THE GALEX VIEW OF "BOYAJIAN'S STAR"

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ABSTRACT

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 ∼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.

The short (days) and long (years) timescale variability discovered for KIC 8462852 has presented a unique set of observational constraints on any single model used to describe the system. For example, if variable dust extinction is responsible for both temporal features, then it 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 (Marengo et al. 2015).

Since optical variability alone has not produced a single explanation for KIC 8462852, multi-wavelength studies are needed to constrain 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`

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

(Million et al. 2016b). This allows us to resample all available GALEX survey data into any desired cadence. In the case of KIC 8462852, GALEX had ~1600 seconds of data available from 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 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

gphoton gives us unique ability look for short timescale variations in the NUV. In Figure 1 we show the four GALEX visits covering KIC 8462852, sampled at a 10-second cadence. small variations are seen in some of the visits. we re-sampled the data at 9- and 11-sec cadence, and these are visible in each. computing a Lomb-Scargle periodogram using `gatspy` (VanderPlas & Ivezic 2015) shows moderate power around 80-seconds. They appear to be primarily due to the ~120 second observing cycle of the GALEX instrument in "Petal Pattern" mode A periodic signal of 0.88 days was found in *Kepler*, which was presumed by Boyajian et al. (2015) to be due to stellar rotation. our data are not able to verify this timescale.

nanosecond optical variability has been searched for this star (Abeysekara et al. 2016), but not much else shorter than was available at 30-min cadence with *Kepler*.

Since the GPhton data for this target is spread over four separate visits, we can also examine the medium-timescale variability over ~70 days. In Figure 2 we show the median flux from within each of the GPhoton visits.
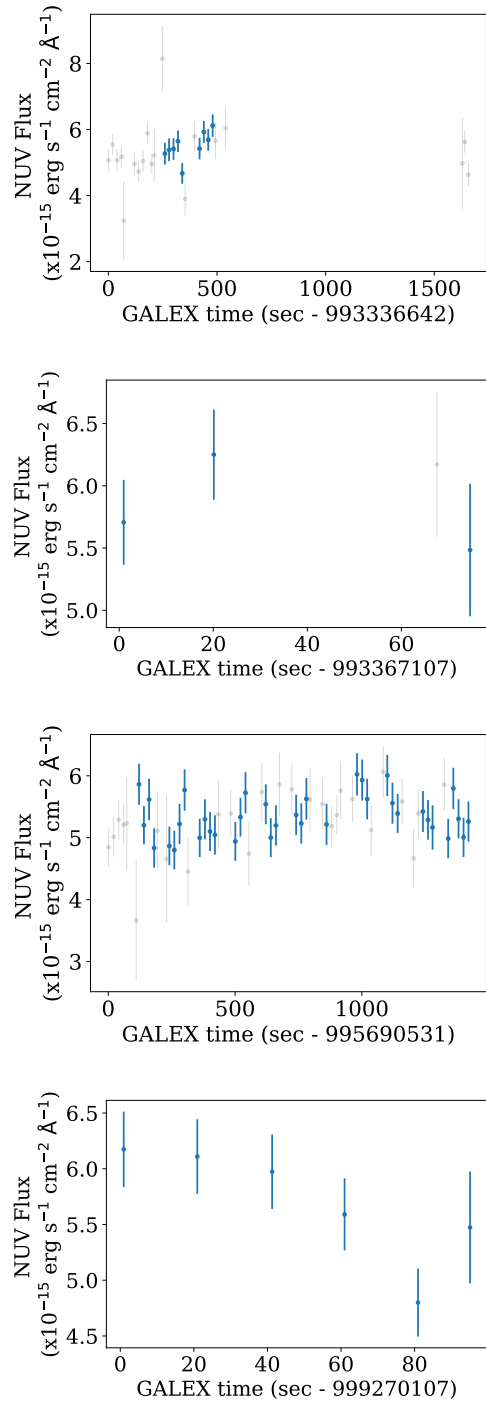

Figure 1. 10-second light curves from gPhoton for the 4 visits in 2012. All epochs shown (grey), and those that have no photometric warning flags set (blue), with the photometric errors for each point computed

No significant variability is seen between these visits.

