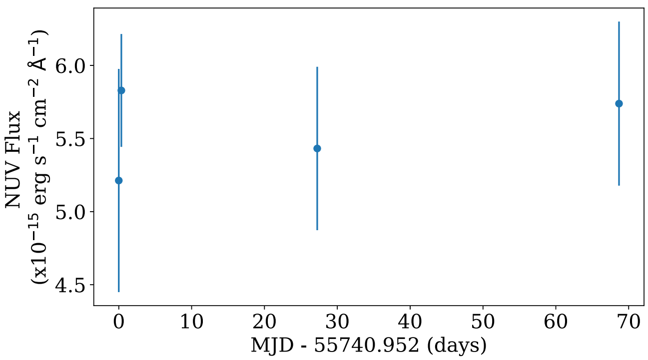

Figure 2. Median flux within each of the four visits spaced over ~70 days in 2011 by *GALEX*. Uncertainties shown are the standard deviation in flux within each 10 s sampled `gPhoton` light curves from Figure 1. No significant change in flux is seen over this 70-day window.

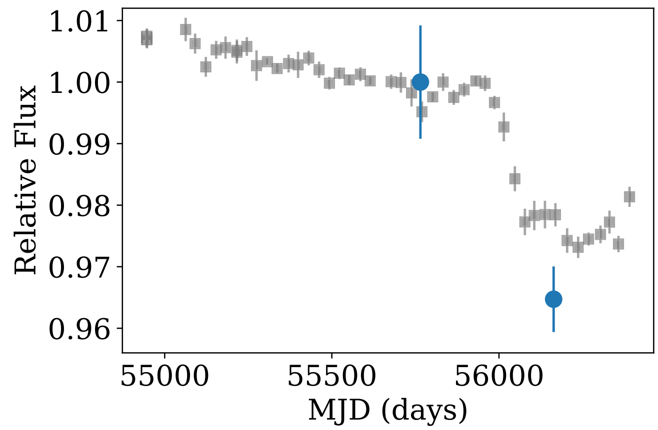

Figure 3. Comparison of the 2011 and 2012 fluxes for KIC 8462852 as measured by *GALEX* (blue circles), with the *Kepler* FFI data shown in Montet & Simon (2016) as reduced with the new "f3" package from Montet et al. (2017) for comparison (gray squares). The amplitude of variability over this time window is nearly identical between the two surveys.

studies have looked at variability on timescales shorter than the 30-minute cadence available with *Kepler*. The four *GALEX* visits in 2011 ranged from ~70 to ~1400 s in duration. Data for each visit was sampled at a 10 s cadence with `gPhoton`, as shown in Figure 1. Small amplitude variability is apparent in several of the visits, with coherent structure over durations of approximately 60–100 s. Computing a Lomb–Scargle periodogram using `gatspy` (VanderPlas & Ivezic 2015) on the entire `gPhoton` light curve, we find moderate power with a broad peak at around 80 s. This appears to be due to the ~120 s observing cycle of the *GALEX* instrument in the standard "Petal Pattern" observing mode, and we believe it is not astrophysically significant.

A periodic signal of 0.88 days was also found in the *Kepler* photometry, which was presumed by Boyajian et al. (2015) to be due to the rotation of starspots in- and out-of view on the surface of KIC 8462852. Each of the four *GALEX* visits shown in Figure 1 are too short to entirely capture this rotation signature. Our periodogram, computed using all four of the `gPhoton` light curves together, also does not show any signs of this 0.88-day period.

Since the standard *GALEX* data for this target was spread over four separate visits, we also examined the medium-timescale variability over ~70 days. In Figure 2, we show the median flux from each of the four `gPhoton`-processed visits. The uncertainties shown are computed as the standard deviation in the 10 s sampled data within each visit, and are ~10× larger than the statistical error on each visit's median flux. Though there is scatter between these four visits in Figure 2, no significant coherent variability is seen on this intermediate timescale with *GALEX*. Unfortunately, this 70-day time window also did not correspond to any of the previously identified dimming events from Boyajian et al. (2015).

4. Long Timescale Variability

In Figure 3, we present the *GALEX* data for this target as observed in 2011 and 2012. The 2011 data represents the final *GALEX* GR6 catalog flux value for KIC 8462852 of 16.46 ± 0.01 mag from Bianchi et al. (2014), and is the integrated flux from all four visits described in Section 3. The 2012 data is from the GCK data from Olmedo et al. (2015), and measured an NUV brightness for KIC 8462852 of 16.499 ± 0.006 mag. Both apparent NUV magnitudes were converted to fluxes, and then normalized to the flux of the 2011 visit. This results in a measured NUV fading of $3.5\% \pm 1.0\%$.

