WFIRST Preparatory Science (WPS) Project: The Circumstellar Environments of Exoplanet Host Stars (NNH14ZDA001N-WPS; PI: Christine Chen)

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Overview:

This document serves as a reference for the procedures associated with simulating WFIRST CGI observations of seven known debris disk systems (61 Vir, Eps Eri, HD 10647, HD 69830, HD 95086, HR 8799, and Tau Ceti) using the HLC coronagraphic mode at 0.575 microns. In addition to simulating the dusty debris disks of these systems, a Neptune- or Jupiter-mass planet has been injected about the host star at a given separation and orbital angle, using realistic flux estimates determined from geometric albedo model spectra (Cahoy et al. 2010, ApJ, 724, 189). Observations of the star+disk+planet systems have been simulated using the WFIRST Coronagraph and Rapid Imaging Spectrograph in Python (CRISPY; Rizzo et al. 2017, SPIE, 10400, 104000B) simulator. In addition to classical reductions performed in CRISPY, the simulations are reduced by Non-negative Matrix Factorization (NMF; Ren et al. 2018, ApJ, 852. 104). The data products resulting from this effort may be used to assist the astronomy community in determining: (1) how WFIRST CGI observations will contribute to our knowledge of debris disks (e.g., discovery of inner dust belts, dust scattering phase functions), (2) what constraints simulated scattered light imaging of debris disk systems place on the detectability of planets orbiting within and outside of dusty disks, and (3) what the general feasibility and expectations will be in detecting Neptune- and Jupiter-mass planets around realistic exoplanetary systems. The following sections reveal more insight into the processes involved in producing the simulated WFIRST CGI data products.

Radiative Transfer Modeling (SEDs and Images):

The spectral energy distributions (SEDs) of the debris disk systems are modeled using the radiative transfer code MCFOST (Pinte et al. 2006, A&A, 459, 797). For each system, the SED models are constructed using previously published star and disk parameters from the literature. However, the model parameters are adjusted as needed to adequately simulate the mid-infrared to millimeter observational fluxes. Using the current WFIRST telescope and HLC coronagraph parameters from the Cycle 7 release (May 24, 2018), an unconvolved model image is produced for each debris disk system at a central wavelength of 0.575 microns. The orientation of the resulting images is North up and East left.

For each debris disk system, the measured flux densities (*_phot.txt), Spitzer-IRS spectrum (*_IRS.sav from Chen et al. 2014, ApJS, 211, 25), MCFOST model SED (*_sed_rt.fits.gz), MCFOST model image at 0.575 microns (*_RT.fits.gz), and model SED figure (*_SED_model.eps) are provided as auxiliary data products. Basic model parameters for individual targets are provided at the end of this document. Note that the final star and disk model parameters for each system are not unique, but adequate for the purposes of carrying out the WFIRST CGI simulations. For a give debris disk system, all SED model data are located within the "SED_model" directory.

Planet Injected Model Images:

The flux density of either a Neptune- or Jupiter-mass planet is calculated for each debris disk system using: $F_p = A_g(R_p/d)^2 F_* \Phi$, where $A_g, R_p, d, F_*,$ and Φ are the geometric albedo from Cahoy et al. (2010), planet radius, orbital semi-major axis, stellar flux density, and planet scattering phase function, respectively. The scattering phase function is approximated as a Lambert phase function and depends on the planet phase angle (α). The planet phase angle is defined from Burrow (2014, arXiv:1412.6097) as: $\cos(\alpha) = \cos(\theta + \omega_p)\sin(i)$, where θ, ω_p and i are the orbital angle, argument of periapsis and disk inclination, respectively. For the purpose of these simulations, the argument of periapsis is defined as 0 degrees (i.e., the periapsis coincides with the ascending node). The planet orbital angle (θ) is measured on the projected plane of the sky in the counterclockwise direction from the backscattering side of the disk (i.e., from the semi-minor axis associated with the far side of the disk). As the Lambert scattering phase function is symmetric about a 360 degree orbit, only planet orbital angles from 0 to 180 degrees are considered when calculating the scattering phase function of the injected planet.

