

Understanding the Liveliness and Volatility of Debris Disks: from the microscopic
properties to causal mechanisms.

by

Zachary Harrison Draper
B.Sc., University of Washington, 2012
M.Sc., University of Victoria, 2014

A Dissertation Submitted in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

Debris disks are a fundamental component of exoplanetary systems. Understanding their relationship with host stars and neighboring planets can help contextualize the evolution of exoplanetary systems. In order to further that goal, this thesis addresses some extreme outlier examples of debris disk systems. First, the highly asymmetric debris disk around HD 111520 is resolved and analyzed at multiple wavelengths to create a self-consistent model of the disk thermal emission and scattered light. The best-fit model is proposed to be an asymmetric disk from a recent collision of large, icy bodies on one side of the disk. In contrast, most debris disks are thought to be in a steady collisional cascade and this disk model could represent a relatively rare event in the creation of debris disks. Secondly, an optical spectroscopic survey of stars is conducted on stars where far-infrared observations exist to detect the presence of debris disks. Specifically, AF-type stars are targeted in order to provide context regarding the Lambda Boo phenomenon, where stars are found to be specifically refractory metal-poor. One mechanism for this was hypothesized to be from planetary

scattering of debris disks, causing the accretion of volatiles from comets. The findings were that over the entire unbiased sample, stars which were refractory metal poor tended to be the stars with brightest debris disks. This supports a planet-disk hypothesis underlying the accretion of volatile gases, since debris disks undergoing active planetary stirring are brighter. This would mean about 13% of stars with debris disk are undergoing strong planetary scattering based on the occurrence rate of Lambda Boo stars relative to debris disk stars. These two tacks in our observational understanding of these extreme examples of debris disks provide constraints on the volatility at work.

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Co-Authorship

The following are collaborators who contributed to the content of this thesis and are co-authors in the publications reproduced within this thesis. Specifically Chapters 2 (Draper et al., 2016a) & 4 (Draper et al., 2018), are published in the *Astrophysical Journal*. Chapter 3 is still in prep. at the time of writing. The broader collaborations of this work are the Gemini Planet Imager Exoplanet Survey (GPIS; PI: Bruce Macintosh) and the Debris Disk Characterization Large and Long Program with Gemini (PI: Christine Chen).

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It seems that the more places I see and experience, the bigger I realize the world to be. The more I become aware of, the more I realize how relatively little I know of it, how many places I have still to go, how much more there is to learn. Maybe that's enlightenment enough: to know that there is no final resting place of the mind, no moment of smug clarity. Perhaps wisdom, at least for me, means realizing how small I am, and unwise, and how far I have yet to go.

— Anthony Bourdain

DEDICATION

For anyone who cares to read this.

Chapter 1

Introduction

Circumstellar disks are a fundamental component to exoplanetary systems. It is within circumstellar disks where the planets are born, and where they can meet an untimely demise. As stars accrete gas and dust onto their surface, the conservation of angular momentum forces some material to be on non-accreting, coplanar orbits. The gas and dust in this disk then has the ability to condense to form ever larger planetesimals and the building blocks of planets. While the main pathway for planetesimal formation is unknown, various methods have been proposed, from disk vortices driven by gas-physics (Lyra et al., 2009; Williams & Cieza, 2011), to rapid accretion of pebbles (Ormel & Klahr, 2010; Levison et al., 2015). This phase in a circumstellar environment is commonly referred to as the protoplanetary stage or protoplanetary disk. In time, the protoplanetary disk will always diffuse away from accretion onto the star, stellar photoevaporation/wind and/or condensing of solids onto planetesimals (Williams & Cieza, 2011). The evolution of protoplanetary disks is thought, particularly in the case of massive disks, to lead to a phase termed a "transition disk" in which dispersal of the inner disk material can manifest as gaps and asymmetries. The material that remains will be fully formed planets ranging from terrestrial-like to gas-giants. Furthermore, there will be a treasure trove of asteroids and comets that, for various reasons, failed to fully accrete onto larger bodies. This material is what will eventually create a new form of circumstellar disk, called a debris disk, where planetesimals will go to die.

The fundamental characteristic of a debris disk is that leftover asteroids/comets achieve a collisional cascade and produce dust faster or equal to the time that it can be dissipated by stellar radiation/wind (Matthews et al., 2014). This often requires some stirring mechanism, which perturbs the orbits of the asteroids/comets to have

a shorter collisional time, in order to keep dust production higher. Some stirring mechanisms include: self-stirring from delayed formation of planetesimals at large stellocentric distances (Kennedy & Wyatt, 2010; Kenyon & Bromley, 2008), planetary scattering (Mustill & Wyatt, 2009; Kalas et al., 2015), to external perturbers, such as the interstellar medium (ISM) (Debes et al., 2009), or stellar neighbors in a fly-by (Kennedy et al., 2014). Each mechanism could be deduced from detailed observations of each system by comparing brightness, disk width, etc. (e.g. Marino et al. (2017)). For example, the disk width can be greatly enhanced when planetary perturbations are at work compared to a self-stirring model. A detailed look at these debris disks can then inform us about the prevalence of one mechanism over the other, in order to have a holistic outlook on the stability of exoplanetary systems.

While the physical distinction between a protoplanetary disk and debris disk is based on the underlying processes, it can be hard to place firm definitions based on our observations for young systems (Hughes et al., 2018). Typically debris disks are much fainter than protoplanetary disks, but there will be a point at which they overlap in brightness given the protoplanetary disk by definition is eventually dissipating. Protoplanetary disks have a much higher volatile gas content (100:1), but given better sensitivity, gas is also being found around debris disks. Still debris disks will generally have smaller gas-to-dust ratios of order unity (Hughes et al., 2018). As sensitivity for gas detections have increased, there have been a number of systems where volatile gas itself has been detected in disks that otherwise appear to be debris disks. Protoplanetary disks are only around young stars by definition, while debris disks can occur at a wide range of ages: after formation, during the main sequence lifetime of the star, and even onto the post-main sequence around stellar remnants (Farihi, 2011). By virtue of their stochastic nature, debris disks are excellent indicators of the stability of an exoplanetary system. Given imprecise age dating methods for stars, distinguishing between them at young ages can be difficult (Soderblom, 2010). An impressionist plot depicting this can be seen in Figure 1.1.

The fact that debris disks can manifest at anytime after exoplanetary formation means they can serve as a diagnostic on the architecture, stability and composition of exoplanetary systems. Since the star, planets, and debris disks are causally connected in their evolution, we can better understand each component by understanding their relationship with each other. In simple terms debris disks can tell us where the planets are not, where planets are based on structure within the disk, or how often planets are migrating into their neighboring disk. It's well known how the metal content, as

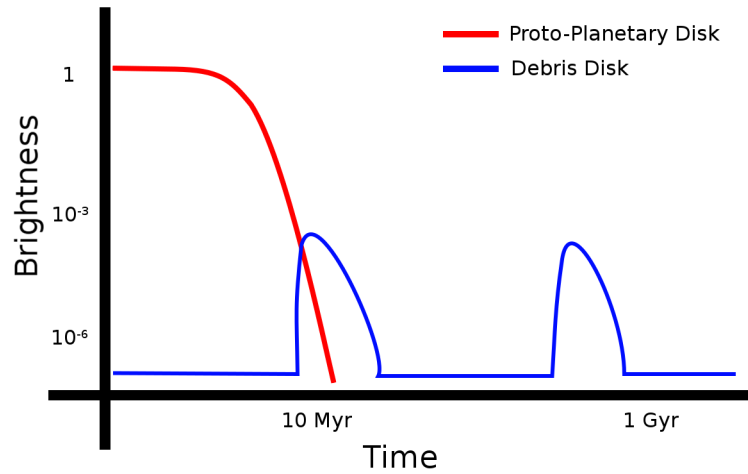


Figure 1.1 This impressionist plot highlights the difference between the protoplanetary disk and debris disks, which occur around a given star over its lifetime. While the material of a protoplanetary disk is seen to dissipate over timescales that vary with wavelength (i.e., hotter material close to the star is removed first), debris disk processes can be stochastic, with bursts of activity superimposed on a gradual collisional cascade. The relative brightness of debris disks are typically much less than protoplanetary disks (i.e. a fractional luminosity of less than 10^{-3} compared to 10^{-2} or brighter, respectively). In general a protoplanetary disk is where material is condensing to form planetesimals, while debris disks are where planetesimals are being destroyed.

measured by the star, must accelerate planetesimal growth since higher metallicity stars are more likely to host gas-giants (Fischer & Valenti, 2005). The debris disks themselves offer us a window towards sampling the dust and gas that successfully formed planetesimals during the protoplanetary disk phase. As we observe debris disks they appear as static entities, but by definition they all must be continually producing dust. This is largely an observer’s bias since the orbital timescale at 40-100 AU from a star is much greater than a characteristic timescale of an astronomer’s career. It is for this reason that collectively studying debris disks, especially the most disturbed cases, we can learn more about the evolution of exoplanetary systems in both composition and architectural stability in astronomically relevant timescales.

Some relatively recent observations have shown the liveliness in debris disks. For example, unresolved observations with *Spitzer* at 3-4 μm over several years have shown that a rapid increase and decline in emission could be traced to a warm belt of dust being created from stochastic collisions of planetesimals (Meng et al., 2015). They furthermore found that stochastic collisions were quite common for very warm debris disks with small stellocentric distances, albeit with low number statistics. In one case of resolved direct imaging, the system AU Mic appears to have waves of material being ejected from the system (Boccaletti et al., 2015). Possible mechanisms proposed were stellar flares or perturbations by a planet, both of which underlay the dynamicism in an exoplanetary system and how debris disks can help trace them. It is this motivation to understand the debris disk dynamics, in the most perturbed cases, that motivate the analysis of resolved imaging of extremely asymmetric debris disks with GPI and a spectroscopic survey of many debris disks, with a potential scattering mechanism, in order to better our understanding of exoplanetary systems.

1.1 Direct Imaging

Direct imaging from the ground or space is a great way to probe the exoplanetary environment because it fundamentally separates the light of the planets and/or debris disk from the star. Other indirect methods can often be contaminated by the properties of the star itself. For example sunspots or eclipsing binaries can interfere with the transit measurements of planets or exocomets. Radial velocity precision required to monitor planets at larger separations or terrestrial masses are limited mostly by ‘astrophysical-noise’ of stellar physics rather than technological developments in instrumentation (Plavchan et al., 2015). Both of these indirect methods are also fun-

damentally limited by our observing angle on a system, whereas direct imaging can access and measure properties of systems independent of inclination. For example, planet mass as determined from radial velocity measurements are always lower limits and a transiting exocomet is more likely to occur when the parent disk is inclined at 90° (i.e. edge on) to our line of sight.

From the ground, using instruments like the Gemini Planet Imager (GPI) offers the ability to measure a spatially-resolved spectrum of the dust. Furthermore, it can probe the scattering efficiency by constraining the microscopic properties of the dust in scattered and polarized light. GPI can observe in Y, J, H, and K near-IR bands (Macintosh et al., 2008). While this is only from $\sim 0.9\text{--}2\ \mu\text{m}$ in wavelength coverage, the color information can still offer important clues into the dust composition. The scattering phase function changes by λ^2 so a factor of 2 change in wavelength, is a factor of 4 scattering intensity (see Section 1.1.1). For example, the minimum dust grain size can greatly influence the scattering at these short wavelengths, since the typical size is on order of a μm . The size distribution of the grains can also increase or decrease scattering with the relative number of the smaller grains. The porosity, or how fluffy/compact the dust grains are, is strongly influenced by the change in polarization with color in the near-IR. Many of these parameters however can be degenerate with the overall dust mass, composition, etc. Since most of the dust mass is in larger grains and larger grains contribute far less to the scattered light in the near-IR, there are unfortunate degeneracies in the dust grain properties. Simply put, you can either have a lot of poorly reflective dust, or fewer very reflective grains to make the same scattered light signal in near-IR.

When observations of dust in astronomy are made, the typical dust grain size an observation samples will be equivalent to the wavelength being observed because of two factors. First, the dust size distribution is strongly weighted towards smaller grains¹. Secondly, smaller grains are very inefficient at emitting photons physically greater than their own size². Therefore the wavelength observed will be the greatest

¹In a collisional model of asteroid size bodies, the material will always break down from larger bodies into smaller ones in a collisional cascade whereby the ejecta is dominated by smaller and smaller dust grains. Two larger bodies will break down into small bodies and so on, such that the smaller ejecta material will outnumber the larger bodies producing the grains. A mathematically rigorous description of this can be seen in Dohnanyi (1969) which shows that this would follow a negative power law ($dn/da \propto N(a)^{-3.5}$).

²If you apply Maxwell's equations to a single spherical particle (as is done with Mie scattering models) the electric field is confined to a finite size proportional to the spherical radius. Therefore the emitted wave logically cannot exceed the grain size.

collective number of grains capable of emitting at wavelengths smaller or equal to their size. These two counter-acting trends make resolving dust at multiple wavelengths quite important. For example, if the debris disk’s dust mass is mostly in larger grains, measuring the flux at longer sub-mm wavelengths can constrain the disk mass. This will then break the degeneracy in dust grain properties at shorter wavelengths that are more sensitive to the dust composition. Since ALMA (Atacama Large Millimeter Array) can resolve sub-mm wavelengths at the same scales as direct imaging (the λ/D resolution of $1\ \mu\text{m} / 8\ \text{meters}$ for GPI is equivalent to $1000\ \mu\text{m} / 8\ \text{km}$ for ALMA), it can be an important complementary tool to near-IR direct imaging.

On top of the compositional information, the resolved disk structure itself can inform us about its exoplanetary environment. Many debris disks are in classical ring structures which could be sculpted by unseen planets (Nesvold & Kuchner, 2015). A growing subset of debris disks show asymmetrical structure indicating some dynamics are at work (Kalas et al., 2015). Recent large collisions have been detected in these disks with variable short wavelength IR emission or clumps of CO gas, both of which are indicative of material which is short lived. In other cases there are warps, spirals, and offsets which are indicative of more longer term perturbations which have molded quasi-static features into the disk itself. These highly perturbed debris disks can offer a unique perspective into disks which are stirred by planets and offer a direct way to measure the composition of the exoplanetary grains.

It is for these reasons that directly resolving a highly perturbed disk, like HD 111520 (see Chapter 2 & 3), can be fruitful in understanding exoplanetary dynamics. The system itself has complementary (albeit unresolved) long wavelength observations from *Herschel* and ALMA, which enables us to better constrain the modeling of the disk in the near-IR from GPI. Understanding the composition and structure can then inform us about how exoplanetary systems evolve.

1.1.1 Mie Scattering

Since the underlying physics for modeling debris disks with direct imaging in scattered light is based on Mie theory. A brief review of the equations and terminology is presented here from Kerker (1969).

First, in Mie theory it is assumed that the grain sizes are proportional to the wavelength of light being scattered. We also assume spherical coordinates, centered on a spherical dust grain as a homogeneous dielectric sphere. With an EM wave

coming in, hitting the particle, and being reflected off, a simple toy model can be constructed to solve Maxwell's equations. In Rayleigh scattering, the dust grain is assumed to be much smaller than the wavelength of light ($\alpha \ll 1$) and has an analytically nice solution.

$$\alpha = \frac{2\pi am_o}{\lambda_o} \quad (1.1)$$

where m_o is the refractive index, a is the grain size, and λ is the wavelength of light.

$$I_\phi = I_o \frac{\lambda^2}{4\pi^2 r^2} i_1 \sin^2 \phi \quad (1.2)$$

$$I_\theta = I_o \frac{\lambda^2}{4\pi^2 r^2} i_2 \cos^2 \phi \quad (1.3)$$

ϕ and θ are spherical coordinates, I_o is the total intensity, r is distance from particle and i is the angular intensity functions. The split into two equations is due to the fact each represents a different polarization state. For unpolarized light this can simplify to

$$I_{scattered} = I_o \frac{1}{r^2} \sigma_{scattered} \quad (1.4)$$

$$\sigma_{scattered} = \frac{\lambda^2}{8\pi^2 r^2} i_1 + i_2 \quad (1.5)$$

where $I_{scattered}$ is the scattering phase function. For Mie scattering, the solution for angular scattering function (i) becomes an infinite series of Legendre Polynomials and Bessel functions. Whats important to note is that infinite series and Legendre polynomials are a functions of angle between incidence and reflection. The Bessel functions are dependent upon the refractive index (m) and the relative size parameter (α). The refractive index is where the composition of the dust grain plays an important role and can be used as an input to scattering models.

1.2 Lambda Boo Stars

A prevailing mystery in astronomy has been a unique class of stars called Lambda Boo stars (Morgan et al., 1943). The namesake of the phenomenon as a whole, λ Boo, has the strongest chemical signature of this metallicity class which only make

up 2% of AF-type stars (Paunzen, 2004). The trademark seen in these stars is that elemental species which are volatile (elements which readily sublime into the gas-state) are roughly solar and representative of the stellar metallicity as a whole, while on the other hand species which are refractory in nature (i.e. tend to be stable and condensed into a solid) are under-abundant in the atmosphere. Various attempts have been made to explain the phenomenon, but none have been able to encompass the uniqueness of this phenomenon in a satisfactory way. Two fundamental properties of the class have been established. First the elemental signature could not be explained from other known mechanisms of chemical peculiarity, since they created completely different signatures (Paunzen, 2004). Second, the class of stars effected were all A-type stars ranging the span of temperatures for which there is no radial convection, and therefore mixing, at the surface. This in particular allows for chemical peculiarities to be instilled and preserved on the surface. An accretion mechanism was first proposed by Venn & Lambert (1990) as the chemical signature was similar to the ISM's relative metallicity. This presented a mechanism where these stars happened to be the fraction of stars which had recently interacted with the ISM. The next test would then be to look for dust being actively accreted onto these stars.

The first example of a main-sequence A-star, interacting with the ISM was δ Velorum. The bow wave was found and resolved with *Spitzer* but the star turned out to not be a member of the Lambda Boo class (Gáspár et al., 2008). It was suggested that perhaps it has not had time to accrete enough material to yield a detectable chemical signature. When *Herschel* came onto the scene, it was uniquely adept to look for dust around stars as the peak flux of cold dust ($\sim 50\text{K}$) was within its wavelength regime of 70 to 160 μm . When it turned its eyes towards Lambda Boo stars it was able to image and uniquely characterize the dust temperature associated with these stars. Draper et al. (2016b) then found that when comparing ISM bow waves and debris disk models, only debris disks were able to simultaneously match the radial extent and temperature of the dust emission around all of the stars. These stars were only the ones within the local bubble, and unfortunately *Herschel* did not observe the Lambda Boo stars farther out where an ISM interaction would be more likely. This ubiquitous correlation with debris disks and Lambda Boo stars presented a new potential accretion mechanism, however. Dust around an A star does not readily accrete onto the star in order to cause a Lambda Boo signature when only considering radiation forces (Draper et al., 2016b). If this were true, then all A-type stars with debris disks would be Lambda Boo stars, and given debris disks are found

around 25% of A-type stars (Thureau et al., 2014), this would not match the relative scarcity of Lambda Boo stars at 2% of A stars. However, it maybe only a subset of debris disk stars that would have the conditions necessary for the Lambda Boo signature.

The exoplanetary environment itself naturally explains the chemical signature. The warm environment can allow the refractory dust to be differentiated from volatile gas species. The radiation pressure will then be more effective on refractory rich dust grains, and allow volatile gas to accrete in greater proportions. This would be caused by a difference in radiation absorption efficiency between the two materials. The polluted surface layer of volatiles will then mask the refractory species in the pristine surface of the star. An important discovery to the phenomenon as a whole is the near ubiquity of the Lambda Boo signature in Type I protoplanetary disks (Kama et al., 2015). Type I disks are those which exhibit a clear second peak in the spectral energy distribution and inferred to be a star with a distinct ring of material. When the protoplanetary disks transition into a disk with gap between it and the star, the dust gets trapped, while the gas is allowed to continue to accrete onto the star. Since the protoplanetary disk is more massive, the system has a ready supply of material to induce the Lambda Boo signature. This however can't explain the Lambda Boo signature around much older stars which will have mixed their surface layers. After all, if it were a static effect and all A stars were Lambda Boo-like at formation then all A stars would be Lambda Boo-like.

One of the proposed stirring mechanisms for debris disks is planetary scattering (Mustill & Wyatt, 2009). It is not known how prevalent this mechanism is over other methods of stirring, since the simultaneous detection of planets and debris disks is limited to a few rare systems (Kalas et al., 2015). One thing planet scattering can do very efficiently is scatter large volumes of debris on short timescales. In fact, there are models which can match the accretion rate of comets near the star, with the accretion rate needed to build up material on the surface of an A star. The potential accretion rates can be faster than the stellar atmosphere can mix the material from secondary convection effects like meridional circulation³ (Bonsor et al., 2012). The debris disk accretion under planetary stirring makes Lambda Boo stars a plausible subset of debris disk stars as a whole (See Figure 1.2). While this would solve the Lambda

³Stars rotate and will be non-spherical as a result. The equator will be farther from the core and therefore have a lower temperature than the poles. Thermal convection will then result from pole to equator within the surface envelope. (Turcotte, 2002)

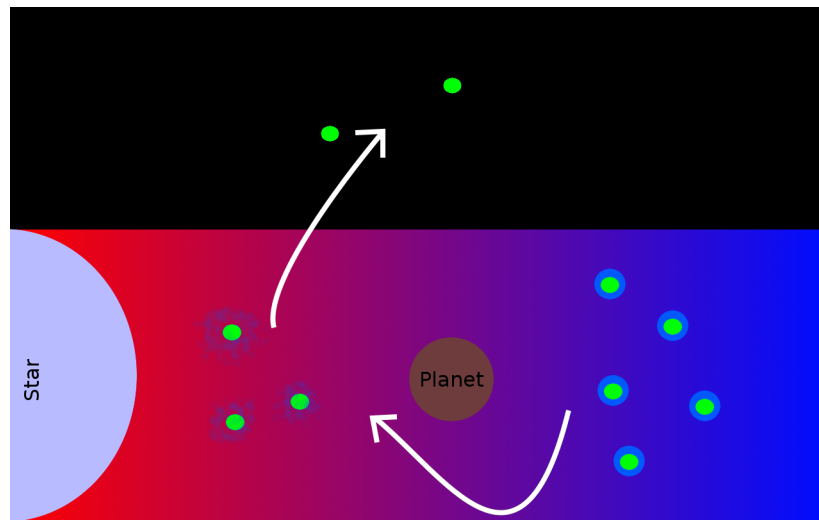


Figure 1.2 The proposed mechanism for accreting volatiles onto the surface of a star. A planet migrates through a debris disk, causing planetesimals to move into the inner solar system where they heat up and sublimate their volatile mass. Refractory rich dust grains will then be more susceptible to radiation pressure and be blown away from the star.

Boo phenomenon for middle-aged stars, it would also provide a uniquely powerful measurement on the stability of exoplanetary systems. Under this paradigm, the detection rate of debris disks and Lambda Boo stars together instantaneously provides a measurement on the rate at which debris disks are currently undergoing strong planetary migration ($25\% / 2\% \approx 13\%$). This puts a constraint on the prevalence of certain debris disk stirring mechanisms and the stability of exoplanetary systems as a whole.

1.3 Thesis Summary

This thesis is divided into 3 main chapters. Each represents a published fraction of work throughout my PhD. Chapter 2 is a discovery paper which sets the stage by outlining the unique observations with the Gemini Planet Imager of a strongly perturbed debris disk around HD 111520, as well as a summary of the ancillary information of the star. Chapter 3 is devoted to follow up observations in total and polarized intensity in J, H, and K bands to characterize the dust around the star. In Chapter 4, I turn towards a spectroscopic survey of stars observed by the DEBRIS survey to characterize the presence of debris disks. By combining the chemical and far IR observations I make a case for the Lambda Boo phenomenon as a debris disk phenomenon. Finally, in Chapter 5, I present conclusions and future work that can be done to build this works analysis. All in all, it is a detailed characterization combined with a broad outlook of disrupted debris disks in the field of exoplanetary astronomy.

Chapter 2

Resolving HD 111520

The following is work published in Draper et al. (2016a). My contribution to this work was as the lead author. The observational data, GPI data reduction pipeline, and the PSF subtraction tools were obtained from collaborators. All figures, text, and analysis work was compiled for publication by myself with the input of others.

Using the Gemini Planet Imager (GPI), we have resolved the circumstellar debris disk around HD 111520 at a projected range of $\sim 30\text{-}100$ AU in both total and polarized H -band intensity. The disk is seen edge-on at a position angle of 165° along the spine of emission. A slight inclination or asymmetric warping are covariant and alters the interpretation of the observed disk emission. We employ 3 point spread function (PSF) subtraction methods to reduce the stellar glare and instrumental artifacts to confirm that there is a roughly 2:1 brightness asymmetry between the NW and SE extension. This specific feature makes HD 111520 the most extreme example of asymmetric debris disks observed in scattered light among similar highly inclined systems, such as HD 15115 and HD 106906. We further identify a tentative localized brightness enhancement and scale height enhancement associated with the disk at ~ 40 AU away from the star on the SE extension. We also find that the fractional polarization rises from 10 to 40% from $0''.5$ to $0''.8$ from the star. The combination of large brightness asymmetry and symmetric polarization fraction leads us to believe that an azimuthal dust density variation is causing the observed asymmetry.

2.1 Introduction

Improved resolution in debris disk imaging has made it possible to uncover many instances of complex morphologies which deviate from the nominally pervasive symmetric ring structures. This offers important insights into the dynamical evolution of the planetary systems, since gaps and asymmetries will result from planet scattering, stellar fly-bys, and ISM interactions (for a review see Matthews et al. 2014). Investigations into these important case studies can determine how planetary architectures shape debris disks, or even create them, through planetary stirring of planetesimals (Mustill & Wyatt, 2009). Even when the planets themselves may be unseen, important constraints can be made based on the disks' structure (Ertel et al., 2012).

This paper presents resolved imaging from GPI and evidence for strong asymmetry in the disk around HD 111520 (HIP 62657) which is seen from $0''.3$ – $1''.0$. GPI is an instrument designed to detect scattered light from dust grains and emission from exoplanets in the near-IR at close separations around nearby stars (Macintosh et al., 2014). HD 111520 is an F5V star and has been identified as a member of the Lower Centaurus Crux (LCC) in the Scorpius-Centaurus Association through Hipparcos proper motions (de Zeeuw et al., 1999). Stellar parameter estimates have ranged from 6500 – 6750 K surface temperature, $2.6 - 2.9 L_{\odot}$, and $1.3 - 1.4 M_{\odot}$ (Chen et al., 2014; Pecaute et al., 2012; Houk, 1978). The distance to the system was measured to be 108 ± 12 pc (van Leeuwen, 2007), which we adopt throughout this study. The median age of the LCC for F-type stars is 17 ± 5 Myr (Pecaute et al., 2012).

An IR-excess was first associated with the star by Chen et al. (2011) based on *Spitzer* MIPS data which derived a dust radius of 48 AU from a fit to the effective temperature of a single blackbody. In combination with *Spitzer* IRS, multiple temperature components have been fit with grain emissivity models to give an inner disk of 115 K at a radius of 16.3 AU and an outer disk of 51 K at 212 AU (Chen et al., 2014). Subsequent detailed grain model fits have been done to IRS spectra to give estimates of an inner disk at 1 AU and an outer disk of 20 AU (Mittal et al., 2015), although this model greatly underpredicts the $70\mu\text{m}$ flux, requiring another outer component. These discrepancies in SED fitting are primarily due to model degeneracies in the absence of a resolved image of the disk structure. The disk around HD 111520 was first resolved in optical scattered light by HST to have a large 5:1 brightness asymmetry with emission extending from $\sim 1''$ – $5''$ (or ~ 110 – 550 AU) from the star (Padgett & Stapelfeldt, 2015). Indeed, all SED models predict a dust location

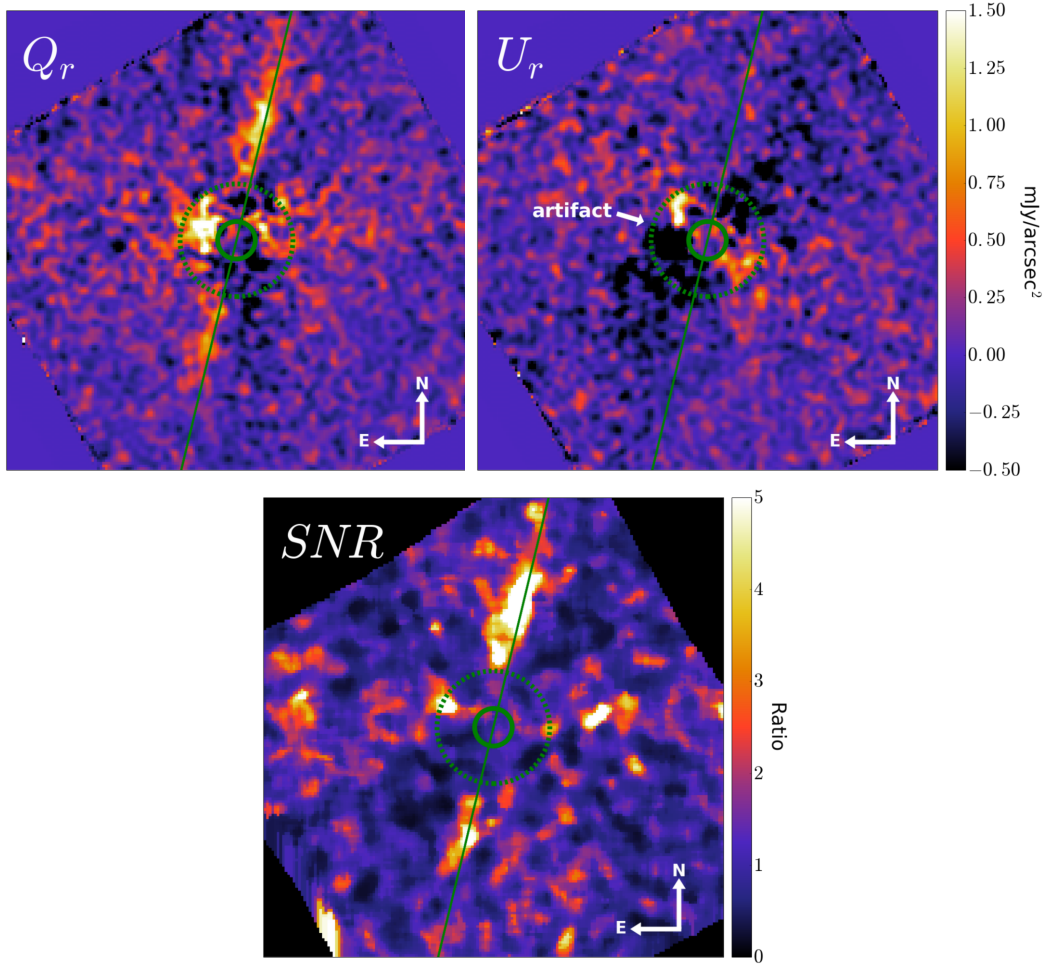


Figure 2.1 *H*-band radial Stokes polarized intensity. The coronagraph is marked by a solid green circle. The FOV of the images is cropped to $2.4'' \times 2.4''$. The dashed green circle denotes a region with enhanced noise out to $0.3''$ in radius from the center. (Left) Radial Stokes Q_r showing that the disk emission is aligned along a position angle (PA) of 165° centered at the star, illustrated by the green line. (Center) Radial Stokes U_r shows polarized light from non-astrophysical sources (assuming single scattering) and is therefore an estimate of the noise in the data. Both Q_r and U_r images are shown using the same color scale. A large artifact $\sim 0.1-0.3$ to the East of the coronagraph appears in both Q_r and U_r and is therefore likely an instrumental effect. (Right) An SNR map showing the detection of the disk.

that is well inside the inner working angle of the discovery HST images, but within the GPI field-of-view (FOV), underlining the importance of GPI for understanding warm debris disk dust. We therefore present GPI data which resolves the disk inside $1''$ to better probe the structure of the disk.