In Figure 3, we also show the slow fading discovered in the *Kepler* FFI's by Montet & Simon (2016). Note that the fact that the *GALEX* and *Kepler* FFI data are normalized to a relative flux of 1 around 2011 (MJD ~ 55,700) is a coincidence. However, the observation that the *GALEX* flux decays coherently with the *Kepler* FFI flux over this time baseline is significant.

To determine what the typical variation in NUV flux is for F stars, we analyzed the variability for over 140,000 GCK stars in common with the *Kepler* Stellar Catalog (Mathur et al. 2017), observed, on average, 15 times over a time interval of 40 days in 2012. Note that the original *GALEX* data was not available over the entire *Kepler* footprint, and was not taken over a single 70-day observing window in 2011 for all targets as for KIC 8462852. A full analysis of this variability, while beyond the scope of our work here, is underway (D. Olmedo et al. 2017, in preparation). We found that stars with temperatures near KIC 8462852 (6750 K) have an average variation of 3.5%. *GALEX* was calibrated using the white dwarf LDS749b, which was repeatedly observed during normal operations. Figure 6 from Million et al. (2016a) finds visit-to-visit scatter of the photon-level data for LDS749b of 2%–3% using `gPhoton`. The *GALEX* calibration work done by Morrissey et al. (2007) finds the photometric repeatability for stars at the brightness of KIC 8462852 is ±1.5%. *GALEX* also provided an estimate for longer-exposure repeatability as a function of magnitude, which indicates an expected ~3% uncertainty for our target.[15] The NUV variation seen for KIC 8462852 is therefore not necessarily abnormal for stars of this spectral type.

As an aside, we also searched for long timescale variability for KIC 8462852 in the infrared from the *WISE* single-exposure source database using the W1-band (3.4 μm). This data set from the original *WISE* mission (Wright et al. 2010), and the NEOWISE extended mission (Mainzer et al. 2014) provides ~2 day clusters of photometry spaced every 6 months due to the spacecraft roll pattern. Unfortunately, the *GALEX* observations for KIC 8462852 occurred during the observation gap between *WISE* and NEOWISE, and thus a direct comparison between the NUV and IR is not possible here. We found no clear long-term variability spanning 2009 through 2017 for

[15] https://asd.gsfc.nasa.gov/archive/galex/FAQ/counts_background.html

KIC 8462852 in the W1-band. However, a more detailed comparison of this rich IR data set to the recently published work from Simon et al. (2017) and Meng et al. (2017) is warranted.

5. Implications for the Nature of KIC 8462852

While many explanations for the nature of KIC 8462852 have been proposed, there is effectively no consensus on the nature of the years-long timescale fading (or variability) observed by Montet & Simon (2016) and confirmed here in the NUV. Critically, with only a single wavelength band available and no apparent characteristic timescale for this variation with the 4-year observing window, little can be constrained from the *Kepler* data alone. Metzger et al. (2017) have argued that the long timescale fading could be due to stellar atmosphere recovery after a planetary in-spiral, and possibly the short timescale dips are due to remaining debris. Montet & Simon (2016) note that the fading in the *Kepler* FFI's may be due to the transit of a dust cloud. However, none of these models definitively explain the long timescale variability observed in Montet & Simon (2016).

By combining the optical *Kepler* FFI light curve with the long timescale *GALEX* NUV data presented here, we can place the first multi-wavelength constraints on KIC 8462852. A natural model to compare the simultaneous variability in the NUV and optical is that of a dust cloud. Extinction by dust in the interstellar medium is well studied, and several models with varying dust compositions are available at these wavelengths. Regardless of *where* the dust originates (i.e., circumstellar versus interstellar), such extinction models are a useful path forward in exploring the fading of KIC 8462852.

To demonstrate the impact dust would have in these two bands, we computed the extinction in the *GALEX* NUV band that would be predicted given the fading observed by Montet & Simon (2016) within the 2011 and 2012 time windows observed by *GALEX*. We used a standard Cardelli et al. (1989) dust model with $R_V = 3.1$, computed using the Python code from Barbary (2016). The comparison of this $R_V = 3.1$ prediction with the flux decrease observed by *GALEX* is shown in Figure 4. The Cardelli et al. (1989) model overpredicts the fading found in the NUV, indicating the fading is more gray (less wavelength dependent) than a standard $R_V = 3.1$ dust model. The NUV decrease measurement is 1.7σ away from the $R_V = 3.1$ model, marginally inconsistent with "normal" interstellar dust as the culprit of the fading observed by Montet & Simon (2016), and supports a circumstellar origin. Given the lack of warm circumstellar dust detection by Thompson et al. (2016), this material must be very cool.

