

IRTF/SPEX OBSERVATIONS OF THE UNUSUAL *KEPLER* LIGHT CURVE SYSTEM KIC 8462852

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ABSTRACT

We have utilized the NASA/IRTF 3 m SpeX instrument’s high-resolution spectral mode to observe and characterize the near-infrared flux emanating from the unusual *Kepler* light curve system KIC 8462852. By comparing the resulting 0.8–4.2 μm spectrum to a mesh of model photospheric spectra, the 6 emission line analyses of the Rayner et al. catalog, and the 25 system collections of debris disks we have observed to date using SpeX under the Near InfraRed Debris disk Survey, we have been able to additionally characterize the system. Within the errors of our measurements, this star looks like a normal solar abundance main-sequence F1V to F3V dwarf star without any obvious traces of significant circumstellar dust or gas. Using Connelley & Greene’s emission measures, we also see no evidence of significant ongoing accretion onto the star nor any stellar outflow away from it. Our results are inconsistent with large amounts of static close-in obscuring material or the unusual behavior of a YSO system, but are consistent with the favored episodic giant comet models of a Gyr old stellar system favored by Boyajian et al. We speculate that KIC 8462852, like the ~ 1.4 Gyr old F2V system η Corvi, is undergoing a late heavy bombardment, but is only in its very early stages.

Key words: circumstellar matter – infrared: stars – planetary systems – radiation mechanisms: thermal – scattering – techniques: spectroscopic

1. INTRODUCTION

KIC 8462852, also known as TYC 3162–665–1 or 2MASS J20061546+4427248, is a $V \sim 12$, $K \sim 10.5$ mag star located in the starfield of the *Kepler* space telescope primary mission (Borucki et al. 2010). This star was identified serendipitously by the Planet Hunters project (Fischer et al. 2012) for its unusual light curve, characterized by deep dimming (down to below 20% of the stellar flux) lasting between 5 and 80 days, and with an irregular cadence and unusual profile (Boyajian et al. 2015, B15 hereafter). Since its discovery, KIC 8462852 has been the subject of intense multi-wavelength monitoring, and has spurred numerous speculations about the nature of the bodies, or structures, responsible for the dimming of its visible flux (see e.g., Wright et al. 2015).

KIC 8462852 was carefully characterized in B15. High-resolution ($R \sim 47000$) spectroscopic observations obtained with the Fibre-fed Echelle Spectrograph (FIES) spectrograph at the Nordic Optical Telescope in La Palma, Spain, revealed that KIC 8462852 is a main-sequence star with an effective temperature $T_{\text{eff}} = 6750 \pm 120$ K, $\log g = 4.0 \pm 0.2$, and solar metallicity, consistent with an F3 IV/V star. The spectral energy distribution (SED) of the source, obtained by combining ground-based $BV(RI)c$ and 2MASS (Skrutskie et al. 2006) JHK_s photometry with space-based NUV Galex (Morrissey et al. 2007) and mid-IR *WISE* (Wright et al. 2010) data, is also consistent with the spectroscopic identification of the source. Careful fitting of the star’s SED with a stellar atmosphere model revealed that the source is located at a distance of 454 pc, with a reddening of $E(B - V) = 0.11$ mag.

Interest in KIC 8462852 is related to the very unusual dips in its *Kepler* time-series photometry. One event near JD 2455626 (2011 March 5) lasting for ~ 3 days and a series of events starting from JD 2456343 (2013 February 19) lasting for ~ 60 days stand out for their unusual shape, lack of periodicity, and

depth. A search through the *Kepler* database for targets with similar dips turned out empty handed. Realistic scenarios for the phenomena observed for this star are discussed at length in B15. They are related to the episodic occultation of the star by a circumstellar dust clump, either produced in the aftermath of a catastrophic collision in the system’s asteroid belt or a giant impact in the system, associated with a population of dust-enshrouded planetesimals, or produced by the breakout of a family of comets.

