A Deep Polarimetric Study of the Asymmetrical Debris Disk HD 106906

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Abstract

Located in the Lower Centaurus Crux group, HD 106906 is a young, binary stellar system. This system is unique among discovered systems in that it contains an asymmetrical debris disk, as well as an 11 MJup planet companion, at a separation of ~735 au. Only a handful of other systems are known to contain both a disk and a directly imaged planet, where HD 106906 is the only one in which the planet has apparently been scattered. The debris disk is nearly edge-on and extends to roughly >500 au, where previous studies with the Hubble Space Telescope have shown the outer regions to have high asymmetry. To better understand the structure and composition of the disk, we have performed a deep polarimetric study of HD 106906’s asymmetrical debris disk using newly obtained H-, J-, and K1-band polarimetric data from the Gemini Planet Imager. An empirical analysis of our data supports a disk that is asymmetrical in surface brightness and structure, where fitting an inclined ring model to the disk spine suggests that the disk may be highly eccentric (e > 0.16). A comparison of the disk flux with the stellar flux in each band suggests a blue color that also does not significantly vary across the disk. We discuss these results in terms of possible sources of asymmetry, where we find that dynamical interaction with the planet companion, HD 106906b, is a likely candidate.

Unified Astronomy Thesaurus concepts: Infrared astronomy (786); Circumstellar disks (235); Circumstellar dust (236); Starlight polarization (1571); Debris disks (363); Planetesimals (1259); Planetary-disk interactions (2204)

1. Introduction

Debris disks can be characterized as gas-poor, dusty disks around main-sequence stars and are important objects to study in relation to better understanding the evolution of exoplanetary systems. Debris disks are formed through collisional cascade, in which colliding planetesimals, such as comets and asteroids, break into millimeter- to submicron-sized dust grains (Wyatt 2008; Matthews et al. 2014; Hughes et al. 2018). For this reason, debris disks are indicators of the successful formation of at least >1 m sized objects during the protoplanetary disk phase. However, processes from the central star(s), such as radiation pressure and stellar winds, cause dust grains under a certain size to be blown out from the system (Augereau & Beust 2006; Strubbe & Chiang 2006). Therefore, in order for a collisional cascade to occur and continually produce smaller dust grains to replenish the disk, planetesimals within the system need to have a sufficient relative velocity to cause fragmentation upon impact, meaning that some sort of stirring mechanism is required to perturb their orbits.

There are several stirring mechanisms that could occur, such as late planetesimal formation at large distances from the star (Kenyon & Bromley 2008; Kennedy & Wyatt 2010), interaction with the interstellar medium (ISM; Debes et al. 2009), close encounters with nearby stars (Kennedy et al. 2014), and planetary scattering (Kalas et al. 2015). The source of stirring may be determined by direct observation, as each of these mechanisms can affect the morphology and properties of the disk in slightly different ways, such as creating warps, eccentric disks, gaps, and rings. In any of these cases, the chances of creating an asymmetrical debris disk in terms of brightness and structure are high. For this reason, asymmetrical debris disks are especially interesting and make great candidates for study as they allow us to gain more insight into the architecture of exoplanetary systems.

The Gemini Planet Imager (GPI; Macintosh et al. 2014) has not only searched for exoplanets but also imaged many debris disks as well. From 2014 November to 2018 October, GPI
conducted its Exoplanet Survey (GPIES; PI: B. Macintosh; Macintosh et al. 2018), which was an 860 hr campaign to search roughly 600 stars for Jupiter-type planets, as well as debris disks observable through scattered light. Through this campaign, 26 debris disk targets were resolved via total intensity and/or polarized scattered light (Esposito et al. 2020).

One of these disks is HD 106906 (HIP 59960), which was first discovered by Spitzer through an infrared survey of 25 stars in the Lower Centaurus Crux group (Chen et al. 2005) and is located ≈103.3 pc away (Gaia Collaboration et al. 2018). It is a unique and interesting system for several reasons. First, it contains an eccentric, tight binary (e = 0.669 ± 0.002) with two F5V-type stars (De Rosa & Kalas 2019). Second, it has a possibly scattered 11 ± 2 MJup planet companion outside of the disk at a separation of 735 ± 5 au (Bailey et al. 2014; Daemgen et al. 2017). And finally, the HD 106906 system hosts a debris disk that features a brightness asymmetry, with a southeast (SE) extension that appears brighter than the northwest (NW) extension in both total and polarized intensity (Kalas et al. 2015; Lagrange et al. 2016; van Holstein et al. 2021).

The Hubble Space Telescope (HST), which has a much larger field of view than GPI, has also taken images of this system at optical wavelengths. The results from HST have shown that the NW side of the disk halo seems to extend to >500 au, creating a “needle”-like structure (Kalas et al. 2015). On the other hand, this same feature is not observed for the SE extension. The HST data also show that the planet has a position angle (PA) ~21° from the NW extension. Because of the wide separation of HD 106906b, its orbit is challenging to constrain; however, recent analysis has presented the first detection of the planet’s orbit. If the planet is bound, this analysis shows a highly eccentric, noncoplanar orbit with a periastion distance that comes reasonably close to the disk (Nguyen et al. 2021).

The fact that HD 106906 hosts an asymmetric debris disk, as well as a planet companion external to the disk, raises questions about whether or not HD 106906b is responsible for this asymmetry. Previous work has shown that if HD 106906b indeed formed within the disk, it could have migrated inward and, consequently, been ejected through dynamical interactions with the stellar binary (Rodet et al. 2017). While an in situ formation scenario for the planet is possible, this is less favored compared to the scattering scenario due to the lack of circumstellar gas at that distance, as well as the planet formation timescale being greater than the lifespan of gas in a fiducial protoplanetary disk. In both formation scenarios, however, secular effects from the orbiting planet could create major asymmetries in the disk (Nesvold et al. 2017; Rodet et al. 2017). If the scattering scenario were true, the planet may have also had dynamical interactions with the disk on its scattered path, leading to a perturbed disk.

The goal of this paper is to better understand the source of the disk’s asymmetry. To do this, we analyzed the latest GPI data, revealing evidence of a geometrically asymmetric and eccentric disk. We further studied the disk through 3D radiative-transfer modeling, gaining a deeper look at the disk’s density structure and dust grain properties. We chose to concentrate on the polarimetric data of the HD 106906 debris disk, as polarimetry allows us to better probe the dust grains and gives a better representation of the total disk structure. We discuss our results in terms of dynamical perturbation from HD 106906b and an ISM interaction.

