

KIC 8462852: THE INFRARED FLUX

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ABSTRACT

We analyzed the warm *Spitzer*/IRAC data of KIC 8462852. We found no evidence of infrared excess at $3.6\ \mu\text{m}$ and a small excess of $0.43 \pm 0.18\ \text{mJy}$ at $4.5\ \mu\text{m}$ below the 3σ threshold necessary to claim a detection. The lack of strong infrared excess 2 years after the events responsible for the unusual light curve observed by *Kepler* further disfavors the scenarios involving a catastrophic collision in a KIC 8462852 asteroid belt, a giant impact disrupting a planet in the system or a population of dust-enshrouded planetesimals. The scenario invoking the fragmentation of a family of comets on a highly elliptical orbit is instead consistent with the lack of strong infrared excess found by our analysis.

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

1. INTRODUCTION

KIC 8462852, also known as TYC 3162–665–1 and 2MASS J20061546+4427248, is a $V \simeq 12$ mag star in the field 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 $\sim 20\%$ 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 wild speculations about the nature of the bodies, or structures, responsible for the dimming of its visible flux (see, e.g., Wright et al. 2015).

The star has been carefully characterized in B15. High-resolution ($R \sim 47,000$) spectroscopic observations obtained with the FIES spectrograph at the Nordic Optical Telescope in La Palma, Spain, revealed that KIC 8462852 is a main-sequence star with an effective temperature $T_{\text{eff}} = 6750 \pm 120\ \text{K}$, $\log g = 4.0 \pm 0.2$, and solar metallicity consistent with an F3V 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 Galax (Morrissey et al. 2007) and mid-IR *WISE* (Wright et al. 2010) data, is also consistent with the spectroscopic identification of the source. Of particular significance is the lack of measurable infrared excess in the *WISE* photometry. 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.

Natural guide star adaptive optics (AO) imaging obtained at the Keck II telescope on Mauna Kea, Hawaii, using the NIRC2 infrared (J , H , and K bands) camera revealed the presence of a fainter source $1''.95$ East from KIC 8462852. The brightness ratio of this source with respect to the primary ($\sim 2\%$), as well as its near-IR colors, is consistent with this source being an M2V companion to KIC 8462852. While the physical association of the two stars cannot be demonstrated with current data, B15 estimated that a chance alignment between

the two sources would be only $\sim 1\%$. If the pair is indeed a physical binary, at the distance of KIC 8462852 their separation would correspond to 885 AU.

As mentioned before, KIC 8462852's claim to fame 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 came up empty. 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 or associated with a population of dust-enshrouded planetesimals, or produced by the breakout of a family of comets. The parameter space for all these scenarios is constrained by the lack of infrared excess above the expected stellar photospheric emission in the *WISE* photometry. For this reason, the breakout of a family of comets remains the most likely possibility, as it requires the least amount of mid-infrared excess.

The *WISE* observations of KIC 8462852, however, were restricted to *Kepler* Q5 nine months before the first dimming event in 2011 March (Q8). The possibility remains that infrared observations of the system, if carried out *after* the dimming events, would be capable of detecting some lingering excess. The star was in fact observed by the IRAC camera (Fazio et al. 2004) on board the *Spitzer Space Telescope* (Werner et al. 2004) in early 2015 as part of the SpiKeS program aimed to map the entire *Kepler* field.

In this Letter, we present the *Spitzer*/IRAC photometry of KIC 8462852. In Section 2, we describe the observations and how we measured the photometry of the source. In Section 3, we analyze the results in order to assess the presence of an infrared excess, taking into account the added flux contributed by the nearby M2 star. The consequences of our measurement on the standing hypothesis for the nature of the dimming events are discussed in Section 4; our results are summarized in Section 5.