The parameter space for evaluating all these scenarios is constrained by the lack of any large excess above the expected stellar photospheric emission in the mid-IR from *WISE* (observing before the dimming events; Boyajian et al. 2015) and *Spitzer*/IRAC (observing after the *Kepler* dimming events; Marengo et al. 2015). However, only moderate constraints have been placed to date on the possibility of very close-in, hot (>1000 K) circumstellar dust and gas within a fraction of an AU of the primary star by the stellar model fits to broadband infrared photometry (Boyajian et al. 2015; Marengo et al. 2015). To broadband photometry, a hot dust excess would appear as an increased Rayleigh–Jeans flux from the stellar photosphere, potentially masking any excess in the mid-IR as well. Such hot dust or gas, created for example by a roasting planet-like WASP-12b, or by a remnant primordial disk (e.g., Sitko et al. 2012), could intercept a large solid angle of starlight and create the observed light curve minima, while re-irradiating the bulk of its energy in the near-IR, invisible to the *WISE* and *Spitzer* spacecraft.

Having recently completed a 25 system survey of northern debris disks using the NASA/IRTF 3 m’s SPeX high-resolution spectrometer at 0.8–5.0 μm (Rayner et al. 2003, 2009; Vacca et al. 2003, 2004; Cushing et al. 2004), including systems showing NIR excesses at the 1%–100% level above the photosphere, we were well placed to observe and characterize the system in the near-infrared. We thus requested