### 2. Observations and Data Reduction

#### 2.1. GPI Observations

We obtained deep polarimetric data of HD 106906 in the H band (peak λ = 1.647 μm) from GPIES. These data have a greater total integration time (2564.79 s compared to 709.94 s) and field rotation (20′3 compared to 7′1) than the polarimetric data presented in Kalas et al. (2015). We also obtained polarimetric J- (peak λ = 1.235 μm) and K-band (peak λ = 2.048 μm) data through one of the Gemini Observatory’s Large and Long Programs (PI: Christine Chen). The H-band data were taken on 2015 June 30 using the GPI’s polarimetric (H-Pol) mode. The J- and K1-band data were later taken over a 4 day period from 2016 March 24 to 28, again in polarimetric (J-Pol and K1-Pol) mode. Due to a malfunction in the GPI’s apodizer wheel at that time, all three observations used the coronagraph apodizing mask that was optimized for the H band (“APOD H G6205”). Further details about the polarimetric observations can be found in Table 1.

#### 2.2. Data Reduction

Each of these sets of data were reduced through the GPI Data Reduction Pipeline (Perrin et al. 2014). In GPI’s polarization mode, a pair of spots is created by each lenslet, representing both orthogonal polarization states Q and U. The first step in the reduction process is to create 3D cubes from the raw data, where the three dimensions contain an image for each orthogonal polarization state. The raw data are dark-subtracted, bad pixel–corrected, and cleaned of correlated detector noise, then combined into polarization data cubes. The images are then corrected for geometric distortion. The position of the star is found by measuring a set of fiducial satellite spots (Wang et al. 2014).

Next, the data cubes are combined to create the final composite data cube. In this final step, the instrumental polarization is measured from the apparent stellar polarization in each data cube by measuring the average fractional polarization inside the occulting mask, which is then subtracted from each cube (Millar-Blanchaer et al. 2015). Additionally, each cube is smoothed with a Gaussian kernel (FWHM of 1 pixel), and the satellite spot–to–star flux is measured in order to determine a photometric calibration.
After this measurement, the 3D cubes are combined to create a single radial Stokes image, consisting of Stokes \(I, Q, U, V\). Finally, using the stellar magnitude and photometric calibration factor for each filter+apodizer combination, the data were calibrated from ADU coadd\(^{-1}\) to Jy arcsec\(^{-2}\) (Hung et al. 2016).

The final images in each filter can be seen in Figure 1, where the left column represents the data in \(Q\), and the right column represents the data in \(U\). The white circles represent the size of the focal plane mask (FPM), with a radius of 0.09, 0.12, and 0.15, respectively.

Figure 1. The HD 106906 debris disk in \(J\)-, \(H\)-, and \(K\)-band polarized intensity as observed with GPI. The left column depicts the disk in \(Q\). The right column depicts the disk in \(U\). White circles denote regions obscured by GPI’s FPM, and black crosses mark the star location.
3. Observational Results

Consistent with previous observations, we find the disk to be very forward-scattering, where mainly the front side of the disk is visible. As seen in Figure 1, a brightness asymmetry can be visually observed in all three bands, where the SE extension is brighter than the NW extension. This asymmetry is most prominent in the $H$ band, although the asymmetry seems to be present in the $J$ and $K_1$ bands as well. Quantifying the surface brightness in these two bands will help confirm this. Figure 2 shows a closer look at the disk in each band, smoothed with a Gaussian ($\sigma = 1$ pixel) and overlaid with contours to accentuate the surface brightness features.

Additionally, we created noise maps at each wavelength from the $U_\phi$ image as the standard deviation at each radius in 1 pixel wide stellocentric annuli. As expected for an optically thin debris disk causing single scatterings, we assume the corresponding $U_\phi$ images contain noise but little or no disk signal, although we acknowledge that a small amount of disk signal could be present due to smearing introduced by the finite size of the point-spread function (PSF; Heikamp & Keller 2019). By dividing these noise maps from our $Q_\phi$ images, we create a signal-to-noise ratio ($S/N$) image for each wavelength, which can be seen in Figure 3. Comparing the $S/N$ between each band, we find that the $H$ band has the highest $S/N$, while the $J$ band has the lowest $S/N$, likely due to lower Strehl and poorer seeing. Using an $S/N$ of $2\sigma$ (corresponding with the outermost contour in Figure 2), we find that the disk extends roughly between $1''0$ and $1''1$ (103–114 au) for the three bands, where we do not observe a significant radial extent asymmetry. This is consistent with results found for the polarized data analyzed in Kalas et al. (2015), where no radial extent asymmetry was found, in contrast to their total intensity data.

3.1. Surface Brightness

For this section, we calculated the peak surface brightness profile in each wavelength in order to quantify the surface

**Figure 2.** The $J$, $H$, and $K_1$-band polarimetric intensity, overlaid with surface brightness contours. Scaling is the same as in Figure 1. Contours represent a surface brightness of 0.3, 0.6, 1.2, and 2.4 mJy arcsec$^{-2}$, where the outermost contour corresponds to $2\sigma$.

**Figure 3.** The $S/N$ maps for HD 106906 in the $J$, $H$, and $K_1$ bands. Note that the $H$ band has the highest $S/N$. White circles denote regions obscured by GPI’s FPM, and black crosses mark the star location.
brightness asymmetry. To do this, we find the peak brightness along the spine of the disk. After rotating the disk to be horizontal, we find the maximum (“peak”) surface brightness along vertical slices. The peak surface brightness is then binned by 3 pixels along the horizontal axis and averaged. These results can be found in Figure 4, showing the peak surface brightness in mJy arcsec$^{-2}$ as a function of projected separation from the star in arcseconds. The error bars are calculated using the noise map in each filter.