2.2 Observations and Data Reduction

On the night of 2015-07-02, data were taken as part of the GPI Exoplanet Survey (GPIS, Macintosh et al., 2014). Weather conditions were good with DIMM (Differential Image Motion Monitor) seeing at $\sim 1''$ and MASS (Multi-Aperture Scintillation Sensor) seeing at $\sim 0''.5$. A total of forty-one 60 s exposures were taken in H -band spectral mode (R ~ 45) with a total of $\sim 35^\circ$ of field rotation. In addition, eleven 60 s exposures in H -band polarization mode were taken for a ‘snap-shot’ observation amounting to 7° of rotation. The field rotation allows for Angular Differential Imaging (ADI) to subtract the instrument PSF (Marois et al., 2006). The pixel scale of GPI data is 14.166 ± 0.007 milli-arcseconds on the sky (updated from Konopacky et al., 2014). The data were reduced using primitives in the GPI Data Reduction Pipeline (see Perrin et al., 2014, and references therein).

For polarimetry mode data, the light is split by a Wollaston prism into two orthogonal linear polarization states that are modulated by a rotating, achromatic half-wave plate. A typical observing sequence involves observations in sets of four different wave plate orientations, which are then combined to produce a Stokes datacube (Perrin et al., 2015). First, the raw frames are dark subtracted and ‘destriped’ using Fourier-filtered raw detector images to remove instrumental microphonic noise (Ingraham et al., 2014a). The microlenslet spot locations from a calibration file are corrected for instrument flexure with a cross-correlation algorithm (Draper et al., 2014). The raw data are then converted to a polarization datacube, where the third dimension contains the two orthogonal polarization states. Systematic variations in the polarization pairs and bad pixels are cleaned by a modified double difference algorithm (Perrin et al., 2014). A geometric distortion correction was also applied (Konopacky et al., 2014). The data are then smoothed by a Gaussian kernel with a width equivalent to a nearly diffraction limited GPI PSF (FWHM = 3 pixels or 45 mas). By measuring the fractional polarization behind the occulted spot, the instrumental polarization is measured and subtracted off from each pixel based on its total intensity (Millar-Blanchaer et al., 2015). Following Hung et al. (2015), flux calibration was performed measuring

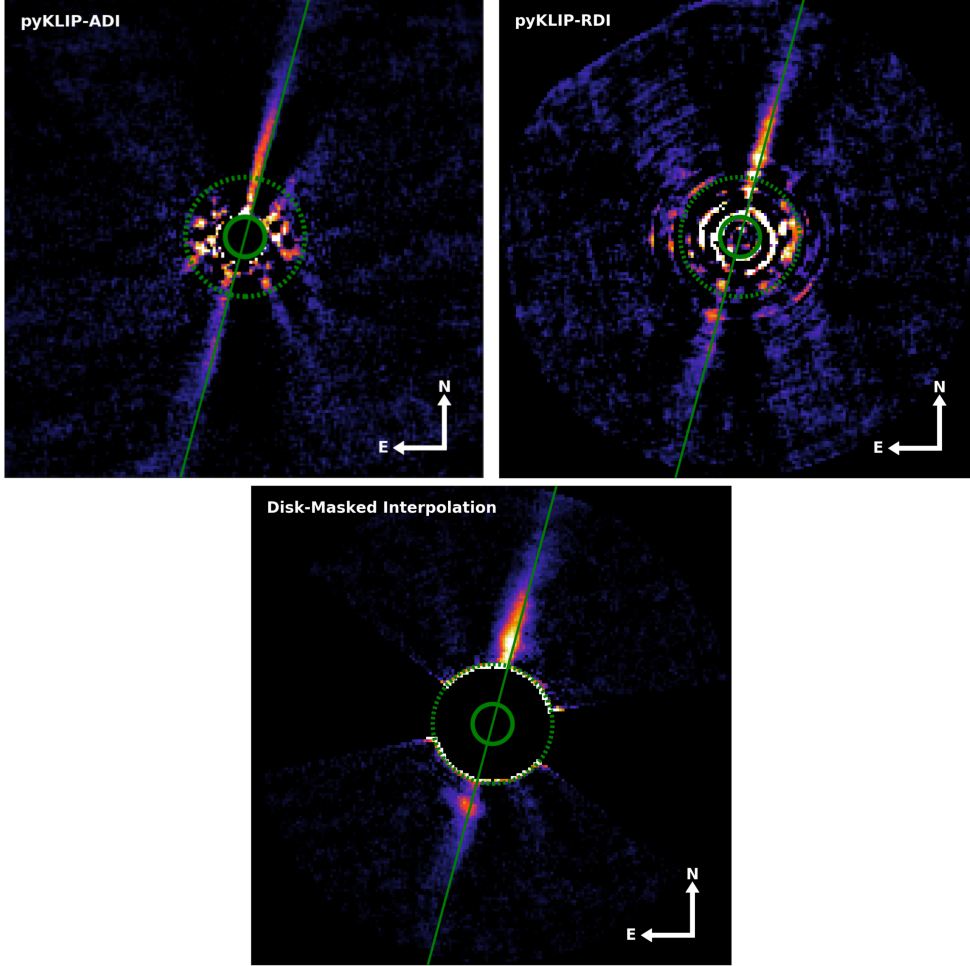


Figure 2.2 Collapsed H -band spectral mode data reduced using various PSF subtraction methods. The FOV of the images is cropped to $2''.4 \times 2''.4$. (Top) Reduced with an ADI-only reduction with pyKLIP. (Center) PSF-subtracted data using a PSF library from GPI Exoplanet Survey data as a reference for a pyKLIP reduction. (Bottom) PSF subtracted by interpolating over disk-masked data as done in Perrin et al. (2014). The solid green circle denotes $0''.1$ which is obstructed by the coronagraph. The dashed green circle denotes a $0''.3$ radius inside of which large artifacts are present in the all of the PSF reductions. The solid line denotes the primary plane of the disk major axis of the emission along a PA of 165° .

the photometry of the satellite spots with elongated apertures with a known conversion to compare with the 2MASS magnitude for the star (7.830 ± 0.057 mag or 0.756 ± 0.040 Jy; below 2MASS saturation limits; Cutri et al. 2003a). All of the polarization datacubes were then combined via a singular value decomposition method to create a Stokes datacube (Perrin et al., 2014). Finally the Stokes cube was converted to the radial Stokes convention: $[I, Q, U, V] \rightarrow [I, Q_r, U_r, V]$ (Schmid et al., 2006). The star location, which is used as the origin of the transformation, is measured using a radon transform-based algorithm that takes advantage of the elongated satellite spots (Wang et al., 2014; Pueyo et al., 2015). The final Q_r and U_r images can be seen in Fig. 2.1.

For the spectroscopy mode data, the raw dispersed frames were dark subtracted, corrected for bad pixels, and ‘destriped’ (Ingraham et al., 2014a). A wavelength calibration using an Ar arc lamp was taken just prior to the observations and corrected using a repeatable flexure model of the instrument as a function of telescope elevation (Wolff et al., 2014). In this case, the correction amounted to a negligible change from the nominal wavelength calibration. To extract into a 3D spectral datacube, a box aperture method was used (Maire et al., 2014a). There were interpolation errors along the wavelength axis at the blue end of the data cubes, so the first three individual spectral channels (or $0.024 \mu\text{m}$ of bandpass) were removed prior to collapsing the cube. A flat field image can have a pixel to pixel standard deviation on order of $\sim 10\%$ and therefore cannot explain surface brightness variations above this level. A microlens-PSF method (Ingraham et al., 2014b; Draper et al., 2014) was also used to optimize the flux extraction and reduce spaxel-to-spaxel noise (i.e. spectral pixels). These cubes did not have bad cube slices but yielded similar results for the PSF subtracted images. To remove persistent bad spaxels, they are identified as being discrepant from a spatial 3×3 box median filtered image per wavelength slice and then smoothed by assigning it the median value of a $3 \times 3 \times 3$ region within the cube centered on the bad spaxel. The satellite spots locations were identified after high pass filtering in order to derive the star location under the coronagraph for each datacube. The star centering accuracy is 0.05 pixels for satellite spots with $\text{SNR} > 20$ for spectral datacubes (Wang et al., 2014). Our data has an SNR around 20 which can be up to 0.1 pixels or 1.4 mas in astrometric precision. Finally, the data were flux calibrated using the satellite spots within the image and the target’s 2MASS magnitude and spectral type (for bandpass color corrections) into surface brightness (Wang et al., 2014). In all, varying the use of any of these data cube reduction steps

did not significantly alter the resulting data cubes to level of spatial flux variation seen in §2.5. Lenslet flat fielding tended to introduce more “checkerboard” or spaxel-to-spaxel noise in the data cubes, likely because they were obtained on a different night with a flexure shift causing the microlenslets to sample different pixels on the detector. Therefore this step was left out of the data reduction procedure.

2.3 PSF Subtraction

The spectral mode cubes require PSF subtraction to remove instrumental scattered light and isolate the astrophysical emission. The spectral mode cubes were combined with pyKLIP (Wang et al., 2015) using ADI-only mode of individual spectral channels (Marois et al., 2006). The resulting image from the collapsed cube is shown in the top panel of Fig. 2.2. The KLIP algorithm uses a principal component analysis method, in concert with the angular rotation of the data sets, to determine the best PSF model to subtract (Soummer et al., 2012). A median of multiple iterations of pyKLIP using 41 KL mode basis vectors with annuli and angular subsections ranging from 5 to 18 equal subdivisions of the image, in both width and angular size, were combined to produce the final image.

In order to confirm that the apparent NW to SE asymmetry seen in the pyKLIP reduction was not due to self-subtraction, we also applied a version of pyKLIP that used reference differential imaging (RDI). Instead of using the target dataset to construct the PSF, this method relied on an extensive broadband PSF library composed of observations of disk- and companion-free reference stars obtained during the GPIES campaign. Broadband images were created either by summing all the wavelength channels in spectroscopy mode datacubes or by summing the two orthogonal polarization states in polarimetry mode data. In this way, data from both observing modes can be used as broadband PSF references. At the time these reductions were carried out, the library consisted of approximately 7400 PSFs. All of the GPIES datacubes were reduced in a similar manner, following the standard reduction recipes (e.g. §2.2). For each spectroscopy mode datacube in the HD 111520 dataset, the 100 most correlated PSFs in the library were selected as reference PSFs and then processed using pyKLIP. The reduction used a combination of 3 and 6 pixel annuli and 10 KL modes, with vector lengths ranging from 7 to 49, which were averaged together to smooth out remaining artifacts. The result can be seen in the center panel of Fig. 2.2. A more detailed description of the broadband PSF library will be

discussed further in an upcoming paper (Millar-Blanchaer et al., in prep).

Another method we employed to preserve disk flux consists of subtracting a PSF model, interpolated from data which had the disk masked, before recombining the data set (bottom panel of Fig. 2.2). The method is similar to the PSF subtraction technique used on GPI data of HR 4796A (Perrin et al., 2015). Each spectral cube is summed along its wavelength axis to make a broadband image. A rectangular region encompassing the extent of the disk is masked. The PSF is sampled outside of the masked region to fit a low-order polynomial over the masked regions. The PSF model is smoothed with a median filter and subtracted from each image before recombining the data by derotating into the same frame of reference on the sky. Depending on the normalization, the absolute flux level can vary by $\sim 30\%$ but does not impart localized surface brightness variations, such that relative differences in surface brightness are preserved.

In general, a pyKLIP-ADI PSF subtraction performs best at subtracting the residual PSF but leads to many artifacts which are not ideal for extended sources (Fig. 2.2). Given the edge-on nature of the disk, disk self subtraction is present, but is not strong enough to preclude it from detection as it would be for a centrosymmetric face-on disk. Also, ringing and radial spokes are noticeable artifacts of this type of PSF subtraction. The NW to SE brightness asymmetry persists when using fewer KL-modes but structure in the fainter SE is less apparent. Overall, this method leads to over subtraction especially on the faint SE extension (compare the different panels of Fig 2.2). Using a PSF library as references for the reduction greatly enhances the optimal subtraction but still leaves some of the KLIP artifacts. On the other hand, the masked PSF fitting leads to the least subtraction of the disk, though at the cost of a slightly larger inner working angle where residual artifacts dominate. We therefore use the latter method to measure the disk’s surface brightness and morphology. Since the polarization mode dataset has fewer observations and less parallactic rotation, we use the spectral mode data to constrain the total intensity. Through flux calibration between both modes respectively, we can compare the polarized intensity to the total intensity to get fractional polarization.

In the polarization mode with GPI, it is possible to isolate scattered light from a disk which is polarized and thereby remove the instrumental PSF which is assumed to be unpolarized. Light which scatters from optically thin dust around the star will have an electric field vector which is oriented centrosymmetrically around the star (parallel or orthogonal to rays emanating from the star), while residual polarized

instrumental noise can be oriented at other orientations. In some cases optical depth effects, grain properties, and viewing geometry may impact this conclusion but it is robust for optically thin disks (Canovas et al., 2015). As expected, the disk can be clearly seen in Q_r with similar morphology to the total intensity (Fig. 2.1 & 2.2). The U_r image however shows correlated noise that we assume to be instrumental in origin just east of the coronagraph between $0''.1$ – $0''.3$. The disk itself seen in Q_r stands out above the noise shown in U_r in relative strength and location.

2.4 Morphology

In order to measure midplane variations of the disk, we fit a functional profile to the disk emission. It can be seen in Fig. 2.2 that all of the PSF subtraction methods show the disk in total intensity. It appears near an inclination of 90° and centered on the star. We have added a green reference line passing through both the north and south extensions of the disk. We rotate the PSF-subtracted image by 75° clockwise to orient the disk horizontally and to measure the disk emission along the spine relative to the green line at a PA of 165° . A Cauchy function (Eq. 2.1) was fit to the surface brightness (I), with a brightness offset (I_o), and constant (C). This technique and function have been used before on edge-on disks such as AU Mic (Graham et al., 2007). The function was fit along each vertical slice of the disk (about 30 pixels wide) in the x direction, perpendicular to the disk axis, to measure the location of central spine of emission (x_o) and its FWHM ($\sim 2h$).

$$I = \frac{C * h}{\pi * (h^2 + (y - y_o)^2)} + I_o. \quad (2.1)$$

Fig. 2.3 shows the disk mid-plane measurements deviating from $y_0 = 0$, indicating disk structure from inclination, warping, or both. The ~ 18 mas offset is significant compared to the upper limit of 1.4 mas astrometric precision. On the SE extension there is a localized offset at 40 AU. If the disk were a symmetric ring inclined close to edge-on, we should see an arc in the disk from one extension to the other (e.g Mazoyer et al. (2014); Fig. 5), while if it were perfectly edge-on we should see a flat zero offset for the entire length of the disk through the star’s position (Kalas & Jewitt, 1995). The deviation in emission along the spine was not significant enough to measure an arc in the disk. Examination leads us to conclude that the disk position angle is 165° measured to the major disk axis east of north. If the general offset on the NW

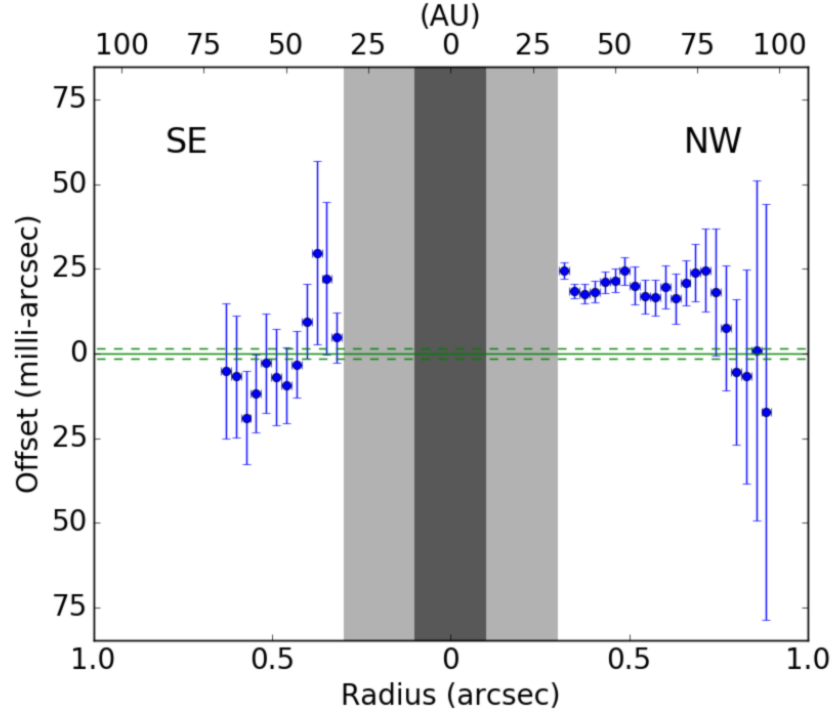


Figure 2.3 Vertical location of the peak disk emission along the spine relative to a line PA of 165° centered on the star. Light grey indicates the region dominated by noise within $0''.3$ and the dark grey shows the region under the chronograph at $0''.1$ (See Fig. 2.2). The dashed green lines represent an upper limit on the uncertainty in the stellar position of 1.4 mas . The disk emission does not appear to be arced, as would be the case for a symmetric ring slightly inclined from exactly edge-on, given the precision of our measurements (indicated by the FWHM/SNR as error bars). The slight offset we observe may nonetheless result from a few degree inclination of a closed ring disk, if the ring radius is significantly larger than the GPI FOV. Alternatively, a small warp producing an 'S' shape may be present but, given the brightness asymmetry, would not be as apparent. A localized offset on the SE extension though is apparent just inside 50 AU corresponding to an enhanced surface brightness feature (see Fig 2.5).

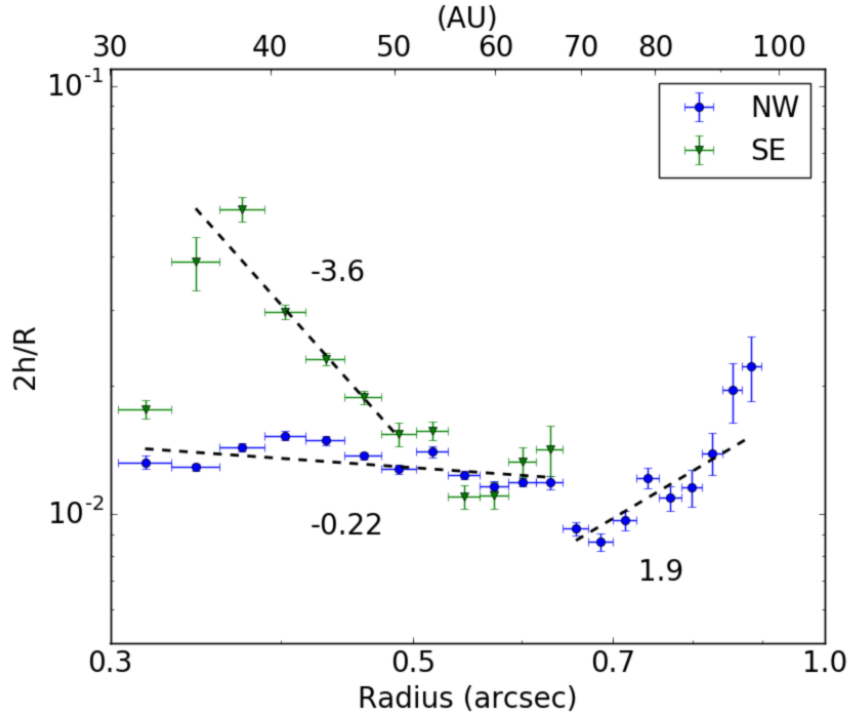


Figure 2.4 Effective vertical FWHM of the disk as a function of stellocentric radius. Green points are the SE extension and blue points are the NW extension. The exponent for each respective power law fit is displayed near the fitted line. An enhancement of the SE extension's scale height relative to the NW extension can be seen inside 50 AU (or $\sim 0''.5$). Outside that point, it returns to a similar power law with distance. Unlike the the SE extension, the NW extension is still detected beyond $0''.7$ and appears to transition to a positive slope.

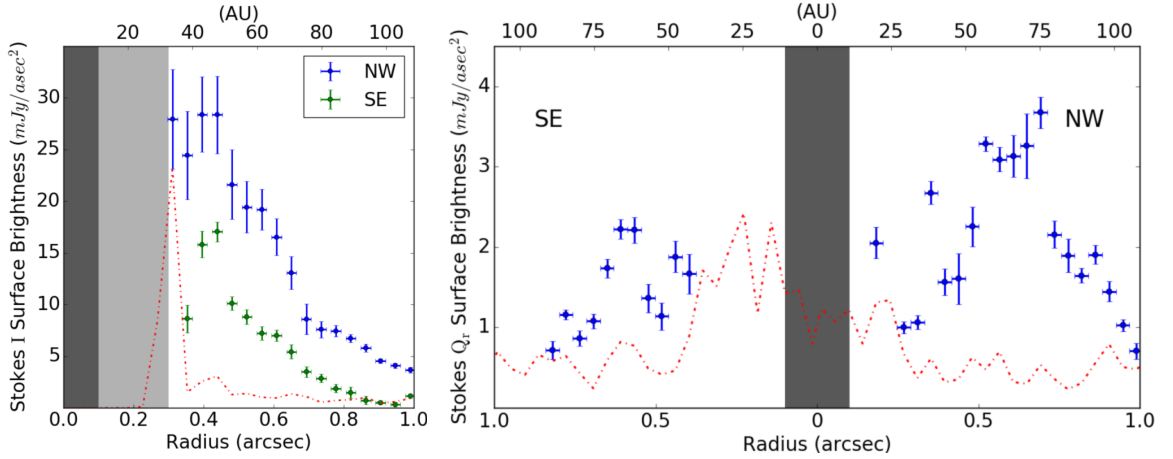


Figure 2.5 H -band surface brightness profiles for the combined spectral mode data in total intensity (left panel) and in polarized intensity (right panel). The blue and green dots denote the respective surface brightnesses of 7 pixel wide apertures with standard deviation error bars binned over 5 pixels. The horizontal error bars show the extent of the binned regions. The dotted red line denotes a noise floor. For total intensity, that is mean plus a $1\text{-}\sigma$ standard deviation in regions of the data without a disk (45° away from the disk midplane). In polarized intensity, it is same except using the U_r image cospatial with the Q_r data. The dark grey region demarks the area under the coronagraph. The light grey area shows the region inside of the dotted green circle in Fig. 2.2 where artifacts from PSF-subtraction are apparent.

extension of the disk is the result of an inclined disk relative to our line of sight, then the offset of the spine of disk emission relative to a line centered through the star would translate to $\sim 1.3\text{--}1.7$ (assuming a disk ring radius of 70-90 AU), making the disk inclination $\sim 88^\circ$ instead of 90° . Since inclination and disk position angle can be covariant given these assumptions, they represent general estimates rather than rigorously modeled parameters. The lateral asymmetry again makes it difficult to distinguish between a warp, offset, and/or inclination.

Furthermore, we examine the projected scale height distribution as a function of separation, in Fig. 2.4. A scale height enhancement can be seen at the same location as the localized offset in the SE extension inside 50 AU, indicating there is some structure to the disk. The scale height is measured from the peak emission and independent of any offset. If the disk is inclined then scale height in this case is rather a projection of emission on the front and back side of the disk. It can be seen that the two sides have different slopes interior to about $0''.5$ and then have a common slope up until $0''.65$ where the emission on the SE is noise-dominated, but the NW extension

appears to change to a positive slope in scale height, suggesting a transition in the disk emission is occurring around 70 AU, which could be indicative of the location of the disk ansae (Graham et al., 2007). While the SE disk blob is present in two different PSF subtraction routines, the possibility remains that this observation may be a spurious artifact from emission which is arcing with parallactic rotation close to the noise-dominated region inside $0''.3$.

2.5 Surface Brightness Distribution

In order to determine the brightness of the disk, we again use the masked PSF subtracted images as it results in the least self subtraction of the disk. We rotate the PSF-subtracted image from the disk-masked interpolation method by 75° to orient the disk horizontally within the image to measure the radial surface brightness of the disk (Fig. 2.5). Using rectangular apertures seven pixels wide in the y (vertical) direction (which is approximately twice the FWHM of a GPI PSF), we measure the surface brightness as a function of distance along the spine of the disk and the standard deviation in each aperture. The data were binned by averaging every five pixels in the x (horizontal) direction with the errors added in quadrature. The noise floor of each image is independently estimated by performing the same operation at a PA 45° away from the disk. Points which are above the red line indicate that the signal in the disk is significant. The SNR varies with stellocentric distance but is on the order of 3-7 sigma in total intensity on the NW extension. We find an asymmetry between the SE and the NW side of the disk in total intensity, where the peak intensity on the NW side of the disk is a ratio of 2:1 brighter than the SE side (left panel of Fig. 2.5). The polarized intensity is also about a ratio of 2:1 brighter on the NW side (right panel of Fig. 2.5). Compared to other debris disk, it is one of the most extreme cases of brightness asymmetry as measured at projected separations interior of the inferred ring radius (See §2.4 & 2.6).

Overall, the total intensity on the NW side has a smooth decline with radius. The SE side however appears to have a resolved peak near 40 AU, the same location as the scale height enhancement. The NW side similarly appears to flatten around 45–50 AU before being dominated by noise at the inner working angle. In the polarized intensity, the surface brightness has a pronounced peak stretching from 50 to 75 AU. Different behaviors are expected in the profiles of total intensity and polarized intensity in the context of a ring made of predominantly forward-scattering dust

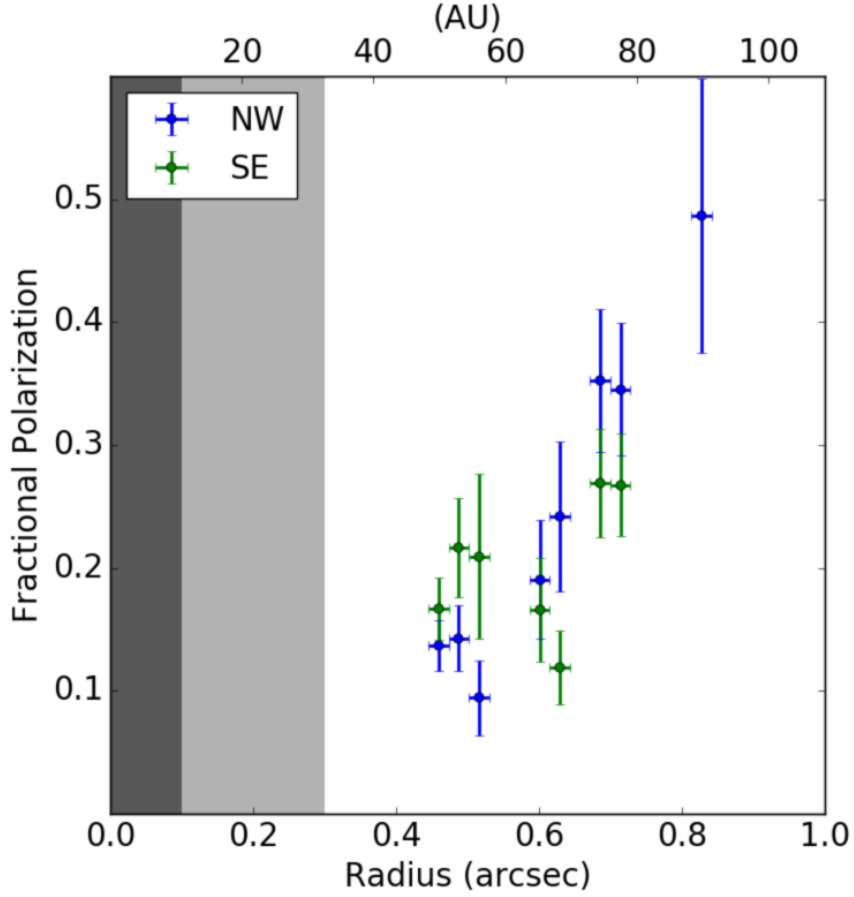


Figure 2.6 Polarization fraction as measured between the spectral mode and polarization mode of GPI. Blue points indicate the NW extension and green points indicate the SE extension of the disk. The polarization fraction trends upward from ≈ 0.1 to ≈ 0.4 in the range of 40 to 80 AU. Error bars indicate the combined SNR of the spectral mode and polarization mode. Both extensions appear to have similar distribution of fractional polarization with separation from the star given the precision of the current measurements. The polarized intensity dominates the error given a short observing sequence. Data in regions with total $\text{SNR} < 3$ are excluded to illustrate where we can confidently measure a fractional polarization. The dark grey region is the region covered by the coronagraph and the light gray region is an area dominated by PSF subtraction artifacts (See Fig. 2.2).

grains. The total intensity along an edge-on disk will be continuously declining with projected separation, with a sharp drop off outside the disk ansae. In contrast, the polarized light may peak in intensity towards increasing scattering angle from the disk. However, this depends on the phase function and the surface density distribution with radius as these two quantities are covariant in total intensity.

