

A planet as the possible cause of the HD 181327 debris disc asymmetry

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ABSTRACT

The debris disc around HD 181327 shows a significant asymmetry in its surface brightness profile when viewed in visible light. Observations from the *Hubble Space Telescope* STIS instrument show an arc of approximately 90° of higher optical depth at a distance of 84 au from the star. Here, we explore whether a planet could be the driver of this asymmetry. Through *N*-body simulations, we find that a 2–4 Jupiter-mass planet on a circular orbit at 70 au can produce and maintain a similar feature if the collisional lifetime of dust in the disc is between 4 and 8 kyr, so long as a modest fraction of the grains are ejected with high ($\lesssim 1 \text{ km s}^{-1}$) speeds. We also find that the surface brightness asymmetry is much less pronounced at larger particle sizes, which may account for the fact that observations of HD 181327 at longer wavelengths have not reported such an arc.

Key words: methods: numerical – planets and satellites: detection – planetary systems: planet–disc interactions – stars: individual: HD 181327.

1 INTRODUCTION

HD 181327 (also known as HIP 95270) is an 18.5 Myr old main sequence F5/6 star in the Beta Pictoris Moving Group (N. Miret-Roig et al. 2020; J. Milli et al. 2024). Its debris disc was first directly observed by G. Schneider et al. (2006) in the near-infrared, and the disc has been the target of many further observations since. J. Lebreton et al. (2012)’s examination of it in the far-infrared revealed the presence of icy plantessimals. S. Marino et al. (2016) reported the presence of exocometary gas in the disc. J. Milli et al. (2024) examined polarization properties of the disc and found evidence for sub-micron particles. Most recently C. Xie et al. (2025), using data from the *James Webb Space Telescope*, found evidence for crystalline water ice and continual collisions within its debris disc.

Most relevant to our work here, C. C. Stark et al. (2014) observed the disc with the Space Telescope Imaging Spectrograph (STIS) on board the *Hubble Space Telescope*. They found a debris disc with optical depth peaking at 84.2 au from the central star. When deprojected, the disc showed a significant azimuthal asymmetry manifesting as a 90° arc of increased optical depth. In that work, the asymmetry was interpreted as a region of higher particle density, with the cause hypothesized as warping due to interaction with the interstellar medium or the result of a catastrophic disruption of a 1 per cent Pluto-mass object within an exo-Kuiper belt. In a related work, G. Schneider et al. (2014) suggested the asymmetry may indicate the presence of unseen planetary companions.

It has long been recognized that debris discs may host unseen planets (M. C. Wyatt et al. 1999) and that planets may produce observable disc structures while the planets themselves may remain unobserved (D. Mouillet et al. 1997; J. C. Augereau et al. 2001; S. Kraus et al. 2013; M. Tabeshian & P. A. Wiegert 2016, 2017, 2018). This is also seen in our own Solar system, where planets form structures by trapping grains in mean motion resonances (S. F. Dermott et al. 1994; J.-C. Liou & H. A. Zook 1999).

Could the visible asymmetry of the debris disc of HD 181327 be created by the gravitational perturbations from a planet? Here, we explore this premise through the use of *N*-body simulations of a hypothetical planet on the inner edge of the HD 181327 disc and constrain the orbital parameters of such a planet.

2 METHODOLOGY

The primary goal of this paper is to determine whether the presence of a planet near the inner edge of the HD 181327 disc provides a plausible explanation for the structures observed by C. C. Stark et al. (2014). In that paper, raw STIS observations were deprojected to produce a face-on map of the normalized optical density, resulting in fig. 6h from that paper. That map of optical density serves as the basis for our work, where we use a Bayesian search coupled iteratively with a numerical integrator to find the planetary parameters that produce a disc that most closely matches the observations. Details of this process are discussed in the following sub-sections.