In all three bands, we observe the same general shape of the surface brightness profiles. Within $\sim 0.50$, the surface brightness peaks closest to the star and decreases steeply toward larger stellar separations. Approximately between 0.50 and 0.70, the surface brightness briefly plateaus before again decreasing more gradually out to $\sim 1.7$. Looking at the relative peak surface brightness between each band, we confirm that there is a brightness asymmetry in all three wavelengths across the disk. Table 2 shows the percentage by which the SE extension is brighter than the NW extension, segmented by radial separation from the star. While the asymmetry differs slightly between each band, all three exhibit an SE extension that is roughly 10-30% brighter than the NW extension. We find that the $H$ band exhibits the greatest asymmetry with 30.9% brighter in the SE extension between the inner working angle (IWA) and 0.40, about 10% greater than that measured in Kalas et al. (2015), and shows another peak of 27.0% $\pm$ 3.9% between 0.60 and 0.80. The asymmetries in the $J$ and $K1$ bands are more modest, with a smaller asymmetry along the disk compared to the $H$ band. While the $J$ and $K1$ bands have larger uncertainties, because these three bands are very close in wavelength, we do not expect that the true surface brightness asymmetry varies too significantly between them. The asymmetry seen in the $H$ band is more likely a better representation of the true brightness asymmetry observed at these near-IR wavelengths due to its much higher S/N. Regardless, this analysis shows that a modest surface brightness asymmetry exists along the disk in all three bands, and that the previously resolved asymmetry does not result from an artifact.

Comparing the flux of the disk to the flux of the star in different bands tells us about the disk scattered-light color. Figure 5 shows the disk color as a function of the difference in the disk surface brightness minus the stellar magnitude between each band. We use the 2MASS $J$, $H$, and $K$-band magnitudes for HD 106906AB (6.946 $\pm$ 0.03, 6.759 $\pm$ 0.038, and 6.683 $\pm$ 0.026 mag, respectively). To measure the color, the disk flux in each band is integrated between 0.30 and 0.85 and over $\sim 0.15$ vertically on both sides of the disk. The total flux is then converted to mag arcsec$^{-2}$ and compared between two bands, where the stellar magnitudes in each band are then subtracted (i.e., $\Delta(M_{\text{disk}} \text{arcsec}^{-2} - M_{\text{star}})$ for $H - K = (H - K)_{\text{disk}} - (H - K)_{\text{star}}$). Here a value above zero indicates a red disk color, a value below zero indicates a blue disk color, and a value of zero indicates a neutral disk color. We find that the disk predominantly exhibits a blue color, where calculating $\Delta(M_{\text{disk}} \text{arcsec}^{-2} - M_{\text{star}})$ between each band gives $J - H = -0.38 \pm 0.06$ mag, $J - K = -0.52 \pm 0.07$ mag, and $H - K = -0.14 \pm 0.05$ mag. The difference between $J - K1$ and $H - K1$ also suggests that the disk color becomes increasingly more neutral toward longer wavelengths, consistent with disk color trends seen with other debris disks, such as HD 15115 and HR 4796A (Rodigas et al. 2012, 2015).

The disk color gives some information about the dust grains in the disk, as color is associated with certain dust grain properties, such as the minimum dust grain size and porosity. For example, at a wavelength of 1.6 $\mu$m ($\sim H$ band) versus 2.2 $\mu$m ($\sim K$ band) and a porosity of zero, numerical simulations have shown that a strong blue disk color could be produced by a submicron minimum dust grain size, whereas a neutral disk color could be produced by a larger minimum dust grain size of several microns. A porosity greater than zero can also increase the estimated minimum dust grain size as well (Boccaletti et al. 2003; Kirchschlager & Woll 2013). The fact that our $H - K1$ color measurement is only weakly blue and close to neutral suggests that the disk may have a larger minimum dust grain size. This being said, the minimum dust grain size is difficult to untangle and quantify from the disk color alone, as dust composition and the scattering phase function (SPF) also have an effect. What is more important is that we do not see a difference in color between the two extensions, implying that the dust grain properties do not significantly vary on either side of the disk.

### 3.2. Vertical Height

To quantify the structure of the disk, we first measured the vertical height via the FWHM of the disk as a function of radial separation from the star. We chose to do this with the $H$ band, as it has the highest S/N. We first rotate our image so that the disk’s major axis is horizontal. Next, we measure the surface brightness along vertical cross sections of the disk at various radial separations from the star until the whole disk has been covered. We then fit a Gaussian to each vertical brightness profile and use this to extract the FWHM at each cross section. The results can be seen in Figure 6, where error bars are taken from fitting the Gaussian to the data.

On both sides, we measure the FWHM out to $r \approx 1.7$. We find the weighted mean FWHM (weights = $1/\sigma^2$) to be $0.16$, represented by the gray dashed line in Figure 6. Comparing this value to the instrumental FWHM of the PSF ($\sim 0.054$) confirms that the disk is fully resolved. This value of $0.16$ is also $\sim 18\%$ larger than the value measured in Kalas et al. (2015) of $\sim 0.13$, although still consistent within the scatter of our FWHM data points. Subtracting the instrumental FWHM from our weighted mean in quadrature gives us an intrinsic FWHM of $\sim 0.15$, or 15.6 au. While the FWHM fluctuates...
Table 2
Brightness Asymmetry between the NW and SE Extensions for Each Band as a Function of Stellar Separation

| Band   | IWA-0°40 | 0°50-0°70 | 0°70-0°80 | 0°80-1°00 |
|--------|----------|-----------|-----------|-----------|
| J      | 26.9% ± 9.7% | 9.7% ± 12.6% | 22.3% ± 10.7% | 18.3% ± 15.0% |
| H      | 30.9% ± 4.4% | 18.9% ± 4.1% | 27.0% ± 3.9% | 21.0% ± 3.9% |
| K1     | 23.4% ± 11.2% | 14.5% ± 11.2% | 18.0% ± 12.3% | 23.9% ± 17.2% |

Note. Units are in a percentage of how much brighter the SE extension is compared to the NW extension.

Figure 5. Disk color between each band as a function of radial separation from the star in arcseconds. Horizontal dashed lines represent the weighted means for $J-K1$ (blue), $J-H$ (green), and $H-K1$ (red).

Figure 6. The $H$-band FWHM profile of the disk as a function of stellocentric distance in arcseconds. The weighted mean FWHM of the disk is represented by the gray dashed line, the intrinsic FWHM is represented by the red dashed line, and the instrumental FWHM is represented by the blue dashed line.

around the weighted mean, there appear to be no significant trends in the FWHM with stellocentric distance. This is consistent with a radially narrow ring, as projection effects would cause an increase in the vertical FWHM with distance if the disk were broad. A narrow ring also aligns with the conclusions made by Kalas et al. (2015) and Lagrange et al. (2016); however, we note that the vertical FWHM is only an indirect measure of the radial width, and we cannot make a firm conclusion based on it alone.