With combined total intensity and polarized intensity, it is possible to measure the fractional polarization as a function of separation from the star. In Fig 2.6, it can be seen that, despite the surface brightness asymmetry, the two extensions of the disk follow roughly the same trend upwards to 30% polarization at 70 AU. Data are excluded if the combined SNR is within 3σ of zero to show only robust detections of the fractional polarization. This largely affects the regions outside the main peaks of polarized intensity from around 50-75 AU, as the noise is dominated by the lower SNR of the polarized intensity detection. The scattering angle increases along the extension of the disk, leading to a peak in polarization fraction at a scattering angle near 90 degrees, at the ansae of an annular disk with an inner gap (Graham et al., 2007). However, the SNR of our images is insufficient to assess whether a plateau in polarization fraction is achieved within GPI’s field-of-view.

2.6 Spectral Energy Distribution

In order to provide context for the GPI observations, we fit an SED model to archival photometry of HD 111520 (Fig. 2.7). Photometry included the optical Tycho-2 survey (Høg et al., 2000) and infrared surveys from 2MASS (Cutri et al., 2003a) and *Spitzer* (Chen et al., 2014). Public archival *Herschel* PACS (Poglitsch et al., 2010) observations (Obs. ID 1342227022-23; PI D. Padgett) and ALMA Cycle 1 Band 6 (1.3 mm) continuum observations (Proj. ID 2012.1.00688.S; PI J. Carpenter), were measured with aperture photometry to better constrain the cold component of the SED (Table 2.1). *Herschel* PACS data was reduced with standard HIPE pipeline (Ott, 2010) and was measured with 12 and 22'' circular apertures for 70 and 160 μm with aperture flux correction factors of 0.8 and 0.82, respectively. ALMA continuum maps were retrieved from the ALMA Science Archive and the flux was measured with an 2''5 aperture. The RMS error was estimated from random apertures of the same size placed in the FOV. Images of the emission associated with HD 111520 can be seen in Fig. 2.8. Whereas, the data are consistent with a point source at 70 μm , there is some extended emission at 160 μm and therefore our aperture photometry leads to an

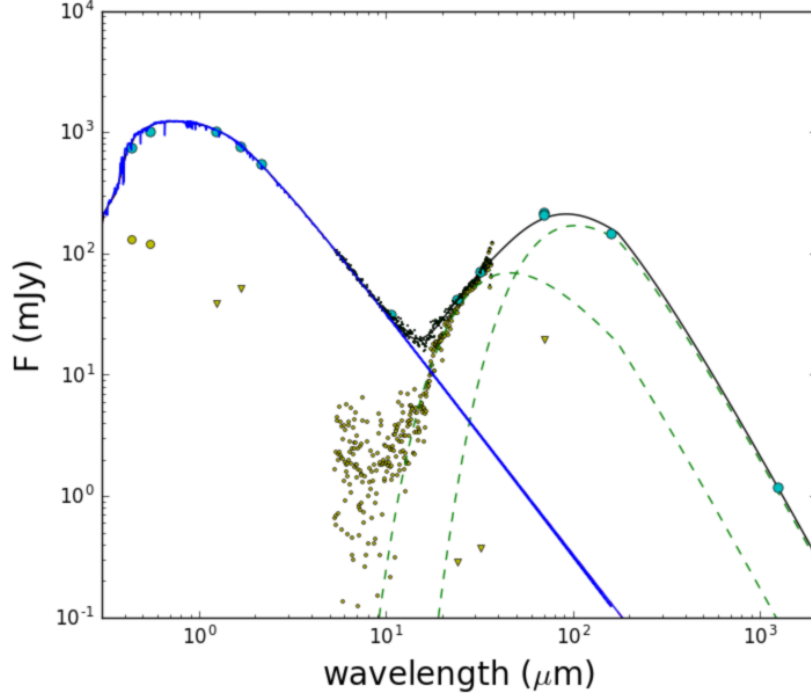


Figure 2.7 Spectral energy distribution for HD 111520. Archival photometry is in cyan. The black line is the total fit to the data. The blue line is a stellar Kurucz Model. The two green dashed lines are the modified blackbody dust components. Yellow points denote the residuals of the SED fit with inverted triangles being within measurement uncertainty. *Spitzer* IRS spectra are seen as black points.

over estimate of the $160\ \mu\text{m}$ flux associated with HD 111520. A second point source is detected in the ALMA map at a PA of 329° , $11''.9$ away from the peak emission of HD 111520 with a flux density of 0.5 mJy. That second source may contribute to the extended emission we see at $160\ \mu\text{m}$. It may also be from a background object, but given the perturbed nature of the disk, it is conceivable that it is dynamically relevant, if it were found to be comoving at a separation of $\sim 1200\ \text{AU}$.

Magnitudes were converted to mJy using the zero points of the respective instruments. *Spitzer* MIPS and *Herschel* PACS have complementary measurements at $70\ \mu\text{m}$ and are consistent within 1σ uncertainties. A Kurucz model was fit to the predominately stellar photometry ($\lambda < 10\ \mu\text{m}$) in Fig. 2.7 with an effective temperature of 6750K. The star subtracted flux densities were then least-squares fit with two modified blackbody SEDs using the photometric uncertainties as weights. The emission is modified by a power law to model the inefficient emission from grains much smaller than the observed wavelength (Wyatt, 2008). The modified slope parameters include

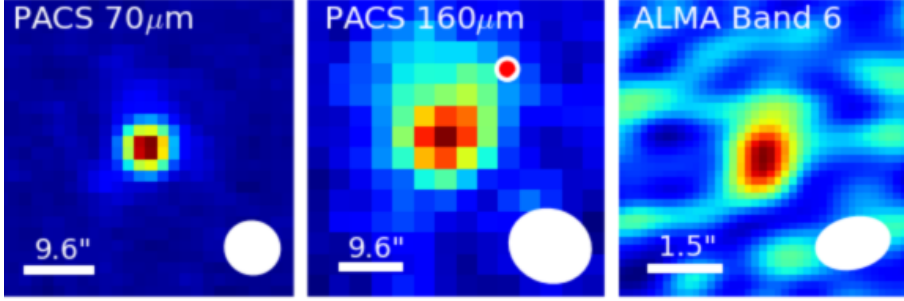


Figure 2.8 Images from *Herschel*/PACS and ALMA showing detections of emission from HD 111520 within their respective wavelengths. The white bars are for image scale and the white ellipses show the respective beam sizes. At PACS 70 μ m and ALMA 1252 μ m the emission is seen as a point source while at PACS 160 μ m there are hints of extended emission to the N side, possibly stemming from the disk, but possibly due to confusion with other background sources. The location of the second ALMA source is plotted as a red dot in the PACS 160 μ m image. The 160 μ m emission seems elongated in a similar direction as the second source, though clearly not all of the flux contamination would be from that source specifically. Note that the ALMA image is shown on a different scale than the PACS observations to best show the emission from HD 111520 and therefore does not reveal the second source.

Table 2.1 Additional photometry from archival observations.

Instrument	Effective Wavelength (μ m)	Flux (mJy)
<i>Herschel</i> PACS	70	205 ± 4
<i>Herschel</i> PACS	160	145 ± 6
ALMA Band 6	1252	1.17 ± 0.08

a knee at $173\ \mu\text{m}$ with a β index of 0.8, but given the lack of photometric coverage near the knee, both parameters remain uncertain. Two components are necessary in order to provide a good fit to all of the data at $\lambda > 10\ \mu\text{m}$. The temperatures of the warm and cold components in the SED are measured to be $111 \pm 2\ \text{K}$ and $49 \pm 2\ \text{K}$, respectively. The total fractional luminosity of the infrared excess ($\text{Log}(L_{\text{IR}}/L_*)$) was -2.65. Uncertainties were determined using the diagonal of the covariance matrix and therefore don't necessarily represent systemic biases such as non-blackbody grains.

This new SED fit is unique compared to previous SED fitting in that it includes the far-IR observations from *Herschel*, which tightly constrain the temperature of the cold dust component. Given a stellar luminosity $2.9\ L_\odot$ and assuming blackbody temperatures for the dust, we find implied disk radii of 11 and 54 AU, respectively, from simple scaling relations (Wyatt, 2008). Given that a 11 AU disk component would be completely under the coronagraph or dominated by noise, we are mostly resolving emission stemming from the cold component disk. If the polarized intensity and scale height trends are indicating that the disk radius is near 70 AU and if the scattered light is tracing the population of larger grains from thermal emission, then the disk radius measurements are reasonably consistent. Since small dust grains are not perfect blackbodies it is not surprising that the actual resolved scattered light radius is larger than the inferred disk radius from the SED fitting (Booth et al., 2013). The $R_{\text{disk}}/R_{\text{BB}}$ ratio has been found to scale with luminosity due to radiation pressure more effectively blowing out the smaller grains which have non-blackbody behavior (Morales et al., 2013). Because of the variation in radiation pressure between small and large grains, the disk itself could have a gradient of dust sizes and therefore complicate the implied disk radius from temperature alone (Thebault et al., 2014). Applying these relations to this star we would expect the R_{disk} to be 2-3 times that measured by the SED, which is about 108-162 AU or right at the edge of the GPI FOV.

2.7 Discussion

The discovery HST optical images of the HD 111520 disk revealed a nearly perfectly edge-on disk with a strong 5:1 brightness asymmetry (Padgett & Stapelfeldt, 2015). Our new *H*-band GPI observations reveal that this asymmetry extends well within the inner working angle of HST, with a 2:1 asymmetry from $0''.3$ to $1''.0$. A possible localized brightness enhancement in total intensity at 40 AU is seen on the SE side

with two PSF subtraction methods. Explanations for this brightness asymmetry could include a localized variation in dust properties, optical depth effects, or strong density perturbations.

Variations in the dust grains scattering efficiency could cause a variation in brightness if perhaps there were two distinct grain populations on either side of the disk. However, the symmetry of the polarization fraction curve between the two extensions suggests that the dust properties are similar on both ansae. Another possibility is that the dust grains themselves might be at slightly different stellocentric distances resulting from an eccentric disk, possibly induced by a perturbing planet (Wyatt et al., 1999). A small brightness asymmetry in thermal emission would then result from the pericenter glow with the brighter side being closer. A similar effect would be observed in scattered light, as shown in potential models of HD 106906 (Kalas et al., 2015). The peak polarized emission on the NW is slightly farther out than the SE side in polarized intensity, suggesting some eccentricity even if we cannot resolve the ansae explicitly. If the disk were eccentric, however, it would cause a brightening on the SE extension rather than the NW extension. Therefore the observed brightness asymmetry is inconsistent with an eccentric disk model where we expect the material closer to the star to be brighter.

Chapter 3

Multiwavelength Characterization of HD 111520

The following work is unpublished at the time of writing. I am the lead author for the data analysis of HD 111520 for the Debris Disk Large and Long Program collaboration (PI: Christine Chen). Some of the data was obtained while I was working on summit, and some from the broader collaboration. Various data analysis tools were obtained from collaborators or from publicly available sources. There was a significant amount of code written by myself in order to combine the output of those various tools. All figures, text, and analysis work was completed by myself with the advice of others.

HD 111520 is observed at J, H, & K1 near-IR bands using both the spectral and polarization modes of the Gemini Planet Imager (GPI). It is resolved as an edge on disk which is strongly asymmetric (roughly 2:1 in all bands) in scattered light between its two extensions. These observations allow for detailed dust modeling, in order to better understand the strong asymmetry in scattered light. In order to simultaneously fit the SED data from multiple facilities and the scattered light with GPI, we find that a few constraints are required. The disk mass needs to be asymmetric and the grain size distribution needs small grains (less than ~ 0.5 micron) on the brighter extension, which is less than the blowout-size for this system. The edge-on nature, with peaked polarized intensity, requires strong scattering at the ansae. Furthermore the dust composition is best matched by dirty ice opacities to reproduce the high total intensity levels. All in all, the findings are consistent with the hypothesis that a very recent collision occurred between ice-rich bodies in the northern extension of the disk. Follow up with ALMA to resolve the asymmetry in dust mass would be

beneficial to better constrain the dust properties on either side of the disk since the spatial dust distribution is the largest uncertainty in modeling this dynamically active system. Furthermore, searching for sublimating volatile byproducts could be fruitful given the evidence for a recent collision of a large amount of sub-blowout sized grains in a spatial constrained region.

3.1 Introduction

As part of the GPIES campaign (Macintosh et al., 2014, 2008), HD 111520 was observed in H-band to reveal the strongly asymmetric disk structure from 1 to 0.3 arc-seconds (Draper et al., 2016a). The system had previously been shown to have an asymmetric, “needle”-like disk structure from Hubble observations out to 6'' or 600 AU relative to the central star (Padgett & Stapelfeldt, 2015). Such a strong asymmetry, could be the result of two main scenarios, either the dust grain properties are significantly different between the two extensions, which changes the dust scattering efficiency, or the planetesimal belt responsible for the collisional dust mass itself is being perturbed by dynamical activity.

Several debris disks have been observed to have asymmetries. The most extreme previous to HD 111520 was HD 15115, colloquially known as the “blue needle” for its color and edge-on view from *Hubble* (Kalas et al., 2007). When the parent belt was resolved with Gemini NICI it was found to have a much smaller asymmetry (Mazoyer et al., 2014). Whereas HST would be sensitive to small grains being blown out of the system, the disk itself was largely unperturbed and could be explained with a possible ISM interaction or recent collision to one side of the disk creating a different grain size distribution. Similarly the debris disk around HD 181327 was found to have a localized asymmetry within its belt of dust (Stark et al., 2014). This asymmetry is however only apparent after analysis of the residuals from fitting a classically symmetric disk with a nominal scattering phase function. In the edge on case of HD 111520, the scattering angles are equivalent from the north and south extensions and therefore cannot explain the asymmetry with a preference for forward vs back scattering. This leaves the potential for such a large-scale asymmetry to be explained by a very recent (i.e. few thousand orbits or about a Myr) giant impact dominating the dust in the debris disk (Jackson et al., 2014). Such events would have implications for our understanding of planetary systems with large bodies formed and/or ejected to large stellocentric distances.

By and large, debris disks are a good indicator of a system’s stability. For example, models of dust belts can serve as indicators for planetary upheaval by large planetary perturbations or whether minor sculpting could be occurring (Esposito et al., 2016; Marino et al., 2017). In some cases disk structure can be directly traced to a known planet sculpting the disk such as in β Pic (Apai et al., 2015). Studying these highly perturbed debris disks can then offer insight into the stirring mechanisms in debris disks. Furthermore the composition of the dust and gas can help constrain the progenitors of the debris itself. Dust grains typically have decreasing polarization with wavelength when the dust is produced by asteroids than compared to comets, which typically have greater polarization with increasing wavelength (Kolokolova et al., 2004). Scattered light data, in combination with thermal sub-mm emission, can also allow us to constrain the bulk composition of the dust. Effectively, the thermal emission can constrain the dust mass and size distribution, while the scattering efficiency in the near-IR is more directly related to the microscopic properties of the dust grains. For example, this has been used to measure the bulk compositions of β Pic (Ballering et al., 2016) and HR 4796 (Rodigas et al., 2015). While the compositions are typical of what we find in local solar system bodies, this doesn’t necessarily have to be the case, given other systems may have different metallicities and therefore pathways to forming planetesimals.

Since HD 111520 is such an unusual system, we attempt to constrain the bulk composition and size distribution of the system to see if it is distinct from other debris disk systems. In principle the asymmetry in scattered light could be due to grains which are more efficient at scattering on the northern extension than the southern extension. In doing so we also motivate the need for resolved sub-mm/radio observations with ALMA, in order to constrain the distribution of dust mass.

3.2 Data

The imaging of HD 111520 from GPI was collected over a range of nights, combining data sets from the GPIES survey in H-band (PI: Bruce Macintosh) and the Debris Disk Large and Long Program in J- and K1-bands (PI: Christine Chen). A summary of the observations can be seen in Table 3.1. In general, the observations were scheduled to maximize field rotation as the source transited the meridian, with a total observing sequence of around an hour (including overheads) with a series of 60 second exposures to optimize PSF subtraction. The H-band in the polarization mode is a

Figure 3.1 HD111520 as seen by HST and GPI. The southern extension is significantly dimmer than the northern extension. The brightness asymmetries are 2:1 within GPI's FOV (Draper et al., 2016a) and 5:1 in HST's FOV (Padgett & Stapelfeldt, 2015). From GPI to HST scales, it is clear that there is a large-scale change in the disk. Possible scenarios could include a warp or an azimuthal gap from an inclined disk. The South to North extension of the disk appear slightly offset with a possible bifurcation, or 'fork', seen on the Northern side (Padgett & Stapelfeldt, 2015). It could also be an optical depth effect from self shadowing of the mid-plane (e.g. see Figure 3.8).

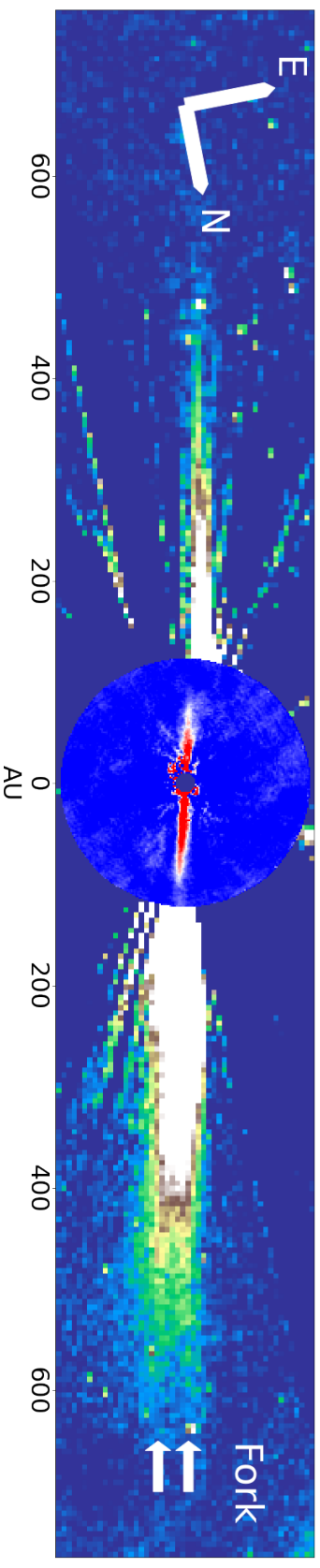


Table 3.1 Summary of the data used in this paper.

Obs Band	Date	Number	Int. Time	MASS Seeing
J Pol	2016 Mar 26	58	3480 s	0.82''
J Spec	2016 Mar 27	51	3060 s	0.45''
H Pol	2016 Mar 18	26	1560 s	0.48''
H Spec	2015 Jul 02	41	2460 s	0.28''
K1 Pol	2016 Mar 28	36	2160 s	1.33''
K1 Spec	2016 Mar 24	30	1800 s	0.59''

longer sequence than the data presented in Draper et al. (2016a) to achieve an SNR comparable to the other bands.

The data reduction in general followed standard practices for GPI data employed in the GPI pipeline (Perrin et al. (2014), and references therein). The polarization mode (pol-mode) is observed as two orthogonal polarization states on the detector and are modulated by an achromatic half-wave plate (HWP) to four different orientations (Perrin et al., 2015). The relative measurement of flux between them can later be used to derive the Stokes parameters in the FOV. The detector images are dark subtracted and ‘destriped’ with a Fourier-filter to remove a standing wave pattern from microphonic noise (Ingraham et al., 2014a). The flexure in the instrument is compensated for using a cross-correlation algorithm to match the detector with the expected positions (Draper et al., 2014). The extracted spot fluxes create the pol-mode data cube and can then be cleaned for bad pixels and systematic offsets using a modified double difference algorithm (Perrin et al., 2014). A geometric distortion correction in the FOV from astrometric standards are then used (Konopacky et al., 2014). The instrumental polarization is also removed based on measurements of the flux under the coronagraph and subtracting the total intensity (Millar-Blanchaer et al., 2015). The data are smoothed by a Gaussian with a FWHM of 3 pixels, equivalent to a resolution element in GPI. The data were then flux calibrated by measuring the satellite spots produced by GPI’s optics with elongated apertures (since the spots are smeared out by diffraction with wavelength in the broad band pol-mode) and compared to 2MASS JHK magnitudes of the star to calibrate the flux within the data cube (Hung et al., 2015). The spots are also used to determine the star center by using a Radon transform algorithm (Wang et al. (2014); Perrin et al. (2015)). The data set at multiple position angles and HWP orientations is then combined with a singular value decomposition on Mueller matrices to create a Stokes data cube. The values are converted to a radial Stokes convention to put the stellocentric polarized emission into a single Stokes mode (Q_r) (Schmid et al., 2006).

In the case of the spectroscopic mode, again standard GPI pipeline data reduction practices are used (Perrin et al., 2014). Each of the individual dispersed light frames, were dark subtracted, had bad pixels masked and were ‘destriped’ from microphonics (Ingraham et al., 2014a). Wavelength calibrations are done using Ar lamp exposures in each respective band (Wolff et al., 2014). Calibration sources are measured prior to the observing sequence, minimizing flexure offsets. For the J- and H-bands a standard box aperture method is used to extract the flux into a wavelength calibrated

data cube (Maire et al., 2014a). In the K1-band, the satellite spots had weaker flux compared to the background, which interferes with the calibrations necessary after cube extraction. The microlens PSF extraction method was then used to extract the data from the detector (Draper et al., 2014; Ingraham et al., 2014a). The SNR improved enough for the pipeline to find the satellite spots in subsequent steps in at least the middle of the K1-band. Sky-subtraction at the 2D detector was attempted but this step appeared to introduce more noise. The sky subtraction was therefore left to PSF subtraction at later steps. For bad spaxel mitigation, a bad pixel identifier and smoothing was applied similar to Draper et al. (2016a). The satellite spots were then identified by centering on a high pass filtered image of the data. A best guess position for a slice with high SNR was identified by eye once for the whole sequence to aid the spot location algorithm. The unfiltered images then had their satellite spots extracted to measure the stellar spectrum convolved with the instruments response function in wavelength and time. The spectrum of each cube was calibrated by comparing the measured flux with the 2MASS magnitude for each respective band. A color correction was applied by comparing the measured spectrum to a real, atlas template spectrum (Pickles, 1998) for a star of HD 111520’s spectral type (F5V). These two factors essentially measure the flux conversion factors for each cube so that the satellite spots have the same absolute flux and spectra as an F5V star. This calibrates the data in the cube to physically relevant units of Jansky. This algorithm was tested on a known white dwarf spectrum in Maire et al. (2014b) and found to be within a 5% flux error with on sky observations. The final images resolving the disk can be seen in Figure 3.2.

3.3 Broad Band Polarized Intensity

One advantage to working with polarized intensity (PI) is that PSF subtraction is largely performed without algorithm dependent artifacts, because it is a direct measurement of the PI from the debris disk (assuming the instrumental polarization was properly calibrated). Furthermore, PI offers a unique and useful insight into the grains’ scattering properties. Therefore, we use the PI in all 3 bands when fitting the disk grain properties. Figure 3.3 shows a measurement of the PI as a function of wavelength. The PI and noise are measured using aperture photometry on/off the disk emission.

Figure 3.2 The polarized (PI) and total intensity (TI) detections of the debris disk around HD 111520. The PI is taken from the rotated stokes frame (Q_r) to isolate the astrophysical emission. The TI has been run through pyKLIP. The images have been rotated by 76° for plotting purposes. The disk is consistently dimmer on the SSE (left) side of the disk compared to the NNW (right) side of the disk. The images have been scaled to the same brightness colorbar across each wavelength band. The disk appears brighter from J to K1, respectively. The K1-band has only a marginal detection of the SSE side in TI.

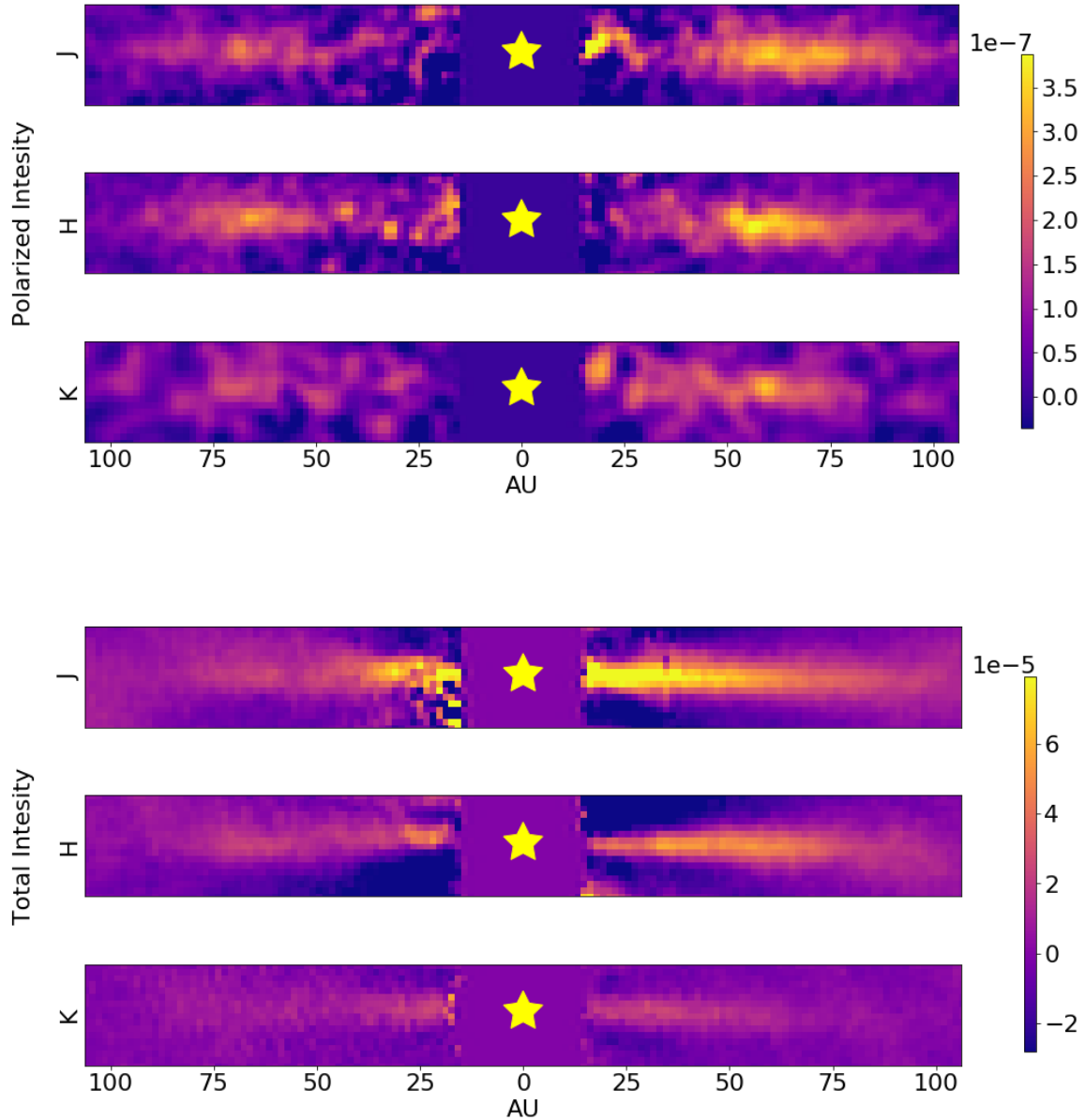
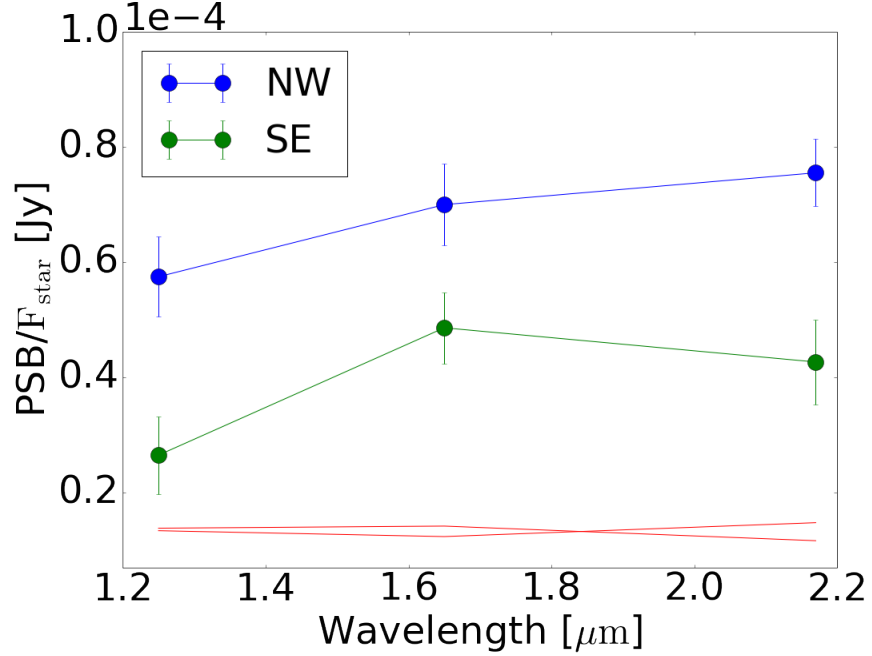


Figure 3.3 The PI of the disk emission as a function of wavelength for both extensions of the disk. In general, both sides have a consistent brightness asymmetry on either side of the disk with wavelength. The red lines indicate the flux measured with the smae method but at an orthogonal axis to the disk to measure the relative noise in the images.