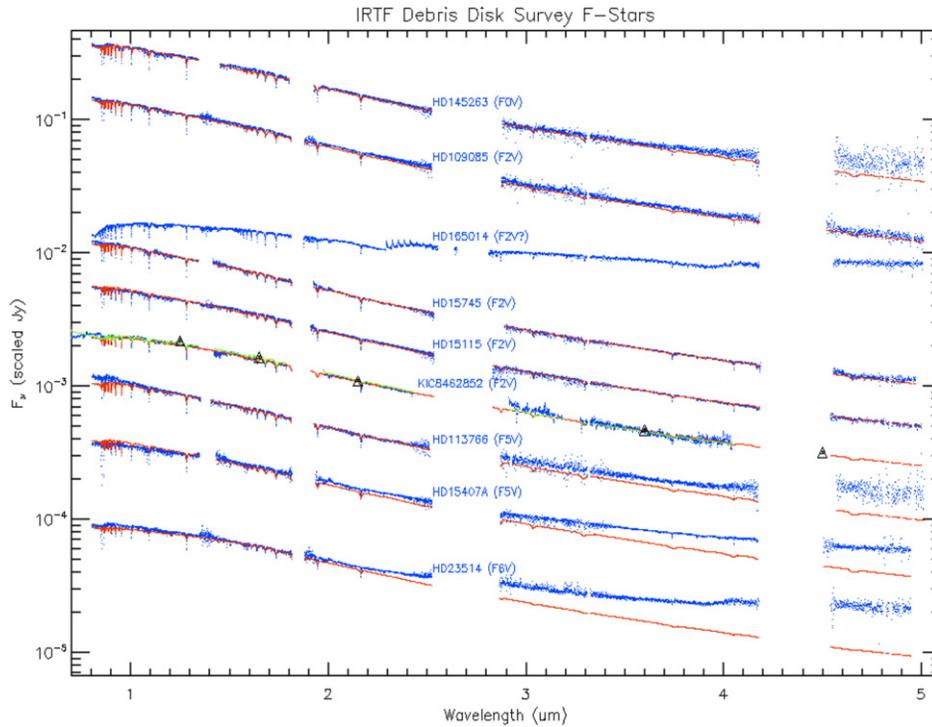


Figure 1. As-observed SpeX KIC 8462852 spectrum in comparison to 8 F-stars of the NIRDS program with reported optical or IR debris disks. Blue points are the as-observed SpeX $R = 1000$ to 2000 spectra, and red curves are solar abundance model Kurucz spectra reddened to the same amount of extinction. KIC 8462852’s spectrum, 6th from the top, with $E(B - V) = 0.11$, is consistent with purely stellar photospheric emission within the uncertainties of our measurements ($\sim 1\%$ at $0.8\text{--}2.55\ \mu\text{m}$, and $\sim 3\%$ from 3.0 to $4.2\ \mu\text{m}$). Also plotted on top of the KIC 8462852 spectrum are the JHK/3.6/4.5 photometry (triangles) and the best-fit Phoenix photospheric model (green) from Marengo et al. (2015).

and received Director’s Discretionary Time from the IRTF to observe the system on 2015 October 31 in the same fashion as for our 25 Near InfraRed Debris disk Survey (NIRDS; C. M. Lisse et al. 2016, in preparation) targets, and we report the results of our observations here.

2. OBSERVATIONS

We observed the KIC 8462852 system from 04:05 to 06:35 2015 October 31 UT (at 18:05–20:35 2015 October 30 *HST* time, or evening twilight) from the NASA/IRTF 3 m on the summit of Mauna Kea, HI. The SpeX instrument provides $R = 2000$ to 2500 resolution observations from 0.8 to $5.0\ \mu\text{m}$ in two orders, termed SXD (for “short cross-dispersed”) and LXD (for “long cross-dispersed”) when configured for use using an $0''.3$ slit and the standard optics chain (Rayner et al. 2003, 2009). Our observational setup was identical to that used for our previous NIRDS debris disk studies, with two exceptions designed to maximize our chances of detecting this unknown, relatively faint source in the 2.5 total hours we had to conduct our observations (most NIRDS objects were of $[K] = 2\text{--}8$, while KIC 8462852 has a 2MASS K-magnitude of 10.54; C. M. Lisse et al. 2016, in preparation). We utilized an $0''.8$ wide slit, and we doubled up on the spectral overlap between our SXD ($0.8\text{--}2.55\ \mu\text{m}$) and LXD orders by utilizing the “short LXD” $1.67\text{--}4.2\ \mu\text{m}$ mode. The result was to produce spectra with $8/3$ the limiting sensitivity per on-target second of our normal survey, with a spectral grasp of $0.8\text{--}4.2\ \mu\text{m}$ and $R = 800\text{--}900$. The nearby A0V star used in our SPEXTOOLS data reduction as a calibration standard (Vacca et al. 2004) was the $[K] = 6.4$ star HD 192538. We observed the standard in SXD mode with a total on-target integration time of 480 s and

in LXD mode for a total time of 960 s. We observed KIC 8462852 in SXD mode for a total time of 2400 s and in LXD mode for a total time of 2340 s. The instrument behavior was nominal and the summit weather was good, with clear skies, a relative humidity of 46% and outside temperature of 4.6°C , a low CFHT Skyprobe camera attenuation value of 0, and a seeing of $\sim 1''$. All objects were observed in ABBA nod mode to remove telescope and sky backgrounds. We observed KIC 8462852 after meridian transit, and the position angle of the slit on the sky was continually adjusted from 160° to 134° to be perpendicular to the horizon, so the 3 mag fainter M-star companion reported by Boyajian et al. (2015) at $2''$ to the east (PA 0°) would not have contributed significantly to our measurements.

3. RESULTS

KIC’s spectrum is consistent with purely stellar photospheric emission, within the uncertainties of the measurement (Figure 1). In comparison to the spectra obtained for 8 F-stars with reported debris disks as part of the NIRDS program, KIC 8462852 clearly does not show the markedly flattened, non-photospheric hot dust continuum $+\sim 2.0\ \mu\text{m}$ CO emission lines of YSO HD 165014, a system that had previously been reported in the literature as a main-sequence star (e.g., Fujiwara et al. 2010). Nor does it show evidence for the warm dust continuum excesses rising toward long wavelengths of the $10\text{--}200$ Myr old systems HD 145263, HD 113766, HD 15407A, or HD 23514, all with known strong 10 and $20\ \mu\text{m}$ IRAS and *Spitzer* excesses (Chen et al. 2006). Instead, KIC 8462852’s spectrum is consistent with that of the purely photospheric systems HD 15745 and HD 15115. It may have a