3.3. Vertical Offset

While the vertical height tells us about the disk structure, measuring the vertical offset, which traces the disk spine, may be even more revealing. The disk spine refers to where the peak surface brightness along the disk is located relative to the star in the vertical direction. To measure this, we refer back to our Gaussian fitting (Section 3.2), where the spine location is related to the mean value of the Gaussian. We can then compare the vertical offset between the spine location and the star as a function of radial separation. These results can be seen as the blue data points in Figure 7, where the error bars are taken from the Gaussian fitting. At first glance, the vertical offset looks to be asymmetric, where past 100 au ($\sim1''0$), the vertical offset dips below $-2$ au in the SE extension, whereas this is not the case for the NW extension.

To investigate this asymmetry further, we generate a simple inclined, circular, narrow ring model, following the same procedure used by Duchêne et al. (2020). Our free parameters include the ring radius ($R_d$), inclination ($i$), PA measured from east of north, and offsets of the ring center from the star along the major and minor axes ($\delta_x$ and $\delta_y$). Here we are assuming that the star is located perfectly at the center of our data; however, it is important to note that some small systematic uncertainties may be present. A best-fitting model can be found by using a Markov Chain Monte Carlo (MCMC) fit via the Python package emcee (Foreman-Mackey et al. 2013); for more details about this method, see Section 4.2. Our best-fitting model can be seen in Figure 7, represented by the orange line. Through this modeling, we find $R_d = 101.84^{+1.75}_{-1.61}$ au, $i = 85.57^{+0.14}_{-0.15}$, and $PA = 104.31^{+0.16}_{-0.30}$, where our inclination and PA are consistent with those derived in Kalas et al. (2015) and Lagrange et al. (2016). More interestingly, we find $\delta_x = 16.48^{+2.04}_{-1.76}$ and $\delta_y = -2.99^{+0.28}_{-0.30}$ au, which implies a significant eccentricity, placing the star closer to the SE extension. While possible systematic uncertainties may lower
the significance of the small offset along the minor axis, this is not the case for the large offset along the major axis. Therefore, we can use \( \delta_x \) to place a lower limit on an eccentricity of \( > 0.16 \). Because modeling the spine suggests an inherently asymmetric disk geometry, a circular ring model is no longer appropriate, where modeling with a proper ellipse will be needed to further probe the eccentricity and disk orientation.

To evaluate whether or not the \( x \)-offset is reasonable, we estimate the expected surface brightness asymmetry from a 16.48 au offset by comparing \( 1/r^2 \) (where \( r \) is the distance from the star to disk) and the SPF between the SE and NW at the same radial separations from the star. We first calculate \( r \) on both sides between \( 0^\circ 45 \) and \( 0^\circ 50 \), roughly halfway across the disk, where the SPF would not be affected by limb brightening near the ansae or the noise present close to the star. Using a disk radius of 101.84 au and a stellar offset of 16.48 au toward the SE extension, we obtain an SE/NW \( 1/r^2 \) ratio of \( \sim 1.4 \).

This means that based solely on the relative distances between the star and the disk, we would expect the SE extension to be about 1.4 times brighter than the NW extension at those separations, about 12\% greater than what we measure with our \( H \)-band data (see Table 2). However, the difference between the SPF at those separations can also affect the expected brightness asymmetry. We therefore calculate the scattering angles between \( 0^\circ 45 \) and \( 0^\circ 50 \) and assume that the SPF in the HD 106906 disk conforms with the generic SPF observed in the solar system and other debris disks (Hughes et al. 2018) to estimate the SPF ratio between the SE and NW. Doing so, using our calculated scattering angles of \( \sim 25^\circ -27^\circ \) for the NW and \( \sim 29^\circ -33^\circ \) for the SE, we find that the NW extension has an SPF \( \sim 1.25 \) times greater than the SE extension. Taking this into account, we expect that the greater SPF in the NW extension partially cancels out the \( 1/r^2 \) effect and therefore decreases the expected brightness asymmetry. While these are only rough estimates, as we do not know the exact SPF of this disk, they show that we would not expect a large brightness asymmetry despite the large offset derived from our spine fitting, and that the more moderate brightness asymmetry observed with our data is reasonable.

4. MCFOST Modeling of HD 106906

4.1. Debris Disk Model

The 3D radiative-transfer code MCFOST is designed to model circumstellar disks around young objects and can create fully polarized, scattered-light, synthetic observations (Pinte et al. 2006). For our models, the “debris disk” option is chosen within MCFOST, where the volume profile is defined by the following equation (Augereau et al. 1999):

\[
\rho(r, z) \propto \exp \left( -\frac{(|z| / h(r))}{h_0} \right)^{\frac{1}{2}},
\]

\[
h(r) = H_0 \left( \frac{r}{R_0} \right)^{\alpha}.
\]

In Equation (1), \( r \) is the radial distance from the star in the plane of the disk, and \( R_c \) is the critical radius inside and outside of which the surface density approaches power laws with indices \( \alpha_{in} \) and \( \alpha_{out} \) respectively. In addition, \( z \) is the height above the disk midplane, and \( h(r) \) describes the scale height profile, with a vertical exponent of \( \gamma \). Equation (2) defines \( h(r) \), where \( H_0 \) is the scale height at a reference radius, \( R_0 \).

To model the dust grain properties, Mie theory is used, where the dust grains are assumed to be spherical and compact. This idealized model, which does not capture the complexities expected in real dust grains, has implications that will be discussed later in this paper. However, for now, this assumption allows for easy and fast scattering computations. In addition, the dust grain size follows a power-law distribution of \( dN(a) \propto a^{-q} \), where \( a \) ranges from the minimum dust grain size \( a_{min} \) up to a size of 1 mm, and \( q \) is the power law for the dust grain size distribution. We also explore dust composition, looking exclusively at the volume fractions of astrosilicates, amorphous carbon, and water ice. The optical indices for each material are obtained from the literature (Si, Draine & Lee 1984; aC, Rouleau & Martin 1991; H2O, Li & Greenberg 1998). The dust compositions (Si, aC, and H2O) are set using effective medium theory, in that they make up one dust grain species (e.g., a single grain could consist of 50\% Si, 25\% aC, and 25\% H2O). First, the porosity is fixed for all dust grains that assume a single power-law size distribution. Then, the composition of the dust grains is allowed to vary as the relative fractions of each component are kept as free parameters.