3.4 Disk Forward Modeling

In order to first resolve the disk structure in detail, we employ forward modeling of the total intensity (TI) through pyKLIP (Wang et al., 2015) using disk models from MCFOST (Pinte et al., 2006). This is an important step in the data reduction because the point-spread function (PSF) subtraction is pivotal to finding the disk emission in the noise of GPI data. However, the KLIP algorithm itself will impart artifacts into the disk emission, as it subtracts the overall noise from the PSF. This must be accounted for in order to back out the most likely physical model of the disk structure. Therefore, in order to fit a model to the data we follow these steps:

1. Reduce the GPI Data set using pyKLIP.
2. Generate a physical model of the disk emission using MCFOST.
3. Use the forward modeling module in pyKLIP to simulate the resulting KLIP image based on the input model.

Table 3.2 Initial set of parameters used in fitting the disk structure based on MCFOST models. The parameters were constrained based upon previous work (Draper et al., 2016a), unless otherwise noted. The PA angle of 165° from (Draper et al., 2016a) is equivalent to 105° here because 165° is the major axis measured east of north (counter-clockwise), where as the MCFOST model convention is the minor axis measured clockwise.

Parameter	Value	Range
Grid [pixels]	281×281	fixed ¹
Image Scale [AU]	431.4	fixed ¹
Distance [pc]	108.58	fixed ²
PA [$^\circ$]	105	[100,110]
Dust Mass [$M_\odot$]	10^{-6}	fixed
R_{in} [AU]	70	[55, < R_c]
R_{out} [AU]	200	fixed
H_0 [AU]	3	[1,10]
α_{in}	-1	[-1,-5]
α_{out}	1	[1,15]
R_c [AU]	100	[60,200]
a_{min} [m]	0.1	fixed
a_{max} [m]	1000	fixed
a_{exp}	3.5	fixed

¹Determined by GPI's lenslet resolution.

²Distance based on parallax from *Hipparcos*. The *Gaia* parallax measurement did not change this value significantly.

4. Compute the log likelihood from a minimal residual between the KLIP processed data and the forward model.
5. Iterate over the parameter space of an MCFOST model using an MCMC computation to find the most likely input model. In our efforts, we use the *emcee* (Foreman-Mackey et al., 2013) package which is a Metropolis based method. In principle any MCMC method could be applied such as a Hamiltonian method which converges quickly and maximizes information used for expensive function calls to compute the log likelihood.

3.4.1 Disk Structure

In order to constrain the overall disk structure, any of the three wavelengths observed could be used. Therefore, we choose the data set with this highest signal to noise. In our case this was the J-band data set, for both highest signal and fewest artifacts from post-processing. We collapse the observations into a single broad band image to maximize the signal to noise of the resulting KLIP processed data and model the disk with the appropriate central wavelength of the GPI J-band. In order to reduce the parameter space, the parameters which strongly influence the disk brightness (composition, mass, grain size) are fixed and instead the flux is allowed to vary with a single arbitrary multiplier. The disk brightness is then allowed to vary from a single parameter but allow the fitting algorithm to only fit parameters such as disk radius, inclination, position angle, scale height, and surface density exponents. Another advantage to this is to reduce the computation time since processing all bands in both modes (PI/TI), over all physical parameter space would be prohibitively long.

The initial model fitting is informed by the previous analysis of Draper et al. (2016a). The disk structure parameters which are free to vary, are also given priors which bound the fitting to reasonable expectations for the disk parameters of an edge-on debris disk. During the initial fitting of the structure, the models have been artificially given a 2:1 brightness asymmetry to better represent the flux levels in the data, without having to double the number of properties to fit either side of the disk. We therefore assume the disk emission on either side of the disk stems from a consistent structure across the disk. The J-band PI is also fit in combination with the total intensity because it can be uniquely diagnostic of the disk radius given the peak scattering occurs around the ansae of the disk (i.e. scattering angle of 90° , Engler

Figure 3.4 The covariance plots for parameters in the disk structure fitting.

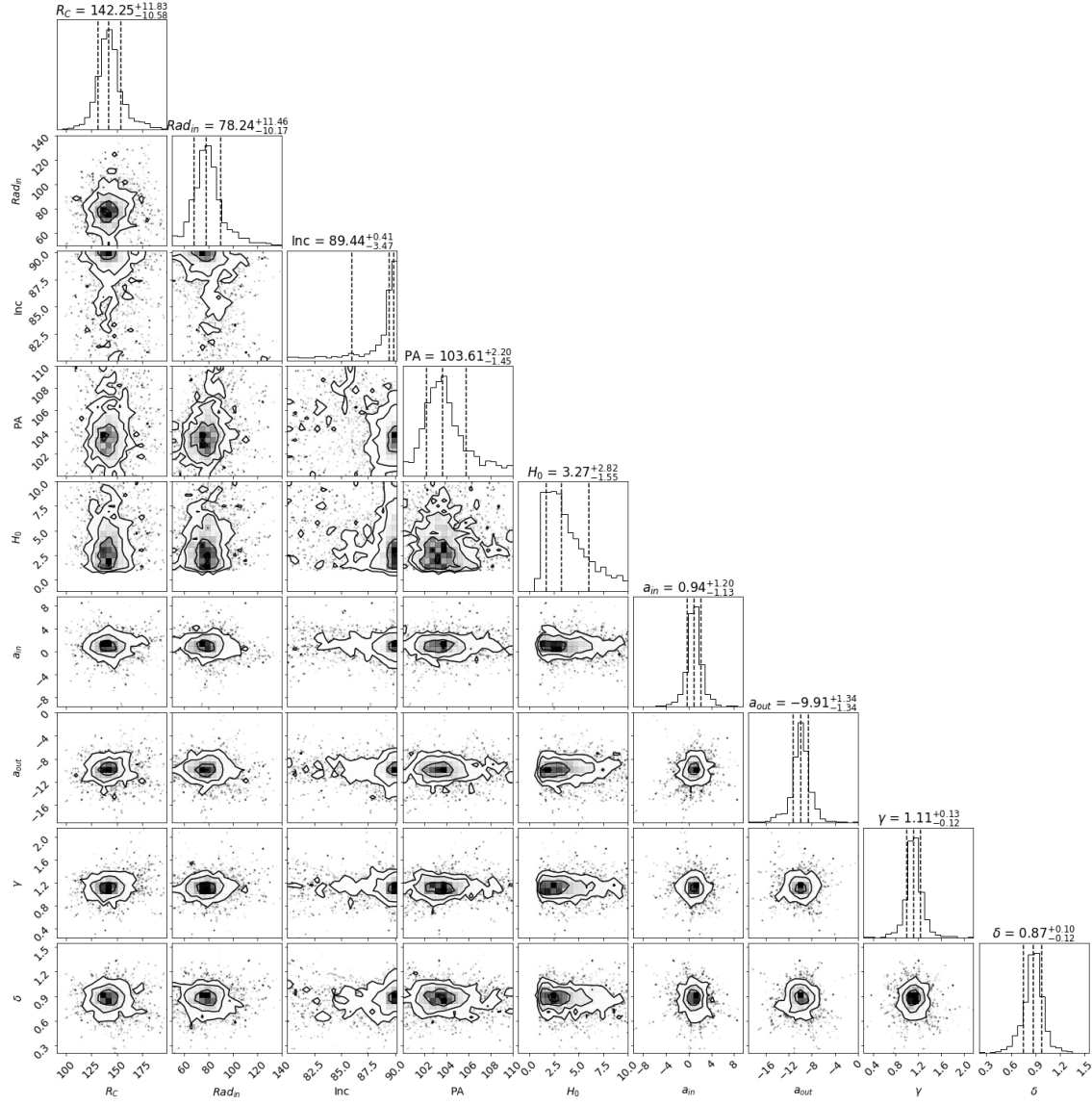


Table 3.3 Derived disk parameters from fitting models of the Northern extension of the disk. The total dust mass is estimated based on the mass in sub-mm grains from ALMA observations (See Section 3.4.2).

Parameter	Value
Radius (AU)	140
Inner Radius (AU)	75
inc ($^{\circ}$)	89.5
PA ($^{\circ}$)	104
H_0 (AU)	1.8
α_{in}	1
α_{out}	-10
Dust Mass ($M_{\odot}$)	5.5×10^{-7}
α_{exp}	3.65
a_{min} (μm)	0.35
porosity	0.1
composition	70% dirty ice
...	30% astro-silicate

et al. (2017)).

After running for 100,000 steps from 500 walkers, the solutions for the 9 free parameters of the disk structure can be seen in Table 3.3. The parameter to parameter covariance from the MCMC fitting can be seen in Figure 3.4.

The disk density structure (ρ) is defined in cylindrical coordinates (r, z) by the following equation (Augereau et al., 1999):

$$\rho(r, z) \propto \sqrt{\left(\frac{r}{R}\right)^{-2\alpha_{in}} + \left(\frac{r}{R}\right)^{-2\alpha_{out}}} \times \exp\left(\frac{-|z|^{\gamma}}{h(r)}\right) \quad (3.1)$$

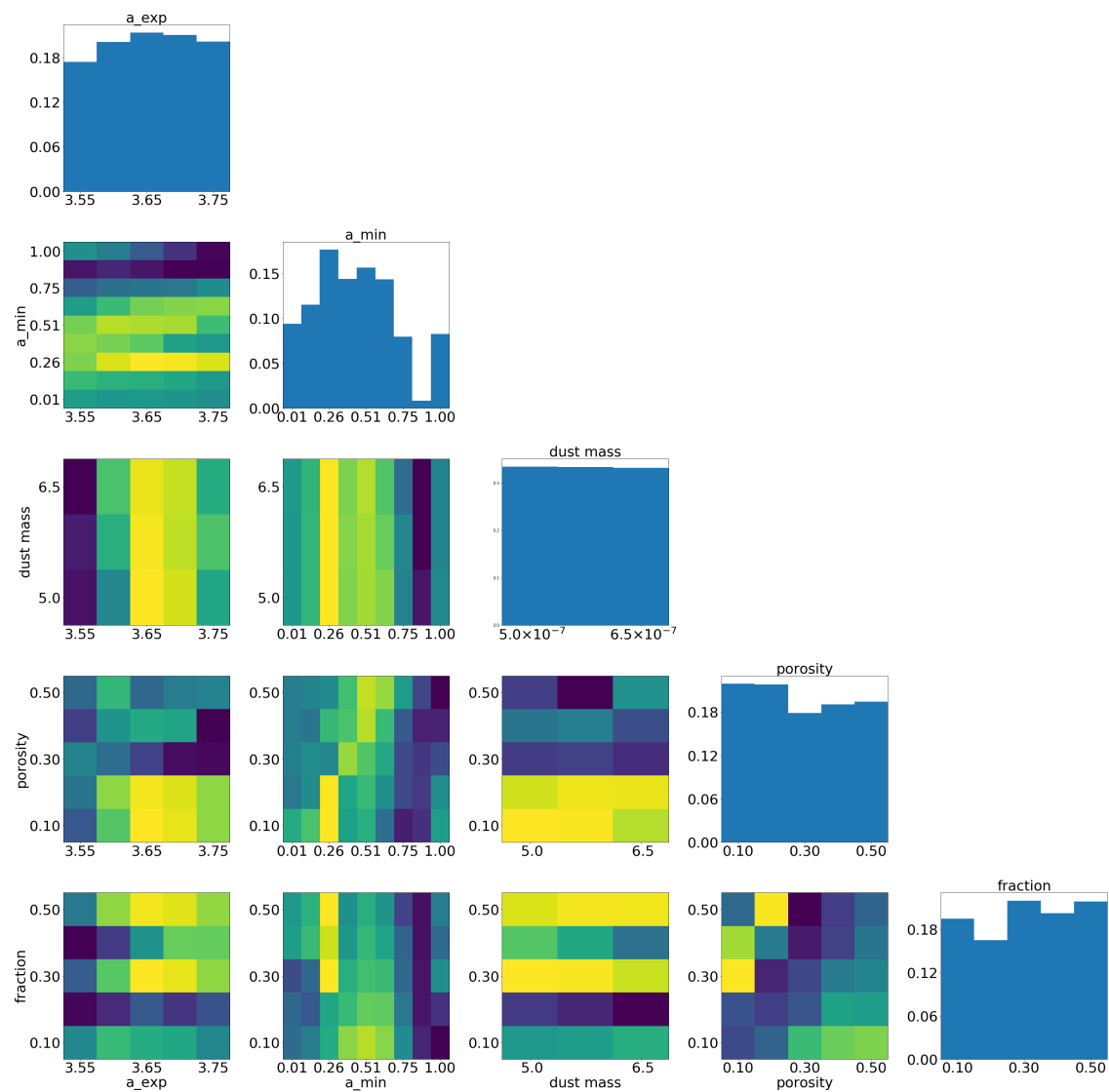
$$h(r) = H_0 \times (r/R) \quad (3.2)$$

where R is the disk radius and H_0 is the scale height at the disk radius, R . Each cell has a grain population with a size distribution (α_{exp}) with a cutoff at small grains less than a_{min} and up to 1000 μm .

3.4.2 Grain Properties

With the structure of the disk emission largely constrained, we now fix those values and adjust the grain properties in order to fit the macroscopic grain properties. The main properties which can constrain the disk brightness in the near-IR are the grain

Figure 3.5 The χ -sqr covariance distributions when fitting the disk brightness model parameters.



size distribution, dust mass, minimum grain size, porosity, and dust composition. Parameters such as dust mass and grain size distribution can be constrained with far-IR and sub-mm observations more readily than they can with just near-IR observations alone. Therefore, we set constraints on these parameters as known priors while fitting the other parameters which are uniquely sampled by GPI's near-IR observations.

Dust Mass

Since HD 111520 was detected in ALMA Cycle 1, we have an independent measurement on the dust mass in millimeter sized grains, given the sub-mm flux. Since other parameters, such as dust porosity, will be degenerate with dust mass, it will be important to constrain this parameter as much as possible. When fit with a multiband SED, HD 111520 shows a two component fit for a modified blackbody (Draper et al., 2016a). The flux observed by ALMA represents the total sub-mm flux at 1.3 mm for the system since the observations were unresolved (Lieman-Sifry et al., 2016). Based on the fit, the relative flux of the cold component in the GPI FOV is 90% of this total. The second, warm component is presumed to be underneath the coronagraph, given the assumed radius from its temperature. The total dust mass in sub-mm grains of the debris disk can be calculated using the sub-mm flux from the following equation (Wyatt, 2008):

$$M_d = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T_d)} \quad (3.3)$$

Where M_d is the dust mass as a function of observed surface brightness (F_ν), distance to the source (d), the dust opacity (κ_ν) and the Planck brightness as a function of dust temperature (T_d). Converting this equation to units which are more applicable to observations and assuming that mass varies linearly with temperature in the Rayleigh-Jeans limits, gives the following equation (Holland et al., 2017):

$$M_d[M_\oplus] = 5.8 \times 10^{-10} \frac{F_\nu[\text{mJy}] d[\text{pc}]^2 \lambda[\mu\text{m}]^2}{\kappa_\nu[\text{cm}^2\text{g}^{-1}] T_d[\text{K}]} \quad (3.4)$$

Using fitted parameters and data from the SED fit in Draper et al. (2016a), we can derive the dust mass for HD 111520 to be $0.184 M_\oplus$. We assume the flux of the cold component is 0.9 of the total flux. The dust opacity at $1252 \mu\text{m}$ is assumed to be $1.24 [\text{cm}^2\text{g}^{-1}]^1$. While we cannot resolve how the flux, and therefore mass, is

¹ $\kappa_\nu = \kappa_o \nu^\beta$: The dust opacity scales with frequency to the power of the sub-mm slope (β_s).

distributed within the resolved disk seen by GPI, we can use this mass to constrain the parameter fitting of the dust properties to prefer models near this total dust mass.

Grain Size Distribution

Dohnanyi (1969) developed the theoretical formalism of a size distribution of bodies in a collisional cascade to follow a power law $dN/da \propto a^{-q}$, where $q = 3.5$. This has since been shown to range from 3 to 4 by several numerical simulations (Pan & Sari, 2005; Pan & Schlichting, 2012; Gáspár et al., 2012). Draine (2006) found that measuring the sub-mm slope of the dust SED itself can be a direct measurement of the grain size distribution. When fit as a modified black body, the β parameter is $\beta = (q - 3)/\beta_s$, where β_s is sub-mm slope of small grains (1.5-2). Therefore, we use the β slope measured based on the SED from Draper et al. (2016a) to get a constraint on the size distribution q to 3.4. However, one of the possibilities is the dust grain size distribution is larger to one side of the disk in order to scatter more light in the near-IR. Therefore we must also try to fit the data around this value.

Minimum Grain Size

The minimum grain size is an important parameter in order to fit the amount of scattered light and the mid to far-IR emission. Small grains are very effective at scattering light. Furthermore, small grains are inefficient at emitting photons greater than their size and will therefore have stronger emission at shorter wavelengths (Wyatt, 2008). This tension makes the grain size an important parameter in multiwavelength fitting such as this. A physical constraint on the minimum grain size is usually the blowout size. The blowout grain size is the size at which grains will experience a force of radiation pressure equal to half as much as the force of gravity ($\beta_{rad} = F_r/F_g = 0.5$). This limit is the condition at which a grain of dust will be ejected onto hyperbolic orbits. The typical blowout sizes are on order of $\sim 1 \mu\text{m}$ (Pawellek et al., 2014; Burns et al., 1979). A few studies of debris disks have fit the minimum grain size from scattered light and found it to be several times the blowout size (5-6 μm) and therefore the β_{rad} relationship represents a lower limit (Ballering et al., 2016; Rodigas et al., 2015).

Using the canonical value of $1.7 \text{ cm}^2\text{g}^{-1}$ for κ_ν at $850 \mu\text{m}$ κ_ν of $1.24 \text{ cm}^2\text{g}^{-1}$ at $1252\mu\text{m}$ can be derived for a β of 0.8.

Free Grain Properties

The other grain properties which effect the brightness are constrained mostly by the GPI data itself. These parameters include the composition and porosity. The minimum grain size can also effect the SED, so it is necessary to simultaneously model the SED and use the available data to constrain the best parameters. Porosity and composition are strongly affected by the relative amounts of polarized and total intensity in the near-IR and are allowed to vary in order to provide the best model fit to the data.

The composition was fit with fractional combinations of different opacities from astrosilicates (Draine & Lee, 1984) and either amorphous carbon (Rouleau & Martin, 1991) and dirty ices (Li & Greenberg, 1998). In order to make the total intensity match the right relative brightness it was found that an ice composition was necessary.

It is certainly possible to fit the GPI data with other silicate and carbon compositions, however, the fluxes produced would clearly exceed the measurements by *Herschel* and ALMA emission. Therefore we test fractional combinations of ice compositions with silicates. The distribution of χ^2 for the various parameters can be seen in Figure 3.5. The parameters derived from the fits can be seen in Table 3.3.

3.4.3 Disk Eccentricity?

It is possible that a brightness asymmetry can result from an offset, eccentric disk. In some cases a “needle”-like morphology could be explained in theoretical models (Lee & Chiang, 2016) where the disk appears extremely one-sided. Usually, this results as an elongated, fainter side and a shorter, brighter side. In these instances the brightest emission at the pericenter of dust orbits can be blocked by the coronagraph, giving it the one-sided or “needle”-like appearance. In this case we appear to resolve the annulus of the disk, as determined by both the SED and polarized intensity. To investigate this, we consider a disk model based upon the best fit model but without a dust mass asymmetry and a single dust grain population on both sides of the disk. A stellocentric offset of 28 AU is put into the model, which corresponds to a disk eccentricity of 0.2. In this regime the disk is still largely circular and can be modeled with a similar dust distribution. The problem that becomes apparent in this model is that the peak in the polarized intensity will become non-symmetric. This is because the polarizability peaks towards near the ansae, which are now at different separations from the star. For HD 111520, however, the peak polarized intensity is at the same

Figure 3.6 The SED of the star and disk emission given the final fitting parameters of the model. The black dots denote measured flux values compiled in (Draper et al., 2016a). The blue line shows the emission from the MCFOST model of the star. The red dot-dashed line shows the flux due to the N extension, while the S extension is the green dashed line. Most of the mid to far IR emission is due to the NW extension because it has an enhanced population of small grains (steeper size distribution and smaller minimum grain size). In the sub-mm, the emission is more equally distributed.

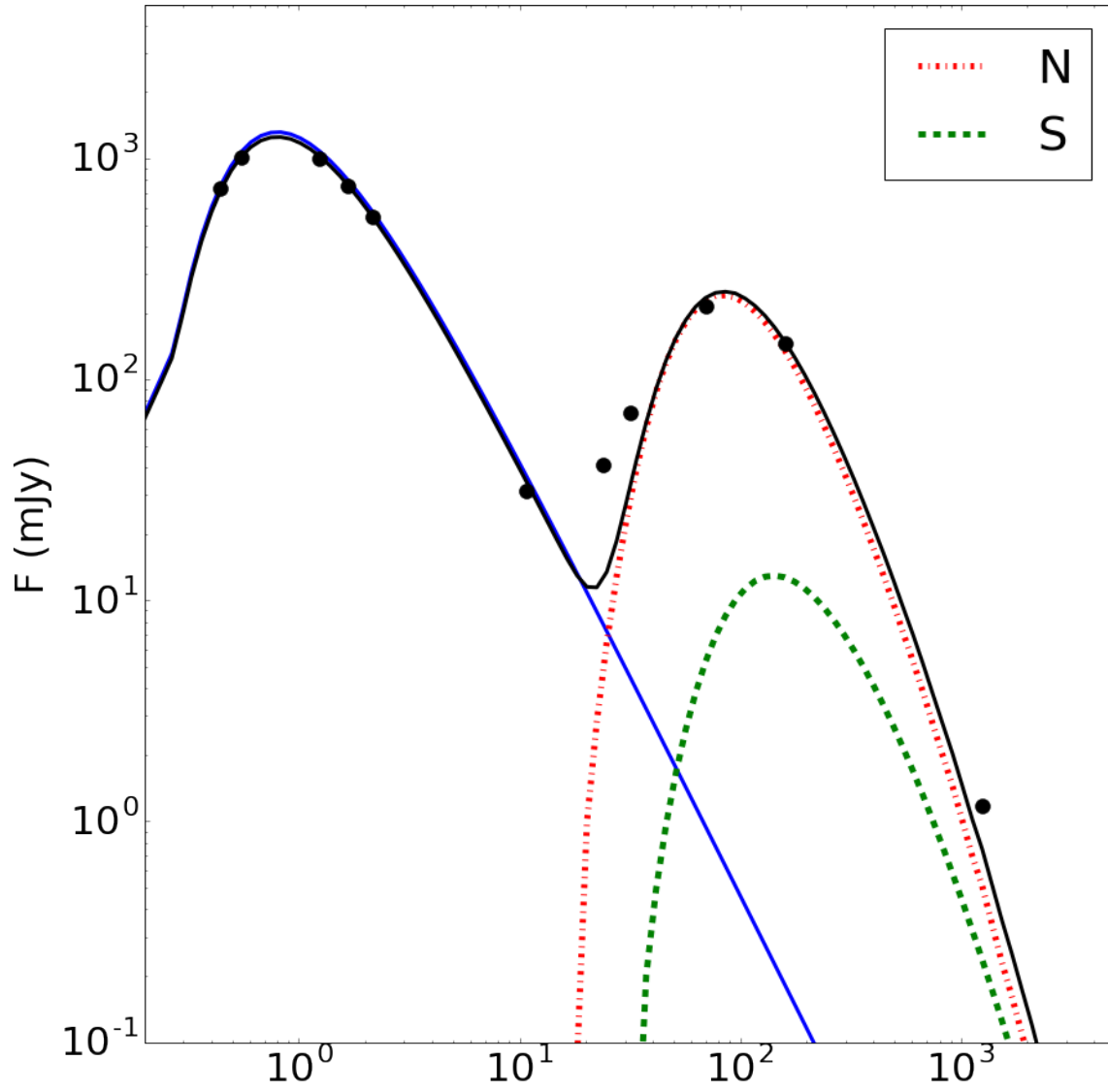


Figure 3.7 A comparison of two models where the the top model has small grains of $0.35 \mu\text{m}$, and the model below has a minimum grain size of $1.0 \mu\text{m}$. In order to have the peaked polarized intensity at the ansae, at this inclination, small grains are required. While this grain size is less than the blowout size, it gives credence to a recent impact hypothesis, where the grains are actively being scattered out of the system in present day, as seen by the extended emission from HST.

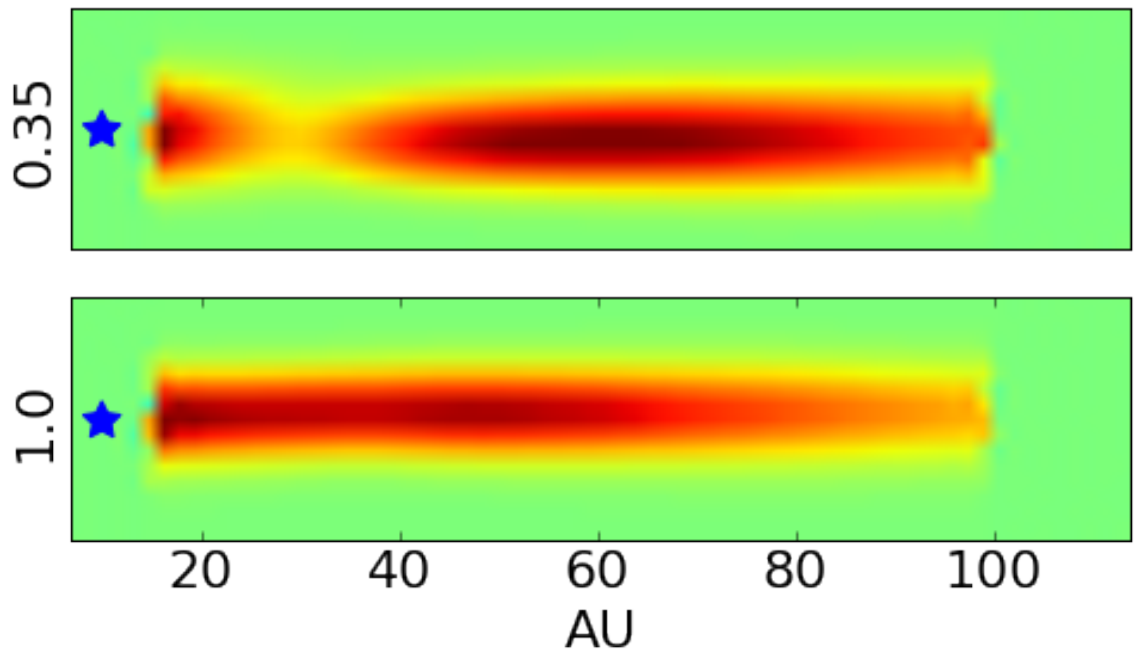
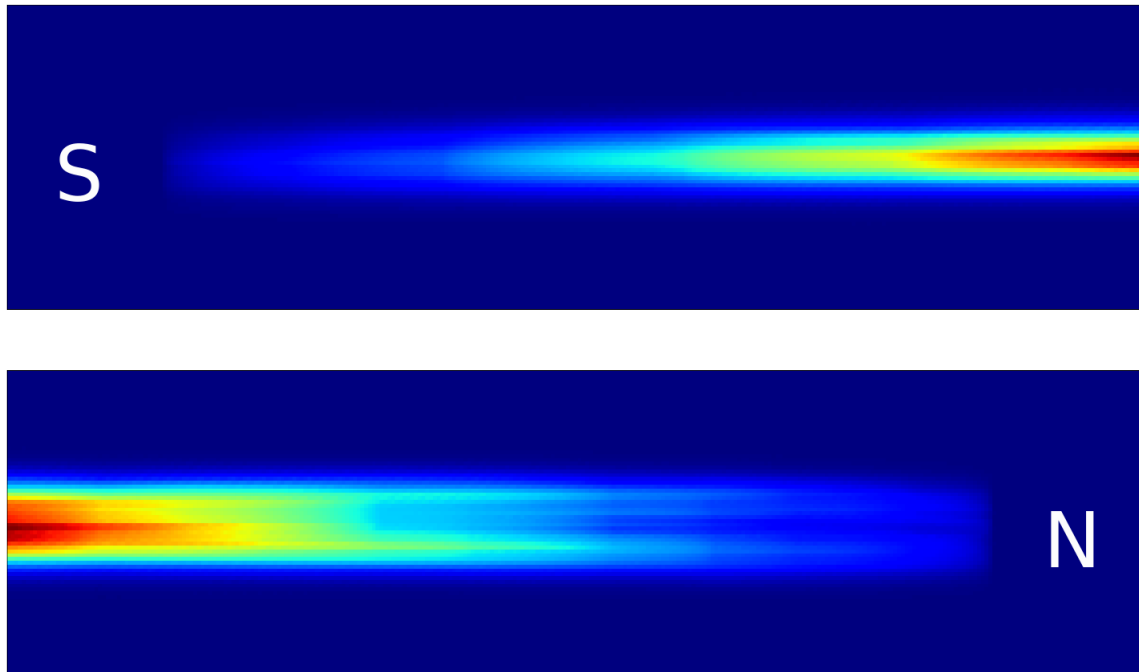


Figure 3.8 In a high resolution model of the disk, a bifurcation can be seen on the northern side as a direct result of the fitted disk properties and the asymmetry factor in dust mass. The south extension on the other hand has no bifurcation. While the GPI images do not show this bifurcation, due to a combination of resolution and KLIP processing, a bifurcation can be seen farther out in HST imaging (See Figure 3.1).



stellocentric distance (Draper et al., 2016a). Therefore the brightness asymmetry can result from an eccentric disk, but it will not have symmetric peaks in polarized intensity. Furthermore, it should be noted that the offset to explain the brightness asymmetry in GPI’s FOV, is in the opposite direction expected by the emission seen in HST’s FOV. If an eccentric disk explains the asymmetry in the disk seen by HST, the ring will be more extended out to the North (i.e. right in this figure) with a bright pericenter in the South. but instead the disk is being shifted to the South (left) in order to increase pericenter glow on the North (right) to be consistent with the observations. In other words, the brightest extension in the disk seen by HST and GPI should flip between the North and South. This is because we are seeing the resolved pericenter for dust orbits with GPI, which are obscured by HST’s coronagraph, and we only see the extended apocenter emission to the North with HST. The fact that we see brighter and more extended emission on the North side from GPI’s to HST’s FOV is inconsistent with an eccentric disk + coronagraph obscuration model. The lack of mid-IR emission in our models could just be the result of a warmer component of dust, albeit at a much smaller fraction than predicted with previous unresolved SED fitting (Draper et al., 2016a). This mid-IR emission could also be largely due to sub-blowout grains, which we see with HST, but are not modeled simultaneously with these GPI images (e.g. see Ballering et al. (2016)). One could imagine a more complex model where the grain properties are radically different on either side along with an eccentric disk in order to compensate, however, it would make the model much more complex and hard to distinguish without more data.