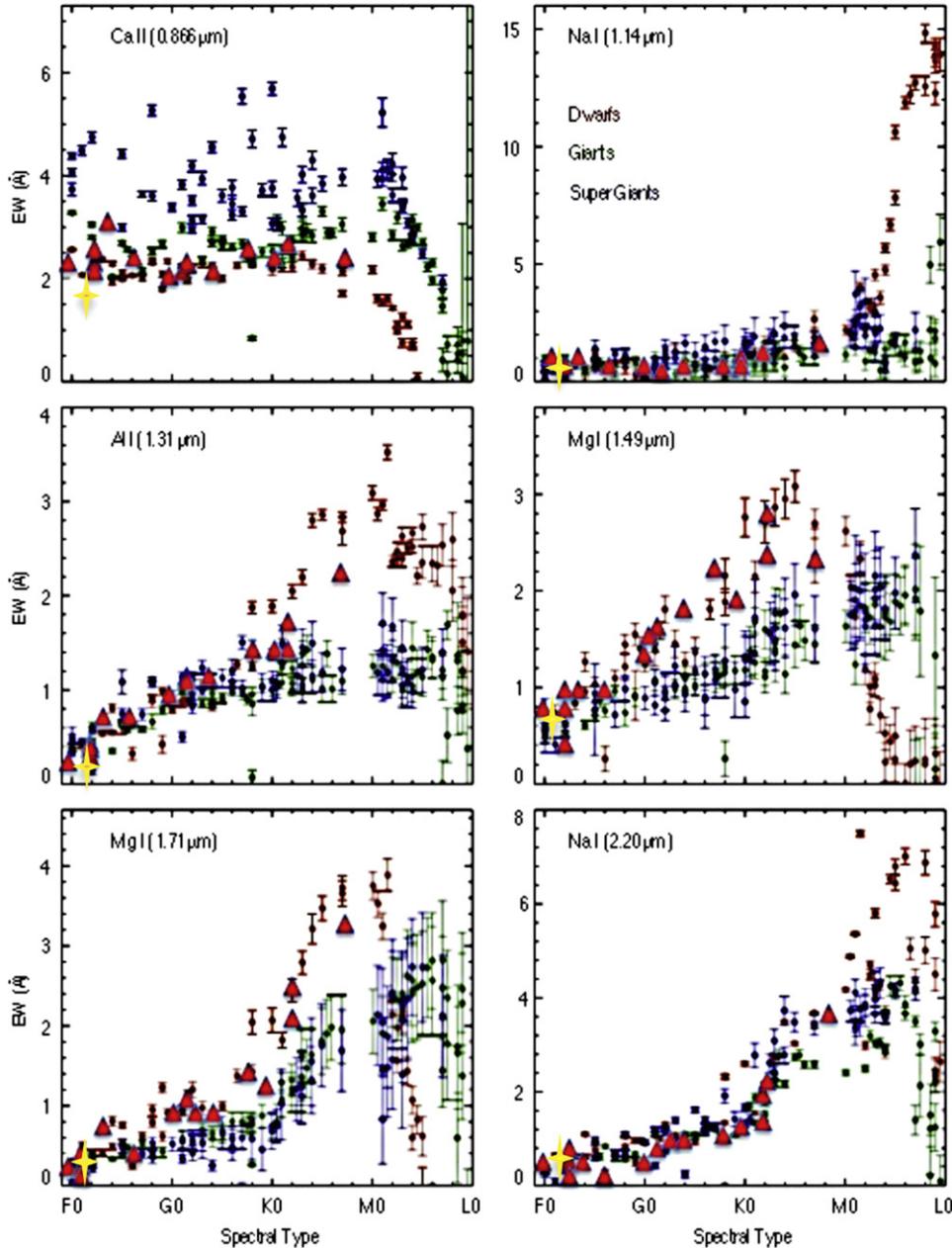


Figure 2. Spectral classification of KIC 8462852 (yellow star) using the SPEX six absorption-line trends of Rayner et al. (2009). The Rayner et al. library stars, dwarfs through supergiants, are shown using the small dark blue, green, and red symbols, while our NIRDS debris disks stars are denoted by the large bright red triangles.

small fractional excess hidden in the noise of our short LXD measurement, but it is clearly less than the $\sim 5\%$ at $3.6 \mu\text{m}$ and 2.5% at $4.5 \mu\text{m}$ we have found for the 1.4 Gyr old HD 109085 (h Corvi) F2V system (Lisse et al. 2012; C. M. Lisse & M. Marengo 2016, in preparation).

We have performed an independent spectral classification of KIC 8462852 using the six absorption-line emission width (EW) trends of Rayner et al. (2009). These trends, based on the SPEX spectra of ~ 200 main sequence stars cataloged in the IRTF spectral library (http://irtfweb.ifa.hawaii.edu/~spex/IRTF_Spectral_Library/), produced consistent determinations with respect to Kurucz model fitting of our NIRDS systems (C. M. Lisse et al. 2016, in preparation; Figure 2). For KIC 8462852, shown as a yellow star in Figure 2, we find EWs of 1.6 (Ca II $0.866 \mu\text{m}$), 0.3 (Na I $1.14 \mu\text{m}$), 0.0 (Al I $1.313 \mu\text{m}$),

0.65 (Mg I $1.485 \mu\text{m}$), 0.25 (Mg I $1.711 \mu\text{m}$), and 0.30 (Na I $2.206 \mu\text{m}$), leading to a stellar classification of F1V to F2V. The rather low EW for Ca II rules out a sub-giant classification. The spectrum of KIC 8462852 also matches well to that of a canonical main-sequence F2V Kurucz