Spectral Evidence for an Inner Carbon-rich Circumstellar Belt in the Young HD 36546 A-star System

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Abstract

Using the NASA/IRTF SpeX and BASS spectrometers we have obtained 0.7–13 μm observations of the newly imaged 3–10 Myr old HD 36546 disk system. The SpeX spectrum is most consistent with the photospheric emission expected from an $L_\ast \sim 20 L_\odot$, solar abundance A1.5V star with little to no extinction, and excess emission from circumstellar dust detectable beyond 4.5 μm. Non-detections of CO emission lines and accretion signatures point to the gas-poor circumstellar environment of a very old transition disk. Combining the SpeX + BASS spectra with archival WISE/AKARI/IRAS/Herschel photometry, we find an outer cold dust belt at ~135 K and 20–40 au from the primary, likely coincident with the disk imaged by Subaru, and a new second inner belt with a temperature ~570 K and an unusual, broad SED maximum in the 6–9 μm region, tracing dust at 1.1–2.2 au. An SED maximum at 6–9 μm has been reported in just two other A-star systems, HD 131488 and HD 121191, both of ~10 Myr age. From Spitzer, we have also identified the ~12 Myr old A7V HD 148657 system as having similar 5–35 μm excess spectral features. The Spitzer data allows us to rule out water emission and rule in carbonaceous materials—organics, carbonates, SiC—as the source of the 6–9 μm excess. Assuming a common origin for the four young A-star systems’ disks, we suggest they are experiencing an early era of carbon-rich planetesimal processing.

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

1. Introduction

HD 36546 hosts a bright, wide circumstellar disk that has just recently been imaged for the first time by Currie et al. (2017) using Subaru/SCExAO. Identified in the WISE all-sky survey as one of the most promising new debris disk detections (Padgett 2011; McDonald et al. 2012; Wu et al. 2013; Liu et al. 2014; Cotten & Song 2016), its extent (~2″ in diameter) and brightness ($L_{\text{excess}}/L_\ast$ value of ~4 × 10^{-3}) make it an important target for further study. Located slightly foreground ($d = 114$ pc; van Leeuwen 2007) to the 1–2 Myr old Taurus–Auriga star-forming region ($d = 130–160$ pc; Kenyon et al. 2008; Luhan et al. 2009; Torres et al. 2009), it was not reported by IRAS in its all-sky survey (Aumann 1985) due to confusion with background Taurus Dark Cloud emission. Few, thus characterizing measurements have been made of the system, even some 30+ years after the IRAS mission—mainly just Michigan survey, Tycho survey, WISE, and AKARI photometry (Vizier photometric database http://vizier.u-strasbg.fr/vizier/; Pickles & Dapeng 2010).

In this Letter we present new 0.7–5.0 μm SpeX (Rayner et al. 2003, 2009; Vacca et al. 2003, 2004; Cushing et al. 2004) and 3–13 μm BASS (Hackwell et al. 1990) spectra of the HD 36546 system taken as part of the 100+ hours Near Infrared Disk Survey (NIRDS; Lisse et al. 2017; C. M. Lisse et al. 2018, in preparation; 50+ systems to date) at the NASA/IRTF 3 m.

Our spectra are novel in that they cover the entire wavelength range from 0.7 to 5.0 μm at high spectral resolution and the 5–13 μm region at all, allowing us to characterize the primary star’s photospheric absorption features and search for warm inner excess emission due to circumstellar gas and dust in the system. We also include new high SNR Herschel photometry in our analysis that extend system FIR measurements out to 160 μm.

2. Observations

We first observed HD 36546 on 2017 January 13 UT from the NASA/IRTF 3 m using SpeX. The instrument provided $R = 2000$–2500 observations from 0.7 to 5.0 μm in two orders, termed SXD (for “short cross-dispersed”) and LXD (for “long cross-dispersed”), configured with an 0″3 slitlet (Rayner et al. 2003, 2009). Our observational setup was identical to that used for other NIRDS debris disk studies (e.g., Lisse et al. 2012, 2013, 2015, 2017). The nearby A0V star used in our Spextool data reduction as a calibration standard (Vacca et al. 2004) was HD 34203 ($K = 5.46$), picked to match the HD 36546 primary ($K = 6.8$) in color, effective temperature, and spatial proximity (the best-fit BvJHKs HD 36546 photometry gave $T_{\text{eff}} = 9450$ K and $(B-V)_0 = 0.07$, consistent with an unreddened A2V star; Pecaut & Mamajek 2013). We observed HD 36546 in SXD mode with a total on-target integration time of 960 s and in LXD mode for 1800 s, while the calibrator star HD 34203 was observed for 480 s in SXD and 1440 s in LXD mode. The instrument behavior was nominal, and the weather was excellent, with < 20% relative humidity at the summit and seeing ~0″6 at K-band, allowing for good sky correction and stellar calibration. Both stars were observed in ABBA nod
mode to remove telescope and sky backgrounds. We observed HD 36546 1.5 hr after evening twilight and before meridian transit, with the position angle (PA) of the slit on the sky between 241° and 265° parallel to the long axis of the circumstellar disk, as described by Currie et al. (2017).