Once the flux density of the planet is determined, the theoretical Neptune- or Jupiter-mass planet is injected as a single pixel into the model image at an assumed separation (0.8, 2, 5, and 10 au) and orbital angle. For a given separation, five orbital angles are typically selected using the statistics of the available angles falling within the inner and outer working angles of the HLC coronagraphic mode; these angles correspond to the minimum, maximum, median, upper quartile, and lower quartile values. In the case of small orbital separations, only three orbital angles may be present. We simulate an additional observation at a different spacecraft roll angle, where the second resulting star+disk+planet model image is rotated by 26 degrees with respect to the first. All model images are converted to photons/s and cropped to 71 pixels x 71 pixels. In addition, information important to the simulations (e.g., planet-to-star contrast, position of planet in the detector frame, orbital angle, etc.) are saved to the fits header. These resulting model images are the input products for the CRISPY simulator and possess the following filename structure: RT_PLANET_##au_##deg_x##_y##.fits, where PLANET is either "Neptune" or "Jupiter", ##au is the orbital separation, ##deg is the orbital angle, x## is the position of the planet along the x-direction of the detector frame, and y## is the position of the planet along the y-direction of the detector frame. For example, within the Tau Ceti directory, the fits file "RT_Jupiter_0.8au_12deg_x31_y43.fits" corresponds to an image of the Tau Ceti system with a Jupiter-mass planet injected at a separation of 0.8 au and an orbital angle of 12 degrees. The resulting planet occupies the pixel position at x,y = 31,43 in the detector frame. Similarly, the fits file “RT_Jupiter_0.8au_12deg_x31_y43_rot.fits” has been rotated by 26 degree in the counterclockwise direction to simulate observations obtained at an additional spacecraft roll angle. Note that these fits filenames are identical except for the appended “_rot” designation.

CRISPY Simulated Images:

For each debris disk system, the star+disk+planet model images are simulated using the WFIRST CGI CRISPY simulator code (for more information and source code visit https://github.com/mjrfringes/crispy). In particular, the CGI Observing Scenario 6 imaging simulations are performed using the simulated HLC image time sequences from John Krist at 0.575 microns. The resulting data products for each simulated debris disk system are provided within the “crispy_output” directory. The NMF reductions are performed using the nmf_imaging package (for more information and source code visit https://github.com/seawander/nmf_imaging).

(1) PSF reference image cube:

   a. RT_PLANET_##au_##deg_x##_y##_references_cube.fits

   b. NMF components calculated using the PSF reference cube:

      RT_PLANET_##au_##deg_x##_y##_references_NMFcomponents_cube.fits

(2) Target image cube (roll 1): RT_PLANET_##au_##deg_x##_y##_roll_minus_cube.fits

(3) Target image cube (roll 2): RT_PLANET_##au_##deg_x##_y##_roll_plus_cube.fits

(4) PSF-subtracted target cube (roll 1):

   a. RT_PLANET_##au_##deg_x##_y##_roll_minus_classicsub_cube.fits

   b. RT_PLANET_##au_##deg_x##_y##_roll_minus_NMFsub_cube.fits

(5) PSF-subtracted target cube (roll 2):

   a. RT_PLANET_##au_##deg_x##_y##_roll_plus_classicsub_cube.fits

   b. RT_PLANET_##au_##deg_x##_y##_roll_plus_NMFsub_cube.fits

(6) Roll-averaged PSF-subtracted target image (~1.83 hr total exposure time per spacecraft roll):

   a. RT_PLANET_##au_##deg_x##_y##_classicsub_roll_avg_2.fits

   b. RT_PLANET_##au_##deg_x##_y##_NMFsub_roll_avg_2.fits

(7) Roll-averaged PSF-subtracted target image (~3.67 hr total exposure time per spacecraft roll):

a. RT_PLANET_##au_##deg_x##_y##_classicsub_roll_avg_4.fits

b. RT_PLANET_##au_##deg_x##_y##_NMFsub_roll_avg_4.fits

The PSF reference image cube is comprised of 14 observational chunks, where a chunk is an average of 55 exposures of 120 s each. The roll-specific target image cubes are individually comprised of 26 observational chunks, where, again, a chunk is an average of 55 exposures of 120 s each. The NMF component cube calculated from the PSF reference cube has 14 components, and is generated sequentially such that more important components are calculated earlier.

The roll-specific PSF-subtracted target cubes are constructed from classical PSF subtraction techniques, using the provided PSF reference star images. The PSF subtraction procedure is performed by the CRISPY code (see source code for more details). For NMF, the roll-specific PSF-subtracted target cubes are reduced using all of the calculated NMF components. The roll-specific PSF-subtracted target cubes possess the same dimensions (i.e., observational chunks) as the target image cubes, with each slice corresponding to ~1.83 hr of total exposure time. Averaging over a selected number of observational chunks will yield different total exposure time scenarios. For example, averaging over the first two chunks (image slices 0 and 1) would result in a observational sequence consisting of ~3.67 hr of total exposure time. Moreover, averaging over the first three chunks (image slices 0, 1, and 2) would yield a total exposure time of ~5.49 hr.