spectrum with $T_{\text{eff}} = 6945 \text{ K}$, $\log g = +4.0$, and $\log [\text{Fe}/\text{H}] = 0.0$ and to a Phoenix next-generation photospheric model with $T_{\text{eff}} = 6890 \text{ K}$, $\log g = +4.0$, and $\log [\text{Fe}/\text{H}] = 0.0$ used by Marengo et al. (2015) to analyze their 2MASS and *Spitzer* photometry of the system.

Following Connelley & Greene (2010, 2014), we have also examined the KIC 8462852 data for HBr γ and CO emission lines due to accretion of hot gas onto the central primary and for He I $1.083 \mu\text{m}$, Fe II $1.256/1.644 \mu\text{m}$, and H2 S(1) 1–0

2.121 μm emission lines due to strong wind outflow, and we find none detectable within the noise of the measurement.

4. DISCUSSION AND CONCLUSIONS

As mentioned in Section 3, there is a small mismatch between the stellar classification results obtained by a Rayner six-line analysis and Kurucz model matching. The six-line classification produces an F1V to F2V, with a very low absorption measure (reminiscent of the depression we saw for HR8789A in our NIRDS survey, a known λ Boo star, versus our other solar abundance objects). The best solar abundance Kurucz model match puts the star somewhere between F2V and F3V due to the flattening or turnover seen at 0.8–1.0 μm . Improving our Kurucz models for non-solar abundance and/or rapid stellar rotation we think is likely to remove this small discrepancy, and we currently trust an F2V assignment based on the strengths of various NIR absorption lines best. Our assignment is close to, but slightly different, than the F3 IV/V classification reported by Boyajian et al. (2015).