Using BASS (Hackwell et al. 1990), we obtained 3–13 μm, \( R = 30–125 \) follow-up observations of HD 36546 at the IRTF on 2017 January 29 UT. Again the weather was very good, and the effective on-target time was \( \sim 15 \) minutes of integration. A N-S chopper throw of \( \sim 10''2 \) was utilized along with the \( \sim 4''2 \) wide BASS beam, which encompassed the system’s whole disk. The nearby star used as a sky calibrator was HD 29139 (\( \alpha \) Tau). The median BASS SNR achieved in the 3.1–5.1 μm region of HD 36546’s spectrum was 54, and in the 8–13 μm region was 5.1.

3. Results

Figure 1 shows our HD 36546 SpeX measurements in the context of six other NIRDS main-sequence early A-type stellar spectra. All of the spectra are as taken and calibrated versus a nearby standard A0V star; no de-reddening has been applied. The typical spectral behavior for our program systems matches the photospheric model well from 0.7 to 1.3 μm, exceeds it slightly (if at all) from 1.3 to 3 μm, then matches it again from 3 to 5 μm. For a small subset of \( \sim 8 \) young NIRDS stars (e.g., HD 113766, HD 15407A, HD 23514; Lisse et al. 2015; Dore et al. 2016), with abundant warm (200–500 K) circumstellar dust, we find a close match to a stellar photospheric spectrum out to \( \sim 3 \) μm, then a rapid, exponential increase in excess from 3 to 5 μm that continues to rise into the large 8–13 μm warm silicate emission complex excesses seen in associated mid-infrared system spectra. The \( \sim 10 \) Myr old star HD 131488 (A3V according to our NIRDS measurements; Melis et al. 2013; Figure 2 inset) shows an unusual excess that begins at \( \sim 1.5 \) μm and increases in a roughly linear fashion outwards to \( \sim 10 \) μm, where it is overtaken by rising thermal emission from cold (\( \sim 100 \) K) circumstellar material. The \( \sim 10 \) Myr old star HD 131488 (A3V according to our NIRDS measurements; Melis et al. 2013 list it as an A1V) shows an unusual excess that begins at \( \sim 3.2 \) μm and is relatively flat outward to 5 μm, then peaks at 6–7 μm, falling afterward at 8–9 μm (Melis et al. 2013; Figure 2 inset). Of all of our NIRDS stars, the coarse spectral behavior of HD 36546 in the near-infrared looks most similar to that of HD 131488, although with smaller excess that is just beginning to be seen at 4.5–5.0 μm in our SpeX data.

We performed a weighted \( \chi^2 \) spectral PHOENIX/NextGen model fit to HD 36546’s photosphere from 0.95 to 2.4 μm in \( (E(B-V), T_{\text{eff}}, \text{and log} \, g) \), with the model normalized to the 0.72–0.82 μm region of our SpeX spectrum. The best-fit parameters, \( E(B-V) = 0.01 \), \( T_{\text{eff}} = 8920 \pm 80 \) K, and \( \log g = 4.50 \pm 0.25 \), fall between the values for a solar
abundance A1V and a solar abundance A2V star in E. Mamajek’s stellar classification scheme (Pecaut & Mamajek 2013). For the given distance of 114 pc from Earth, the $V = 6.95$ Tycho magnitude for HD 36546 is consistent with $L_\ast \sim 20 L_\odot$, which compares well with the Hipparcos $L = 25 L_\odot$ for A1V Sirius at 2.68 pc. The excellent model fit is consistent with WISE and NIR 2MASS and Tycho synthetic photometry (Vizier photometric database http://vizier.u-strasbg.fr/vizier/; Pickles & Depagne 2010) of HD 36546 except at the longest wavelengths, where circumstellar excess flux becomes important. Our 0.7–5.0 μm SpeX results for HD 36546 are shown in detail in Figure 2 in black, in comparison to the best-fit PHOENIX/NextGen photpheric model. There are no detectable HBγ and CO emission lines due to fluorescing circumstellar gas or accretion, nor any He I 1.083 μm, Fe II 1.256/1.644 μm, and H$_2$ S(1) 1-0 2.121 μm emission lines due to strong wind outflow within the noise of the measurement (Connelley & Greene 2010, 2014). No emission lines due to neutral PAHs are seen at 3.29 μm. (These lines were easily detected in the NIRDs survey for the gas-rich A star YSO 51 Oph and the bright Nova Oph, so we know that we are capable of detecting them with SpeX if they are present.)