The MCFOST code creates each model at a user-specified wavelength. For our purposes, we choose 1.647 \( \mu \)m (where the \( H \) filter throughput peaks). Here MCFOST produces a 4D fits image, which includes the final model in Stokes \( I, Q, U, V \) intensities. The \( Q \) and \( U \) maps for each model are converted to Stokes \( Q_e \), and convolved with an instrumental PSF. Both our \( H \)-band data and models are masked at radial separations greater than \( 1/2 \) and smaller than \( 0/12 \) to ensure that noisy pixels are left out.

4.2. MCMC Analysis

To determine the best-fitting values for each parameter explored, the models must be compared to the data. To do this, we again utilize the Python package emcee (Foreman-Mackey et al. 2013). It uses MCMC, which allows us to find confidence intervals and best estimates for each parameter defining the density structure and dust grain properties of the disk.

In this process, we model the \( H \)-band data alone, as they have the highest S/N. To begin with, properties that are related to the density structure of the disk are first allowed to vary over a range of priors. The parameters that would most strongly affect the disk brightness are kept constant; this includes dust grain properties such as the minimum grain size and composition. This is done to limit parameter space and therefore speed up computation time. A list of density structural parameters, the initial value for each, and their prior range can be viewed in Table 3.

Our free parameters for the density structure include \( H_0, \gamma, R_c, \alpha_{in}, \) and \( \alpha_{out} \). We also include stellar offset parameters, \( x_s \) and \( z_s \), where \( x_s \) is the offset along the disk major axis and \( z_s \) is the offset in the vertical direction relative to the disk. The parameter, \( x_s \), is related to \( \delta_x \) from our disk spine fitting in Section 3.3, where the main difference is that the star itself is being offset instead of the inclined ring, meaning that an offset toward the SE extension would be negative rather than positive. The parameter, \( z_s \), differs from \( \delta_z \), as it represents an offset above or below the disk midplane, where \( \delta_z \) is the projected offset along the minor axis. While our parameterized models do

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not account for geometrical asymmetries (the synthetic disk remains circular), so as to not make our models overly complex, a stellar offset can still be used to create a surface brightness asymmetry. Important structural parameters, such as inclination and PA, were not considered in this analysis, as they are already well defined from previous work, as well as our spine fitting, to be $\sim 85^\circ$ and $\sim 104^\circ$, respectively (Kalas et al. 2015; Lagrange et al. 2016). Therefore, we fix these parameters in order to reduce the parameter space and computational time. Additionally, the inner radius is set to 50 au, based on observations from Kalas et al. (2015), and the outer radius to 200 au (roughly twice the outer radius observed in our data), where $R_0$ is fixed at 100 au. After we model the density structure, we then hold these values constant at the median (50th) percentile values and instead vary the dust grain parameters. A list of the dust grain parameters, the initial value for each, and their prior range can be viewed in Table 3. Here $M_{\text{dust}}$ is the total dust mass in Earth masses, porosity defines how fluffy or compact the dust grains are (where zero porosity corresponds to a perfectly compact dust grain), $V_{\text{Si}}$ is the volume fraction of astronomical silicate, $V_{\text{ac}}$ is the volume fraction of amorphous carbon, and $V_{\text{HO}}$ is the volume fraction of water ice. Finally, $a_{\text{min}}$ is the minimum dust grain size, and $q$ is the power law for the distribution of dust grain sizes.

For each run, 200 walkers are deployed to explore the parameter space, starting at the initial values as stated in Table 3. These walkers move around freely in order to find the maximum log-likelihood values for each parameter, as well as their posterior distributions. The likelihoods between our models and $H$-band data are calculated pixel by pixel using the $\chi^2$ function. This occurs for up to several thousand iterations until after the parameters have clearly converged or the log likelihood for the walkers is no longer increasing.

### 4.3. Results

For the MCMC analysis of the density structural parameters, emcee was allowed to run for a few thousand iterations, until well after convergence, to make sure that we had the best results. We then reran the MCMC analysis, where this time, the density structural parameters were kept fixed using the median percentile values (50%) obtained in the previous run. This analysis was allowed to run again until the log likelihood was no longer noticeably changing. The results for both the density structure and dust grain parameters can be found in Table 4, which lists the 16th, 50th, and 84th percentiles. The final model, created from the median percentile values from each parameter’s confidence intervals, can be seen in Figure 8.

From our MCMC modeling, we obtain an $H_0$ of 4.34 $^{+0.04}_{-0.03}$ au with a vertical profile exponent of $\gamma = 0.715^{+0.01}_{-0.01}$. This would give the scale height to disk radius a ratio of $h/r \approx 4\%$, which is consistent with the $h/r$ found for other debris disks such as β Pic, Fomalhaut, and AU Mic (Kalas et al. 2005; Krist et al. 2005; Millar-Blanchaer et al. 2015). However, the shallow $\gamma$ appears to be in contradiction to the Gaussian profile used in Section 3.2, driven by the shape of our data, where a shallow $\gamma$ would suggest a more Lorentzian profile. Given our limited S/N and model limitations, we note that it may be difficult to firmly establish the nature of the vertical profile. Next, we obtain a critical radius, $R_c$, of 72.21 $^{+3.10}_{-3.30}$ au, which lies roughly halfway between the set inner radius (50 au) and our disk radius of 101.84 au derived in Section 3.3. We also find surface density power laws of $\alpha_{\text{in}} = 1.03^{+0.23}_{-0.22}$ and $\alpha_{\text{out}} = -2.26^{+0.11}_{-0.08}$. These shallow power laws give the disk a dust density distribution ranging from a fixed inner radius of 50 au to a half-maximum at $\sim 111$ au and an $R_{\text{peak}}$ (radius of peak density) of $\sim 64$ au, consistent with that derived in Lagrange et al. (2016). However, this is in contradiction to the assumption of a radially narrow ring based on our vertical FWHM profile, as these values give $\Delta R/R = 0.95$, consistent with a radially broad disk. Although projection effects may still be present within our limited S/N data, another possibility is that the inner radius lies beyond 50 au. Given that the near-edge configuration of the disk makes it difficult to constrain $R_{\text{in}}$, we can only put an upper limit on $\Delta R/R$ of 0.95. Future modeling and analysis of polarized and spectral data may be able to help shed more light on the location of the inner radius.