Our observations are consistent with a normal main-sequence star without sufficiently large amounts of circumstellar gas or dust, or inflowing or outflowing material, to produce a SpeX detection via the scattering or thermal re-radiation of the star’s insolation. Our observations have eliminated the possibility that there is a sizable amount of very close-in, very hot (>1000 K) material along our line of sight to the star during the IRTF observations on 2015 October 31. Such a population of hot dust could obscure a large solid angle for a highly inclined, nearly edge-on system, and account for the up to 20% drops in the *Kepler* light curve flux, and was not previously ruled out, as obscuration by asteroidal or Kuiper belt dust was, by the high-resolution optical spectroscopy and multi-wavelength photometry presented in Boyajian et al. (2015). We can further state that there are none of the hallmarks of a young, pre-main-sequence system for KIC 8462852. It lacks the usual “flat,” non-photospheric 2–4 μm flux continuum and the gas emission lines seen in other YSO spectra from our NIRDS survey, like HD 51 Oph, HD 166191, or HD 165014.

Presuming we observed the system during its quiescent, or non-obscured, phase (a more than 99% probability, assuming the two major *Kepler* light curve dips reported by Boyajian et al. (2015) were 3 days wide and repeat every 750 days), any model for this system’s strongly varying *Kepler* light curve will have to meet these baseline constraints on material outside the stellar photosphere, i.e., the source of the obscuring material must be episodic in nature, with a localized source reservoir and sink, surrounding a mature, Gyr old star. Otherwise the material would have been detected by re-radiation of intercepted starlight in the infrared wavelengths. (Our observations cannot, however, rule out any artificial structure with an abnormally low ($<1\%$) emissivity pointed in our direction.)

The cometary infall and breakup model most favored by Boyajian et al. (2015) fits our new constraints well. Considering the minimum amount of dust mass required to obscure 20% of a star’s light, though, requires the conversion of a very large number of 1 km radius comets ($\sim 10^5$ or more) every 750 days into ephemeral 1 μm dust particles, the smearing out of $>10^5$ 1 km radius comets into >100 μm radiation pressure stable heavy dust grains along an orbital trajectory, or the violent outgassing of one very big comet-like body of >100 km radius (aka as a Centaur or Kuiper belt object (KBO) in our solar

system) passing near the star’s corona. These scenarios are interesting, in that we have been studying for some time now (using cold and warm *Spitzer* and *SpeX*) another mature, early-type F-star with many similarities, the F2V η Corvi system (Lisse et al. 2012; C. M. Lisse & M. Marengo 2016, in preparation). Wyatt et al. (2005) drew the community’s attention to this system, demonstrating how it had a bright, inclined ($\sim 45^\circ$ to the line of sight) disk-shaped Kuiper belt to go along with its IRAS excess; Chen et al. (2006) showed that the system had a very interesting mid-IR excess spectrum as well as an inner belt of warmish dust at ~ 350 K. Our 2012 follow-up work demonstrated a spectral connection between the warm dust and the cometary and KBO material in the system and posited the formative mechanism as the infall from the Kuiper belt of primitive icy bodies (either $>10^4$ comets/year or 1 large KBO of >130 km radius) due to an ongoing late heavy bombardment. However, unlike KIC 8462852, η Corvi also demonstrates an NIR excess flux above the stellar photosphere of a few percent (Figure 1), and thus an inner belt or ring of permanent circumstellar material. Could these two systems be both undergoing late heavy bombardments, but the one in KIC 8462852 is just starting?

The SPEX data used in this work were obtained by the authors as Visiting Astronomers at the Infrared Telescope Facility, which is operated by the University of Hawaii under contract with the National Aeronautics and Space Administration, Science Mission Directorate, Planetary Astronomy Program. Our NIRDS observations take advantage of and add to the SPEX spectral library of ~ 200 cool FGKM stars (Rayner et al. 2009), and we are deeply indebted to J. Rayner for providing his time and expertise to this project. The authors also wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. The authors would also like to gratefully acknowledge the support of the NASA NExSS program at ASU in producing this manuscript.

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