For convenience, roll-averaged PSF-subtracted target images have been provided for observational sequences consisting of ~1.83 hr and ~3.67 hr for each spacecraft roll angle. The NMF results are handled identically. For these products, the slice-averaged “roll_plus” PSF-subtracted image are rotated 26 degrees and subsequently averaged with the “roll_minus” PSF-subtracted image to simulate a total on-target exposure time of ~3.67 hr and ~ 7.34 hr, respectively. However, using the roll-specific PSF-subtracted target cube, the user may choose to average over any number of observational chunks (image slices) to simulate a number of different observational sequences.

For each debris disks system, EPS files of the CRISPY simulated images are provided as an auxiliary data product. More specifically, these EPS files correspond to the roll-averaged PSF-subtracted target images with total exposures times of ~1.83 hr and ~3.67 hr per roll angle. For a give debris disk system, all crispy input model images (star+disk+planet) are located within the “crispy_simulation/crispy_input” directory. Similarly, all crispy output simulated images are located within the “crispy_simulation/crispy_output” directory. Although the NMF reduction results are not obtained within CRISPY, they are also contained in the “crispy_output” directory.

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Individual Radiative Transfer Modeling Notes (assumed disk and geometrical parameters):

(1) — 61 Vir — SED model parameters based loosely on work by Marino et al. (2017, MNRAS, 469, 3518) and Wyatt et al. (2012, MNRAS, 424, 1206)

effective temperature = 5500 K, log g = 4.5

inclination = 77 degrees

distance = 8.6 pc

semi-minor axis PA = 335 degrees (back-scattering side of disk measured East of North)

dust mass = 1.96e-9 solar masses

inner radius = 25 au

outer radius = 150 au

scale height = 0.5 au (at inner radius)

surface density exponent = 0.1

minimum grain size = 0.8 microns

maximum grain size = 1000 microns

grains size power law slope = -3.5

grain shape: irregular (Distribution of Hollow Spheres, fmax=0.7)

dust composition via effective medium theory: amorphous silicates (70%), amorphous carbon (15%), water ice (15%)

(2) — Eps Eri — SED model parameters based loosely on work by Booth et al. (2017, MNRAS, 469, 3200), Su et al. (2017, ApJ, 153, 12), and MacGregor et al. (2015, ApJ, 809, 47)

effective temperature = 5000 K, log g = 4.5

inclination = 34 degrees

distance = 3.2 pc

semi-minor axis PA = 266 degrees (back-scattering side of disk measured East of North)

dust mass = 5.38e-13 solar masses (zone 1), 6.0e-9 solar masses (zone 2)

inner radius = 3 au (zone 1), 63 au (zone 2)

outer radius = 21 au (zone 1), 76 au (zone 2)

scale height (at inner radius) = 1.3 au (zone 1), 3.15 au (zone 2) surface density exponent = -1 (zone 1), 0 (zone 2)

minimum grain size = 1 microns (zone 1), 1 microns (zone 2)

maximum grain size = 1000 microns (zone 1), 1000 microns (zone 2)

grains size power law slope = -3.5 (zone 1), -3.5 (zone 2)

grain shape: irregular (Distribution of Hollow Spheres, fmax=0.7)

dust composition via effective medium theory (zones 1 and 2): amorphous silicates (100%)

(3) — HD 10647 — SED model parameters based loosely on work by Schuppler et al. (2016, MNRAS, 461, 2146)

effective temperature = 6000 K, log g = 4.5

inclination = 70 degrees

distance = 17.34 pc

semi-minor axis PA = 324.2 degrees (back-scattering side of disk measured East of North)

dust mass = 4.48e-11 solar masses (zone 1), 5.08e-8 solar masses (zone 2)

inner radius = 3 au (zone 1), 70 au (zone 2)

outer radius = 10 au (zone 1), 125 au (zone 2)

scale height (at inner radius) = 0.15 au (zone 1), 3.5 au (zone 2)

surface density exponent = 0 (zone 1), -1.5 (zone 2)

minimum grain size = 2 microns (zone 1), 2 microns (zone 2)

maximum grain size = 1000 microns (zone 1), 1000 microns (zone 2) grains size power law slope = -3.5 (zone 1), -3.5 (zone 2)

grain shape: irregular (Distribution of Hollow Spheres, fmax=0.7)

dust composition via effective medium theory (zones 1 and 2): amorphous silicates (70%), water ice (30%)