For the stellar offset parameter, $z_{\text{tot}}$, we find values that are very close to zero (0.25–0.29 au), meaning that the star lies within the midplane of the disk, as we would expect. Surprisingly, the MCMC favors a stellar offset of only $\sim 3.58$ au toward the SE extension of the disk, which is much smaller than the stellar offset of $\sim 16.5$ au predicted from our spine fitting. An offset this small is unable to match the surface

### Table 3

The Density Structural Parameters and Dust Grain Properties Chosen to Be Constrained, Along with the Initial Value and Prior Limits Chosen for MCMC Analysis

| Param. | Initial Val. | Limits |
|--------|--------------|--------|
| $H_0$ [au] | 5.0 | [1.0, 10] |
| $\gamma$ | 0.0 | [0.1, 3.0] |
| $R_0$ [au] | 100 | [50, 200] |
| $a_{\text{in}}$ | 0.5 | [0.0, 1.5] |
| $a_{\text{out}}$ | $-1.0$ | $[-5.0, -0.5]$ |
| $x_{\infty}$ [au] | 0.0 | $[-40.0, 40.0]$ |
| $z_{\infty}$ [au] | 0.0 | $[-10.0, 10.0]$ |
| $M_{\text{dust}}$ [M$_\oplus$] | 0.033 | [0.000033, 3.33] |
| Porosity | 0.5 | [0.0, 1.0] |
| $V_{\text{Si}}$ | 0.5 | [0.0, 1.0] |
| $V_{\text{ac}}$ | 0.5 | [0.0, 1.0] |
| $V_{\text{HO}}$ | 0.5 | [0.0, 1.0] |
| $a_{\text{min}}$ [μm] | 1.5 | [0.3, 4.0] |
| $q$ | 3.5 | [2.0, 6.0] |

### Table 4

MCMC Results for Density Structural and Dust Grain Parameters

| Param. | 16% | 50% | 84% |
|--------|-----|-----|-----|
| $H_0$ [au] | 4.07 | 4.34 | 4.38 |
| $\gamma$ | 0.708 | 0.715 | 0.723 |
| $R_0$ [au] | 68.92 | 72.21 | 75.31 |
| $a_{\text{in}}$ | 0.79 | 1.03 | 1.32 |
| $a_{\text{out}}$ | $-2.34$ | $-2.26$ | $-2.16$ |
| $x_{\infty}$ [au] | $-3.63$ | $-3.58$ | $-3.35$ |
| $z_{\infty}$ [au] | 0.25 | 0.27 | 0.29 |
| $M_{\text{dust}}$ [M$_\oplus$] | 0.012 | 0.02 | 0.11 |
| Porosity | 0.02 | 0.1 | 0.29 |
| $V_{\text{Si}}$ | 0.19 | 0.39 | 0.53 |
| $V_{\text{ac}}$ | 0.06 | 0.38 | 0.70 |
| $V_{\text{HO}}$ | 0.04 | 0.20 | 0.46 |
| $a_{\text{min}}$ [μm] | 0.91 | 3.17 | 3.72 |
| $q$ | 2.99 | 3.19 | 3.30 |

Note. This includes the values for the 16th, 50th, and 84th percentiles.
brightness asymmetry observed in the $H$ band. This can be seen in Figure 8, where there is a large residual remaining in the SE extension. One reason why the MCMC might prefer models with a smaller stellocentric offset could be the lack of a radial extent asymmetry in our data, as a larger offset would create a truncated SE extension. This would be an issue caused by the fact that, despite having a stellocentric offset, our models are geometrically symmetric circles.

While our confidence intervals for the density structure parameters were well constrained, constraining the dust grain parameters proved to be much more difficult. We obtain a total dust mass of $0.02^{+0.009}_{-0.008} M_\odot$. This is on the same order as the masses derived from millimeter ($\sim 0.05 M_\odot$; Kral et al. 2020) and mid-IR observations (0.067 $M_\odot$; Chen et al. 2011); however, our confidence interval is large and spans two probability peaks at $\sim 0.016$ and $\sim 0.11 M_\odot$. We obtain a porosity of $0.10^{+0.19}_{-0.08}$, showing a significant preference for grains with a low porosity or compact grains. The composition is nearly unconstrained, with all three compositions (Si, aC, and H$_2$O) having very large confidence intervals and multiple peaks in their posterior distributions. The MCMC results slightly favor larger fractions of Si and aC, with smaller fractions of H$_2$O; however, we cannot make strong conclusions about the composition given their broad posteriors.

For the minimum dust grain size, we obtain $a_{\text{min}} = 3.17^{+0.55}_{-0.26} \mu m$, where we have a large probability peak at 0.91 $\mu$m and a second, smaller peak between 3 and 4 $\mu$m. While a minimum dust grain size of 0.91 $\mu$m is more consistent with the calculated blowout size for the system ($\sim 0.85/\mu$m), a larger size may be more consistent with the disk color measured in Section 3.1. To test this, we compute $\Delta (M_{\text{disk}} \text{ arcsec}^{-2} - M_{\text{all}})$ over the same integrated distances as in Section 3.1 for our median model at all three wavelengths. This is done for an $a_{\text{min}}$ of both 0.91 and 3.17 $\mu$m. We find that an $a_{\text{min}}$ of 3.17 $\mu$m is more consistent with the observed disk color ($H - K_1 = -0.15$ mag), compared to our model with an $a_{\text{min}}$ of 0.91 $\mu$m, which exhibits a much stronger blue color ($H - K_1 = -0.66$ mag). Therefore, we find that the data favor a larger minimum dust grain size, although $a_{\text{min}}$ could be further informed in future work using the degree of linear polarization.

Finally, we obtain a power law for the dust grain size distribution of $q = 3.19^{+0.11}_{-0.20}$. This is slightly smaller than the predicted size distribution slope of $q \approx 3.5$ for a collisional cascade (Dohnanyi 1969; Marshall et al. 2017); however, other debris disks have been found to deviate from this value. Additionally, our obtained value for $q$ is comparable to the size distribution slope found for the millimeter observations of $3.36 \pm 0.13$ (Kral et al. 2020) within 1$\sigma$.

Comparing our $H$-band data with the best-fit model, we see that while the NW extension seems to be modeled well with no lingering residuals, as stated before, the SE extension features a significant residual along the disk. We find this to be more evidence for a geometrically asymmetric and likely eccentric disk, as our symmetric/circular models are unable to fully model both the disk structure and surface brightness asymmetry simultaneously. This may have affected our final modeling results, since we would need a model that has an asymmetric dust density profile to more accurately model our asymmetric disk. However, we leave this more complex modeling for future work.