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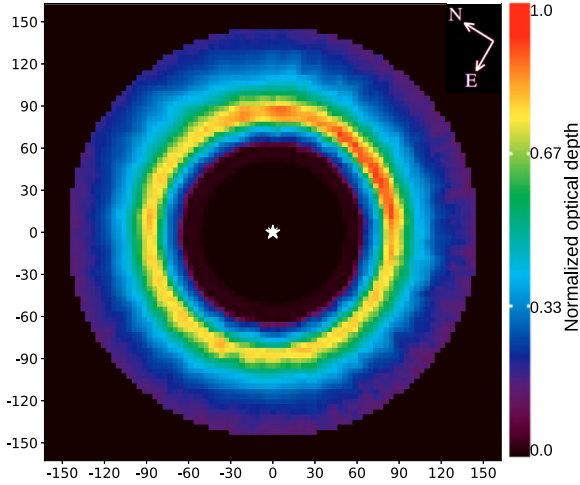


Figure 1. Our revised Target Map of HD 181327, used for all comparisons in our simulations. This is based on the original from C. C. Stark et al. (2014), but with data outside of 150 au removed. This is the map our simulations aim to replicate via the influence of a shepherding planet. The arc is near-centred on the western side.

2.1 Update of distance values

C. C. Stark et al. (2014) reported the peak of the HD 181327 ring at a distance of 90.5 au from the central star. That work (and several others) use a distance for the system of 51.8 pc. However, updated values from *Gaia* DR2 put the stellar distance of HD 181327 at 48.21 ± 0.13 pc (Gaia Collaboration 2018), and our work will be performed using this value. Rescaling Stark’s distance with the newer distance estimate results in a ring radius of 84.2 au. We scale all of Stark’s (and other sources) distance values throughout this paper accordingly.

2.2 Creating the target map

Our first step was to adapt fig. 6h of C. C. Stark et al. (2014) to our purposes. This is the deprojected, normalized, optical depth map of the STIS image. We extracted a subset of Stark’s original map, sized to cover the majority of the disc but excluding the faint edges well beyond the visible asymmetries. This corresponds to an outer radius of 150 au. Our resulting map extent is 89×89 pixels, with each pixel being equivalent to 3.646 au across. We chose to use the same colour scale for optical depth values as Stark’s. For each pixel, we found the colour hex code of Stark’s image, matched that to the hex code value of the colour scale, and recorded the corresponding optical depth value.

Our revised map, adapted from the original fig. 6h from Stark, is seen in Fig. 1 where we have adopted the same colour scale as Stark et al. Henceforth, we refer to this as ‘Target Map’ or ‘Target Disc’, which we aim to replicate via our simulations.

2.3 Simulation initial conditions

2.3.1 Dust grain sizes

Our simulations examine particles of different sizes, their dynamics being characterized by β , the ratio of the force from stellar radiation to the star’s gravitational force. β may be expressed as

(S. P. Wyatt & F. L. Whipple 1950):

$$\beta = \frac{F_{\text{rad}}}{F_{\text{grav}}} = \frac{3L_{\star}Q_{\text{pr}}}{16\pi GM_{\star}c\rho s} \quad (1)$$

where c is the speed of light, G is the gravitational constant, $L_{\star}$ is the luminosity of the star, and Q_{pr} is the radiation pressure coefficient. For HD 181327, equation (1) becomes

$$\beta = 1.396 \left(\frac{s}{\mu\text{m}} \right)^{-1} \left(\frac{\rho}{\text{g cm}^{-3}} \right)^{-1} \quad (2)$$

where ρ is the grain density, s is the grain radius, and Q_{pr} is assumed to be unity.

J. Lebreton et al. (2012) attempted to constrain the composition and size distribution of the HD 181327 disc. They found the best-fitting minimum grain size of $0.9 \mu\text{m}$. J. Milli et al. (2024) also found evidence for sub-micron grains. The best model from J. Lebreton et al. (2012) consisted of a disc composed of porous amorphous silicates and carbonaceous material and ice, suggesting low density ($< 1 \text{ g cm}^{-3}$) particles. However, more recently J. Milli et al. (2024) found that their observations required a more refracting component such as iron-bearing material, which would have a significantly higher density.