However, the NUV response of dust models is highly dependent on grain composition. This can be explored in standard dust models by modifying the R_V parameter. We then tuned a dust model to match both the observed *Kepler* optical and *GALEX* NUV dimming by varying the R_V and specific extinction (A_V) parameters. To fit the fading in both wavelengths simultaneously requires a dust model with $R_V = 5.0 \pm 0.9$. While this is not typical for interstellar extinction material, such a high R_V has been reported, for example, around young protostars (e.g., Hecht et al. 1982). Competing dust models can produce significantly different NUV extinctions. For example, by modeling the *Kepler* and *GALEX* fading for KIC 8462852 shown in Figure 3 with a Fitzpatrick & Massa (2009) dust model, we find a best-fit

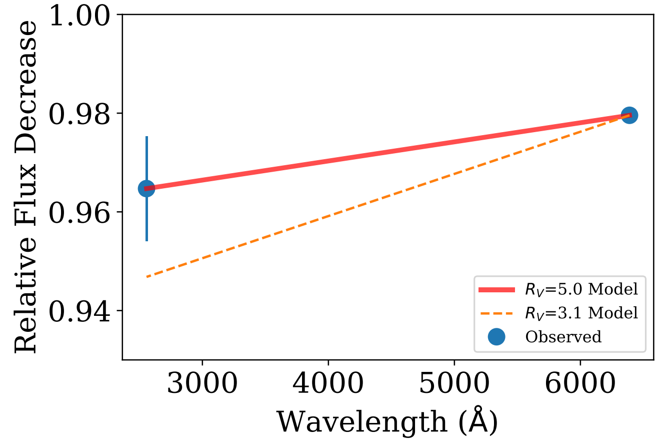

Figure 4. Comparison between the flux decrease observed at the effective wavelengths of the *GALEX* NUV and *Kepler* bands (blue circles), a corresponding $R_V = 3.1$ dust model from Cardelli et al. (1989) tuned to pass through the *Kepler* data (orange dashed line), and a $R_V = 5.0$ dust model that passes through both the *Kepler* and NUV data (red solid line). The standard $R_V = 3.1$ dust model overpredicts the NUV flux decrease given the observed *Kepler* fading.

parameter of $R_V = 5.8 \pm 1.6$. According to Simon et al. (2017), the dimming is weaker at redder optical wavelengths, broadly consistent with either dust extinction or temperature variations. A similarly large value for the reddening law ($R_V > 5$) was recently reported for KIC 8462852 over a comparable timespan after the *Kepler* mission using follow-up near-ultraviolet, optical, and NIR monitoring by Meng et al. (2017). However, the long timescale variation in *uvm*2-band flux was comparable to the intrinsic light curve uncertainty in their comparison stars. A joint analysis of the *GALEX* data presented here and the Swift/UVOT data from Meng et al. (2017) may provide an improved understanding of the extinction properties of circumstellar dust around KIC 8462852.

Besides dust extinction, another simple model that can be invoked to fit the long timescale variations of KIC 8462852 is changes in the star's effective surface temperature. We carried out a toy model calculation of this cooling, assuming a quiescent blackbody temperature of 6750 K for the star, and flux variations in each wavelength band due to changes in blackbody temperatures. The *Kepler* FFI fading seen by Montet & Simon (2016) over the same time windows as our *GALEX* observations requires a temperature change of 41 ± 3 K. This temperature change, in turn, predicts a drop in the NUV flux of 5%, which is in weak tension with our observed flux change of $3.5\% \pm 1.0\%$.

6. Summary

We have undertaken the first exploration of the NUV variability for KIC 8462852, using *GALEX* data on a range of timescales. No significant variability is found on 10–100 s timescales using NUV light curves produced with `gPhoton`. Over four visits spanning 70 days in 2011, we also find no significant medium-term variability.

Comparing coadded data from 2011 with the follow-up GCK study of the *Kepler* field in 2012, we find that KIC 8462852 faded by $3.5\% \pm 1.0\%$ in the NUV. This fading coincides with the slow variation reported by Montet & Simon (2016), and is the first verification that this star is variable in the NUV. A preliminary examination of the typical variance between the

GALEX and GCK data shows an average NUV change of ∼3.5% for bright F-type stars. Thus we believe the NUV fading observed for KIC 8462852 is real, but not necessarily atypical at these wavelengths.

Though the long timescale NUV light curve is very sparsely sampled, the combination of NUV and optical wavelengths provides a powerful constraint on the nature of this slow dimming. We explored both dust extinction and thermal variations as possible causes for the long timescale fading. Our favored explanation from these NUV data is that KIC 8462852 may be occulted by a slowly changing column density of dust with $R_V = 5$.

Finally, *GALEX* provides us with a valuable new data set for use in the search for other objects of this class. We are able to expand the search criteria beyond dramatic short timescale events and slow dimming as observed with *Kepler*, to now include slow variability in the NUV. If other F-type stars are found with similar multi-wavelength variability over long timescales, it will shed light on the occurrence rate and the possible lifetime of "Boyajian's Star" type variables.

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Software: gPhoton (v1.28.2; Million et al. 2016b), gatspy (VanderPlas & Ivezic 2015), f3 (Montet et al. 2017).

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