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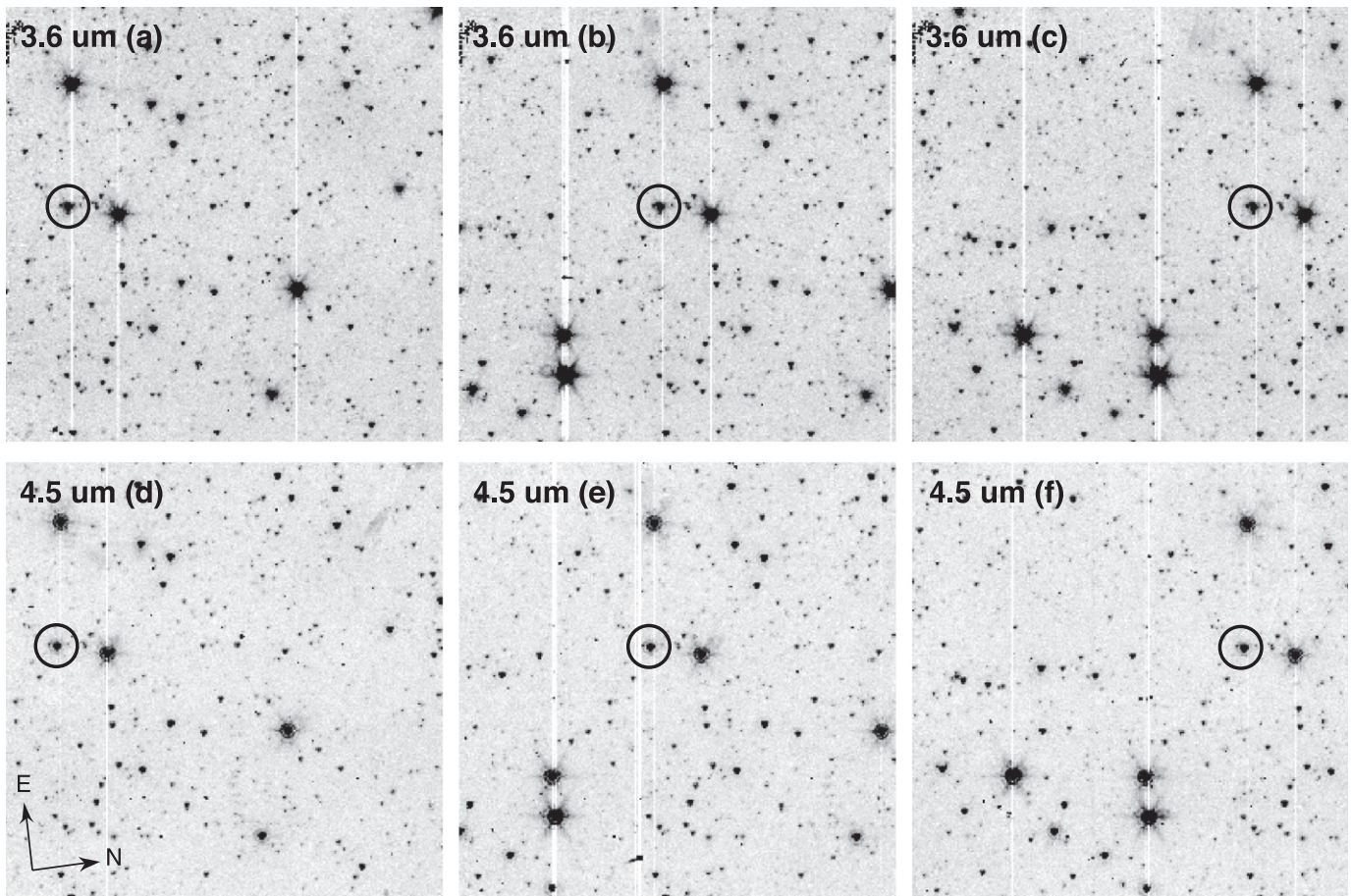


Figure 1. IRAC BCDs containing KIC 8462852 ($3.6 \mu\text{m}$, top row; $4.5 \mu\text{m}$, bottom row). The target is marked with a circle ($15''$ radius). Note the significant vertical lines (column pull-down artifacts) caused by the nearby source KIC 8462934, especially strong at $3.6 \mu\text{m}$. One $4.5 \mu\text{m}$ frame (panel (e)) is also affected by even stronger pull-down artifacts from cosmic rays at the bottom of the frame. The images are in array coordinates (position angle $82^\circ 66'$).

2. SPITZER/IRAC OBSERVATIONS AND PHOTOMETRY

KIC 8462852 was observed on 2015 January 18 (JD 2457040.87) as part of the *Spitzer Kepler* Survey (SpiKeS; PID 10067, PI M. Werner) aimed at mapping the entire *Kepler* field with warm IRAC. The program uses a shallow mapping strategy consisting of overlapping frames, with the standard 12 s frame time Astronomical Observation Template (equivalent to a 10.4 s exposure time), organized in such a way that each point in the sky is observed in at least three consecutive frames (for a total of 31.2 s) in both warm IRAC bands (3.6 and $4.5 \mu\text{m}$). KIC 8462852 was observed as part of AOR 52340480. The Basic Calibrated Data (BCD) from the observation are publicly available from the *Spitzer* Heritage Archive and have been processed by the *Spitzer* pipeline, version S19.1.0.