For this paper, we are only concerned with the dynamical behaviour of the particles, not their exact composition or sizes. For convenience, we assume a mean density of 2 g cm^{-3} , similar to our own Solar system. With this density, our range of examined β values from 0.05 to 0.8 would correspond to a physical radius range of 14 to $0.8 \mu\text{m}$, respectively, which are effective light scatterers at STIS wavelengths: a central bandpass of $0.585 \mu\text{m}$ with a FWHM of $0.441 \mu\text{m}$ (S. C. Medallion, E. F. Rickman & J. Brown 2023). Even if our assumed typical grain density is $4\times$ too low, the particles for this range of β would still be effective scatterers in optical wavelengths.

2.3.2 Initial particle distribution and parameters

Here we first describe a simplified particle size and speed distribution adopted as a result of positive results in initial experiments, and then assess our model’s sensitivity to that distribution in Section 3.8.1.

The disc of HD 181327 consists of a central ‘parent ring’ and an extended outer cloud. The parent ring is a relatively narrow annulus of ongoing collisions (C. Xie et al. 2025). For our simulations, this region served as the source of all particles. Each of these particles was assigned a random β value between 0.05 and 0.8. We explored various subsets of particles within this range. The particles are initially uniformly distributed within an annulus with a speed and direction appropriate to a circular orbit. To represent the grain’s creation due to a collision, a random kick velocity (using sphere-point picking method) is then applied. Particles that move out of the central ring at the farther limits of their orbits, bound and unbound, populate the outer cloud.

During our initial simulations and experiments, we found the best match to the Target Disc when a substantial component of the dust had $\beta \approx 0.5$. Particles with $\beta > 0.5$ are often assumed to be quickly lost from the system (‘beyond the blow-out threshold’) because a particle with $\beta > 0.5$ released at zero speed from a parent body on a circular orbit will immediately find itself on an unbound orbit and leave the system. However, particles with $\beta > 0.5$ can remain bound to the star if they are given sufficient ejection speed and direction from the planetesimal.

To simulate this, the particles were initially given an eccentricity of 1.0, matching what a $\beta = 0.5$ particle would have if released from the planetesimal with no relative velocity. These particles were then given a random ‘kick’: a burst of velocity in a random direction (including the z -axis) to represent their explosive non-isotropic ejection as the result of a collision. Most particles are ejected with low speeds, and thus remain on hyperbolic orbits. These particles are lost in just a few hundred years. The few particles with sufficient ejection speed and direction to put them into bound orbits are retained, and thus contribute more to the visible disc than the ejected particles in the long-term.

For the case of HD 181327, to put a $\beta \approx 0.5$ particle into a circular orbit the ejection speed required is 1.1 km s^{-1} relative to the parent body. The orbital speed at 84.2 au is $v_{\text{orb}} = 3.8 \text{ km s}^{-1}$ (for a circular orbit). Since particle ejection speeds reach maximum values comparable to the impact speed (K. R. Housen & K. A. Holsapple 2011; M. Jutzi, P. Michel & D. C. Richardson 2019), and impact speeds go like $\langle e \rangle v_{\text{orb}}$ where $\langle e \rangle$ is the average eccentricity (T. Löhne, A. V. Krivov & J. Rodmann 2008), we can expect ejection speeds to reach the needed values if $\langle e \rangle \sim 1.1/3.8 = 0.29$. We will find that such eccentricities are common within our simulation. Since high-speed ejecta is only a small fraction of the total released by an impact, production of a sufficient amount of high-speed material remains a potential difficulty of the planetary model adopted here. The presence of the planet itself provides a natural source (via gravitational scattering) of higher eccentricity particles, and higher collision speeds, further creating more high-eccentricity particles. None the less, we proceeded on the premise that our collisions of $\sim 1 \text{ km s}^{-1}$ could similarly produce ejecta of $\sim 1 \text{ km s}^{-1}$, and reexamined this issue later. (See Sections 3.8.3 and 4.1.)

The random kick of this magnitude is found to leave a collection of particles with many eccentricity values, averaging to ~ 0.3 . The relative speed of the particles with respect to planetesimals is of order $e \times v_{\text{orb}} \sim 1.4 \text{ km s}^{-1}$ (and given the large range of eccentricities seen later, even higher relative speeds are possible), so our model is self-consistent with respect to the collision/ejection speeds expected. Thus in our model while the disc appears circular, it primarily consists of particles with eccentricities of 0.2 to 0.8 (see the results in Section 3.5) and it is this configuration that produces a continual creation of particles with sufficient collisional and ejection speeds.

