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THE GALEX VIEW OF "BOYAJIAN'S STAR"

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ABSTRACT

rewrite! The enigmatic star KIC 8462852, also known as "Boyajian's Star", has puzzled for both its short (days) length dimming events, and a years-long secular dimming observed by the *Kepler* mission. GALEX provides both short timescale sampling from the photon-counting data, and longer baseline data from multiple campaigns that imaged this field/ also providing a wide wavelength baseline to compare with the optical *Kepler* data, and provide important constraint for models of this system. here we investigate both the short and long timescale data. from 4 GALEX visits totaling 1600 seconds of exposure time in 2011, spread over 70 days, we find no coherent NUV variability in the system on 10–100 sec timescales during these time windows. 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 of KIC 8462852. This decrease is the first validation of the secular fading reported by Montet & Simon (2016) not in optical wavelengths. The similar amplitudes between the NUV and optical data rule out typical interstellar dust as the cause of this fading.

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 up to 20% in the *Kepler* 30-min cadence data (Boyajian et al. 2015). Though the *Kepler* mission (Borucki et al. 2010) obtained data at a 30-min cadence for $\sim$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).

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 to date found no strong detection (e.g. Marengo et al. 2015), further complicating attempts to attribute the variability to dust structures.

Since optical variability alone has not produced a single explanation for KIC 8462852, multi-wavelength studies are needed to constrain the nature of the long timescale fading and short timescale dimming. Follow-up multi-band photometric and spectroscopic campaigns are underway[1], which will provide an improved understanding of any future "dips". However, to date no contemporaneous, multi-wavelength measurement of the mysterious variability for KIC 8462852 has been available.

Archival photometry at ultraviolet wavelengths from the GALEX mission (Martin et al. 2005) is now available, and provides an important new dataset for understanding KIC 8462852. This data includes NUV monitoring over a range of time baselines, from seconds to more than a year. Time-tagged photon data has recently been made 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 all available GALEX main survey data into any desired cadence. In the case of KIC 8462852, the primary GALEX survey obtained ∼1600 seconds of data during four separate visits spread across a ∼70 day baseline in 2011. In §2 we analyze this NUV data with `gPhoton` sampled at a 10 second cadence, and over the whole 70 day period.

The *Kepler* field was then revisited by GALEX during a special campaign, dubbed the GALEX-CAUSE Kepler (hereafter GCK) survey. This survey occurred in 2012, and overlapped a portion of the Quarter 14 operations of the original *Kepler* mission. Using a "scan" observing mode that differed from the standard GALEX survey, the GCK catalog had 1413.8 seconds of data available for KIC 8462852, which was combined into a single stacked exposure of this region (Olmedo et al. 2015). Unfortunately, since the observing mode differed from the standard GALEX survey, this GCK data is not available for analysis with `gPhoton` presently. In §3 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 §4 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 §5 we summarize this work, and discuss the potential utility of GALEX in the study of other rare and unusual variable *Kepler* objects.