Looking at the range of allowed models, we find that A0.5V–A2.5V models with $E(B-V) \sim 0.01$ are allowed by our data; models earlier than A0.5V require $E(B-V) > 0.06$ and very high values of $\log g$ (for a young A star), and even then they produce a worse fit to the continuum between the hydrogen absorption lines. Low extinction photpheric models are consistent with HD 36546 at $d = 114$ pc (van Leeuwen 2007) being foreground to the 1–2 Myr old Taurus–Auriga star-forming region at $\sim$140 pc (Kenyon et al. 2008; Luhman et al. 2009; Torres et al. 2009). Our best-fit photphere models show some slight differences with the B9V–A1V spectra type derived by Currie et al. (2017) from optical spectra. In either case, the Tycho survey $V - K = 0.205$ photometric color for HD 36546 is consistent with an unreddened $\sim$A1V, both optical and near-IR spectra are inconsistent with spectral types earlier than A0, and neither solution affects our detection of excess NIR flux from circumstellar dust surrounding the star.

Adding in AKARI, WISE, and Herschel 3–160 μm photometry, we find a combined SED dominated by stellar photpheric emission at short wavelengths and an excess in the 20–160 μm range due to cold outer system dust. The long wavelength excess is normal, as we see it in more than half of all NIRDs + Spitzer IRS combined SEDs (C. M. Lisse et al. 2018, in preparation). The total flux excess for the cold ($T \sim 135$ K) outer dust is $L_{\text{cold excess}}/L_\odot \sim 4 \times 10^{-3}$.
consistent with previous reports (McDonald et al. 2012; Wu et al. 2013; Liu et al. 2014; Cotten & Song 2016).

The SpeX spectrum + AKARI/WISE/Herschel photometry suggested an unusual spectral behavior: a secondary local SED maximum at ∼8 μm, not the usual 9–11 μm created by silicaceous dust species. Our new BASS 3–13 μm spectrum confirms this. Figure 2 shows that while the excess observed in the 3–12 μm AKARI/WISE photometry, with maximum near 8 μm, can be fit with a blackbody model at \( T \approx 570 \) K (dashed cyan curve), the BASS spectra and AKARI 8.8 μm photometry cannot. The BASS excess is similar to the unusual T-ReCS spectra reported for HD 131499 and HD 121191 by Melis et al. (2013), with their apparent peaks shortward of 8 μm (Figure 2).

Searching through the Spitzer/IRS 600+ disk, 5–35 μm survey database (Mittal et al. 2015) for more proof of this unusual excess behavior, we found a very good match with the excess (over the photosphere) spectrum of HD 148657. This Spitzer flux excess has been scaled and overlaid in Figure 2; the match to HD 36546’s SED is clear, as is the non-blackbody shape of HD 148657’s 5–12 μm excess.

4. Discussion

Comparing the HD 36546 SED to that of other well-studied A-star circumstellar disk systems showing excesses without narrowband gas line features (Chen et al. 2014; Mittal et al. 2015), we find some similarities and differences. In the outer-belt-dominated systems, seen in roughly half of our NIRDS observations, there is a large peak at long wavelengths due to cold 50–150 K dust (C. M. Lisse et al. 2018, in preparation). In systems with strong warm rocky dust emission, seen in ∼15% of our NIRDS systems (Lisse et al. 2015; Dore et al. 2016; C. M. Lisse et al. 2018, in preparation), strongly rising near-infrared excesses associated with 250–500 K warm dust and prominent mid-infrared maxima at 9–11 μm are found. Both of these contributions can exist, e.g., in the A6V β Pic SED system (Chen et al. 2007). But for HD 36546, while we find that the long wavelength excess is due to thermal emission from cold outer system dust, the near-infrared excess is only slowly increasing, if at all, toward longer wavelengths, and a secondary minor mid-infrared peak is found in the 7–8 μm range, clearly different from the normal 9–11 μm silicate dust maxima or the rarer ∼9 μm silica dust maxima (e.g., A7V HD 172555; Lisse et al. 2009).