KIC 8462852 is easily identified based on its coordinates, provided in B15. Figure 1 shows the six BCDs (three for each IRAC channel) containing the source. Given the crowding of *Kepler*'s field, the images are heavily affected by vertical electronic artifacts caused by saturated sources (known as *column pull-down*). One of these artifacts (due to the nearby $V \simeq 11.5$ mag source KIC 8462934) affects KIC 8462852 in all frames. One of the $4.5 \mu\text{m}$ frames is also affected by two more pull-down artifacts from cosmic rays at the bottom of the frame. These artifacts need to be removed as they can affect the photometry of the target. For this reason in the following

analysis, we have used the artifact-corrected frames (CBCDs) where the offset in the columns affected by pull-down is determined separately above and below the triggering source and corrected.

We have then determined the magnitude of KIC 8462852 following the prescriptions in the *Spitzer* Science Center 2013 July 18 memo.⁴ We performed aperture photometry separately on each individual CBCD, with the aperture position determined with flux-weighted moments, and then applied corrections for array location-dependent and pixel-phase photometry. The main source of photometric uncertainty with this method is related to IRAC's point-spread function (PSF) undersampling, causing small photometric variations from frame to frame. To take this issue into account, we have estimated the photometric uncertainty as the standard deviation of our three measurements, corrected for bias (by a factor of $1/0.866$ appropriate for $n = 3$).

We adopted an aperture of 3 IRAC pixel radius (corresponding to $3''.65$) with a sky annulus of 3 to 7 IRAC pixels radius for background subtraction. The aperture corrections for such a combination of aperture and sky annulus (the same used for the IRAC absolute calibration) is equal to 0.1286 at $3.6 \mu\text{m}$ and 0.1256 at $4.5 \mu\text{m}$ (Carey et al. 2012). The conversion from instrumental to Vega magnitudes was done relying on IRAC's absolute photometric calibration (using the warm mission flux

⁴ <http://ssc.spitzer.caltech.edu/warmmission/news/18jul2013memo.pdf>

Table 1
KIC 8462852 Infrared Magnitudes

Band	Magnitude	Reference
<i>J</i>	10.763 ± 0.021	2MASS
<i>H</i>	10.551 ± 0.019	2MASS
<i>K_s</i>	10.499 ± 0.020	2MASS
[3.6]	10.4768 ± 0.0059	IRAC
[4.5]	10.4374 ± 0.0107	IRAC
<i>W1</i>	10.425 ± 0.023	(ALL) WISE
<i>W2</i>	10.436 ± 0.020	(ALL) WISE

conversion factors of 0.1253 and 0.1469 MJy sr⁻¹ per DN s⁻¹ and the Vega fluxes of 280.9 and 179.7 Jy at 3.6 and 4.5 μm, respectively).

The IRAC magnitudes we obtained with the process outlined above are listed in Table 1, together with the 2MASS and *WISE* (*W1* and *W2* bands only) photometry for comparison. The magnitudes listed in Table 1 are before color correction and do not include the uncertainty due to the instrument absolute photometric calibration. As shown in Carey et al. (2012), the uncertainty in the IRAC absolute calibration can be split in two parts. One is the statistical error in the IRAC flux conversion factors, equal to 0.6% and 0.5% at 3.6 and 4.5 μm, respectively. We have included this uncertainty in the analysis described in the next section. The other is the error in the calibration zero points, which can be as high as 1.5%. It should be noted, however, that the IRAC calibration zero point is based on observed spectra and models of a set of calibrators whose absolute normalization relied on their 2MASS magnitudes (Cohen et al. 2003; Reach et al. 2005). The absolute calibration of *WISE* is similarly tied to the one of *Spitzer* (Wright et al. 2010; Jarrett et al. 2011). This was done to ensure that the comparison between IRAC, 2MASS, and *WISE* fluxes is not affected by systematic errors to the same degree as their absolute calibration zero points. A test performed comparing the IRAC photometry of a set of calibrators to the *Hubble Space Telescope* CALSPEC database indeed found no systematic bias (Carey et al. 2012).