2. SHORT TIMESCALE VARIABILITY

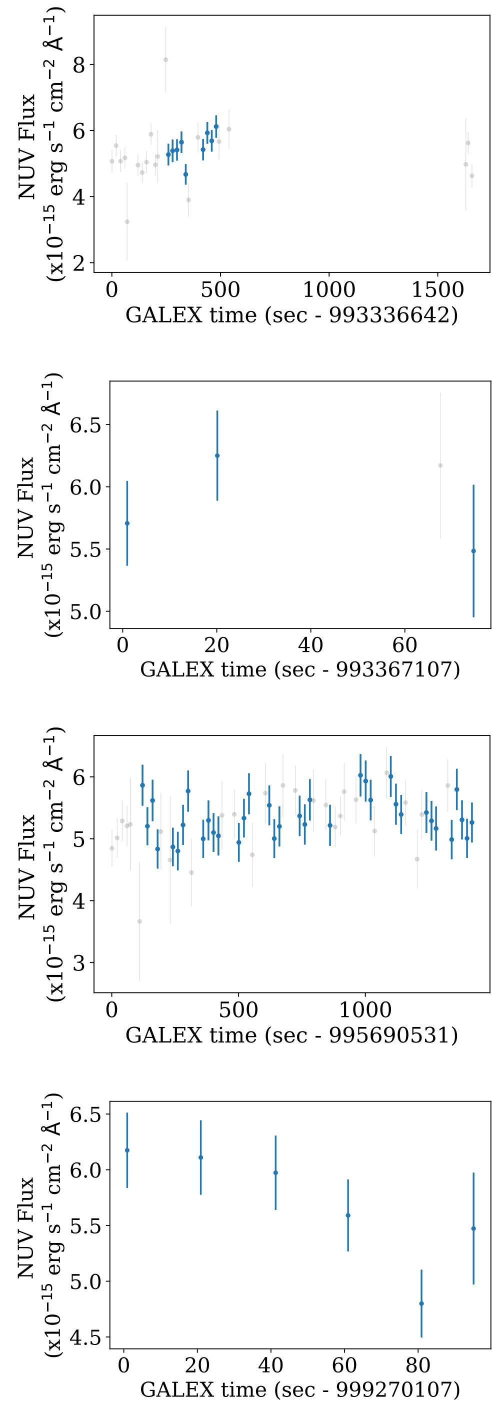

Figure 1. Light curves from `gPhoton` sampled at a 10-second cadence for the 4 visits in 2012. All epochs are shown (grey), while those having no photometric warning flags set are highlight (blue). Error bars shown are the photometric errors for each point computed by `gPhoton`.

Within each of the four primary mission GALEX visits available for KIC 8462852 we searched for short timescale variability using `gPhoton`. While nano-second optical variability has been investigated for this target (Abeysekara et al. 2016), few other studies have looked

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

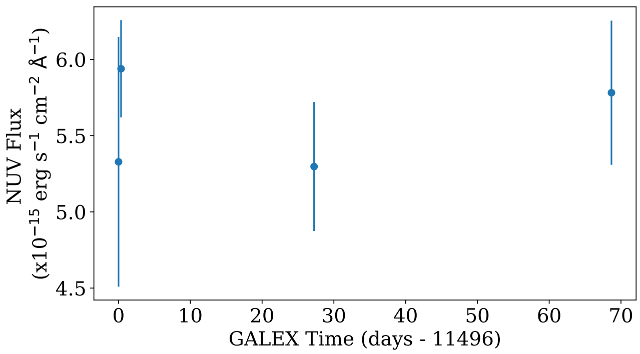

Figure 2. Median flux within each of the four visits spaced over ~70 days in 2011 by GALEX. Uncertainties shown are the standard deviation in flux within each 10-sec sampled `gPhoton` light curves from Figure 1. No significant change in flux is seen over this 70 day window.

at variability on timescales shorter than the 30-minute cadence available with *Kepler*. The four GALEX visits in 2011 ranged from ~70 to ~1400 seconds in duration. Data for each visit was sampled at a 10-second 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 seconds. Computing a Lomb-Scargle periodogram using `gatspy` (VanderPlas & Ivezic 2015), we find moderate power with a broad peak at around 80-seconds. This appears to be due to the ~120 second observing cycle of the GALEX instrument in the standard "Petal Pattern" observing mode, and we believe is not astrophysically significant. **FINAL WORD: nearby star from David Wilson doesn't show this structure. Is this the Petal Pattern or not?**

A periodic signal of 0.88 days was found in *Kepler*, 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. However, the four GALEX visits shown in Figure 1 are too short to capture this rotation signature, and thus our GALEX data are not able to explore variability at this timescale.

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

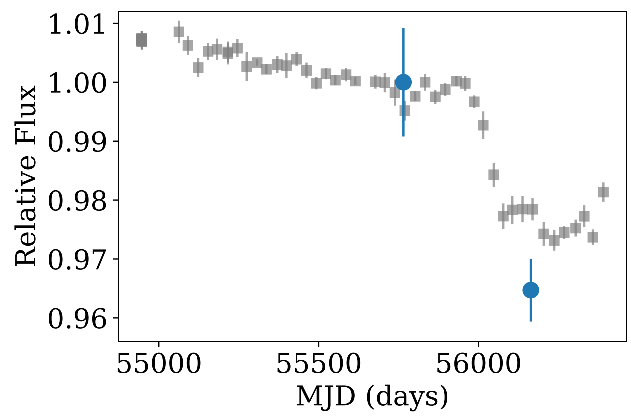

Figure 3. Comparison of the 2011 and 2012 fluxes for KIC 8462852 as measured by GALEX (blue circles), with the *Kepler* FFI data shown in Montet & Simon (2016) as reduced with the new "f3" package from Montet et al. (2017) for comparison (grey squares). The amplitude of variability over this time window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

3. LONG TIMESCALE VARIABILITY

While the standard GALEX survey data available within `gPhoton` only sampled ~70 days within 2011, the *Kepler* field was fortunately re-observed with GALEX in 2012. As part of the GALEX Complete All-Sky UV Survey Extension (CAUSE) program, 104 square degrees within the *Kepler* field were re-observed in the NUV, creating the GALEX-CAUSE Kepler survey (GCK). This GCK data was obtained using a drift-scan mode, which was processed using a custom pipeline, and is therefore not available for photon-counting analysis with the `gPhoton` toolkit at this time. 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 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), while the 2012 data is from the GCK data of 16.499 ± 0.006 mag from Olmedo et al. (2015). Both data were converted to fluxes, and then were normalized to the flux of the 2011 visit. For comparison we also show the slow fading discovered in the *Kepler* FFI's by Montet & Simon (2016). Note: the fact that the GALEX and *Kepler* FFI data are normalized to a relative flux of 1 around 2011 (MJD~55700) is a coincidence. However, the fact that the GALEX flux decays coherently with the *Kepler* FFI flux over this time baseline is significant. Importantly, this is the first multi-wavelength confirmation of the slow fading reported by Montet & Simon (2016) for KIC 8462852.