3.5 Discussion

The best fit model to the GPI data can be seen in Figure 3.11-3.13. The subsequent SED can be seen in Figure 3.6. In order to simultaneously fit both the SED and scattered light, several things became apparent.

First, the NW side requires a significant population of small grains, such that the data were only fit by having at least a minimum grain size of $0.35 \mu\text{m}$. That size is needed in order to cause a peak in polarized emission at the ansae of the disk (See Figure 3.7). However, this value is below the blow out size for dust in this system ($0.6\text{-}0.8 \mu\text{m}$). Furthermore, the disk cannot contain small grains across its entirety, as it would increase the far-IR flux beyond what is observed by *Herschel* and *Spitzer*. Therefore there must be a heterogeneous population of grains on either side of the

Figure 3.9 Example of an asymmetric brightness created by an eccentric disk (0.2 eccentricity, 28 AU offset parallel with spine of disk emission) as seen in J-band. The change in brightness resembles the data, but the peak polarized intensity on the brightest extension moves inward. This is a direct result of the polarizability peaking toward the ansae, which have now been shifted by eccentricity. Since the observed polarized intensity peaks at the same stellocentric distance, an eccentric disk alone cannot explain the brightness asymmetry without further complicating the model.

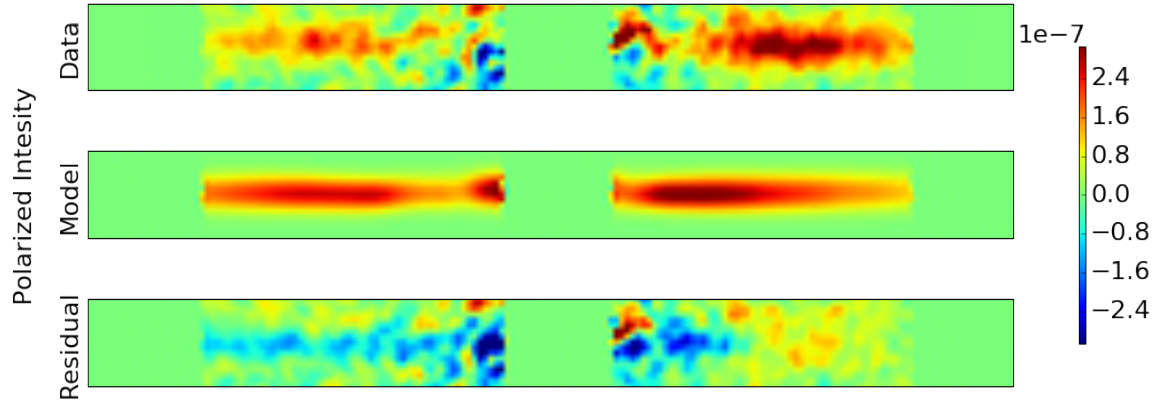
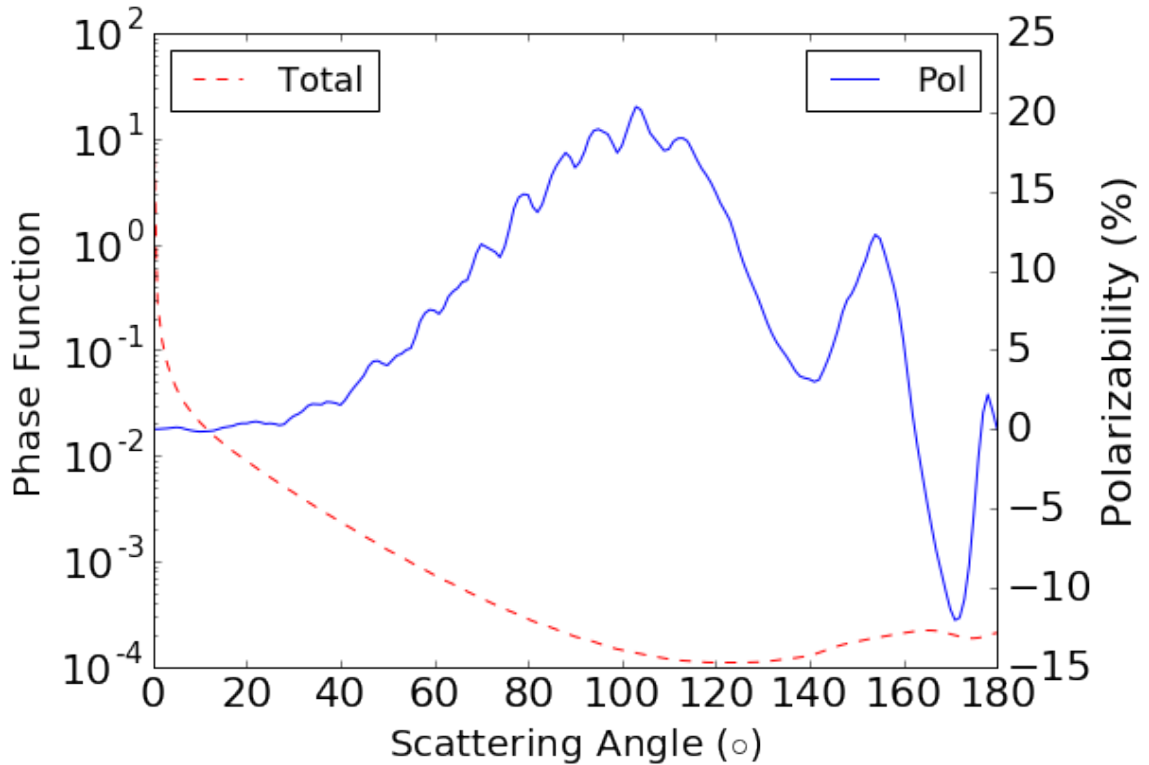


Figure 3.10 The modeled phase function and polarizability of the best fit model. It can be seen that the peak in polarized intensity occurs at around 100° , which corresponds to near the geometric ansae of the disk. The edge on nature of the disk makes the disk emission closely follow the phase function from 0 to 90° (i.e. scattering angle $\propto$ stellocentric distance.) where back-scattering occurs at angles greater than 90° .



disk to cause the asymmetry in scattered light brightness, peaked polarized emission at the ansae and have far-IR flux match what is observed.

Secondly, the dust on the Northern side requires a steeper grain size distribution (~ 3.65) and opacities consistent with dirty ice compositions, in order to match the amount of total intensity in scattered light. The dust mass itself needs to be asymmetric in order to make the disk model bright enough in combination with the dust grain properties asymmetry. In other words, the brightness asymmetry in scattered light cannot be explained by changing the dust grain properties alone. The degree to which the dust mass distribution is asymmetric is indeterminate until the disk can be resolved at longer wavelengths (i.e. with ALMA), but the emission in scattered light and SED was fit using a 2:1 dust mass asymmetry.

Third, the dust mass is high enough at the midplane and viewed at an inclination close enough to 90° , that the disk starts to self-shadow. This can be seen in Figure 3.8 with a high resolution image the final disk model. The bifurcation in the model is removed after convolution with the GPI PSF and processed through pyKLIP, which is why it is not observed in GPI data. Yet, it would be a natural way of explaining the bifurcation seen farther out in the small tenuous dust grains by HST (See Figure 3.1). Either JWST at visible wavelengths or HST using STIS BAR5 to improve the inner working angle, could resolve the disk down to GPI’s FOV (Schneider et al., 2018).

In summary, it is proposed that a very recent collision occurred between two ice rich bodies in the disk of HD 111520. This explains the composition being closest to dirty ice and the increase in dust mass and size distribution localized on the Northern extension. Since the grain size is less than the blowout size, the collision would have occurred with orbital timescales. The grain size being less than the blowout size also implies that the collision was very recent as the grains are actively being scattered out of the system. A change in grain size distribution and collection of smaller grains at the collision point of the disk is a prediction of models for recent large impacts between two bodies (Jackson et al., 2014).

For context, there are a few multiwavelength studies to constrain the dust composition in debris disks. Often the parameter space is quite large, but by resolving the debris disk from the near-IR to the sub-mm, composition becomes measurable because the thermal and scattering properties can be constrained in unison. For example, Rodigas et al. (2015) analyzed resolved imaging of HR 4796A at multiple wavelengths and constrained the composition of that disk to a mixture of silicates

($\sim 60\text{-}70\%$) and iron dust ($\sim 30\%$) when fitting the SED and scattered light. The results were distinct from an analysis of scattered light imaging alone, which suggested the presence of amorphous carbon. Similarly, Ballering et al. (2016) did a multi-wavelength study of beta Pic and found that a mixture of 60% silicates and 40% amorphous carbon best fit the resolved scattered and thermal light.

Since we typically do not have spectral information identifying individual features due to specific compounds, SED fitting and resolved thermal and scattered light imaging is the best approach to modeling composition with the current facilities. These comparative studies can determine the most probable compositions in debris disks as an ensemble and how much variation in composition is apparent. The fact that HD 111520 is unique compared to HR 4796A and β Pic supports the idea of a rare, but recent, impact by icy bodies. Furthermore, this scenario explains why this system has such a large brightness asymmetry compared to many other debris disks undergoing a steady collisional cascade.

Figure 3.11 Final disk models of the Northern extension using the best-fit parameters for structure and grain properties, whilst simultaneously being constrained by the SED. The model assumes a 2:1 asymmetry in dust mass between the two extensions of the disk. The image scale is linear in units of Jy.

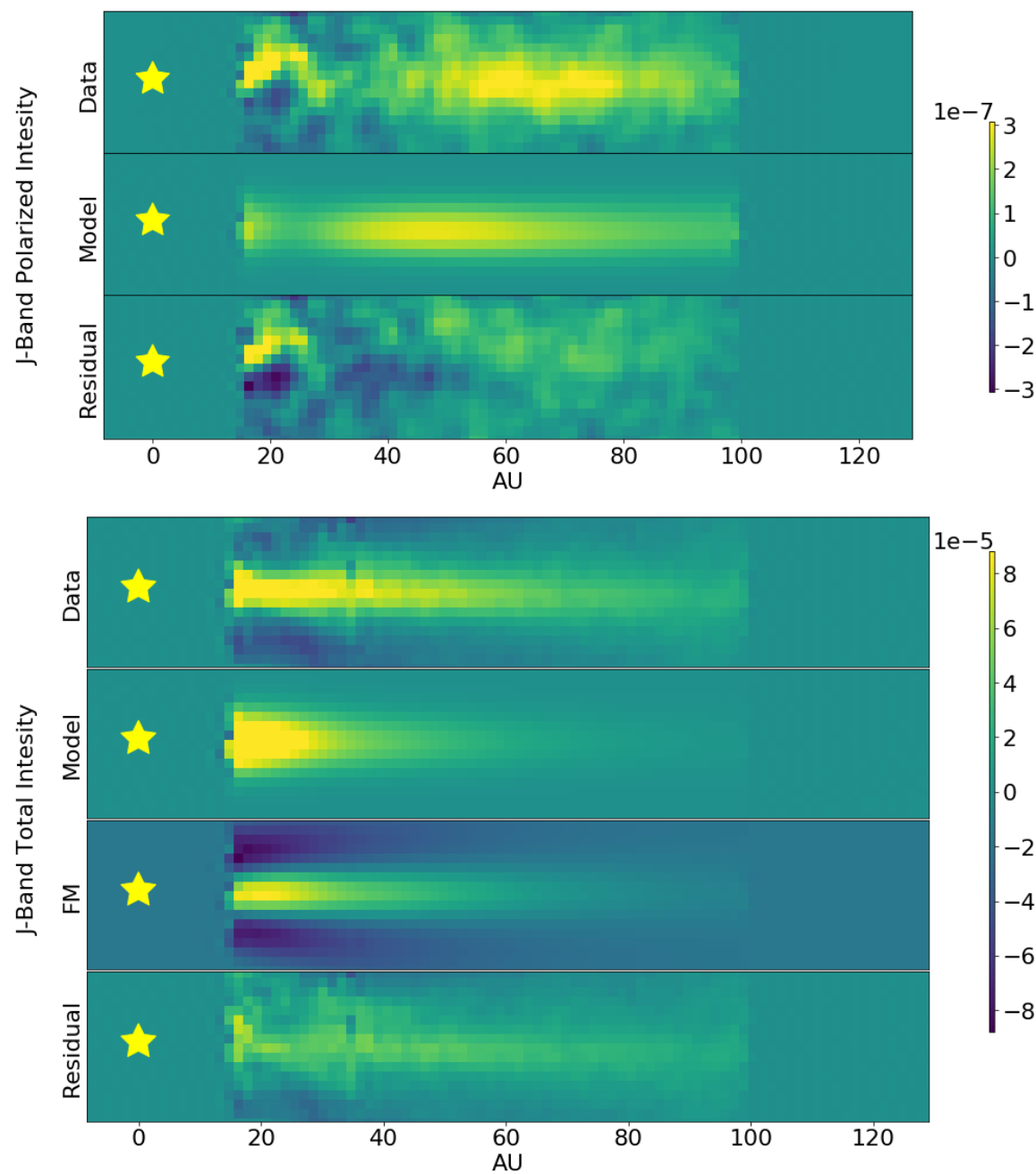


Figure 3.12 Final disk models of the Northern extension using the best-fit parameters for structure and grain properties, whilst simultaneously being constrained by the SED. The model assumes a 2:1 asymmetry in dust mass between the two extensions of the disk. The image scale is linear in units of Jy.

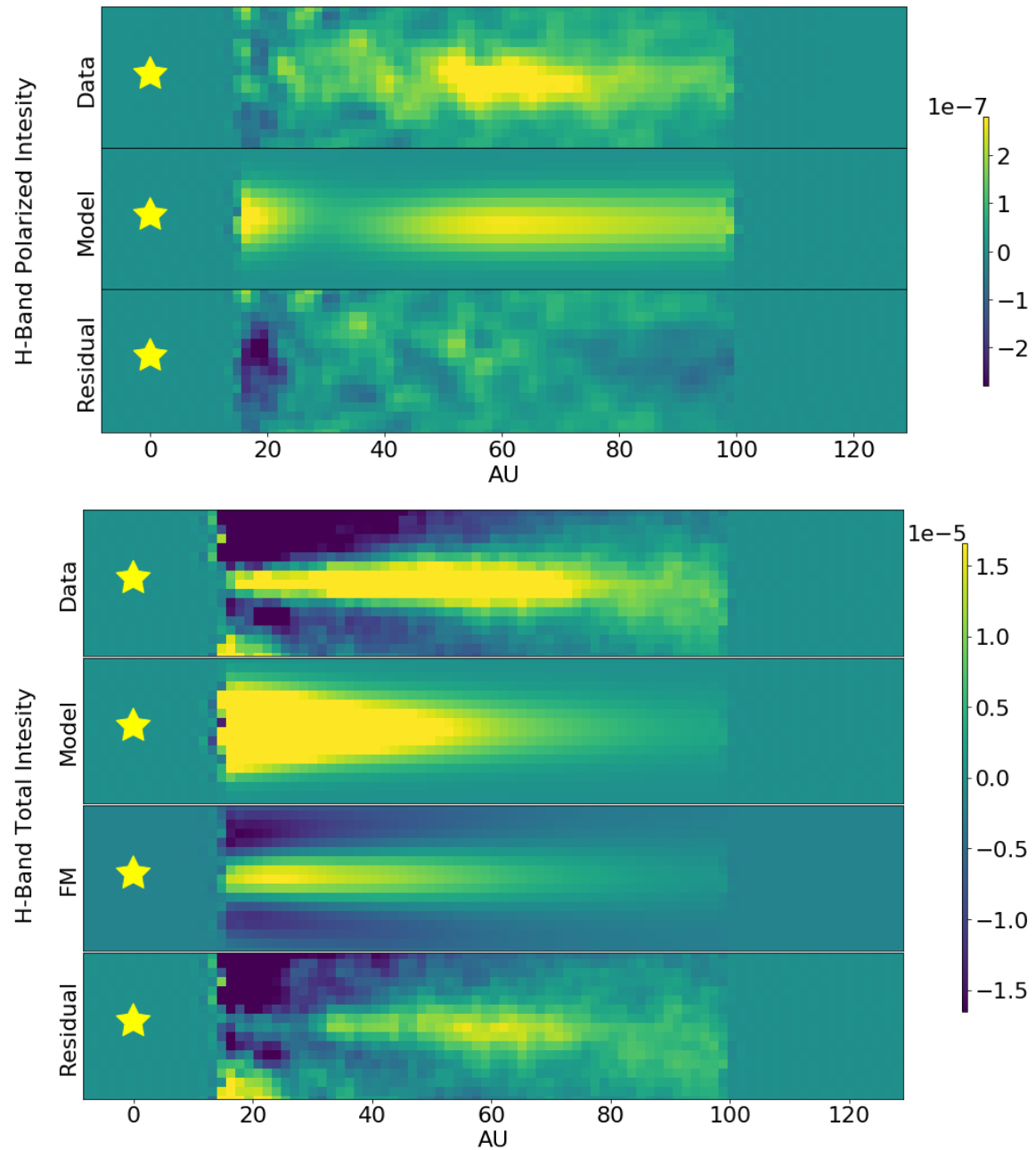
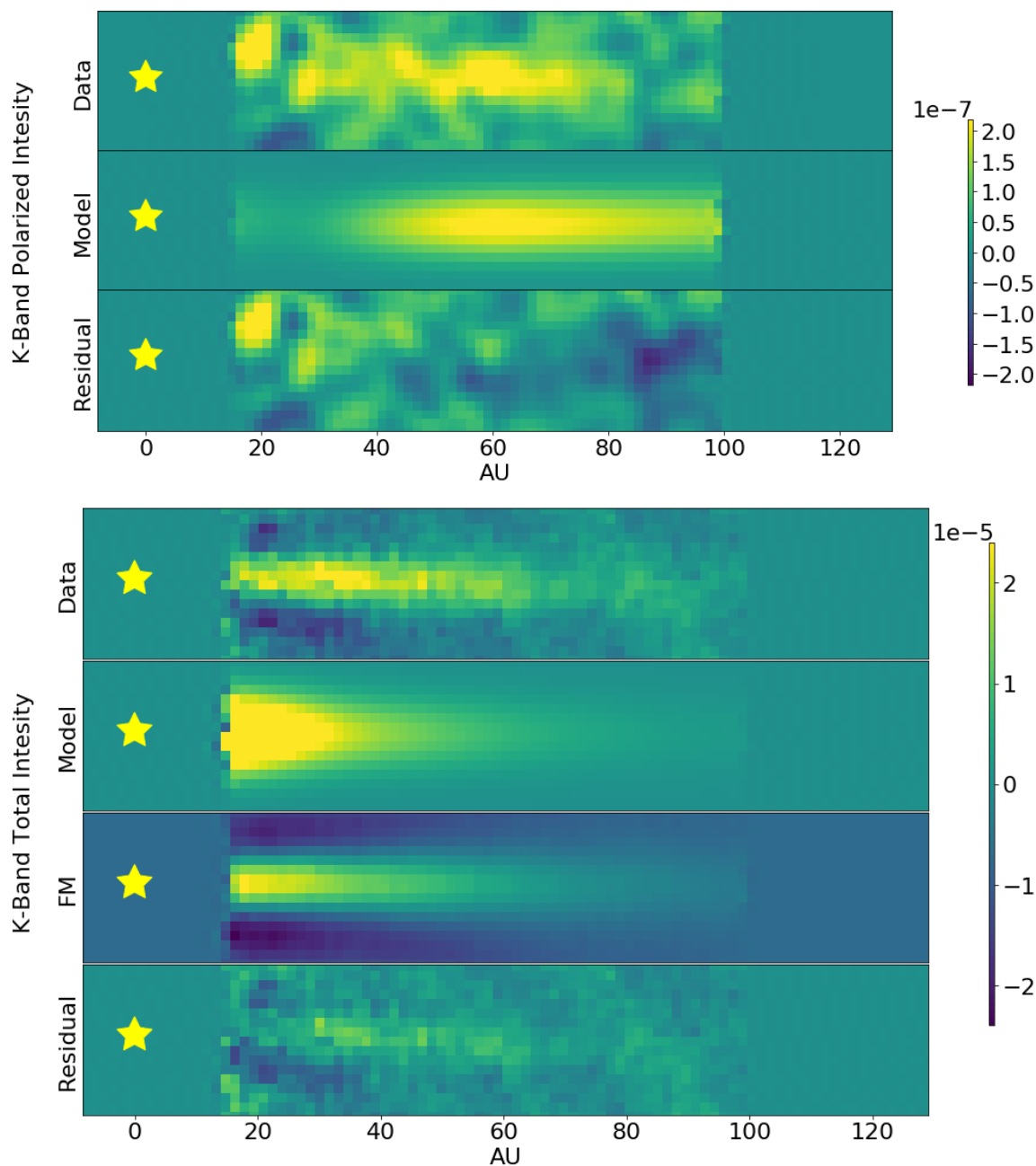


Figure 3.13 Final disk models of the Northern extension using the best-fit parameters for structure and grain properties, whilst simultaneously being constrained by the SED. The model assumes a 2:1 asymmetry in dust mass between the two extensions of the disk. The image scale is linear in units of Jy.



Chapter 4

A-type Stellar Abundances: A corollary to *Herschel* observations of debris disks.

The following is work published in Draper et al. (2018). My contribution to this work was as the lead author. I obtained the spectroscopy data for roughly half of the stars presented here and compiled the other half from archival data. I wrote a data reduction pipeline to analyze the data from scratch, which compiled other analysis tools from others when noted. All figures, text, and analysis were completed by myself with the advice of others.

In order to assess the relationship between metallicity and exoplanetary systems, we compare the abundances of AF-type main-sequence stars with debris disk properties assessed using *Herschel* observations of an unbiased survey of nearby stars. Such hot stars are not as commonly observed, given their unique constraints in data reduction, lack of metal lines, and ‘astrophysical noise’ from rotation speed. Here, we address that deficiency using new and archival spectra of 83 AF-type stars. We measure the abundances of a few species in addition to Fe in order to classify the stars with Ap/Am or Lambda Boo signatures. Lambda Boo stars have a chemical signature of solar-abundant volatile species and sub-solar refractory abundances that is hypothesized to be caused by the pollution of volatiles. Overall, we see no correlation between debris disks and metallicity, primarily because the sample size is cut significantly when using only reliable fits to the spectroscopic data. The abundance measured from the Mg II 4481 blend is a useful diagnostic because it can be reliably

measured at large $v \cdot \sin(i)$ and is found to be lower around stars with bright debris disks. We find that Lambda Boo stars have brighter debris disks compared to a bias-free sample of AF stars. The trend with disk brightness and Mg abundances suggests pollution effects can be significant and used as a marker for the stability of planetary systems. We explore trends with other species, such as with the C/O ratios, but are significantly limited by the low number of reliable detections.

4.1 Introduction

A fundamental parameter to explore in the construction and evolution of exoplanetary environments is metallicity. There is evidence for the early, rapid growth of gas giants in systems with super-solar metallicity, as seen in both radial velocity (Fischer & Valenti, 2005) and transit surveys (Buchhave et al., 2014). The metallicity trend for terrestrial mass planets is less apparent, but has its proponents (Zhu et al., 2016). Because debris disks coexist with planets within the circumstellar environment, it would logically follow that metallicity should have some impact on their brightness and evolution. However, comparative metallicity studies with IR-excesses levels reveal no correlation in solar-type stars (Maldonado et al., 2012). Gáspár et al. (2016) have claimed that there is a deficit of debris disks at sub-solar metallicity when accounting for the dust mass, given the disk’s age and flux. This result, however, assumes a steady-state model and ignores the effect of stochastic processes, which can play a role in the evolution of debris disks. Even when considering a variation in metallicity beyond just iron abundance, there is no significant correlation, although there is tentative evidence for the slope of refractory metals versus condensation temperature to be linked to the presence of planets (Maldonado et al., 2015). It is important to look beyond just iron, because within an exoplanetary environment there will be a variation in condensation temperatures. Some elements will be in the gas state, available to be accreted, rather than locked onto dust grains, which can be blown out by radiation pressure. These processes become even more important when the central star has a shallow convection layer, such as in AF-type stars, which allow for accretion effects to build on the surface.

Often, abundances versus planetary environment observations are limited to FGK (solar-type) stars. In the case of radial velocity surveys, the number of available lines and narrow widths produces a bias against detecting planets around hot stars, making trends with metallicity hard to measure. The best measurements thus far

use evolved giants, which were once main-sequence A-type stars, and infer a similar trend to that seen for FGK stars (Niedzielski et al., 2016; Zieliński et al., 2012). However, chemical evolution of the post-main-sequence giants may have changed the stellar metallicity relative to the natal environment in which the planets formed. Abundances for main-sequence A-type stars are problematic in and of themselves, given various effects on their spectrum including, line blending/broadening, fewer absorption lines, and continuum offsets from Stark-broadened Balmer lines, all by virtue of their temperature, surface gravity, and rotation. Furthermore, their lines can be impacted by non-local thermal equilibrium (NLTE) effects, which can result in derived abundances that vary depending on which line is used, by upwards of ~ 1 dex (Takeda, 1997).

In this study, we take predominately A-type stars from the DEBRIS *Herschel* Survey and measure their abundances for several species and compare to see if any correlations between chemical abundances and disk properties (e.g brightness) exist. Some common spectral analysis techniques are poorly suited for hot stars. Equivalent width analysis will often encounter problems with broad, blended metal lines. Data-driven methods would struggle to have an adequate training set to train the analysis, as A-stars are typically ignored due to their unique challenges. Given the unique challenges with reducing hot star spectra, we develop a pipeline to systematically analyze both the stellar parameters and synthesize absorption lines of the entire dataset. This greatly enhances the ability to track systematic errors.

In Section 4.2, we outline the optical spectra used in the abundance analysis and the multiwavelength photometry used to characterize the debris disks. Section 4.3 discusses the analysis of the spectra and disk properties. A more detailed discussion of methodology used in the spectral pipeline is included in the Appendix. Finally, in Section 4.4, the spectral abundances are discussed relative to the debris disk observations.

Table 4.1: Summary of the spectroscopic data used in this study. The data were taken either from a PI program at McDonald Observatory using the 2D coude’ Robert Tull spectrograph or from archival European Southern Observatory spectra at several telescopes. ARCFILE keyword names for the ESO data have been listed.