2.3.3 Particle count and stacking

Our simulated disc begins with 4800 particles, and another 4800 are added at each timestep, representing the creation of new particles. Snapshots of the disc are taken at 100 evenly spaced time intervals throughout the simulation, which are then stacked together. The total length of the simulation thus corresponded to the collisional lifetime of the dust and includes particles of a range of ages; for simplicity we assumed that all the dust survives for the entire simulation and is destroyed at the end. The stacked snapshots thus represent the quasi-equilibrium state resulting from the continual creation, evolution, and destruction of particles through their lifetime. The number of particles used in the final comparison could potentially be as high as $4800 \times 101 = 492\,880$. However, due to radiation pressure and the applied ejection kick, more than half of newly created particles are lost in just a few hundred years as they are immediately put on unbound orbits. During the entire evolution of the disc about

80 per cent of them are lost (see Sections 2.3.2 and 2.5). After stacking, the total particle count is typically around 200 000.

2.4 Running the simulations: Numerical integrator

The numerical integrator we use for modeling the disc is based on the Wisdom–Holman fast symplectic integration scheme (J. Wisdom & M. Holman 1991), with a time step of 500 d. This time-step is approximately 5 per cent of the planet’s period when its semimajor axis is 10 au (within the lower limit of the prior, Section 2.7). This allows for adequate sampling of all particles throughout their orbit regardless of the planetary semimajor axis chosen. Only planets interior to the disc are considered. Radiation pressure and Poynting–Robertson drag are included for particles with $\beta > 0$. The duration of our simulations depended upon the expected collisional lifetime of the particles, described in the next section.

2.5 Simulation duration / particle lifetimes

The simulated disc is affected by the adopted collisional time-scale of the particles, as the particles have only this amount of time to respond to the presence of the planet and develop any resulting structures.

We can estimate the collisional lifetime of the HD 181327 disc from the particle density as determined by the amount of light received at Earth. The surface brightness of a pixel in terms of power received by *Hubble*’s STIS instrument is:

$$P_H = A_H \frac{L_p}{4\pi D^2} \quad (3)$$

where A_H is the collecting area of *Hubble*’s primary mirror (4 m^2), L_p is the power reflected by the dust in that pixel, and D is the distance to the star (48.2 pc). The raw STIS data from C. C. Stark et al. (2014) (fig. 1 of that paper) has a pixel width of $W = 2.446 \text{ au}$ (this is adjusted from the original Stark value, using the updated *Gaia* distance), a peak value of 6 counts, and a CCD Gain of 4 (G. Schneider et al. 2014). Assuming an average photon wavelength of $0.585 \mu\text{m}$, the central bandpass of STIS (S. C. Medallion et al. 2023), we estimate the peak power received at *Hubble* from one pixel as $8.15 \times 10^{-18} \text{ W}$.

The power reflected by one dust grain is:

$$L_{\text{grain}} = \alpha \pi s^2 \frac{L_*}{4\pi r^2} \quad (4)$$

where L_* is the luminosity of the star, α is the albedo of the dust particle, r is the distance of the particle from the star and s is the radius of the dust particle. J. Lebreton et al. (2012) put the observed albedo at 0.13 which we will adopt here though this is at $1.1 \mu\text{m}$, slightly above the upper wavelength limit of STIS.

Combining equations (3) and (4), we can derive the number N of particles inside of one image pixel as:

$$N = \frac{16\pi D^2 r^2 P_H}{\alpha L_* A_H s^2} \quad (5)$$

The surface density is the number of particles in a square pixel (width $W = 2.446 \text{ au}$) divided by its area. The vertical optical depth τ (surface density $\times$ particle cross-sectional area) can be expressed as:

$$\tau = \frac{16\pi^2 D^2 r^2 P_H}{\alpha L_* A_H W^2} = 0.005 \left(\frac{\alpha}{0.13} \right)^{-1} \left(\frac{D}{48.2 \text{ pc}} \right)^2 \quad (6)$$

This gives us an estimated peak optical depth of $\tau = 0.005$, which confirms that we are dealing with an optically thin disc.