5. Discussion

5.1. Model Limitations

There are several limitations with our MCFOST models that could impact our results. The first, as discussed above in Section 4.3, is that our models are not inherently eccentric. While we are able to offset the star, we assume the disk to be circular with a symmetric dust density profile, which would not be the case for a truly eccentric disk. This assumption has likely caused our final model to underestimate the surface brightness asymmetry, as seen in the residual in Figure 8. Following the same steps as in Section 3.3, we compute $1/r^2$ and the SPF between 0$''$45 and 0$''$50, this time using a stellar offset of 3.58 au. Doing so, we find that the effects from $1/r^2$ and the SPF at these radial separations almost completely cancel each other out, meaning that no brightness asymmetry would be seen with an offset this small. While a larger offset is needed to reach the observed brightness asymmetry, increasing the stellar offset in our symmetric models creates a more ill-fitting model, as this creates a radial extent asymmetry not observed in our data. This leads us to believe that in order to better represent the disk, we need a model that is eccentric with an asymmetric dust density profile.

Another limitation is that our models assume a smooth dust mass distribution defined with only one power law, which may not necessarily be realistic, as certain sizes of dust grains may

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18 Assuming a combined mass of 2.71 $M_\odot$ for HD 106906AB (Rodet et al. 2017) and a luminosity of $6.56 \pm 0.04 L_\odot$ (Gaia Collaboration et al. 2018), we approximate the blowout size ($a_{\text{blouw}}$) for this system to be $\sim 0.85/\mu$m (Burns et al. 1979; Pawellek & Krivov 2015). Dust grains below this size should be blown out of the disk by radiation pressure from the central binary.
be missing or the distribution may more closely resemble a function composed of more than one power law (Strubbe & Chiang 2006). High-resolution Atacama Large Millimeter/submillimeter Array data would be useful in this case to constrain the dust mass distribution with millimeter observations, which can then be used within MCFOST to create a more realistic model.

The final limitation comes from the use of Mie theory in our models. As mentioned before, Mie theory uses compact spherical grains, which makes computations much faster and easier but is unrealistic. In reality, dust grains are not perfectly spherical but rather irregularly shaped aggregates. This may strongly affect the accuracy of our results for the dust grain properties, as they rely heavily on this assumption and how light is scattered. For example, Min et al. (2015) found that the SPF differed between Mie dust grains and realistic aggregates for scattering angles greater than 90° (back side of the disk). Where for Mie grains, the SPF generally decreased, they found that for aggregates, the SPF either increased or stayed flat. Another discrepancy due to Mie theory is the effect this has on the blowout size. Arnold et al. (2019) calculated $a_{\text{blow}}$ for aggregates with a porosity of 76.4% and found that, in general, it was two to three times higher than for Mie compact grains. In addition, multiple studies of other debris disks have also found that Mie theory is unable to match the observations (Milli et al. 2017; Arriaga et al. 2020; Duchêne et al. 2020). While we leave more complex modeling with realistic aggregates for future work, we believe our results are still useful in comparing to previous work done on HD 106906 and other debris disks.

5.2. Dynamical Interaction with HD 106906b

In this section, we compare our results to previous simulation work, including both works focused specifically on HD 106906 and more general disk–planet interaction studies.

The empirical analysis of our data supports a significant eccentricity; this could be due to interaction with HD 106906b, either as it was ejected from the disk or due to secular orbital effects. There are two previous studies that consider these scenarios using particle simulations (Nesvold et al. 2017; Rodet et al. 2017). While Rodet et al. (2017) examined the morphological outcomes of the disk from both the planet being ejected and secular effects, Nesvold et al. (2017) solely examined the secular effects.

Rodet et al. (2017) found that the ejection of the planet from the disk was able to reproduce the asymmetries on larger scales, as seen with HST, where particles are blown out to high eccentricities on the right side of the disk. However, the ejection was not able to reproduce the SE/NW asymmetry on smaller scales, as seen with GPI in this work and Kalas et al. (2015). On the other hand, the effect of the planet on an eccentric, inclined orbit was able to reproduce the smaller-scale asymmetries with a larger density in the SE than the NW. This also gives rise to a needle-like halo at larger distances, but not as strongly as the ejection scenario, suggesting that the two effects together could explain the observations on large and small scales.

In contrast, Nesvold et al. (2017) conducted an in-depth study of the effect on the disk from the planet, initially located at 700 au (in situ) with an adopted eccentricity of 0.7, as it orbits at different inclinations. Through this alone, they were able to recreate both the small- and large-scale asymmetries, where a needle-like structure was seen up to 500 au, while closer in, the SE extension is brighter than the NW extension. The simulation also predicts that the planet should induce a large eccentricity on the disk, up to $\sim0.3$, which agrees well with the large eccentricity ($e \gtrsim 0.16$) we derive from our spine fitting. One caveat is that this model predicts a greater surface brightness asymmetry than we observe in our GPI data, particularly past 50 au ($\sim50\%$ brighter SE extension compared to $\sim18\%–27\%$ derived in Section 3.1); however, this is taking into account the total scattered light compared to polarized light.

In a more general case, Lee & Chiang (2016) looked at a number of different debris disk morphologies induced by a single eccentric planet companion. One of these morphologies is the “Needle,” which is described as an eccentric and vertically thin disk viewed nearly edge-on. In their analysis, they found that a single planet with an eccentricity of 0.7 creates a radial length asymmetry, where one side extends much farther than the other, as well as a brightness asymmetry. In this case, the shorter side of the disk is brighter closest to the star, but eventually, at larger distances, the longer side becomes brighter. This is consistent with observations of the HD 106906 debris disk, as the “Needle” is observed with HST at large radial separations in the NW extension, where a brightness asymmetry is observed with GPI at smaller radial separations. While in these simulations, the planet has a mass of 10 $M_\oplus$ and is orbiting interior to the disk, the results produced are similar to the simulations done with a larger planet on an eccentric orbit outside of the disk for HD 106906. While we cannot fully discriminate against a planet perturber interior to the disk, HD 106906b is still a likely cause for the observed disk morphology.