HD	HR	Instrument	Obs. Date	Archive Filename
HD 110411	HR 4828	FEROS	2009-06-04	ADP.2016-09-23T09:05:28.563
HD 16555	HR 778	FEROS	2008-11-13	ADP.2016-09-23T06:51:13.288
HD 16970	HR 804	FEROS	2004-11-23	ADP.2016-09-21T06:44:02.167

HD 19107	HR 925	FEROS	2008-11-13	ADP.2016-09-23T06:51:13.298
HD 197157	HR 7920	FEROS	2015-07-06	ADP.2016-09-28T06:54:53.157
HD 210418	HR 8450	FEROS	2009-06-03	ADP.2016-09-23T09:05:28.479
HD 222345	HR 8968	FEROS	2008-11-12	ADP.2016-09-23T06:51:12.945
HD 222603	HR 8984	FEROS	2008-11-12	ADP.2016-09-23T06:51:12.955
HD 223352	HR 9016	FEROS	2009-06-03	ADP.2016-09-23T09:05:28.491
HD 2262	HR 100	FEROS	2015-07-01	ADP.2016-09-28T06:54:52.364
HD 105452	HR 4623	UVES	2006-01-16	ADP.2013-09-26T16:43:43.707
...	...	...	2006-01-16	ADP.2013-09-26T16:43:43.727
...	...	...	2004-03-26	ADP.2013-09-26T05:20:08.217
...	...	...	2006-01-16	ADP.2013-09-26T16:43:43.660
HD 109536	HR 4794	HARPS	2009-04-21	ADP.2014-09-23T11:05:00.440
HD 109787	HR 4802	UVES	2011-05-21	ADP.2013-09-28T04:42:26.883
...	...	...	2011-05-21	ADP.2013-09-28T04:42:26.243
HD 11171	HR 531	UVES	2001-11-22	ADP.2013-09-25T06:07:14.723
...	...	...	2001-11-22	ADP.2013-09-25T06:07:14.770
...	...	...	2001-11-22	ADP.2013-09-25T06:07:15.037
...	...	...	2001-11-22	ADP.2013-09-25T06:07:14.823
HD 118098	HR 5107	HARPS	2006-05-25	ADP.2014-09-16T11:04:46.913
HD 119756	HR 5168	UVES	2004-03-25	ADP.2013-09-26T05:18:23.410
...	...	...	2004-03-25	ADP.2013-09-26T05:18:23.370
HD 120136	HR 5185	UVES	2004-04-01	ADP.2013-09-26T05:32:21.853
...	...	...	2004-03-29	ADP.2013-09-26T05:27:02.840
HD 130109	HR 5511	FEROS	2012-05-20	ADP.2016-09-27T07:02:46.276
HD 15008	HR 705	HARPS	2004-09-30	ADP.2014-10-01T10:23:01.147
HD 172555	HR 7012	FEROS	2016-03-29	ADP.2016-09-28T11:26:16.365
HD 187642	HR 7557	UVES	2002-09-30	ADP.2013-09-25T19:04:50.557
...	...	...	2002-09-30	ADP.2013-09-25T19:04:50.523
...	...	...	2002-09-30	ADP.2013-09-25T19:04:51.287
HD 188228	HR 7590	FEROS	2016-03-28	ADP.2016-09-28T11:26:17.546
HD 18978	HR 919	HARPS		
HD 202730	HR 8140	HARPS	2006-05-19	ADP.2014-09-16T11:04:29.547
HD 210049	HR 8431	UVES	2009-09-17	ADP.2013-09-27T21:14:15.353
...	...	...	2009-09-17	ADP.2013-09-27T21:14:15.293
...	...	...	2010-06-16	ADP.2013-09-28T00:10:00.877

HD 212728	HR 8547	HARPS	2007-12-06	ADP.2014-09-17T11:22:12.560
HD 213398	HR 8576	HARPS	2007-12-06	ADP.2014-09-17T11:24:46.150
HD 215789	HR 8675	UVES	2009-08-17	ADP.2013-12-06T16:44:36.067
HD 29875	HR 1502	HARPS	2004-09-30	ADP.2014-10-01T10:19:08.070
HD 55892	HR 2740	UVES	2001-11-21	ADP.2013-09-25T06:02:47.413
...	...	...	2001-11-21	ADP.2013-09-25T06:02:47.380
...	...	...	2001-11-21	ADP.2013-09-25T06:02:47.553
...	...	...	2001-11-21	ADP.2013-09-25T06:02:47.327
HD 71155	HR 3314	HARPS	2007-01-01	ADP.2014-09-17T11:22:52.083
HD 88955	HR 4023	HARPS	2006-02-09	ADP.2014-09-16T11:04:44.387
HD 99211	HR 4405	HARPS	2006-02-13	ADP.2014-09-16T11:06:20.390
HD 137898	HR 5746	FEROS	2010-03-01	ADP.2016-09-23T12:25:53.302
HD 110379	...	UVES	2011-04-08	ADP.2013-09-28T04:09:42.250
...	...	...	2011-04-0	ADP.2013-09-28T04:09:42.300
...	...	...	2011-04-0	ADP.2013-09-28T04:09:42.287
...	...	...	2011-04-0	ADP.2013-09-28T04:09:42.277
HD 115892	HR 5028	FEROS	2005-05-27	ADP.2016-09-21T08:16:13.629
HD 56537	HR 2763	McD. Tull	2014-04-24	N/A
HD 58946	HR 2852	McD. Tull	2014-04-22	N/A
HD 60178	HR 2890	McD. Tull	2014-04-22	N/A
HD 60179	HR 2891	McD. Tull	2014-04-22	N/A
HD 76644	HR 3569	McD. Tull	2014-04-23	N/A
HD 78209	HR 3619	McD. Tull	2014-04-22	N/A
HD 79439	HR 3662	McD. Tull	2014-04-22	N/A
HD 80081	HR 3690	McD. Tull	2014-04-22	N/A
HD 85376	HR 3900	McD. Tull	2014-04-22	N/A
HD 87696	HR 3974	McD. Tull	2014-04-22	N/A
HD 89021	HR 4033	McD. Tull	2014-04-23	N/A
HD 91312	HR 4132	McD. Tull	2014-04-23	N/A
HD 95418	HR 4295	McD. Tull	2014-04-23	N/A
HD 95608	HR 4300	McD. Tull	2014-04-23	N/A
HD 97603	HR 4357	McD. Tull	2014-04-24	N/A
HD 102124	HR 4515	McD. Tull	2014-04-24	N/A
HD 102647	HR 4534	McD. Tull	2014-04-24	N/A
HD 103287	HR 4554	McD. Tull	2014-04-23	N/A

HD 104513	HR 4594	McD. Tull	2014-04-23	N/A
HD 106591	HR 4660	McD. Tull	2014-04-23	N/A
HD 110379	HR 4825	McD. Tull	2014-04-24	N/A
HD 110380	HR 4826	McD. Tull	2014-04-24	N/A
HD 112412	HR 4914	McD. Tull	2014-04-23	N/A
HD 112413	HR 4915	McD. Tull	2014-04-23	N/A
HD 116656	HR 5054	McD. Tull	2014-04-22	N/A
HD 116657	HR 5055	McD. Tull	2014-04-22	N/A
HD 125161	HR 5350	McD. Tull	2014-04-22	N/A
HD 125162	HR 5351	McD. Tull	2014-04-22	N/A
HD 128167	HR 5447	McD. Tull	2014-04-24	N/A
HD 137909	HR 5747	McD. Tull	2014-04-24	N/A
HD 139006	HR 5793	McD. Tull	2014-04-22	N/A
HD 140436	HR 5849	McD. Tull	2014-04-22	N/A
HD 141795	HR 5892	McD. Tull	2014-04-22	N/A
HD 156164	HR 6410	McD. Tull	2014-04-22	N/A
HD 159541	HR 6554	McD. Tull	2014-04-22	N/A
HD 159560	HR 6555	McD. Tull	2014-04-22	N/A
HD 165777	HR 6771	McD. Tull	2014-04-23	N/A
HD 172167	HR 7001	McD. Tull	2014-04-24	N/A
HD 177196	HR 7215	McD. Tull	2014-04-22	N/A
HD 180777	HR 7312	McD. Tull	2014-04-24	N/A
HD 184006	HR 7420	McD. Tull	2014-04-23	N/A
HD 61421	HR 2943	UVES	2002-02-27	ADP.2013-09-25T11:23:49.730
...	...	...	2002-02-27	ADP.2013-09-25T11:23:50.063
...	...	...	2002-02-27	ADP.2013-09-25T11:23:49.750

4.2 Data

The initial sample of stars in the survey were selected from the A- to F-type stars in the DEBRIS survey (Thureau et al. (2014); Sibthorpe et al. (2018)). The motivation of this selection was to sample the A0-F3 spectral range for which the Lambda Boo phenomenon is observed (Paunzen, 2004). We extended the spectral range a bit farther into the F-type regime to allow for more survey overlap with previous studies,

for verification of data reduction practices. The DEBRIS Survey only targeted main-sequence stars based on their proximity to the zero age main-sequence (ZAMS) in order to exclude giants (Phillips et al., 2010). The age estimates for these stars are distributed fairly evenly between 10 Myr and 1 Gyr (Vican, 2012). A summary of the 83 stellar spectra compiled for this study can be seen in Table 4.2.

4.2.1 McDonald

Stars within the sample that are in the northern hemisphere were observed over three nights at the McDonald Observatory. The 2.7 meter Harlan J. Smith telescope, with its Robert Tull Coudé 2D cross-dispersed echelle spectrograph was used to obtain $R \sim 60,000$ spectra from 3800-9000 Å (Tull et al., 1995). Basic CCD data reduction techniques were followed using standard IRAF practices for an echelle spectrograph. This process was automated using PyRAF¹ to subtract dark frames, divide by flats, and extract flux from each echelle order. Wavelength calibration used ThAr lamps, which were identified against a reference ThAr lamp spectrum using a python GUI (see the appendices for more details).

4.2.2 ESO Archive

Spectra for stars in the southern hemisphere were collected from the ESO archive. Various facilities and instruments were used, such as UVES (Dekker et al., 2000), FEROS (Kaufer et al., 1999), and HARPS (Mayor et al., 2003). These data are already processed into flux-normalized and wavelength calibrated, phase 3 products. UVES data, which were in separate wavelength channels, are combined into a continuous 1D spectra to be consistent with the other data products. The pipeline was designed to minimize human intervention and handle 1D spectra independent of the instrument used.

4.2.3 DEBRIS Survey

In order to categorically identify stars with and without debris disk detections in an unbiased way, we utilized the DEBRIS survey conducted with the *Herschel Space Observatory*. The survey used PACS 100 and 160 μm observations, ideal for detecting

¹PyRAF is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.

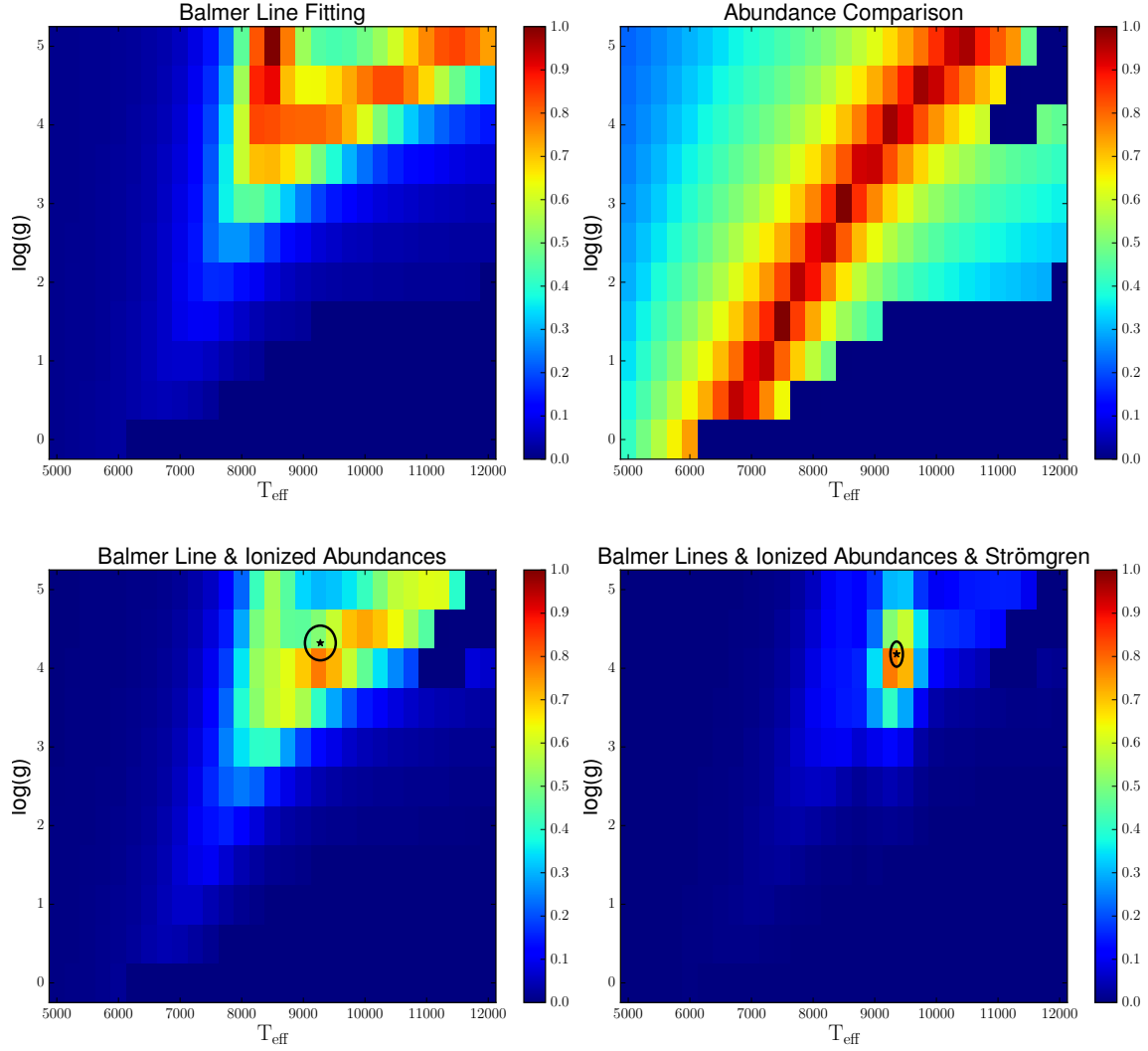


Figure 4.1 Correlation matrices for models over a range of parameter space, using different diagnostics on the spectrum of Vega. Matrices are normalized by the maximum overall correlation to the data, where blue is a low correlated model near zero and red is a high correlation near 1. On top, Balmer line fitting and matching species of two ionization states (e.g., Fe I = Fe II) are shown. In the bottom left panel, the Balmer line and abundance comparison diagnostics are combined. Given that a broad spread in correlation persists, Strömgren photometry is used to isolate a specific temperature in the bottom right figure.

debris disks in the temperature range of cold Kuiper Belt analogs (Wyatt, 2008). The DEBRIS sample is volume-limited and therefore unbiased in disk brightness or specifically their $[\text{Fe}/\text{H}]^2$ (Phillips et al., 2010). We therefore constrain the spectral comparison to this ideal subset of hot stars from 6700 to 10,000 K to assess the correlation of debris disks to stellar metallicity. The stellar temperature cut in the sample was based on stellar effective temperature SED fits to broadband photometry short of $10\ \mu\text{m}$.

4.3 Analysis

Throughout this study we tested and experimented with systematic choices in the data reduction. All of the steps described here were implemented into a series of custom Python routines. This provided the framework for using other specialized programs such as MOOG (Snedden, 1973) and Balmer9 (Sbordone et al., 2004; Kurucz, 1993) to generate specific solutions. Furthermore, these routines automated reduction into a pipeline to test the entire sample quickly and efficiently so as to determine the best ways to systematically approach the data reduction rather than a specialized reduction of every target³.

4.3.1 Fundamental Stellar Parameters

In order to derive spectral abundances, we first sought to constrain the stellar effective temperature and $\log(g)$. To do this, several techniques were employed (see Figure 4.1). Given our spectral range of predominantly hot A-type stars, we choose to use the Balmer line profiles and match derived abundances of ionization species ($\text{Fe I} = \text{Fe II}$, $\text{Mg I} = \text{Mg II}$). For this analysis, we used a broad range of Kurucz ATLAS9 models over the expected range from 5000 K to 12,000 K and 5 to 0 $\log(g)$ (Kurucz, 1993). The grid size was in steps of 250 K and 0.5 $\log(g)$ which is sufficient to achieve 0.1 dex precision for the abundances, given the errors in those stellar parameters alone (See Section 4.3.2).

²The selection bias of stars near the sun does have some effect in making most stars have a solar-like metallicity.

³code to be made available on GitHub

Balmer Lines

The Balmer lines are sensitive to both surface gravity and temperature in AF-type stars. They are often strongly Stark-broadened due to an electric field from nearby free electrons and protons on the surface of these hot stars. With proper modeling, the profile along the broadened wings of the line can be a sensitive diagnostic of the stellar parameters. Balmer9 computes the Balmer line profiles for H β , H δ , and H γ (See Figure 4.2). Each spectrum had hydrogen lines selected and then shifted in wavelength to rest frequencies through a process of binning and minimum finding. This was essential in terms of batch-processing the spectral data in order to correct for any residual radial velocity offsets from the Earth’s motion or CCD data reduction. A residual matrix was created by taking the sum of residuals between the models and data. The inverse was taken to make larger values mean higher correlation and then normalized by the maximum value. The wings of the profile were specifically selected by excluding the core of the line around 1Å to either side of the line center. An example of this residual matrix can be seen in the top left panel of Figure 4.1.

Table 4.2: Derived spectroscopic stellar parameters for stars in this survey. Literature classifications have also been listed from Renson & Manfroid (2009) (Am/Ap catalogue), Murphy et al. (2015) (Lambda Boo catalog), and Pourbaix et al. (2004) (spectroscopic binaries (SB) catalog)

HD	HR	Temp.	logg	$v \cdot \sin(i)$	AmAp	Lam Boo	SB
HD 110411	HR 4828	8812	4.2	160	...	member	...
HD 16555	HR 778	8449	4.6	...	...	...	...
HD 16970	HR 804	8603	4.1	166	...	...	...
HD 19107	HR 925	8217	4.1	166	...	...	...
HD 197157	HR 7920	8326	4.4	91	doubtful nature	...	...
HD 210418	HR 8450	9008	4.2	146	...	non-member	...
HD 222345	HR 8968	8326	4.4	75	...	...	...
HD 222603	HR 8984	8217	4.1	49	...	...	...
HD 223352	HR 9016	9345	4.4	300	...	probable	...
HD 2262	HR 100	8217	4.1	198	...	...	...
HD 105452	HR 4623	7209	2.9	29	...	...	...
HD 109536	HR 4794	7905	3.8	80	doubtful nature	...	...
HD 109787	HR 4802	8900	4.2	197	...	...	...
HD 11171	HR 531	7215	2.9	65	...	...	...
HD 118098	HR 5107	8468	4.1	150	...	...	...
HD 119756	HR 5168	6914	2.9	...	...	...	...
HD 120136	HR 5185	6466	2.4	...	...	...	...

HD 130109	HR 5511	9008	4.2	300	doubtful nature	...	...
HD 15008	HR 705	9078	4.4	172	...	...	...
HD 172555	HR 7012	8094	4.1	115	...	...	...
HD 187642	HR 7557	5000	0.0	...	...	...	...
HD 188228	HR 7590	9393	4.5	92	...	...	...
HD 18978	HR 919	8440	4.1	124	doubtful nature	...	...
HD 202730	HR 8140	8305	4.1	104	misidentified	...	...
HD 210049	HR 8431	9147	3.5	...	...	...	...
HD 212728	HR 8547	7942	3.8	220	...	...	...
HD 213398	HR 8576	9599	4.3	180	...	...	...
HD 215789	HR 8675	5000	0.0	...	...	...	...
HD 29875	HR 1502	7198	3.4	56	doubtful nature	...	...
HD 32297	...	8194	4.6	84	...	...	...
HD 55892	HR 2740	5000	0.0	...	misidentified	...	...
HD 71155	HR 3314	9537	4.3	144	...	...	...
HD 88955	HR 4023	9098	4.3	90	...	...	...
HD 99211	HR 4405	7986	3.9	127	...	...	...
HD 137898	HR 5746	8326	4.4	112	...	...	...
HD 110379J	...	7504	3.1	25	doubtful nature	...	...
HD 115892	HR 5028	9160	4.3	79	...	...	...
HD 56537	HR 2763	8680	4.1	161	...	...	...
HD 58946	HR 2852	7163	2.8	72	doubtful nature	...	...
HD 60178	HR 2890	9157	5.0	22	...	...	...
HD 60179	HR 2891	9473	4.9	17	...	...	binary
HD 76644	HR 3569	8242	3.7	138	...	...	...
HD 78209	HR 3619	7733	3.5	40	...	...	...
HD 79439	HR 3662	8155	4.0	174	doubtful nature	...	...
HD 80081	HR 3690	8629	4.2	382	...	non-member	...
HD 85376	HR 3900	7741	3.8	110	...	...	...
HD 87696	HR 3974	8198	4.0	129	...	non-member	...
HD 89021	HR 4033	9082	4.3	51	doubtful nature	...	...
HD 91312	HR 4132	7999	4.0	119	...	...	...
HD 95418	HR 4295	9448	4.3	38	...	...	...
HD 95608	HR 4300	9088	4.4	17	...	...	...
HD 97603	HR 4357	8428	4.2	178	...	...	...
HD 102124	HR 4515	8234	4.1	150	...	...	...
HD 102647	HR 4534	8881	4.4	130	...	...	...
HD 103287	HR 4554	9308	4.3	168	...	...	...
HD 104513	HR 4594	7514	3.5	71	...	...	...
HD 106591	HR 4660	8860	4.3	370	...	...	...
HD 110379	HR 4825	7429	3.7	33	...	...	...
HD 110380	HR 4826	7445	3.2	72	...	...	...

HD 112412	HR 4914	7184	3.7	32	doubtful nature	...	...
HD 112413	HR 4915	7334	3.1	30	AP star	...	...
HD 116656	HR 5054	8526	3.9	...	doubtful nature	...	binary
HD 116657	HR 5055	8482	4.2	53	...	...	...
HD 125161	HR 5350	7990	3.4	132	...	...	...
HD 125162	HR 5351	8883	4.4	120	...	member	...
HD 128167	HR 5447	6931	3.7	15	...	non-member	...
HD 137909	HR 5747	8084	3.9	23	...	...	...
HD 139006	HR 5793	9303	4.2	120	...	...	...
HD 140436	HR 5849	8982	4.6	100	...	...	...
HD 141795	HR 5892	8530	3.9	25	...	...	...
HD 156164	HR 6410	8673	4.0	250	...	...	...
HD 159541	HR 6554	7517	3.2	69	...	...	...
HD 159560	HR 6555	7488	3.3	47	...	...	...
HD 165777	HR 6771	8647	4.3	56	doubtful nature	...	...
HD 172167	HR 7001	9296	4.4	15	...	probable	...
HD 177196	HR 7215	8194	4.1	125	...	...	...
HD 180777	HR 7312	7544	4.4	55	...	...	...
HD 184006	HR 7420	8385	3.6	250	...	...	...
HD 61421	HR 2943	7008	2.9	...	...	...	...

Ionization Abundance Matching

Another diagnostic that is sensitive to effective temperature and surface gravity is the balance between abundances derived from species in different ionization states. Here, we used Fe and Mg lines because they have the greatest number of lines for single-ionized and double-ionized species. A small line list was used that had lines with high to moderate equivalent widths, and that were often in isolation from other lines (see Appendix A.4). Each line was found and fit with a Gaussian profile to identify the line. The equivalent width was measured from the data and passed into MOOG *abfind* in order to compute the abundances. Every model in our range of parameters was then used to derive an abundance value for each ionization state. A residual matrix was made using the inverse square of the differences, such that small differences in the derived abundances were highly correlated to the input model. The matrix was again normalized by its maximum value to ensure that the matched ionization abundance would have an equal weight as the Balmer line method. An example of a residual matrix from this method with data from Vega can be seen in the top right panel of

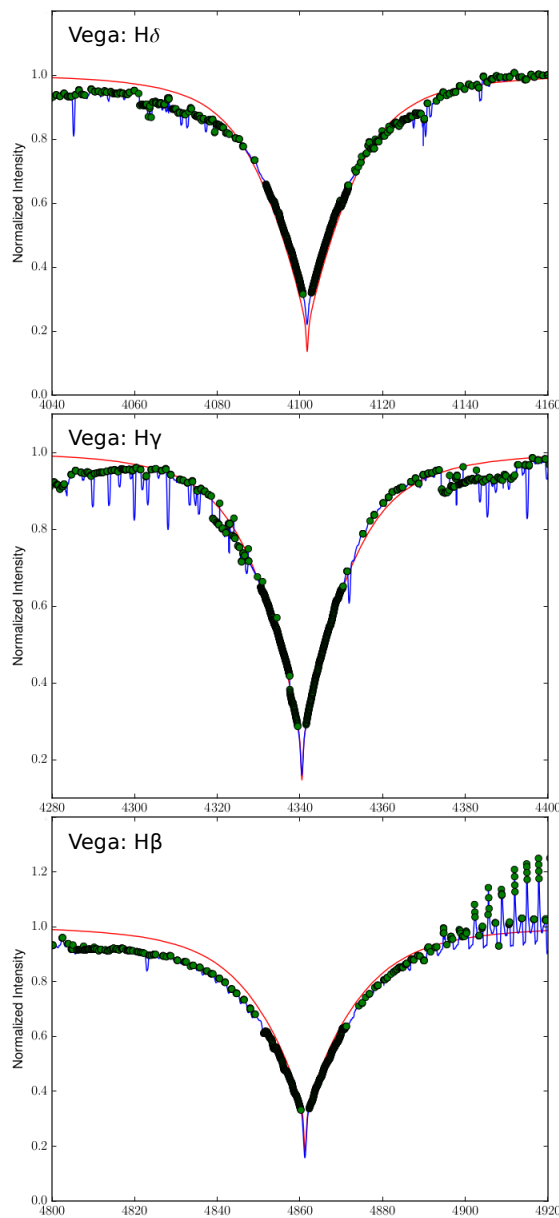


Figure 4.2 A python wrapper routine was developed to call Balmer9 in order to generate Balmer line models. Above are the Balmer line profiles for Vega, after the best-fit model was selected after the combination of various methods of stellar parameterization. They do not represent the best Balmer line chisqr fit. The data are in blue while the model are in red. The green points are the data points selected for chisqr fitting based on the local derivative and proximity to the line core. A derivative selection isolates the continuum from trace metal lines. The central core 1 Å core of the lines is ignored and the 10 Å to either side of the lines are included. Spurious emission features near H_{β} are unfortunately still selected, but have a lower weight compared to most data points used in the fit. It can also be seen that continuum normalization can still be imperfect and discontinuities exist from merging Echelle orders. This is why using multiple methods can help reduce artifacts from one particular method, in order to seek the most likely model.

Figure 4.1.

Photometric Methods

Combining the two previous diagnostics would often leave A-type stars still marginally uncertain (see Figure 4.1, bottom left), therefore we investigated photometric methods to determine the effective temperature and in turn the corresponding surface gravity. When spectra are continuum-normalized, the relative flux per wavelength is lost, and therefore using a photometric technique offers ancillary information to the previous methods.

One way to constrain the effective temperature is to fit a broad UV-to-mid-IR model SED with archival photometry for each of the stars. (see Section 4.3.6). This method was also compared with the Strömgren method whereby narrowband photometry is compared against synthetic photometry of models to derive effective temperature and $\log(g)$ (Moon & Dworetzky, 1985; Napiwotzki et al., 1993). The most degenerate parameter remaining after the two previous methods are applied is surface temperature, which is simply derived from the (b-y) color. It was found that there is a 1σ dispersion offset between the Strömgren and SED effective temperature of ~ 150 K (see Appendix A.3). The offset appears to have effect on A-type stars and not F-type stars, with a transition around 7000 K. The Strömgren method was selected over the SED method for two reasons. First, the Strömgren photometry more closely matched Vega’s derived temperature which we adopted as a standard star⁴. Second, since the Strömgren method is strongly related to where the absorption lines are being created in the stellar atmospheres, the derived temperature may be more closely related to the effective temperature in the line of sight where abundances are measured.

4.3.2 Abundances

In order to compute the abundances, a broad line list was used based on the Takeda et al. (2007) atlas of Vega (see Appendix A.4). Given the broad range of spectral types, lines were included because of their proximity to lines of interest, as they would have more significant absorption at lower temperatures. For example, Mg II 4481 lines

⁴Vega’s stellar parameters were adopted from Castelli & Kurucz (1994) to be $T_{\text{eff}}=9550$ K, $\log(g)=3.95$. The surface temperature varies by ~ 2000 K due to rapid rotation, making a single effective surface temperature problematic, and is rather the temperature along the given line of sight. (Yoon et al., 2010; Monnier et al., 2012)

can become blended with Fe I 4482 lines at temperatures less than ~ 8500 K while being undetectable at temperatures above ~ 8500 K.

For each line, a sub region spanning $10 \text{ \AA}$ was selected. Each region was then synthesized using MOOG *synth*. In order to compare a model spectrum to an observed spectrum in a reliable way, the data must be precisely calibrated to a flat continuum and shifted to the exact rest wavelength. To ensure both of these criteria are met systematically and reliably across numerous lines and stars, many methods were tested. The best method to flatten the continuum was to use a calculus derivative method to determine which parts of the spectrum are part of an absorption line and which are part of the continuum. To precisely shift the spectrum, a 1D cross-residual is made with a solar abundance model to align the absorption features. More details on the specifics of these methods can be seen in Appendices A.1 and A.2.

Each line was presorted based on whether or not it had a neighboring line within $4 \text{ \AA}$. In cases where lines were sufficiently isolated, the $v \cdot \sin(i)$ was allowed to vary. This is because the depth of the line will vary with the abundance, while the width of the line will vary predominantly with $v \cdot \sin(i)$; however both parameters can be degenerate. In cases where multiple species were blended nearby, $v \cdot \sin(i)$ becomes too covariant with the elemental abundances. Therefore, using regions of single-element fits allowed the $v \cdot \sin(i)$ of each star to be measured reliably, to fix $v \cdot \sin(i)$ for blended lines with multiple elements (see Figure 4.3). In particular, Mg I 5183, Ti II 4468, Ti II 4501, Si II 6347, and Si II 6371 were isolated from blends and strong enough across the range of stellar temperatures to be trusted to derive $v \cdot \sin(i)$ reliably. Si II 6347 does have a blend with Mg II that can make an abundance measurement difficult, but the line itself appears as one line. Mg II 4481 was also useful for this in the constraint of A-type stars, because at the relevant temperatures it does not blend with Fe I 4482. Mg and Fe abundances are then coupled to the same metallicity to improve minimization fitting and measurement of the $v \cdot \sin(i)$. It should also be noted that imposing boundary conditions of 0 to 300 km s^{-1} and -2 to 2 dex in abundances becomes necessary to reduce minimization time and provide realistic fits.

Errors in abundances due to uncertainties in either effective temperature or $\log(g)$ were measured by repeating the spectrum synthesis and fitting with models of the nearest offset in the model grid. These errors were on the order of ~ 0.1 dex (See Table A.4) and would be less significant than systematic errors stemming from continuum normalization or wavelength offsets from automation. To represent this in the derived abundances error, the residual sum of squares (RSS) for the synthetic fit was added

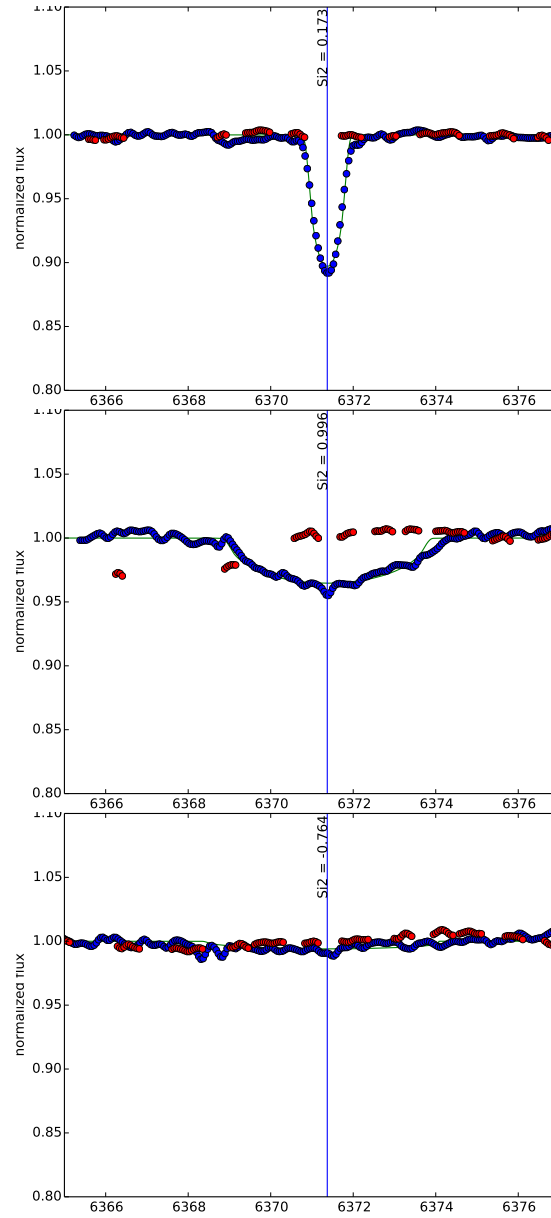


Figure 4.3 Synthetic model fits to Si 6371 for stars of different $v \cdot \sin(i)$. From top to bottom: HR 7001 (Vega) at 22 km s^{-1} , and HR4534 at 111 km s^{-1} , and HR 6410 at what the code determined was 144 km s^{-1} (although this is likely a lower limit). As $v \cdot \sin(i)$ approaches 125 km s^{-1} the ability to measure $v \cdot \sin(i)$ significantly degrades (and in turn the abundances). The line center is plotted as a vertical line, with the abundance relative to the input model of -0.5 dex displayed. The red dots indicate samples of the original data before continuum and wavelength offsets were measured.

in quadrature to the error in abundance due to temperature and $\log(g)$. This represents a better estimate of the error and flag lines for which the fitting process were reasonable minimization attempts but would not result in a visually good match to the data. Specific lines were also rejected if their equivalent widths were very small ($0.05 \text{ \AA}$) or if the RSS was too large (0.01). In most cases, this results in rejection if the line is too weak due to rapid rotation, an offset wavelength, a blended line, or a combination of those factors. The final compilation of the derived abundances and stellar parameters used in this paper can be seen in Table A.4.