The IRAC magnitudes of KIC 8462852 are consistent with the corresponding *WISE* photometry, despite the small differences in the transmission curves of the photometric systems adopted in the two instruments. The photometric uncertainty of the IRAC measurements at 3.6 and 4.5 μm, however, are about 4 and 2 times smaller than the corresponding *WISE* magnitude uncertainties.

3. INFRARED EXCESS

To search for evidence of an IRAC infrared excess in KIC 8462852, we performed a χ^2 fit of the star’s photometry with available stellar atmosphere models. We have derived synthetic photometry for each passband by convolving the model spectra with the appropriate transmission curve and then compared them with the measured in-band fluxes after applying color corrections.

We determined the normalization of the models by fitting the 2MASS near-IR photometry, rather than the whole optical and near-IR SED (as done by B15) in order to limit the effects of the systematic uncertainties in the cross calibration between optical and infrared data. While this choice could partially alias an infrared excess in the IRAC bands if a near-IR excess is also present, this is an unlikely scenario as it would require very hot

Table 2
Infrared Excess (Reference Model)

Band	F_ν (Model) (mJy)	F_ν (Primary) (mJy)	Excess (mJy)
<i>J</i>	84.61 ± 0.98	84.65 ± 1.53	...
<i>H</i>	63.79 ± 0.74	63.36 ± 1.08	...
<i>K_s</i>	41.85 ± 0.48	42.17 ± 0.78	...
[3.6]	17.74 ± 0.20	17.82 ± 0.15	0.09 ± 0.25
[4.5]	11.37 ± 0.13	11.79 ± 0.13	0.43 ± 0.18

dust close to the star, which is rejected by the analysis in B15. Furthermore, the 2MASS magnitudes were measured many years before the *Kepler* dimming events: finding an excess in the 2MASS observation would imply that the KIC 8462852 phenomenon existed for a long time before being discovered by *Kepler*.

Before normalizing the stellar models with the 2MASS photometry, however, we need to perform two different sets of corrections. The first is to correct the magnitudes in Table 1 for the $E(B - V) = 0.11$ reddening measured by B15. We adopted the Cardelli et al. (1989) reddening law for 2MASS and the total-to-selective extinction reported in Monson et al. (2012) for the two IRAC bands. The second correction requires the subtraction of the flux from the M dwarf companion found with the Keck/AO imaging. Regardless of the physical association with the primary, this red source is close enough to the primary to be blended in the IRAC, 2MASS, and *WISE* photometry. To separate the contribution of the M dwarf companion from the total flux measured by 2MASS, we used the accurate *J*, *H*, and *K* magnitude differences reported by B15. Assuming that the source is indeed an M2V companion, we extrapolated its flux to the IRAC bands from the 2MASS flux in the *K* band. For this task, we used *Spitzer*’s flux estimator for stellar point sources (STAR-PET⁵) for an M2V spectral type. The fluxes of the corrected KIC 8462852 primary photometry are listed in Table 2.

We started with an ATLAS9 model grid (Castelli & Kurucz 2004), which is the same used for the IRAC and 2MASS absolute calibration (Carey et al. 2012), setting gravity and metallicity to the values measured by B15 ($\log g = 4.0$ and $\log[Z/H] = 0.00$). The best fit temperature for the primary was determined by minimizing the χ^2 of quadratically interpolated models with temperatures between 6750 and 7250 K. The best fit was obtained for $T_{\text{eff}} = 6950$ K ($\chi^2 = 0.36$) close to the spectroscopically determined effective temperature ($T_{\text{eff}} = 6750 \pm 120$ K, yielding instead $\chi^2 = 1.42$). Since the 2MASS photometry of KIC 8462852 has a relative error of 0.020 mag (or $\sim 2.00\%$), we attributed to the atmosphere model normalization factor an uncertainty of $2\%/\sqrt{3} \simeq 1.13\%$. The good agreement of the 2MASS photometry with the best fit model supports the absence of a detectable IR excess in the 2MASS data.