3. LONG TIMESCALE VARIABILITY

While the standard GALEX survey data available within GPhoton only sampled ~70 days within 2011, the *Kepler* field was fortunately observed again by the
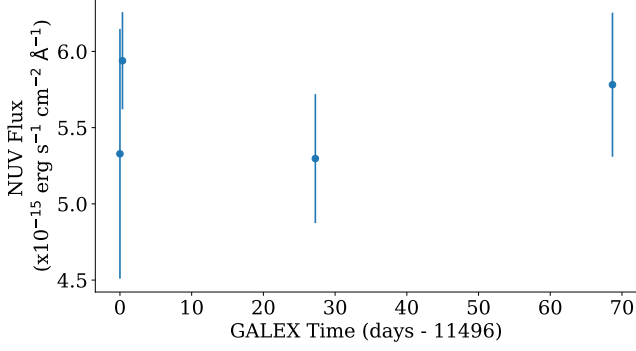
Figure 2. median flux of the 10-sec sampled data over the ~70 days of 2011 visits by GALEX. Uncertainties shown are the standard deviation in fluxes within each 10-sec sampled visit from Figure 1.
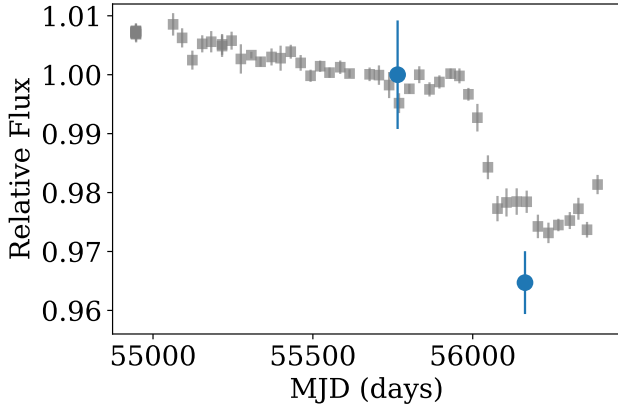

Figure 3. comparison of 2011 and 2012 fluxes (blue circles), with the *Kepler* FFI data shown in Montet & Simon (2016) but reduced with the new "f3" package from Montet et al. (2017) for comparison (grey squares).

CAUSE/GCK survey. [INSERT DETAILS OF THIS DATA]. A catalog of the integrated fluxes and uncertainties for *Kepler* targets observed in the CAUSE survey 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 is the final GALEX GR6 catalog flux for KIC NNNN of 16.46±0.01 from Bianchi et al. (2014), while the 2012 data is from the GCK data of 16.499 ± 0.006 Olmedo et al. (2015). Both data were converted to fluxes and were normalized to the flux of the 2011 visit. For comparison we also show the FFI decay from 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 GALEX flux decays with the *Kepler* FFI flux over this time baseline

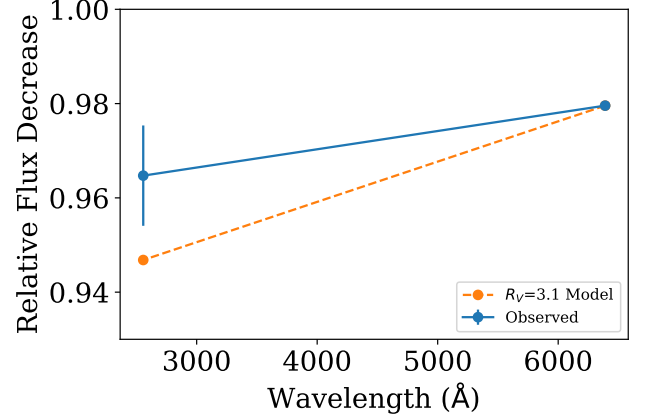## 4. IMPLICATIONS FOR THE NATURE OF KIC 8462852

Figure 4. comparison of flux decrease observed at the effective wavelengths of the NUV and *Kepler* bands (blue solid line) and a corresponding $R_V = 3.1$ dust model from Cardelli et al. (1989) tuned to pass through the *Kepler* data (orange dashed line). The standard dust model over-predicts the NUV flux decrease given the observed *Kepler* decrease from Montet & Simon (2016).

fit with Cardelli et al. (1989) dust model, using Python code from Barbary (2016).

Metzger et al. (2017) argued long-time fading due to stellar atmosphere recovery after a planetary in-spiral. (and possibly short-time dips due to debris)

our added data from GALEX adds important constraint on the nature of the long timescale fading. If its dust, must have $R_V = 5.0 \pm 0.9$ to satisfy the optical and NUV dimming. This is not typical for interstellar extinction material, though is seen for young protostars (e.g. Hecht et al. 1982). based on different prescriptions of the NUV extinction law, which can be very sensitive to the large "bump" near the GALEX NUV center wavelength. for example, models from Fitzpatrick & Massa (2009) give $R_V = 5.8 \pm 1.6$

If the slow variability is due to dust, we can further put a weak 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 corresponds to a column density of $N_H \sim 5 \times 10^{19}$ cm^{-2} . Similarly, using the relations from Rachford et al. (2002) that have some dependence on dust composition (R_V), we get an estimated $N_H \sim 4.0 \times 10^{19}$ cm^{-2} .

5. SUMMARY

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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