We now seek to estimate the collisional lifetime of a particle. From equation (6), we estimate a particle volume density by assuming a disc scale height of 6 au (G. Schneider et al. 2006; C. C. Stark et al. 2014; J. Milli et al. 2024), and then estimate a mean free path of 867 au. Combining typical orbital distance (≈ 120 au for a $e = 0.3$ particle with periastron of 84.2 au), inclination (6 au / 84.2 au $\approx 4^\circ$) and eccentricity (~ 0.3), the typical relative speed between crossing eccentric particles is ~ 0.9 km s $^{-1}$ (and can be much greater for higher eccentricities). These particles will sweep out the mean free path in ~ 6.1 kyr. This represents the typical lifespan of a particle ejected from the parent disc.

We note that the literature contains various formulae for collisional lifetimes of the smallest particles, and estimates for particle lifetimes vary significantly. Formulae based on the angular velocity and optical depth, $t_{\text{coll}} = (\Omega\tau)^{-1}$, are frequently used to estimate the lifetime of the smallest particles (M. C. Wyatt et al. 1999; P. Thébault & J. C. Augereau 2007; J. Lebreton et al. 2012) and produce collision times for HD 181327 from as low as 7600 yr to 20 kyr. However, numerical model-derived lifetimes indicate particles smaller than 0.1 mm in a typical disc can have longer lifetimes by multiple orders of magnitude (P. Thébault & J. C. Augereau 2007), potentially up to ~ 1 Myr. Most recently, C. Xie et al. (2025) predicted a lifetime of 3300 yr, and acknowledged the difficulties with making such estimates.

Hence, given the complexities in computing particle lifetimes and our own simplifications, our simulations were performed over a range of particle lifespans: from 3 kyr to 20 kyr.

2.6 Conversion of simulated particle surface density to optical depth map

Our Target Map is an 89×89 grid of optical depth values, while our simulation is comprised of individual particles. This disc is normalized to the Target Disc in terms of the total optical depth (the sum of values of all pixels). The disc of HD 181327 has been determined to be optically thin (G. Schneider et al. 2006; J. Lebreton et al. 2012), so the surface density of our simulated particle disc is simply linearly related to the optical depth of the disc. We scale the optical depth of our simulated discs so that the total optical depth of all the pixels in the simulated disc is equal to the sum of the optical depths of all the pixels in the Target Disc.

To be sure that each simulated disc is fairly compared, each simulation is rescaled according to the number of particles remaining at the end of the simulation, not just the number initialized at the beginning. For example, if in one simulation half the particles are lost by the end of the simulation, then each remaining particle has to account for twice the optical depth.

2.7 Comparing simulated discs to the Target Disc: A Bayesian search

To find the planetary parameters that best reproduce the Target Disc, we used MultiNest, a Bayesian Inference Tool (F. Feroz, M. P. Hobson & M. Bridges 2009), coupled with our numerical integrator (Section 2.4). Our MultiNest search included five parameters: the semimajor axis of the planet (assumed to be on a circular orbit), the mass of the planet, the center of the parent disc annulus, the width of the annulus (full width), and the random

Table 1. Planet and disc priors.

	Limits	Units
Planet mass	[0.1, 13.1]	M_J
Planet semimajor axis	[30.0, 80.0]	au
Parent disc centre	[70.0, 100.0]	au
Parent disc width (full)	[5.0, 40.0]	au
Particle ejection speed	[800, 1400]	m/s

‘kick’ velocity (see Section 2.3.2). We use uniform priors for all parameters. For the mass, the prior extends from 0.1 to 13.1 M_J masses, with the upper limit being the approximate lower limit for brown dwarfs. For the semimajor axis, the prior is 30 to 80 au; the inner chosen so it is inside the limit set by T. J. Rodigas, R. Malhotra & P. M. Hinz (2014), and the outer limit chosen so that it overlaps the inner edge of the Target Disc. The priors of the parent disc center was 70 to 100 au to account for the possibility that the observed disc may evolve from a different initial location. The parent disc width prior ranged from 5 to 35 au, designed to more than cover the observed disc and account for evolution. Finally, the random ejection (‘kick’) prior had limits of 800 to 1400 m s $^{-1}$. This range is based on the required speed to put a $\beta \approx 0.5$ particle on a 0 eccentricity orbit, 1100 m s $^{-1}$. The priors are summarized in Table 1.