The fluxes of the ATLAS9 atmosphere described above (“reference model” hereafter) are listed in Table 2, and the synthetic spectrum (together with the 2MASS and IRAC photometry) is shown in Figure 2. The IRAC photometry of the KIC 8462852 primary is consistent with no excess at 3.6 μm. A small excess of 0.43 ± 0.18 mJy (corresponding to a

⁵ <http://ssc.spitzer.caltech.edu/warmmission/propkit/pet/starpet/index.html>

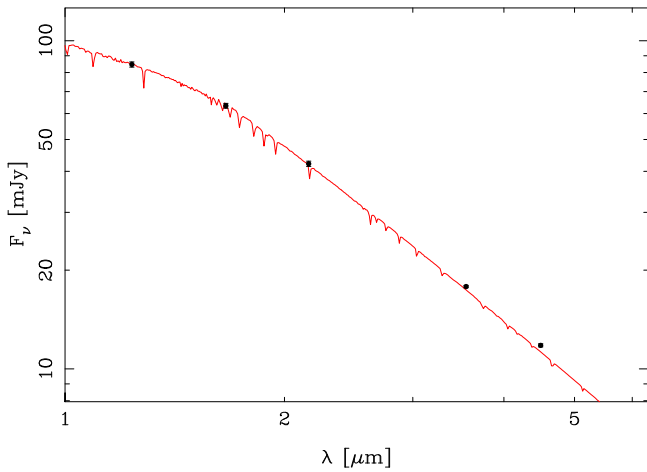


Figure 2. Our reference ATLAS9 model atmosphere for an F3V star normalized with the 2MASS photometry. IRAC photometry shows a $\sim 2.4\sigma$ excess at $4.5 \mu\text{m}$. Error bars for the IRAC bands are smaller than the symbols used in the figure.

significance of 2.4σ) is found above the photosphere model at $4.5 \mu\text{m}$. Letting $\log g$ and $\log[Z/H]$ vary within their measurement uncertainty has a small effect on the $4.5 \mu\text{m}$ excess, and its significance remains in the 2.2σ to 2.5σ range. To test the effect of using different model atmospheres, we repeated the same exercise using the PHOENIX grid (Brott & Hauschildt 2005). These models tend to have larger mid-IR emission, as suggested by Sinclair et al. (2010), lowering the significance of the $4.5 \mu\text{m}$ excess to the 1.8σ to 2.1σ range.

The low significance of our measurement prevents us from concluding that the fluxes in Table 2 represent a detection of mid-IR excess from KIC 8462852. They are nevertheless suggesting that in 2015 January this excess could have been present at $4.5 \mu\text{m}$, where its significance is above 2σ for most models. In absence of a firm detection, however, we set 3σ limits in the KIC 8462852 excess equal to 0.75 mJy at $3.6 \mu\text{m}$ and 0.54 mJy at $4.5 \mu\text{m}$.

4. DISCUSSION

A mid-IR detection of excess emission from KIC 8462852 (or a detection limit) would provide strong constraints on the nature and the location of the objects responsible for the dimming of the star. In particular, the fractional brightness of the excess listed in Table 2 at $4.5 \mu\text{m}$ ($f_{4.5} = F_{4.5}^{\text{dust}}/F_{4.5}^{\text{star}} \simeq 4.6 \times 10^{-2}$) can be translated into a total fractional luminosity $f = L_{\text{dust}}/L_{\text{star}}$ as a function of the dust temperature T_d . Following B15, this relation is shown in Figure 3 (dotted line). The solid line is instead the upper limit in the fractional luminosity based on our 3σ upper limit in the excess. The dashed line on the plot represents the relation between the fractional luminosity and the dust temperature estimated by B15 by integrating the optical depth inferred from the *Kepler* light curve. This estimate assumes that the dust clumps responsible for the dimming are similar in size to the star and are on a circular orbit. Based on these hypotheses, our 3σ limit in the excess corresponds to a maximum fractional luminosity $f \approx 8 \times 10^{-4}$, a maximum dust blackbody temperature $T_d \approx 800 \text{ K}$, and an orbital radius larger than $\approx 0.2 \text{ AU}$.

The absence of strong infrared excess at the time of the IRAC observations (after the dimming events) implied by our