(4) — HD 69830 — SED model parameters based loosely on work by Beichman et al. (2011, ApJ, 743, 85) and Smith et al. (2012, MNRAS, 422, 2560)

effective temperature = 5400 K, log g = 4.5

inclination = 70 degrees

distance = 12.56 pc

semi-minor axis PA = 60 degrees (back-scattering side of disk measured East of North)

dust mass = 1.5e-13 solar masses

inner radius = 0.8 au

outer radius = 1.3 au

scale height = 0.04 au (at inner radius)

surface density exponent = -1

minimum grain size = 0.7 microns

maximum grain size = 10 microns

grains size power law slope = -3.9

grain shape: irregular (Distribution of Hollow Spheres, fmax=0.7)

dust composition via effective medium theory: amorphous silicates (50%), amorphous crystalline silicates (50%)

(5) — HD 95086 — SED model parameters based loosely on work by Su et al. (2017, ApJ, 153, 12), Su et al. (2015, ApJ, 799, 146), and Moor et al. (2015, MNRAS, 447, 577)

effective temperature = 7400 K, log g = 3.5

inclination = 30 degrees

distance = 83.8 pc

semi-minor axis PA = 7 degrees (back-scattering side of disk measured East of North)

dust mass = 1.2e-10 solar masses (zone 1), 7.5e-7 solar masses (zone 2), 7.5e-8 solar masses (zone 3)

inner radius = 7 au (zone 1), 106 au (zone 2), 320 au (zone 3)

outer radius = 10 au (zone 1), 320 au (zone 2), 800 au (zone 3)

scale height (at inner radius) = 0.35 au (zone 1), 5.3 au (zone 2), 16 au (zone 3)

surface density exponent = 0 (zone 1), -0.5 (zone 2), -1.5 (zone 3)

minimum grain size = 1.8 microns (zones 1 and 2), 1 microns (zone 3)

maximum grain size = 1000 microns (zones 1 and 2), 10 microns (zone 3)

grains size power law slope = -3.65 (zone 1), -3.5 (zones 2 and 3)

grain shape: irregular (Distribution of Hollow Spheres, fmax=0.7)

dust composition via effective medium theory (zone 1): amorphous silicates (100%)

dust composition via effective medium theory (zones 2 and 3): amorphous silicates (70%), water ice (30%)

(6) — HR 8799 — SED model parameters based loosely on work by Su et al. (2015, ApJ, 799 146), Su et al. (2009, ApJ, 705, 314), and Wilner et al. (2018, ApJ, 855, 56)

effective temperature = 7500 K, log g = 4.5

inclination = 32.8 degrees

distance = 41.29 pc

semi-minor axis PA = 54.4 degrees (back-scattering side of disk measured East of North)

dust mass = 3.3e-12 solar masses (zone 1), 3.6e-7 solar masses (zone 2), 5.7e-8 solar masses (zone 3)

inner radius = 6 au (zone 1), 104 au (zone 2), 361 au (zone 3)

outer radius = 8 au (zone 1), 361 au (zone 2), 1000 au (zone 3)

scale height (at inner radius) = 0.3 au (zone 1), 5.2 au (zone 2), 18.1 au (zone 3)

surface density exponent = 0 (zone 1), -0.4 (zone 2), -1 (zone 3)

minimum grain size = 1.5 microns (zone 1), 10 microns (zone 2), 1 microns (zone 3)

maximum grain size = 4.5 microns (zone 1), 1000 microns (zone 2), 10 microns (zone 3)

grains size power law slope = -3.5 (zone 1), -3.3 (zone 2) and -3.5 (zone 3)

grain shape: irregular (Distribution of Hollow Spheres, fmax=0.7)

dust composition via effective medium theory (zone 1): amorphous silicates (100%)

dust composition via effective medium theory (zones 2 and 3): amorphous silicates (70%), water ice (30%)

(7) — Tau Ceti — SED model parameters based loosely on work by Lawler et al. (2014, MNRAS, 444, 2665) and MacGregor et al. (2016, ApJ, 828, 8)

effective temperature = 5400 K, log g = 4.5

inclination = 35 degrees

distance = 3.6 pc

semi-minor axis PA = 15 degrees (back-scattering side of disk measured East of North)

dust mass = 1.9e-10 solar masses

inner radius = 6.2 au

outer radius = 52 au

scale height = 0.31 au (at inner radius)

surface density exponent = -0.3

minimum grain size = 15 microns

maximum grain size = 1000 microns

grains size power law slope = -3.5

grain shape: irregular (Distribution of Hollow Spheres, fmax=0.7)

dust composition via effective medium theory: amorphous silicates (100%)