We currently know of three other systems with matching spectral behavior: all are A0-A8V and young. The NIR excess for HD 131488 (A3V, ∼10 Myr) in our SpeX measurements is even larger in magnitude and extends down to ∼3.2 μm (Figure 1), suggesting a larger population of unusual inner system dust in this system. The disk morphologies for HD 131488, as revealed by new GPI data, is similar as well. HD 121191 (A8V, ∼10 Myr) also demonstrates a warm and cold dust excess, although at lower SNR in the MIR (Melis et al. 2013), while imagery by Herschel (Vican et al. 2016) finds an extended cold dust disk for the system. A search through the 600+ Spitzer/IRS disk spectral survey (Chen et al. 2014; Jiang-Condell et al. 2015; Mittal et al. 2015) turned up an excellent match to the HD 36546 SED excess for the young A-star system, HD 148657, with a similar broad maxima over the photosphere in the 5–13 μm region and a large cold (∼135 K) dust maximum (Figure 2). The warm flux excess for HD 148657 shows a maximum in the 7–8 μm region dominated by C–C, C–Si, and C–H vibrational stretching modes, and minima in the ∼6 μm water H–O–H bending mode region and the 9–12 μm Si–O stretching region.

What could be the cause of an apparent relative maximum at 7–8 μm in the HD 36546, HD 131488, HD 121191, and HD 148657 SEDs? A-stars illuminate and irradiate their massive primordial disks very strongly, so they are expected to evolve rapid disk evolution (Melis et al. 2013; Chen et al. 2014; Mittal et al. 2015) and a high frequency of detected debris disks (Wu et al. 2013). The 7–8 μm emission peak can be sourced by species such as carbonates, SiC, or aliphatic/aromatic hydrocarbons, which are all carbon-rich. By reference to our own solar system, if the HD 36546 circumstellar material was located around Sol, the dust population producing the warm, ∼570 K excess would be located inside the orbit of Mercury, while the cold ∼135 K dust would be located in the outer regions of our asteroid belt.

Putting these ideas together, we can synthesize a few likely possibilities for the observed SEDs: (1) The relative maximum at 7–8 μm could be coincidental, and each system could simply be hosting an inner belt at a few astronomical units from the primary star that is currently producing a large amount of carbon-rich dust via collisional grinding and/or aggregation of carbon-planetisimals. (2) It could be that a giant impact has recently occurred involving a carbonaceous parent body (like a KBO or comet from the outer cold disk population) in the inner portions of these systems, producing carbon-rich dust warm enough to express a 6–9 μm emission feature. (3) it could be that we are finding emission pinned to the ∼550–600 K sublimation range of common primitive dust species, such as ferromagnesian sulfides, as the host A star evaporates the last remnants of its primordial disk material, and the sublimation is also releasing hot carbonaceous material previously held in matrix.

A final possibility we mention for completeness’ sake is (4) that the unusual A-star SEDs are composed of the typical photospheric + cold outer dust flux contributions plus “contamination” from background interstellar cirrus (Zubko et al. 2004; Flagey et al. 2006; Compiègne et al. 2011). After all, HD 36546 was not listed in the original IRAS catalog of Vega-like stars (Aumann 1985) precisely because it was confused with the highly structured Taurus dark cloud complex. However, this would seem to require an unlikely large cirrus contribution for HD 36546’s 0.3 Jy @ 8 μm flux that is not removed by the usual chopping/nodding performed in MIR observations, is at odds with the small value of \( E(B–V) = 0.01 \) found in our photospheric fits, and is not consistent with the compact MIR point sources seen in AKARI and WISE imagery. It would also require that the other three systems that we have identified as similar, HD 131488, HD 121191, and HD 148657, all be “contaminated” as well.