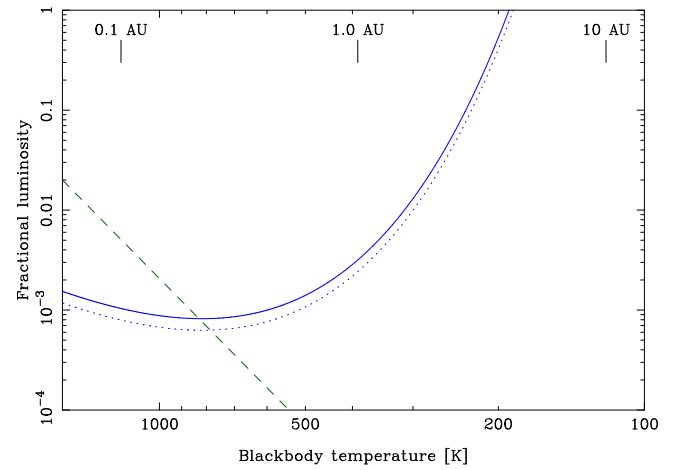


Figure 3. Fractional luminosity of a clump of dust in proximity to KIC 8462852 as a function of its blackbody temperature. The dotted line corresponds to the 2.4σ excess derived at $4.5 \mu\text{m}$ with our reference Kurucz model. The solid line is instead the upper limit based on our 3σ limit for the excess in the $4.5 \mu\text{m}$ IRAC band. The green dashed line is the dust fractional luminosity estimated in B15 by integrating the optical depth in the *Kepler* light curve, assuming that the clumps are similar in size to the star and are on a circular orbit. The distances at the top of the figure are the reference blackbody orbital radii from B15.

$4.5 \mu\text{m}$ 3σ limit suggests that the phenomenon observed by *Kepler* produced a very small amount of dust. Alternatively, if a significant quantity of dust is present, it must be located at a large distance from the star. As noted by B15, this makes the scenarios very unlikely in which the dimming events are caused by a catastrophic collision in KIC 8462852 asteroid belt, a giant impact disrupting a planet in the system, or a population of dust-enshrouded planetesimals. All these scenarios would produce very large amount of dust dispersed along the orbits of the debris, resulting in more mid-IR emission than what can be inferred from the optical depth of the dust seen passing along our line of sight to the star. Our limit (two times lower than the limit based on *WISE* data) further reduces the odds for these scenarios.

The giant impact hypothesis would be entirely ruled out if the 2.4σ excess from our reference model is real and if all dust transited the star during the *Kepler* dimming event, since in these hypotheses, Figure 3 would imply that the impact must have happened just beyond 0.2 AU from the star. This would be in contradiction with the requirement, based on the time lag between the two dimming events in the *Kepler* light curve, that the impacted body had an orbital radius of $\approx 1.6 \text{ AU}$. If these hypotheses are not verified, a giant impact could still be possible at radii below our solid line and to the right of the dashed line in Figure 3.

The hypothesis of the disruption of a family of comets is the preferred scenario in B15 because it dispenses with the requirement of a circular orbit, allowing the cloud of dust produced in the comets' fragmentation to rapidly move away from the star on a highly elliptical orbit. It remains the most likely hypothesis even with our $4.5 \mu\text{m}$ 3σ limit since the 2 year gap between the *Kepler* events and the IRAC observations would have been sufficient for the cometary debris to move several AU away from the tidal destruction radius of the star. At such a distance, the thermal emission from the dust would be peaked at longer wavelengths and undetectable by IRAC. A robust detection at longer wavelengths (where the fractional

brightness of the debris with respect to the star would be more favorable) will allow the determination of the distance of the cometary fragments and constrain the geometry of this scenario.

5. SUMMARY AND CONCLUSIONS

We have analyzed the warm *Spitzer*/IRAC images of KIC 8462852 obtained in 2015 January 18 as part of the SpiKeS survey of the *Kepler* field. Our mid-IR photometry is in agreement with the photospheric emission from the star at $3.6\ \mu\text{m}$ and shows a small excess of $0.43 \pm 0.18\ \text{mJy}$ at $4.5\ \mu\text{m}$, below the required 3σ confidence level for a detection. This reveals that 2 years after the dimming event observed by *Kepler*, no significant amount of circumstellar dust can still be detected. This further reduces the odds that the phenomena observed in 2011 and 2013 are caused by catastrophic collisions in the asteroid belt of this star, by a giant impact on one of its planets, or by a population of dust-enshrouded planetesimals because such extreme systems (e.g., BD+20 307) do present a large excess detected in the $3\text{--}5\ \mu\text{m}$ spectral region (see, e.g., Meng et al. 2015 and references therein). The scenario in which the dimming in the KIC 8462852 light curve were caused by the destruction of a family of comets remains the preferred explanation for the undetectable amount of infrared excess associated with the *Kepler* events.

Our measurement is not sufficient to constrain the temperature and the magnitude of the fractional luminosity of the dust that would be associated with the comets. However, if combined with detections at longer wavelengths (where the fractional infrared brightness is expected to be higher) and long-term infrared monitoring, it will allow constraining the temperature and location of the dust cloud and possibly the

geometry of the catastrophic event at the root of this unusual phenomenon.

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Facilities: *Spitzer* (IRAC), *Kepler*.

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