FINAL WORD: get 50 nearby stars, make sure GALEX vs GCK data isn't a systematic problem

For comparison we also examined the WISE single-exposure source database using the W1-band (3.4μm) to search for long timescale variability. This dataset 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 KIC 8462852 in the W1-band. However, a more detailed comparison of this rich IR dataset to the recently published work from Simon et al. (2017) and Meng et al. (2017) is warranted.

4. 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. Critically, with only a single wavelength band available from *Kepler*, 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 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 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

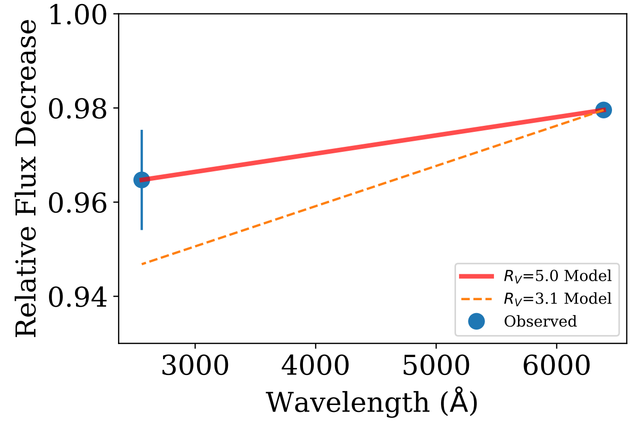

Figure 4. Comparison between the flux decrease observed at the effective wavelengths of the GALEX NUV and *Kepler* bands (blue circless), a corresponding $R_V = 3.1$ dust model from Cardelli et al. (1989) tuned to pass through the *Kepler* data (orange dashed line), and a $R_V = 5.0$ dust model that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

$R_V = 3.1$, computed using the Python code from Barbary (2016). The comparison of this prediction with the flux decrease observed by GALEX is shown in Figure 4. The Cardelli et al. (1989) model over-predicts the fading found in the NUV, indicating the fading is more gray (less wavelength dependent) that a standard $R_V = 3.1$ dust model. This rules out "normal" interstellar dust as the culprit of the fading observed by Montet & Simon (2016).

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 $R_V = 5.0 \pm 0.9$. 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 parameter of $R_V = 5.8 \pm 1.6$. Note that a similarly large value for the reddening law ($R_V > 5$) was recently reported for KIC 8462852 over a different timespan by Meng et al. (2017).

If the slow fading is indeed due to the transit of a dust cloud or circumstellar material, we can further put a constraint on how much dust should be present. Based on relations from (Güver & Özel 2009), we find that an extinction of $A_V = 0.026$ mag is needed to fit the fading with the Cardelli et al. (1989) dust model, which corresponds to a column density of $N_H \sim 5\times10^{19}$ cm^{-2} . Similarly, using the relations from Rachford et al. (2002) that have some dependence on dust composition (R_V), we find an estimated column density of $N_H \sim 4.0\times10^{19}$ cm^{-2}, given $A_V = 0.026$ and $R_V = 5.08$. However, this high of a column density poses an intriguing challenge given the lack of warm circumstellar dust detection by Thompson et al. (2016).

Simon et al. (2017) find the dimming is weaker at redder optical wavelengths, broadly consistent with either dust extinction or temperature variations.

BLACKBODY INFO if we match the *Kepler* drop and assume a quiescent temperature of 6750, requires a blackbody change of 41+/-3 K. this in turn predicts a NUV drop of 5%, which is in weak tension with the observation of 0.965+/-0.010 flux from GALEX.

5. SUMMARY

explored short timescale variability with `gPhoton` on seconds timescales, and on 70 day window. nothing significant at NUV wavelengths.

using 2011 and 2012 detections with GALEX we have provided the first independent verification of slow fading of this target though the long timescale light curve is very sparsely sampled, the combination of NUV and optical wavelengths provides a powerful constrain on the nature of this slow dimming.

In the hunt for other objects of this class, we are able to expand our search criteria beyond the dramatic short timescale events and slow dimming observed with *Kepler*, to now include slow variability in the NUV.

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