4.3.3 Microturbulence

Microturbulence is the turbulence in the atmosphere which is at a relatively small spatial scale from minor convective flows or shearing instabilities. Microturbulence around AF-type main-sequence stars is known to range from 1 to 5 km s^{-1} . Takeda et al. (2008a) fit the oxygen lines in 6158 and 7771, but the derived microturbulence from each synthetic line fit would often disagree. Gebran et al. (2014) conducted this analysis again on more slowly rotating A-stars in clusters and found a slightly lower distribution with a peak in average microturbulence of 3 km s^{-1} around $\sim 8000 \text{ K}$. This parameterization would be the only way to diagnose the microturbulence in rapidly rotating AF stars, since the microturbulence and $v \cdot \sin(i)$ broadening in each single line profile are degenerate. Even in these measurements, the scatter can be on order of 30%, ranging from 1 to 4 km s^{-1} in a given temperature bin (Gebran et al., 2014). Traditional methods of fitting microturbulence by flattening abundances as a function of equivalent width (because microturbulence affects stronger lines more readily than weaker lines) is not applicable when the number of lines drops significantly from rapid rotation. Therefore, the only lines consistently measured are the stronger lines, which can have significant deviations in abundances due to microturbulence. In this study, we set the microturbulence of the Kurucz models at 2 km s^{-1} . If the microturbulence is increased to 4 km s^{-1} , typical Mg II 4481 abundances can change by -0.1 to -0.3 dex. For this line in particular, the abundances will consistently be less than those derived with a lower microturbulence. This is because the change in the line profile will always result in a lower $v \cdot \sin(i)$, since a portion of the line broadening is due to the microturbulence, which in turn requires the abundance of the line to drop in order to reduce the core depth of the line. We accept these as a systematic errors that cannot be fit effectively within a single line profile. There is no reason to believe

the microturbulence is correlated with debris disk properties, even if a trend with stellar temperature exists across this spectral range, because the disk properties are not correlated with stellar temperature.

4.3.4 Limb-darkening

Another effect that can alter the line profile of metal lines is limb-darkening. Stars that rotate rapidly will become non-spherical and have their surface temperature vary dramatically from the pole to the equator. Therefore, the inclination of the system, in tandem with the rotation speed, can alter the line profile and change the derived abundance values. Yoon et al. (2008) and Takeda et al. (2008b) apply non-spherical, limb darkened models to Vega, after having a known inclination and darkening from resolved near-IR interferometry (Monnier et al., 2012). Takeda et al. (2008b) note that the result for lines which show flattened or “V” profiles have an overestimate of about 0.2 dex. For Mg II 4481, the effect due to rotation versus non-rotational models in Vega amounts to less than 0.1 dex (Yoon et al., 2008). Since the rotation and inclination are not known independently for the entire sample, we accept this as a systematic error in abundances.

4.3.5 NLTE Abundance Corrections

It is important to note that MOOG synthesizes lines under the assumption of local thermodynamic equilibrium (LTE), when in reality these stars’ atmospheres are more complex. We investigate how deviations from LTE affect the abundances relying on the NLTE calculations from the literature. We take into account deviations from LTE for the lines of the investigated species, where NLTE abundance corrections⁵ are available in the literature. For an overview of NLTE in A-stars, see Kubát & Korcáková (2004).

Oxygen

The NLTE abundance corrections for oxygen can be very large, depending on the set of lines chosen, and have appreciable variations across effective temperature (Takeda, 1997; Sitnova et al., 2013). The difference between LTE and non-LTE abundances

⁵The NLTE abundance correction, $\Delta_{\text{non-LTE}}$, is defined for individual lines as a difference between the NLTE and LTE abundance.

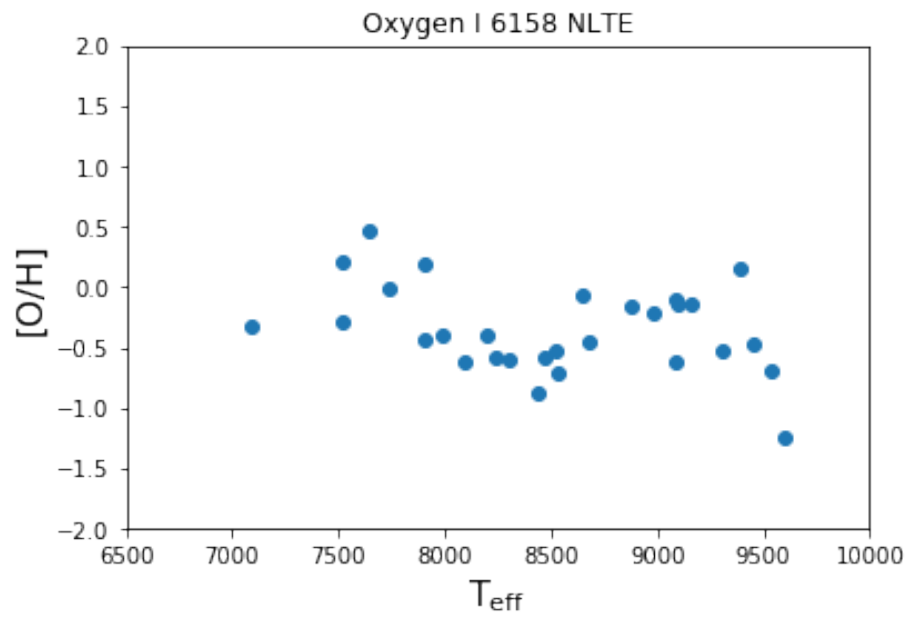


Figure 4.4 Derived oxygen abundances as a function of effective temperature. In O 6158, the NLTE correction is small relative to NLTE.

in oxygen lines increases with higher temperature and lower $\log(g)$ (Sitnova et al., 2013). For our study we use the O I 6158 blend. O I 7771 tends to significantly over predict the derived surface abundances in LTE and require NLTE corrections. We use Takeda (1997) as it has a range of corrections that are valid for our sample of stars. The results for O I 6158 as a function of effective temperature can be seen in Figure 4.4. Due to the lack of reliable fits in O I 7771 as a broad feature, we utilize O I 6158 in our analysis of oxygen.

Carbon

There are two carbon lines that were found to be of interest in this stellar spectral range, 5052 and 7113 Å. Alexeeva & Mashonkina (2015) and Alexeeva et al. (2016) note that for most G- to A-type main-sequence stars, the NLTE correction is small. For the C I 5052 Å line, the NLTE abundance correction is -0.03 dex for the Sun (Alexeeva & Mashonkina, 2015) and -0.04 dex for Vega (Alexeeva et al., 2016). The NLTE abundance correction for C I 7113 Å line is -0.06 dex for Vega (Alexeeva et al., 2016). Therefore, the corrections are nearly negligible across this spectral range and are not applied to the data.

Silicon

Wedemeyer (2001) investigated NLTE corrections for silicon, albeit not in the same temperature range. For the Sun, the NLTE correction for Si 6347 Å is -0.1 and for Si 6371 Å is -0.06. Si 5052 NLTE correction was measured for Vega and was only -0.06 dex. We do not correct any trend across our sample due to NLTE effects, though they appear to be small, on the order of -0.1 dex.

4.3.6 SED Fitting

In order to measure if a debris disk is present or not around a given star, and to what brightness, we utilize *Herschel* PACS photometry that was taken as part of DEBRIS. Photometry at 100 and 160 μm is ideally suited to measure the peak brightness of a cold component of dust typical of a Kuiper belt analog. Aperture corrections were applied as described in Balog et al. (2014) to *Herschel* photometry. In addition to *Herschel*, archival photometry from optical surveys (Hauck & Mermilliod, 1998), *Spitzer* (Su et al., 2006), 2MASS (Cutri et al., 2003b), *WISE* (Wright et al., 2010), and *Akari* (Ishihara et al., 2010) were used to construct a multiwavelength SED. From

this data, a PHOENIX Ames-COND model was fit to wavelengths less than $10\mu\text{m}$ to determine the stellar contribution. A blackbody SED was fit to the longer wavelength photometry if a 3σ IR-excess was found above the expected stellar contribution (e.g. Draper et al. (2016b); Booth et al. (2013); Kennedy & Wyatt (2014)). We utilize the fractional luminosity of the dust (or lack thereof) to compare with the spectral abundances.

4.4 Discussion

4.4.1 Oxygen

After selecting reliable abundance measurements (25/79 stars), we divide the remaining sample into stars of 11/79 with disks and 14/79 without disks. We then compare if there is any distinguishable difference between the two samples that we could infer as being a result of the debris disk's presence. For oxygen, we take the NLTE of O I 6158 abundances and compare the cumulative distributions with a KS test. As shown in Figure 4.5, there is no indication that the two samples are from a different underlying population of oxygen abundances. It should also be noted that this is likely a result of the reduced sample size because $v \cdot \sin(i)$ reduces the statistical power of the sample, rather than necessarily a fundamental agreement.

4.4.2 Lambda Boo stars

Lambda Boo stars are a type of Population I chemically peculiar star that varies from A0- to F3- type (Paunzen, 2004). This is likely due to the fact that the stars are non-convective in their outer envelopes and instead supported by radiation pressure, which allows normally second-order effects to change the surface abundances (Turcotte, 2002). Lambda Boo stars' chemical signature is that species with sublimation temperatures above ~ 1200 K (i.e. refractory) exhibit sub-solar abundances, while species with low sublimation temperatures (i.e. volatile) are solar-abundant (Paunzen, 2004; Draper et al., 2016b). Several mechanisms have been proposed, but none have been proven beyond a reasonable doubt. One subset of theories is the accretion hypothesis, whereby gas and dust differentiate near the star, such that volatile gas accretes onto the star, while refractory rich dust gets blown out from the system by radiation pressure (Venn & Lambert, 1990; Turcotte & Charbonneau, 1993; Draper

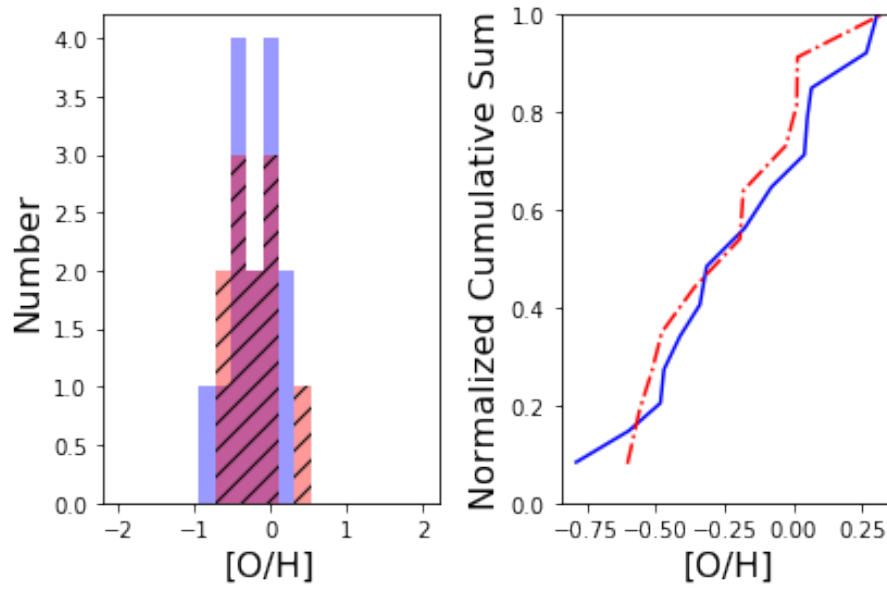


Figure 4.5 Histograms and cumulative distributions of elemental abundances comparing stars with disks (red, dashed) and stars without disks (blue, solid). Since the number of stars with measured oxygen abundances is a fraction of the total sample (due to poor fitting stemming from 'astrophysical' noise of stellar rotation) the variations in the two samples are not statistically significant. Both are consistent with a distribution around solar.

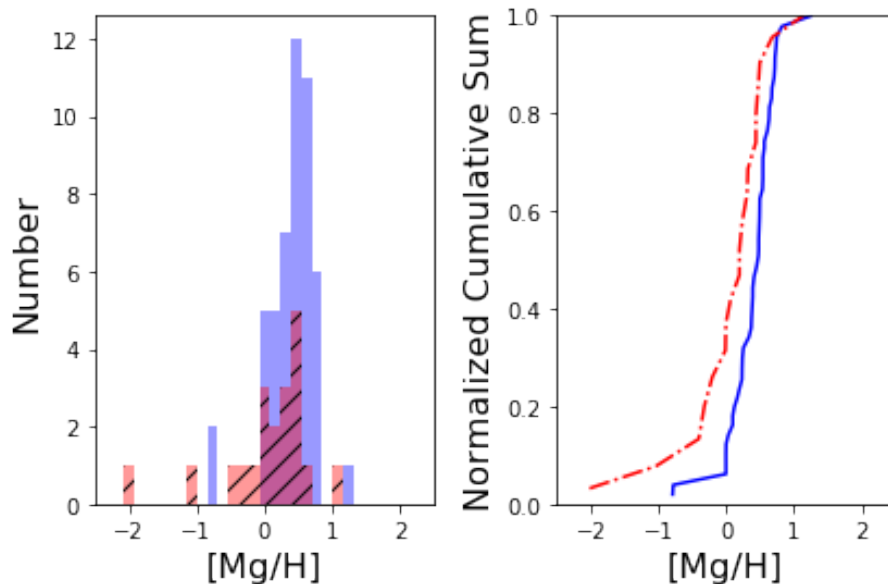


Figure 4.6 Histogram and cumulative distribution of Mg 4481 measured across the sample. Red denotes stars with a debris disk detected by *Herschel*. Blue denotes stars without any far-IR excess, as measured by *Herschel*. There is a tendency (p-value = 0.05 from a 2 sample KS test) for stars with disks to be Mg-weak.

et al., 2016b). One potential source could be an actively perturbed debris disk that has a high flux of comets near the star (Draper et al., 2016b). By polluting the surface with volatiles, the relative surface refractory abundances drop. The accretion rates needed to sustain a Lambda Boo signature on the central star are much higher than what a kinematically cold debris disk can provide, therefore a dynamic instability from a planet needs to be invoked to perturb the disk (Draper et al., 2016b).

Stars in our sample had oxygen abundances that are around solar, so the requirement that they have solar-abundant volatiles was already largely achieved. This is likely a result of the target selection only being stars in the solar neighborhood, in order to be targeted by *Herschel* in DEBRIS. We therefore test if the star has metal-poor refractories in Mg and Si. The contribution of rotational broadening contributes to the 'astrophysical' noise in trying to detect a Lambda Boo star. In some cases, it's only possible to measure Mg II 4481 because it is one of the strongest metal lines in this spectral range.

If we use Mg II 4481 as a diagnostic for the Lambda Boo classification, (since they are Mg-weak stars), we can obtain a broad measure of the prevalence of the Lambda Boo phenomenon in our sample. While we cannot confirm the solar abundance of

volatile elements in all of the stars, we infer for stars that we do measure in the solar neighborhood that oxygen abundances are roughly solar (see Figure 4.5). It may therefore be the case that Lambda Boo stars have gone unconfirmed because their rotational broadening prohibits clear classification of volatile elements.

Splitting the sample between stars with and without debris disks detected by *Herschel*, we can see a slight preference for stars to have a lower Mg abundance if they have a debris disk (see Figure 4.6). From a two-sample KS test, the variation in the cumulative distributions has a low p-value of 0.05. Therefore, it is unlikely that the two samples stem from the same underlying distribution of metallicity at the 2σ level. This suggests the pollution effect is far more prevalent in debris disk systems as a whole, rather than just Lambda Boo stars, which are strongly metal poor. This implies there could be a gradient of possible accretion and mixing rates related to the Lambda Boo phenomenon (Turcotte, 2002).

In the DEBRIS sample there were 100 AF-type hot stars, but only 79 are presented here. In the full sample, there were 2 previously known Lambda Boo stars (Lambda Boo; HD 125162 & ρ Vir; HD 110411) (Booth et al., 2013). This is approximately consistent with the overall prevalence of Lambda Boo stars, which accounts for $\sim 2\%$ of all field A-stars (Paunzen, 2004). There are two other stars that have been identified as probable members including Vega and HD 223352. All four of these stars have an IR-excess. This in turn would be supportive of potential mechanisms that require a debris disk to cause the accretion of volatile gas out of planetesimals grinding down to create a second-generation gaseous disk (Draper et al., 2016b).

In Figure 4.7, we compare the abundances for stars with a debris disk, as measured by the total fractional luminosity between the disk and star. The fractional luminosity is proportional to both the mass and temperature (and similarly radius) of the disk (Wyatt, 2008). The Lambda Boo stars with a Mg metallicity near or below -0.5 dex all have debris disks that are relatively bright at $\text{Log}(F_{\text{IR}}) > -4.8$, compared to other stars observed in the DEBRIS sample with *Herschel* which have been detected down to $\text{Log}(F_{\text{IR}}) = -5.5$. The outlier at $\text{Log}(F_{\text{IR}}) \sim -3.0$ is HD 172555, which is thought to be a unique case due to a cataclysmic impact of terrestrial-sized objects (Lisse et al., 2009). Therefore, stars with more massive, closer in debris disks, will tend to be more likely Mg-weak, compared to debris disks with farther out, less massive disks. This supports a hypothesis that the pollution effect is due to active perturbations stirring a debris disk, causing an accretion rate of comets that is high enough to cause the Lambda Boo effect. As a result, not all debris disk stars will have the Lambda Boo

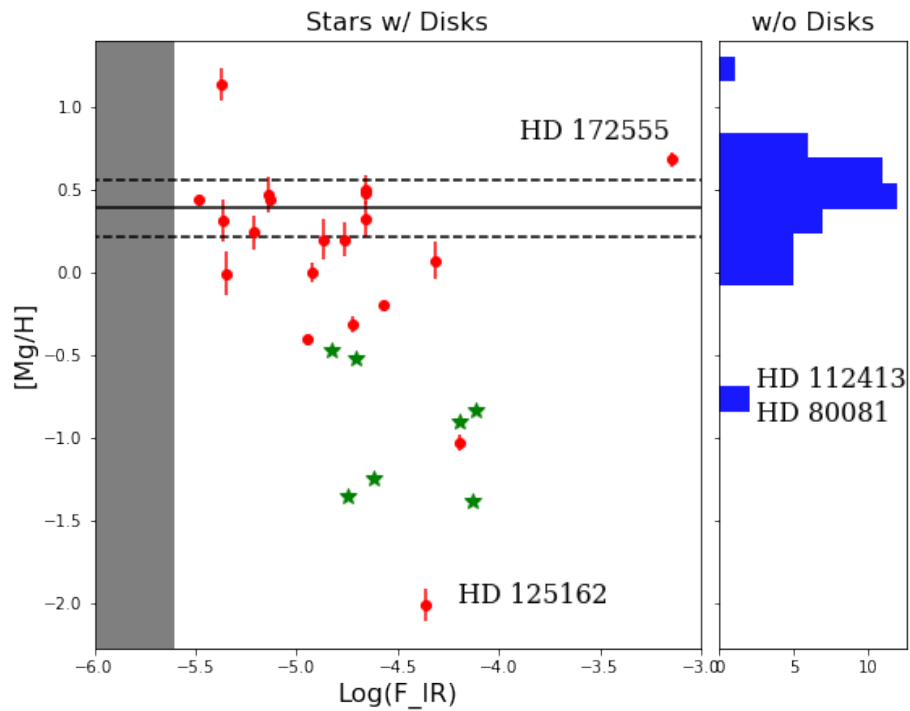


Figure 4.7 Fractional luminosity as a function of Mg abundance. The red points are stars with a debris disk found in the DEBRIS sample discussed here. The green points are known Lambda Boo stars observed with *Herschel* from Draper et al. (2016b). The black line denotes the average Mg abundance of stars without a debris disk from the DEBRIS sample at ~ 0.3 , or slightly above solar. The trend for brighter debris disks having weaker Mg abundance is consistent with the Lambda Boo phenomenon hypothesis of secondary accretion via a stirred debris disk.

signature, but the brightest debris disks, with active planetary scattering, are more likely to have the Lambda Boo signature than the stars associated with fainter debris disks.

HD 80081 and HD 112413

The only evidence to the contrary from this study are the two stars that have a low Mg abundance but do not have a debris disk. One such star is HD 112413 (HR 4915), which we can verify is an Ap star (high Si abundance, low $v \cdot \sin(i)$), and therefore chemically peculiar for a different reason (Richer et al., 2000; Renson & Manfroid, 2009). The other is HD 80081 (HR 3690). This star was once classified as a Lambda Boo star due to the weak Mg 4481 abundance. However, after review of its UV spectrum, it was found to not be metal weak as required for a designation of a Lambda Boo star (Paunzen & Gray, 1997). It was then downgraded from Lambda Boo status. The only explanation offered so far is that it is a spectroscopic binary, which gives the appearance of a weak Mg line at 4481, but not in the UV where the A-star dominates the flux (Murphy et al., 2015). This could be confirmed with resolved AO spectroscopy from the ground to separate the contribution from either star. In concurrence with fits from Takeda et al. (2008a), the refractory and volatile elements are similarly sub-solar, and therefore not exhibiting a Lambda Boo signature.

HD 223352

HD 223352 is an interesting case study given its Lambda Boo status. The star is a quadruplet of an AB pair with the B component being a binary (Ba and Bb components) and a C component farther out (De Rosa et al., 2011; Phillips, 2011). Furthermore, both the A and C component have dust detected with *Herschel*, which makes it one of two unique systems observed thus far to have debris around each individual star in a binary (Rodriguez et al., 2015). The stellocentric distance of the disk around A compared to the projected binary separation of AB leaves the disk around A in an unstable regime, which could lead to a short lifetime as the debris is dissipated from gravitational perturbations from the binary (Rodriguez et al., 2015). However, in this case a clear mechanism exists – a stellar companion (B) causing the instability – rather than having to invoke an unobserved planet. Therefore, it may be the first system that has a clear causal mechanism for a Lambda Boo phenomenon by an actively perturbed debris disk. The spectra observed for the system would have a

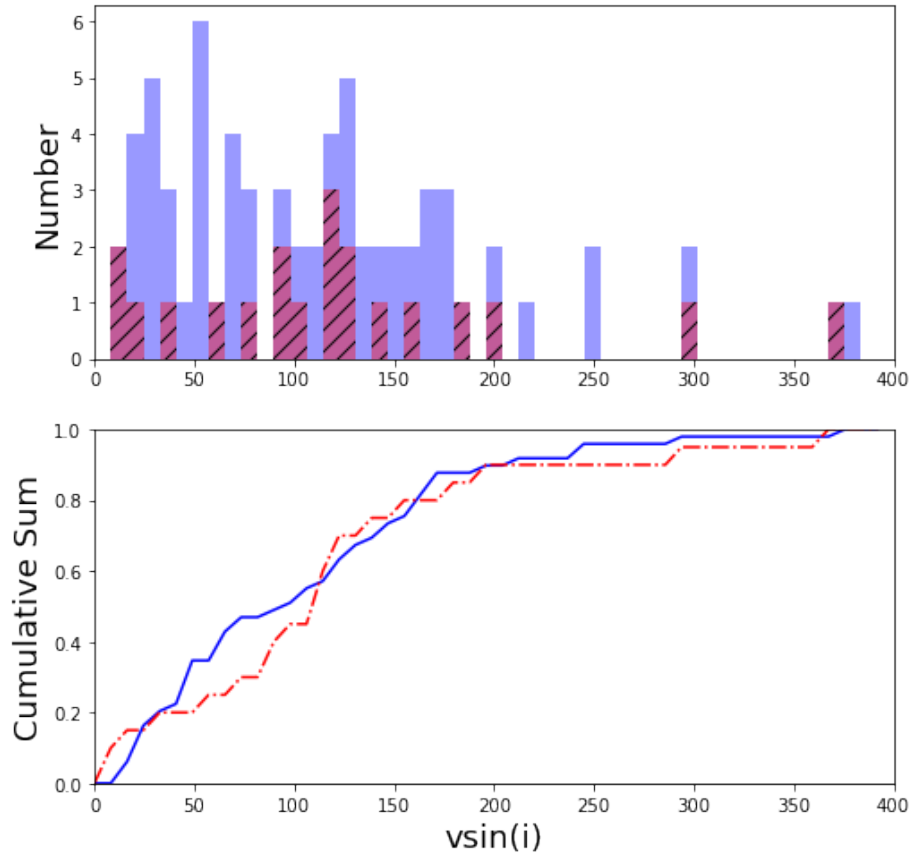


Figure 4.8 The distribution of $v \cdot \sin(i)$ as measured from the Mg II 4481 line. A relative paucity of stars rotating at $\sim 75 \text{ km s}^{-1}$ is likely due to a gyrochronology effect, such that stars with debris disks are often younger, and rotate more rapidly than older stars.

combination of A and B components given the spatial separation of $3''.5$; however the B component is ~ 3 orders of magnitude dimmer than the central star (Dommanget & Nys, 2002). The membership of this star to the Lambda Boo class is only questionable due to the fact that the high rotation velocity precludes the measurement of volatile elements.

4.4.3 $v \sin(i)$ versus IR-excess

One trend that stands out was the variation between IR-excess to rotation speed. Stars with bright debris disks are more likely to be observed around younger stars, as they grind down their planetesimals' mass with time (Wyatt, 2008). Furthermore, older stars will often spin down as they lose angular momentum with age (Sku-

manich, 1972). Therefore, we are likely seeing a gyrochronological effect, such that most of our debris disk stars have $> 100 \text{ km s}^{-1}$ rotation speeds. Given that $v \cdot \sin(i)$ is a primary source of astrophysical noise in measuring the stellar abundances, this can have bias against the Lambda Boo phenomenon because the sample of stars with debris disks will have a greater likelihood of blended lines with the continuum. It was first noted that Lambda Boo stars tend to have higher rotation speed than the ‘normal’ A-type stars in Paunzen & Gray (1997). Given that $v \cdot \sin(i)$ was used as a selection criteria at one time, it was thought to be a possible bias. However, that trend would be naturally explained by a planet-disk hypothesis, given the gyrochronology.

In terms of the Lambda Boo effect, the rotation speed will dictate the meridional circulation, which controls the timescale for the surface envelope to mix and dissipate any pollution effect. Therefore, young stars that have higher rotation speeds should reduce the Lambda Boo signature instilled early-on, as in the case of young Lambda Boo stars observed in the protoplanetary phase (Kama et al., 2015). Older stars observed with the Lambda Boo signature will then need a second-generation gaseous accretion disk, given the mixing timescale is on order of $\sim 10^6$ years (Turcotte, 2002); unless, however, the variation in gas to dust accretion is so strong at birth, that the entire surface envelope is depleted of refractory metals. It is unclear how strong or what conditions are necessary to permanently instill the signature at birth. If the effect was not transitional, then it is not clear why Lambda Boo stars seem to all have bright debris disks (Draper et al., 2016b). Otherwise, they should have a similar rate of detected debris disks as the general population of A-type stars, 25% (Thureau et al., 2014). A survey of Lambda Boo stars in the far-IR without a bias toward Lambda Boo stars with known IR-excesses is needed to verify the higher prevalence of debris disks around Lambda Boo stars (e.g., Gray et al. (2017)).

4.4.4 Planetesimal Formation Chemistry

Through simulations of planet formation that trace the chemical evolution of planetesimal growth, there is evidence that the range of stellar abundances could change the pathways of grain growth (Carter-Bond et al., 2012). Key ratios can then alter the planet formation process to grow planets significantly different than our own. We therefore would like to also know if these key ratios impact the planetesimal growth for the progenitors of debris disks.

C/O ratio

The C/O ratio between planets and stars has been found to vary. It is possible that the planetary C/O ratio itself traces where the planet formed in the protoplanetary disk versus where it is currently located. In our sample the quality of the extracted abundances is limited by the ability to fit the lines of several species. Again, this stems mostly from the ‘astrophysical noise’ of stellar rotation making line fitting problematic. In Figure 4.9, the C/O ratio for stars with and without debris disks can be seen. The measurements rely on C 5052, C 7113, and O 6158. The smaller sample set means the deviations found are not statistically significant, though there seems to be a preference of sub-solar C/O ratio in the sample stars. Since the bias is for low $v \cdot \sin(i)$ stars to have more easily measured abundances, there may be radiative forces effecting the ratio due to differential diffusion of elements in Ap/Am stars which occur at low rotation speeds. Therefore, the intrinsic C/O ratio would likely be offset to lower carbon and higher oxygen (i.e. lower C/O ratios), potentially by 0.2 dex (Richer et al., 2000).

4.5 Conclusions

In this study, we measured the metal abundances in stars for which the debris disk properties were known consistently and reliably through far-IR observations from *Herschel*. The main conclusions we draw are the following.