These simulations show that a single eccentric planet on both an internal and an external orbit can cause a debris disk to become eccentric, as well as produce a brightness asymmetry consistent with what we observe with our GPI data. Additionally, Lee & Chiang (2016) and Nesvold et al. (2017) showed that this is sufficient to create the needle-like halo that is observed with HST. The recent constraints of HD 106906b’s orbit also indicate that it most likely has a misaligned and eccentric orbit, with a periastron distance that comes reasonably close to the star (Nguyen et al. 2021). This is similar to the conditions used for the planet’s orbit in Nesvold et al. (2017), which are able to reproduce both the small- and large-scale asymmetries, providing further evidence for the planet being the disk’s perturber. Based on simulation work and our observations, dynamical interaction with HD 106906b remains a strong candidate for the source of the disk’s asymmetries.

5.3. ISM Interaction

Another possibility for the observed surface brightness asymmetry is an interaction with the ISM (Debes et al. 2009). If a debris disk passes through a dense cloud of interstellar gas, small grains can be stripped from the disk into the halo due to ram pressure. This has been used as one attempt to explain the morphological features in other debris disks, such as the “wing” feature for HD 32297 and HD 61005 (Schneider et al. 2014), as well as the “needle” feature for HD 15115 (Rodigas et al. 2012).

An ISM interaction comes up as a scenario for HD 106906 because of the disk’s asymmetrical needle-like halo, where passing through a dense ISM cloud would cause small dust grains to be blown into the NW extension of the halo, as
observed in the optical with HST (Kalas et al. 2015). For this to occur, we would expect the proper motion of the binary to be in the opposite direction of the needle (SE direction). Here HD 106906AB has a proper motion of $-39.014 \text{ mas yr}^{-1}$ in R.A. and $-12.872 \text{ mas yr}^{-1}$ in decl. (Gaia Collaboration et al. 2018), meaning that the proper motion is pointing in the SW direction. This is inconsistent with what we would expect for an ISM interaction. In addition, we do not see a difference in the color along the disk, where we might expect an ISM interaction to cause the NW extension of the disk to be more blue due to the direction of small grains blown and distributed toward the NW.

Taking these inconsistencies into consideration, we determine that an ISM interaction is unlikely to be the source of the disk’s asymmetry. Based on our findings of an asymmetric structure and consistent disk color for both extensions, the source of asymmetry should be an event that changes the dust density distribution without greatly changing the dust grain size distribution. In this case, we find that dynamical interaction with the planet companion is more consistent with observations.

6. Conclusion

With GPI, we have obtained deeper polarimetric data for HD 106906’s disk in the $H$ band, as well as the $J$ and $K1$ bands. With these data, we conclude the following.

1. We detect a surface brightness asymmetry along the disk’s major axis in all three bands, where the SE extension is brighter than the NW extension. This asymmetry peaks within $0^\circ.4$ and again between $0^\circ.6$ and $0^\circ.8$ for the $H$ band. We also estimate the disk color by comparing the magnitude of the disk with the stellar magnitude in each band, where we find the disk to have a blue color in polarized light. We also do not observe a difference in color between the two extensions, implying that the dust grain properties do not significantly vary across the disk.

2. For the structure of the disk, we find an intrinsic vertical FWHM of $\sim0^\circ.15$ or $15.6$ au. While we do not observe a strong asymmetry in radial extent or in the vertical FWHM, we observe a strong asymmetry in the vertical offset. Fitting a simple inclined ring model, we find a disk radius of $\sim101.9$ au, an inclination of $\sim85^\circ.6$, and a PA of $\sim104^\circ.3$, where the inclination and PA are consistent with those derived in Kalas et al. (2015) and Lagrange et al. (2016). Additionally, we derive a disk offset of $\sim16.5$ au along the major axis and $\sim3.0$ au along the minor axis, both toward the SE extension. This would give the disk a significant eccentricity of $\gtrsim0.16$, which could help to explain the surface brightness asymmetry observed. While an elliptical fitting is needed to further probe the eccentricity and disk orientation, this confirms that the disk is in fact geometrically asymmetric.

3. Using MCFOST within an MCMC framework, we were able to model the disk and constrain its density structure and dust grain parameters. While our best model fits the NW extension well, the surface brightness is underestimated in the SE extension. We find this to be more evidence of the HD 106906 disk being structurally asymmetric, as our structurally symmetric models are unable to capture both the disk structure and surface brightness simultaneously.

4. We considered two possible sources of the disk’s asymmetry: dynamical interaction with the planet companion, HD 106906b, and an interaction with the ISM. We find that our observations are more consistent with a disk shaped by interaction with the planet companion, where our analysis strongly suggests a disk that is asymmetrical in structure but does not significantly vary in dust grain properties based on the disk color. An interaction with the ISM is deemed unlikely, as the proper motion of the system does not align with the direction we would expect in order to produce the needle-like halo.

Our results reveal further insights into the structure and asymmetries of the HD 106906 debris disk. Compared to previous studies, we find similar trends in surface brightness, as well as certain geometrical properties, such as inclination and PA. Additionally, with our higher-S/N $H$-band data and multiwavelength $J$- and $K1$-band images, we have further constrained the structure and color of the disk. Most interestingly, our spine fitting reveals strong evidence of a disk that is geometrically asymmetric and likely eccentric, something that has not been shown before. For future work, we plan to apply an elliptical fitting to probe the eccentricity and disk orientation further. In the case of radiative-transfer modeling, using a model that has an asymmetrical dust density distribution, as well as utilizing realistic aggregates, would help shed more light on the density structure and dust grain properties of the disk.

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Software: MCFOST (Pinte et al. 2006), Gemini Planet Imager Pipeline (Perrin et al. 2014, http://asci.net/1411.018), emcee (Foreman-Mackey et al. 2013, http://asl.net/1303.002), corner (Foreman-Mackey 2016, http://ascl.net/1702.002), matplotlib (Hunter 2007; Droettboom et al. 2017), iPython (Perez & Granger 2007), Astropy (the Astropy Collaboration et al. 2018), NumPy (Oliphant 2006, https://numpy.org), SciPy (Virtanen et al. 2020, http://www.scipy.org/).
Appendix
Corner Plots

Below are the corner plots from our modeling and MCMC analysis (Foreman-Mackey 2016). Figure 9 shows the posterior distributions for the density structural parameters modeled with the $H$ band data, while Figure 10 shows the posterior distributions for the dust grain properties modeled with the $H$ band data.

Figure 9. Corner plot for MCMC results of density structural parameters.
**Figure 10.** Corner plot for MCMC results of dust grain parameters.

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