MultiNest chooses the parameters from the prior, which are then fed into the numerical integrator. The simulation is run and the particles at different time-steps are collected (see below). The combined disc particles are converted to a grid of 89×89 optical densities with the total optical depth scaled to the Target Disc total (see Section 2.6). MultiNest then compares this map to the Target Disc values. For quality of comparison, we used the log-likelihood, based on the usual χ^2 metric.

$$\ln L = \sum_{i=0}^N \left(\left(\ln \frac{1}{\sigma_i \sqrt{2\pi}} \right) - \frac{(x_i - \mu_i)^2}{2\sigma_i^2} \right) \quad (7)$$

In equation (7), x_i is the simulated optical depth, μ_i is the observed optical depth, and σ_i is the error in the observed optical depth, which we set to 0.1, chosen as a conservative estimate of the source disc from C. C. Stark et al. (2014). The log-likelihood is computed for each pixel over the entire disc.

Each simulation is run for an amount of time representing the typical collisional lifespan of the particles: we examined lifespans of 3 to 20 kyr (see Section 2.5). In our model we assume that the particles observed in reflected light are created continuously from an underlying population of larger planetesimals. To represent the continual evolution of these particles from creation (at 0 kyr) to collisional destruction, 101 snapshots (including $t = 0$ kyr) taken at equal intervals of time of the disc’s evolution are stacked together. All data is plotted in the planet-centric frame. In this way, a steady-state disc is achieved which includes particles of all ages from creation to destruction. However, for simplicity we do not model the time-dependence of the collisional removal, and all particles of all ages count for the same weight in our optical depth maps. The entire disc is then rotated to the best possible alignment with the Target Map.

For our model, MultiNest typically requires 4000 to 6000 iterations to produce the posteriors. A typical single MultiNest search takes 3–4 d to complete running in parallel on a machine with 48 Intel(R) Xeon Silver 4214 CPUs. Owing to the lengthy nature of the search we chose not to add additional parame-

Table 2. Posteriors and best-fitting results at different particle lifetimes. The three χ^2 per pixel entries correspond to specific portions of the disc: entire disc from 60 to 140 au, the parent ring refers to the annulus from 70 to 100 au, and the arc refers 70 au and 100 au of the upper-right (western) quadrant only.