- Stars with faint debris disks tend to have Mg abundances that are consistent with stars that do not have a known debris disk.
- Stars that are comparatively Mg-weak tend to be around stars with debris disks and those disks are relatively brighter than the typical sample of debris disks seen in this paper.
- The lack of Lambda Boo stars at low rotation speeds could be explained by the variation in $v \cdot \sin(i)$ distributions due to younger stars having faster rotation speeds and therefore more likely having a bright debris disk.
- HD 80081 can be an interesting case study in the future because it is Mg-weak, but does not have a debris disk to explain a pollution effect.

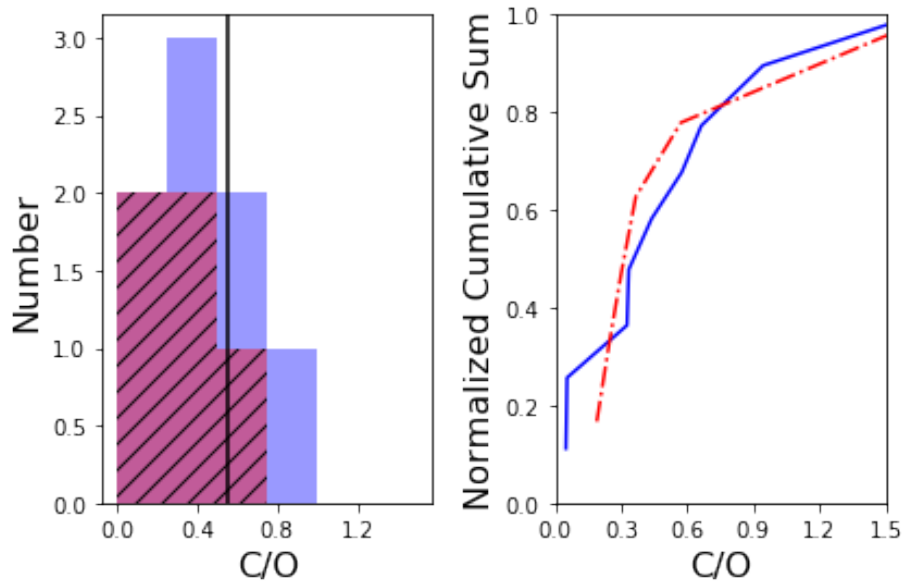


Figure 4.9 Carbon to Oxygen ratio for the sub-sample of stars which had a sufficiently good fit to the Carbon and Oxygen lines. The black line denotes the solar value of C/O. The difference between stars with and without debris disks is not statistically significant due to low numbers. A general favoring of sub-solar C/O is found, though this would be in the right direction for differential diffusion in slow rotating A stars (Am phenomenon) (Richer et al., 2000). Their slow rotation, also makes their C and O abundances easier to measure, introducing a potential bias.

- HD 223352 would also be an interesting case study because it is a Lambda Boo candidate with a debris disk that is known to be unstable from a stellar companion and has a solar-type companion to investigate the natal metallicity of the system.

The fundamental data reduction issues for A-type stars were addressed and allowed for systematic analysis of possible errors in a consistent manner. Many other pipelines that perform spectral analysis on large samples are not adequate for handling specific challenges of hot stars. The issues that limited the conclusions of this study were largely astrophysical. Stars with large rotation speeds greater than 125 km s^{-1} did not produce strong enough absorption profiles to measure independently from the continuum, resulting in them being dropped from the sample for trace elements like carbon and oxygen. Mg 4481, however, allowed for nearly the whole sample to be studied as a function of metallicity regardless of $v \cdot \sin(i)$. Furthermore, A-type stars can have strong NLTE effects which have to be accounted for, but correction tables are not widely available in the literature. The selection of only *Herschel* DEBRIS targets meant most stars were confined to the solar neighborhood, which limited the range of metallicities studied. Unresolved debris disk surveys of stars at greater distances in the far-IR should be considered to reach lower metallicity regions. In the future this type of analysis could be extended to solar-type stars, which will not suffer from the lack of spectroscopic lines, albeit while still being limited by the far-IR observations only being in the solar neighborhood.

With the aim of understanding the Lambda Boo phenomenon, we have searched for more class members in a sample of stars that were systematically searched for debris disks. We did not find any new Lambda Boo stars. Therefore, if the Lambda Boo phenomenon is linked to debris disks, the phenomenon itself is not the explicit result of debris disks. There does, however, tend to be brighter debris disks associated with Lambda Boo stars relative to the unbiased DEBRIS sample. While we cannot suggest that, given the low numbers, all Lambda Boo stars should have debris disks, we find that they do, both in this broad survey of A-type stars and in a targeted *Herschel* program (Draper et al., 2016b).

If the Lambda Boo phenomenon were caused by planetary scattering of a debris disk, it could provide an important constraint on the broad stability of exoplanetary systems. Since there are other scattering mechanisms (i.e. self-stirring, ISM interactions) it may be possible that you can have a bright debris disk around an A-star but

not achieve an accretion rate high enough to cause an abundance anomaly. Relatively average levels of $v \cdot \sin(i)$ can erode a detailed abundance analysis; therefore many A-stars are not classifiable. For example, Vega’s designation as a Lambda Boo star is assisted by its pole-on viewing geometry. If we only viewed the Mg profile we would only conclude it was partially Mg-weak, while having no constraint on its volatile abundance content, a requirement to make it a ‘probable’ Lambda Boo member given the definitively solar oxygen content. It may be that some of the fast-rotators in this sample are similar to Vega, but lack the volatile element spectral features to reliably classify them. If it can be linked to planetary scattering, than roughly 12.5% of stars with debris disks are undergoing a planetary instability (0.25 fraction of stars with debris disks / 0.02 fraction of Lambda Boo stars).

Chapter 5

Conclusions

5.1 Results

Through this thesis, a better understanding of the role of debris disks in exoplanetary systems has been realized. In one case, through a detailed case study of a particularly unusual debris disk, and another through a more global survey of debris disk stars.

First, the most asymmetric debris disk yet observed was analyzed through resolved near-IR imaging in order to classify the dust grain properties. The major result being that the disk has likely experienced a recent collision of large bodies with an ice like composition. This very unique system can then put into context how often major impacts at ~ 75 AU collide to create dust in debris disk systems. This has ramifications on planet formation and stability. While this is the small number statistics of one, it is at least one compared amongst the many other systems that host a debris disks and have been resolved in scattered light. Follow up on the byproducts of a very recent collision could better inform the internal composition of the planetesimal belt.

Secondly, a systematic survey of stars observed for debris disks has been compared with their spectroscopic abundances and we have gleaned some important information about the global stability of systems against planetary scattering. By comparing refractory metal abundances with the fractional brightness of debris disk, it can be seen that the stars which are more refractory metal poor, are the ones which host relatively bright debris disks. This supports the hypothesized mechanism being planetary scattering of the disk, in order to accrete enough material to cause a Lambda Boo effect. As a result, we'd expect about 13% of debris disk systems to be undergoing active planetary scattering by roughly a Jupiter mass body (based on models

from Bonsor et al. (2012)).

5.2 Future Work

Of course, this work is limited by the time and data sets available. In the future there are several possibilities for this body of work to be further analyzed and new data sets taken to test the conclusions of this thesis.

HD 111520

For example, one of the biggest uncertainties in the analysis of the debris disk around HD 111520 is the distribution of dust. Since the disk is clearly structured, it is not fair to assume smooth power-law parameters to describe the location of the dust as with typical debris disks. Changing the dust mass changes the brightness of the resulting model and could therefore change the derived grain properties. In order to address this, the ideal data set would be to resolve the sub-mm emission using ALMA. Given the brightness of the disk from Cycle 1 observations and the edge-on nature from scattered light observations, it is possible to resolve the disk. Using a moderate baseline distance, a total of 13 beams could be resolved along the disk at an expected SNR of $\sim 3-5$ in only a few hours. This information can be used to constrain the location of the dust and reduce the uncertainty in the dust structure. Since the grains which would be observed by ALMA are closer to a millimeter in size, they are less susceptible to radiation pressure and more likely to trace the location of the planetesimal belt.

In terms of the GPI data, the fractional composition of the dust is sensitive to the relative brightness between the polarization mode and the spectroscopic mode. It has been found that the flux calibration is sometimes in disagreement by up to $\sim 10-20\%$ because of observing conditions. This has to do with the fact that the flux calibration is done with the satellite spots in GPI. When the AO system is struggling to keep up with turbulence in the atmosphere, the PSF is elongated in the wind direction vector, causing it to blur in with the noise of speckles and halo around the coronagraph. The change in Strehl from observing conditions will then change the flux calibration factors.

The seeing variations are particularly bad for debris disk for a few reasons. First the flux extraction is different between the satellite spots and the disk. For a planet,

the same aperture size can be used and the effect on one point source is the same to another point source. The encircled energy function, or how much flux falls inside a given aperture, is not well known. This aperture correction is not well known because the PSF can change with seeing and it is hard to measure with multiple noise sources near the spots themselves. Second, since a debris disk has a host of spatial frequencies, a blurred PSF puts more flux into lower spatial frequencies causing the observed brightness of the disk to change if it can't be adequately measured. Developing a better flux calibration method based on PSF extraction of the satellite spots would be a good step forward.

Furthermore, the disk is clearly bright enough to be observed by HST, however, it is not clear how the disk resolved by GPI is connected with the extended emission seen by HST. A new coronagraphic technique has been developed to use the BAR5 segment on HST's STIS instrument to reduce the inner working angle to be comparable to GPI's FOV ($0.3''$). This can then resolve the gap between the two instruments. The bifurcation seen in HST can then be traced down to where the collision and density enhancement is located to see if in fact it is an optical scattering effect. The visible wavelengths with HST will also give greater leverage on the dust grain properties with wavelength dependent scattering, such as composition, porosity, etc. Other future facilities, such as the *James Webb Space Telescope*, could also offer better resolution in the visible bands.

Lambda Boo Stars

For Lambda Boo stars, there is plenty of room to still advance the planetary scattering hypothesis. The most pressing is the fact that no Lambda Boo star has had its debris disk resolved. The best results thus far have been the far-IR emission being resolved at a few FWHM of the nominal PSF. In order to show planetary scattering is happening, the disk would first need to be resolved in detail to see perturbations in the dust. Furthermore, if a planet could be resolved near the disk it would serve as the “smoking gun” for the hypothesis. If the disk was highly perturbed, it's feasible that the disk is widely disbursed and therefore harder to resolve since its at a lower surface brightness. Furthermore, the planetary perturber could be fainter than the current detection limits (e.g. a Neptune mass planet around an older star could be possible but we can only directly image a few Jupiter masses around young stars). Even still there are systems with planets perturbing their debris disks, but are not

Lambda Boo like (e.g. β Pic). Some analysis would be needed to explain whether or not these systems have an accretion rate lower than what is required.

Besides an observational smoking gun, theoretical modeling has not been sufficiently developed to tackle this problem specifically. The build up in mass is a competition between two rates: the amount of volatile gas accreting and the amount of dissipation in the atmosphere from meridional circulation. 3D models of stellar convection from rotation are only just being developed. Many of them are trying to solve basic problems in our lack of understanding around thermal convection, much less secondary convection effects like meridional circulation. On the other side of the equation, N-body simulations can bring enough volatile mass in comets to the warm, inner few AU. However, modeling the beta ratios (force of radiation pressure over gravity) for dust grains versus volatile gas, are going to be crucial for explaining the last step in how the gas reaches the stellar surface and the dust is blown out.

In a broader observational scheme, it would also be important to nail down the ubiquity of debris disks or far-IR emission around Lambda Boo stars. With a larger survey of Lambda Boo stars, one could target them to find excess emission. The occurrence rate of debris disks would have to be much higher than compared to AF-type stars in general, if the debris disk was apart of the causal mechanism. This could be done with short baseline ALMA configurations or possibly future facilities such as SPICA.

Appendix A

Additional Information for HotSAP Data Reduction

A.1 Continuum Normalization

For steps that required continuum normalization, a general prescription was used to find the continuum points in the spectrum. This could either be at the echelle blaze function, extracting from the CCD or in each synthesis window. When normalizing the blaze function, a prescription from Zhao et al. (2006) was used. The general procedure is to normalize to the maximum value that flattens inflection points. Strong lines are identified and ignored as large offsets to record the high point values. The values left over are selected from the unmodified data to then fit a polynomial to normalize the spectra.

In a second iteration, each window of a given line of interest is normalized again to remove any residual continuum offset to more adequately match a synthesized spectrum. Sousa et al. (2007) outlines an effective way to automate this procedure. Effectively, the first and second derivative of every point in the spectrum are taken. This allows the identification of flat regions (the first derivative near zero) and places where the slope is not actively changing (the second derivative near zero). Some tuning has to be done to set a threshold for how close the zero-points should be selected based on the noise level in the data. Smoothing the data was also very effective at improving the solution. Identifying points this way can then allow a polynomial fit to normalize the data before spectrum synthesis occurs.

A.2 Wavelength Corrections

The spectra are wavelength-calibrated using ThAr lamps to be at the Earth-centric reference frame. Since the abundances are the primary concern, we need to employ a broadly applicable method to get all the stellar spectrum into the rest-frame with milli-angstrom accuracy to adequately synthesize the spectrum. This is done in successive stages to continually improve the wavelength solution to better accuracy.

First, each spectrum is aggressively median-filtered to smooth the spectrum devoid of lines other than broad Balmer lines. Then, broad search windows of $\sim 100\text{\AA}$ can find the minimum value from the rest frequency of Balmer lines. A linear shift can be calculated to match the unfiltered data and account for the largest shift, which is due to Earth's motion.

In a second iteration, strong metal lines are added as reference points and found as minimum values in narrower search windows of $\sim 10\text{\AA}$. This gives broader wavelength reference points across the entire spectrum. At this point, it is beneficial to fit the spectrum with a quadratic, as errors in the wavelength calibration of the instrument could be impactful by a few $\text{\AA}$ from one end of the spectrum to the other. By fitting with a quadratic and applying this shift, it is possible to get a fully consistent spectrum, in an automated way, to within a few $\text{\AA}$ accuracy.

Finally, in a third iteration, to achieve sub-Angstrom precision applicable for spectrum synthesis, without human intervention, a cross-correlation is used. For each window centered on a line of interest, a synthetic model of solar metallicity, at $25\text{ km s}^{-1} v \cdot \sin(i)$ is created to use as a reference. Then, the model is shifted with respect to the data, multiplied, and summed to give a vector of correlation with respect to wavelength shift. The continuum-normalized spectrum is inverted above 1, so that when absorption lines match up, the larger the resulting value will be. The shift is allowed to go $3\text{\AA}$ to match the precision of the previous iteration. In cases where multiple lines are present, or blended, it can be even more accurate, as it can match strong to strong and weak to weak lines at the right separations. Even though $v \cdot \sin(i)$ of the model reference often will not be accurate, the relative correlation at the core of the lines is still larger and therefore representative of the wavelength shift.

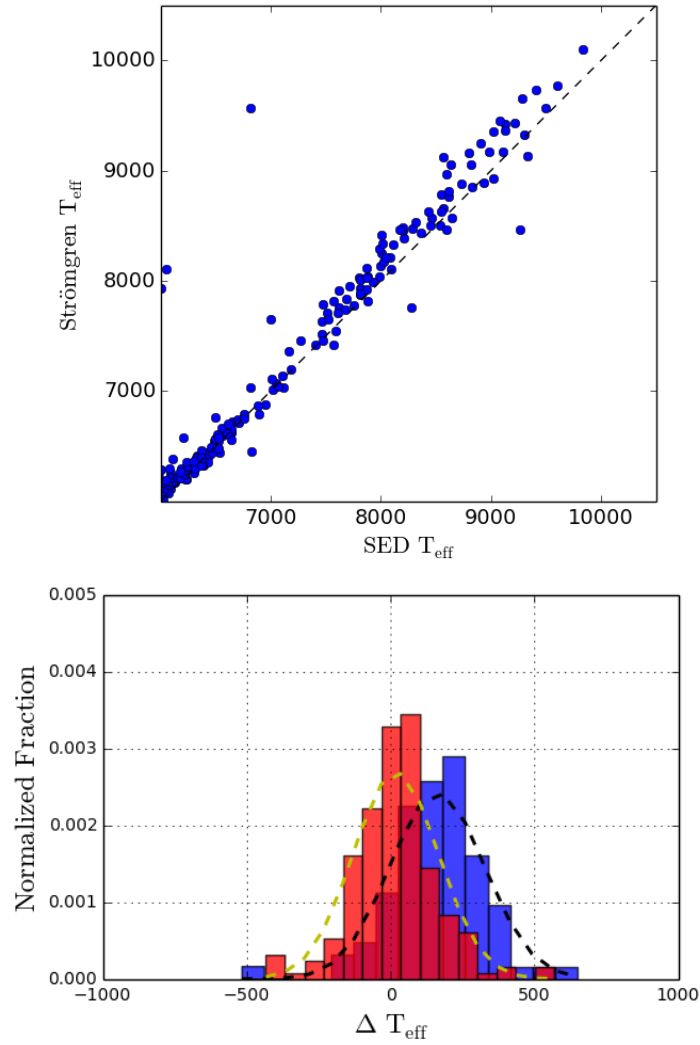


Figure A.1 (Left) Scatter plot showing the DEBRIS survey comparing SED temperature to Strömgren temperature. A one-to-one line is overplotted. At about 7500 K, the agreement between the two methods has a marked departure. (Right) Normalized distributions of the difference between the two methods. Gaussians are fit to each distribution and show that the stars greater than 7500 K have a 1σ offset of 150 K versus the lower temperature stars that are in good agreement.

A.3 Strömgren versus SED Effective Temperatures

In order to determine the spectral effective temperature, we investigated two photometric methods on the entire DEBRIS sample as a consistency check. The Strömgren method uses photometry from (Paunzen, 2015) and computes the effective temperature using the prescription from Moon & Dworetzky (1985) implemented in the IDL code *uvbybeta.pro*¹. The SED method compiles photometry from multiple all sky surveys, when data is available (cite a Grant paper) and fits a PHOENIX model atmosphere (Brott & Hauschildt, 2005). The surveys utilized include optical-to-mid-IR from Hauck & Mermilliod (1998) and Mermilliod (2006), 2MASS (Cutri et al., 2003b), *WISE* (Wright et al., 2010), *Spitzer* (Su et al., 2006; Chen et al., 2009; Morales et al., 2009), and *Akari* (Ishihara et al., 2010).

We find that there is a systematic trend for stars to be hotter from the Strömgren method than the SED method. However, this appears to only affect stars greater than 7500 K, which are predominantly the stars of interest in this paper. Stars greater than 7500 K seem to be offset by $\sim 150\text{K}$ which also happens to be the FWHM of both populations, giving a 1σ offset between the two temperature ranges.

A.4 Line List

In this study, selected lines were taken from the Takeda et al. (2007) atlas of Vega. For reference, the selected line properties that were used in this paper are repeated here (see Table A.1). When trying to determine the stellar parameters, a wider list of Mg and Fe is used (See Table A.2).

¹Source: NASA IDL Code Library

Table A.1 Spectral line data used to synthetically fit and derive metal abundances in this paper (Takeda et al., 2007). Only some of the stars in this sample have measurable lines and therefore may not have a corresponding abundance measurement for each of these lines.

Species	Wavelength (Å)	eV	log(gf)
Mg II	4481.126	8.863	0.740
Mg II	4481.150	8.863	-0.560
Mg II	4481.325	8.864	0.590
Fe I	4482.252	2.223	-1.649
Fe I	4482.325	3.654	-1.350
C I	5052.167	7.685	-1.648
Mg I	5183.604	2.717	-0.180
O I	6155.961	10.740	-1.401
O I	6155.971	10.740	-1.051
O I	6155.989	10.740	-1.161
O I	6156.737	10.740	-1.521
O I	6156.755	10.740	-0.931
O I	6156.778	10.740	-0.731
O I	6158.149	10.741	-1.891
O I	6158.172	10.741	-1.031
O I	6158.187	10.741	-0.441
Si II	6347.109	8.121	0.297
Si II	6371.371	8.121	-0.003
C I	7113.178	8.647	-0.350
O I	7771.944	9.146	0.324
O I	7774.166	9.146	0.174
O I	7775.388	9.146	-0.046

Table A.2 Spectral line data used to determine the stellar parameters by matching abundances between species in different ionization states. Only lines which had a reliable fit are used and vary depending on the data/star. Therefore these lines are just the complete list of lines which were searched for in the spectrum. This list is different then the preceding list (Table A.1) because a greater diversity of Mg and Fe lines are useful for the ionization state matching in slowly rotating stars and they are not necessarily lines which can be measured in every star (i.e. high $v \cdot \sin(i)$ stars). (Takeda et al., 2007).

Species	Wavelength (Å)	eV	log(gf)
Mg I	4702.991	4.346	-0.67
Mg I	5183.604	2.717	-0.18
Mg I	5711.088	4.346	-1.83
Mg I	5528.405	4.346	-0.62
Mg II	4242.448	11.56	-1.07
Mg II	4242.542	11.56	-1.23
Mg II	4427.994	9.995	-1.21
Mg II	4481.126	8.863	0.74
Mg II	4481.150	8.863	-0.56
Mg II	4481.325	8.864	0.59
Fe I	3920.26	0.120	-1.75
Fe I	3997.39	2.730	-0.39
Fe I	4005.25	1.560	-0.61
Fe I	4045.82	1.480	0.28
Fe I	4063.60	1.560	-0.61
Fe I	4071.74	1.610	-0.02
Fe I	4202.03	1.480	-0.71
Fe I	4235.94	2.430	-0.34
Fe I	4260.48	2.400	0.02
Fe I	4282.41	2.180	-0.81
Fe I	4466.55	2.830	-0.59
Fe II	3922.91	7.516	-1.20
Fe II	4233.17	2.580	-2.00
Fe II	4472.92	2.860	-2.21
Fe II	4508.28	2.860	-2.21
Fe II	4515.34	2.840	-2.48
Fe II	4520.23	2.810	-2.60
Fe II	4522.63	2.840	-2.03
Fe II	4541.52	2.860	-3.05
Fe II	4576.33	2.840	-3.04
Fe II	4582.84	2.840	-3.10
Fe II	4583.83	2.810	-2.02
Fe II	4629.34	2.810	-2.37

Table A.3: Full table of derived stellar parameters and abundances used in this paper. $v \cdot \sin(i)$ here are measured from the Mg 4481 line. Errors in this table represent the measurement errors between the models and the data and do not represent the systematic error that goes into the model assumptions. Error from uncertainty in the temperature and surface gravity are the only errors propagated here. See text for more details.

HD	HR	Temp.	$\log(g)$	$v \cdot \sin(i)$	Mg II 4481	$\pm$ error
HD 9672	HR 451	9084	4.4	...	...	...
HD 110411	HR 4828	8812	4.2	160	-1.032	0.08
HD 16555	HR 778	8449	4.6	...	...	...
HD 16970	HR 804	8603	4.1	166	0.243	0.05
HD 19107	HR 925	8217	4.1	166	0.236	0.01
HD 197157	HR 7920	8326	4.4	91	0.72	0.08
HD 210418	HR 8450	9008	4.2	146	0.003	0.09
HD 222345	HR 8968	8326	4.4	75	0.724	0.10
HD 222603	HR 8984	8217	4.1	49	0.478	0.06
HD 223352	HR 9016	9345	4.4	300	-0.2	0.00
HD 2262	HR 100	8217	4.1	198	0.441	0.04
HD 105452	HR 4623	7209	2.9	29	0.035	0.10
HD 109536	HR 4794	7905	3.8	80	0.452	0.04
HD 109787	HR 4802	8900	4.2	197	0.1	0.11
HD 11171	HR 531	7215	2.9	65	1.139	0.14
HD 118098	HR 5107	8468	4.1	150	0	0.06
HD 119756	HR 5168	6914	2.9	...	...	...
HD 120136	HR 5185	6466	2.4	...	...	...
HD 130109	HR 5511	9008	4.2	300	0	0.10
HD 15008	HR 705	9078	4.4	172	0.257	0.12
HD 172555	HR 7012	8094	4.1	115	0.683	0.07
HD 187642	HR 7557	5000	0	...	...	...
HD 188228	HR 7590	9393	4.5	92	0.312	0.19
HD 18978	HR 919	8440	4.1	124	0.124	0.05
HD 194280	...	8869	4	...	...	...
HD 202730	HR 8140	8305	4.1	104	0.443	0.03
HD 210049	HR 8431	9147	3.5	...	...	...
HD 212728	HR 8547	7942	3.8	220	0.5	0.00

HD 213398	HR 8576	9599	4.3	180	0	0.03
HD 215789	HR 8675	5000	0	...	...	...
HD 21997	HR 1082	7095	3.9	70	-1.7	0.30
HD 29875	HR 1502	7198	3.4	56	0.825	0.13
HD 32297	...	8194	4.6	84	-0.115	0.02
HD 55892	HR 2740	5000	0	...	...	...
HD 71155	HR 3314	9537	4.3	144	0.069	0.17
HD 88955	HR 4023	9098	4.3	90	0.24	0.12
HD 99211	HR 4405	7986	3.9	127	0.387	0.00
HD 137898	HR 5746	8326	4.4	112	0.71	0.07
HD 110379	...	7504	3.1	25	0.1	0.19
HD 115892	HR 5028	9160	4.3	79	0.47	0.17
HD 56537	HR 2763	8680	4.1	161	0.635	0.11
HD 58946	HR 2852	7163	2.8	72	0.34	0.20
HD 60178	HR 2890	9157	5	22	0.489	0.07
HD 60179	HR 2891	9473	4.9	17	0.166	0.07
HD 76644	HR 3569	8242	3.7	138	0.643	0.08
HD 78209	HR 3619	7733	3.5	40	0.546	0.12
HD 79439	HR 3662	8155	4	174	0.539	0.04
HD 80081	HR 3690	8629	4.2	382	-0.777	0.00
HD 85376	HR 3900	7741	3.8	110	0.495	0.03
HD 87696	HR 3974	8198	4	129	0.48	0.00
HD 89021	HR 4033	9082	4.3	51	0.414	0.14
HD 91312	HR 4132	7999	4	119	0.545	0.05
HD 95418	HR 4295	9448	4.3	38	0.199	0.18
HD 95608	HR 4300	9088	4.4	17	0.324	0.16
HD 97603	HR 4357	8428	4.2	178	0.498	0.08
HD 102124	HR 4515	8234	4.1	150	0.395	0.02
HD 102647	HR 4534	8881	4.4	130	0.5	0.13
HD 103287	HR 4554	9308	4.3	168	0.2	0.16
HD 104513	HR 4594	7514	3.5	71	0.613	0.06
HD 106591	HR 4660	8860	4.3	370	-0.008	0.00
HD 110379	HR 4825	7429	3.7	33	0.396	0.00
HD 110380	HR 4826	7445	3.2	72	0.739	0.06
HD 112412	HR 4914	7184	3.7	32	0.379	0.01

HD 112413	HR 4915	7334	3.1	30.27	-0.786	0.04
HD 116656	HR 5054	8526	3.9	...	...	...
HD 116657	HR 5055	8482	4.2	53	0.68	0.10
HD 125161	HR 5350	7990	3.4	132	0.674	0.06
HD 125162	HR 5351	8883	4.4	120	-2.011	0.15
HD 128167	HR 5447	6931	3.7	15	-0.4	0.00
HD 137909	HR 5747	8084	3.9	23	1.254	0.14
HD 139006	HR 5793	9303	4.2	120	0.2	0.15
HD 140436	HR 5849	8982	4.6	100	0	0.20
HD 141795	HR 5892	8530	3.9	25	0.483	0.07
HD 149757	HR 6175	5987	4.5	...	...	...
HD 156164	HR 6410	8673	4	250	...	...
HD 159541	HR 6554	7517	3.2	69	0.238	0.06
HD 159560	HR 6555	7488	3.3	47	0.75	0.06
HD 165777	HR 6771	8647	4.3	56	0.373	0.09
HD 172167	HR 7001	9296	4.4	15	-0.318	0.07
HD 177196	HR 7215	8194	4.1	125	0.545	0.04
HD 180777	HR 7312	7544	4.4	55	0.566	0.02
HD 184006	HR 7420	8385	3.6	250	...	...
HD 61421	HR 2943	7008	2.9	...	...	...

Table A.4: Derived abundances for Oxygen and Carbon for stars which had reliable measurements. Errors in this table represent the measurement errors between the models and the data and do not represent the systematic error that goes into the model assumptions. Error from uncertainty in the temperature and surface gravity are the only errors propagated here. See text for more details.

HD	O I 6158	error	C 5052	error	C 7113	error
HD 197157	...	...	...	...	-0.28	0.01
HD 109536	0.27	0.02	...	...	...	...
HD 118098	-0.48	0.01	...	...	...	...
HD 172555	-0.56	0.03	...	...	...	...
HD 188228	0.32	0.03	-0.46	0.03	...	...
HD 18978	-0.79	0.01	-0.31	0.15	...	...
HD 202730	-0.51	0.06	...	...	...	...
HD 213398	-0.60	0.00	...	...	...	...
HD 21997	-0.29	0.00	...	...	...	...
HD 32297	-0.31	0.00	-0.55	0.09	...	...
HD 71155	-0.19	0.01	-0.18	0.04	...	...
HD 88955	0.02	0.03	-0.16	0.04	...	...
HD 99211	-0.31	0.00	-0.41	0.09	...	...
HD 115892	0.01	0.03	-0.18	0.05	...	...
HD 56537	-0.34	0.04	...	...	...	...
HD 76644	-0.47	0.04	-0.387	0.07	...	...
HD 85376	0.07	0.02	0.356	0.10	...	...
HD 89021	0.05	0.04	...	...	...	...
HD 95418	-0.18	0.03	-0.385	0.04	...	...
HD 95608	-0.48	0.08	...	...	...	...
HD 102647	-0.03	0.03	-0.193	0.06	...	...
HD 104513	0.31	0.01	...	...	...	...
HD 116656	-0.41	0.05	...	...	...	...
HD 139006	-0.36	0.00	0.139	0.05	...	...
HD 140436	-0.08	0.04	...	...	...	...
HD 141795	-0.60	0.03	...	...	...	...
HD 159541	-0.18	0.03	...	...	...	...
HD 165777	0.04	0.03	...	...	...	...
HD 172167	...	...	-0.106	0.05	...	...

HD 177196	...	...	-0.315	1.12	...	...
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