Using forward modeling, Currie et al. (2017) found an imaged HD 36546 dust disk with radius 85 ± 10 au (FWHM). Assuming simple blackbody behavior and a total luminosity \( L_\star = 20 L_\odot \) for HD 36546, this dust should radiate as blackbodies with temperatures between 69 K (75 au) and 61 K (95 au). Blackbody dust at ∼135 K, as found in the longest wavelength source peaking at ∼40 μm of our HD 36546 SED (Figure 2) would have to be located at ∼20 au from a 20 \( L_\odot \) primary. Allowing for the superheat ratio \( T_{\text{dust}}/T_{\text{BB}} = 100 \text{K}/71 \text{K} = 1.41 \) found by NIRDS for dust in the HR 4796A (A0.5V) ring at ∼75 au from its primary (Lisse et al. 2017) moves this location out to ∼40 au, closer to the Currie et al. estimate. The remaining discrepancy between the
spectral and imaging radial distance estimates might be due to our poor current characterization of the MIR−FIR SED peak; to our lack of understanding of the superheat behavior of the HD 36546 outer dust (values of $T_{obs}/T_{BB}$ out to 5–15 have been reported by Rodriguez & Zuckerman 2012 and Vican et al. 2016); or to the different sensitivities of scattered light ($\propto$ surface area’albedo) versus thermal emission ($\propto$ surface area’emissivity’$T^4$) measurements of circumstellar dust in a thick disk, which will weight closer-in dust thermal emission most highly (Watson et al. 2009 and references therein).

Using the $T \sim 570$ K fit to the continuum underlying the warm SED excesses in Figure 2, we find that the dust component creating the $\sim8\ \mu$m peaked emission would have to lie somewhere near 1.1 au for pure blackbody behavior, or near 2.2 au for superheated grains with thick disk, which will weight closer-in dust thermal emission most highly (Watson et al. 2009 and references therein).

5. Conclusions

(1) The HD 36546 primary is a nearly unextincted early A star, not a late B star. Our modeling favors A1.5V +/−1 subclass, which is slightly later than the A0V classification found from optical spectra (Currie et al. 2017). Both optical and near-IR spectra rule out spectral types earlier than A0. The best-fit photospheric models require very low or no extinction, implying that HD 36546 is in the front of the 1–2 Myr old Taurus–Auriga star-forming region as seen from Earth, and that there is little to no in-system extinction of the primary star.

(2) There are no detected 2.1–2.5 µm CO emission lines due to fluorescing circumstellar gas, no HBr emission lines due to accretion, and no He i 1.083 µm, Fe II 1.256/1.644 µm, or H2 S(1) 1.0 2.121 µm emission lines due to strong wind outflow. No emission lines due to neutral PAHs are present at 3.29 µm.

(3) From 0.7 to 4.0 µm, the SED is not “flat” or “filled-in” by inner-disk hot dust as in YSOs or transition disks. There are the beginnings of warm dust excess flux in the 4.5–5.0 µm region, agreeing with archival JHKLM photometry of the system (triangles in Figure 2) showing a rise in M-band and WISE W2.

(4) There are indications of an unusual local maximum in the SED at 6–9 µm. A similar feature was seen in the A3V, ~10 Myr old debris disk system HD 131488 and at lower SNR for the similarly bright HD 121191 system (A8V, ~10 Myr) by Melis et al. (2013) using T-ReCS. The Mittal et al. (2015) Spitzer/IRAS disk survey contains another good spectral match, the HD 148657 (A7V, 12 Myr) system. The only good laboratory analog matches producing emission peaks in this wavelength range—organics, carbonates, SiC, PAHs—are all carbon-rich.

(5) If the observed SED at long wavelengths is due to thermal emission from two populations of dust with temperatures of ~570 K and ~135 K, respectively, then these two populations of dust are densest and hottest at 1.1–2.2 au and 20–40 au from the ~20 L⊙ primary, likely at the inner edges of their corresponding belts. The ~1.6 au dust disk may be the last remnant of the system’s primordial disk, or due to sourcing from an aggregating or grinding asteroid belt in an old transition disk/very young debris disk. The ~30 au outer dust population does not match up very well with the ~85 au radial extent for the system’s disk found by Currie et al. (2017) using H-band scattered light imaging, unless this outer belt is very wide and is dominated in the thermal IR by highly superheated dust at the belt’s inner edge closest to the primary.

6. Summary

This system is a nearly mature transition disk, without the gas found in primordial and young transition disks. If it is of ~3–10 Myr age, as argued by Currie et al. (2017), we favor the higher end of this range as the most likely due to the gas-poor, nearly cleared-out nature of the disk. There are two belts of material making up the system’s disk, a hot inner one at a few astronomical units from the star, and the cold outer one imaged by Currie et al. (2017).

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