	3 kyr	4 kyr	6 kyr	8 kyr	10 kyr	14 kyr	20 kyr
Posterior mass (M_J)	$3.7^{+4.7}_{-2.1}$	$3.6^{+2.7}_{-2.5}$	$3.1^{+2.6}_{-2.1}$	$2.7^{+1.1}_{-1.8}$	$2.0^{+1.7}_{-1.3}$	$4.1^{+2.6}_{-2.8}$	$2.4^{+2.3}_{-1.6}$
Posterior semimajor axis (au)	$71.6^{+3.1}_{-4.1}$	$71.8^{+2.7}_{-3.2}$	$71.3^{+3.5}_{-1.9}$	$71.5^{+2.8}_{-2.0}$	$70.8^{+3.1}_{-2.1}$	$70.8^{+3.8}_{-2.9}$	$71.5^{+3.5}_{-2.7}$
Posterior parent width (au)	$16.9^{+4.3}_{-3.6}$	$18.6^{+5.6}_{-4.0}$	$17.6^{+6.6}_{-3.8}$	$17.7^{+4.0}_{-4.5}$	$19.8^{+3.1}_{-4.5}$	$17.7^{+4.1}_{-3.0}$	$18.5^{+6.8}_{-4.1}$
Posterior parent center (au)	$89.2^{+1.0}_{-0.9}$	$90.2^{+1.5}_{-1.6}$	$89.8^{+1.9}_{-0.9}$	$89.9^{+1.4}_{-1.5}$	$90.3^{+2.1}_{-1.3}$	$89.5^{+1.3}_{-1.2}$	$89.9^{+2.3}_{-1.3}$
Posterior ejection speed (m s^{-1})	1273^{+22}_{-20}	1261^{+26}_{-25}	1265^{+8}_{-12}	1258^{+28}_{-15}	1260^{+14}_{-14}	1276^{+23}_{-26}	1273^{+21}_{-25}
Best-fitting mass (M_J)	2.65	2.44	3.64	3.65	3.71	4.62	3.83
Best-fitting semimajor axis (au)	72.82	73.61	70.15	69.48	68.72	53.76	69.38
Best-fitting parent width (au)	21.26	19.83	13.86	13.22	15.27	21.88	20.15
Best-fitting parent centre (au)	88.99	90.27	88.94	88.34	89.00	91.73	88.63
Best-fitting ejection speed (m s^{-1})	1263.5	1251.5	1265.8	1263.2	1274.2	1264.6	1275.6
χ^2 per pixel of entire disc	0.144	0.102	0.091	0.094	0.092	0.119	0.098
χ^2 per pixel of parent ring	0.288	0.189	0.142	0.143	0.148	0.210	0.175
χ^2 per pixel of 90° of arc	0.302	0.227	0.175	0.160	0.208	0.223	0.225

ters to the MultiNest search. Since our purpose is only to show that a planet can plausibly explain the structure seen in HD 181327 and not necessarily to determine that planet's parameters with high precision, this approach is sufficient to achieve our goal.

3 RESULTS

3.1 Initial observations and particle segmentation

In our first set of simulations, we examined a range of particles with $\beta = 0.05$ to 0.8 . As part of our initial analysis, we divided the particles into different β ranges to see how behaviour differed. We found that only a subset of particles, those with $\beta \sim 0.5$, were able to quickly produce an arc. If β were significantly higher ($\beta \geq 0.6$), the particles are too easily lost. Conversely, the larger particles ($\beta < 0.2$) were found not to be driven into an arc of high density (for the same planetary parameters). As discussed in Section 2.3.2, particles with $\beta \approx 0.5$, despite being at or above the notional blowout limit, can persist in the disc in stable orbits depending on their relative ejection speed from their source body. We therefore focused our efforts on a disc of particles where each particle had a randomly determined β value between 0.4 and 0.6 distributed uniformly.

3.2 Best-fitting results

We found that models with $0.4 < \beta < 0.6$ and a range of collisional time-scales were able to closely approximate the disc observed by C. C. Stark et al. (2014). The posteriors and best-fitting results for each time-scale can be seen in Table 2 and figures for some representative cases are included below. The MultiNest results indicate a complicated parameter landscape, and different sets of coupled parameters (usually mass and semimajor axis) can produce similar quality results. Several combinations are presented below for comparison. Our single best-fit was for the 6 kyr time-scale, but the 4 and 8 kyr lifetimes are close, each with their own quirks that make them slightly worse fits than the 6 kyr.

We found there were two broad classes of solutions for all time-scales. The first requires a planet of $M_J \approx 2\text{--}4$ with a semimajor axis of $68\text{--}72$ au. The other requires a more massive planet of $7\text{--}12 M_J$ but with a semimajor axis between 50 and 55 au. For

particle lifetimes of less than 10 kyr, the smaller planet solution is the better fit, producing usually better log-likelihood values. Conversely, for particle lifetimes of 10 kyr or more, the more massive planet solutions produced better fits. However, Z. Wahhaj et al. (2013) placed a lower mass detection limit of $3.5 M_J$. For this reason, we concentrated our efforts on lower-mass solutions (see Section 4.2).

Most of our simulations were able to match the extended disc very well, as indicated by low χ^2 values beyond 100 au. Similarly, we are able to reproduce the Target Disc's region between 60 and 100 au. The width and location of the parent ring in our simulations are similar to the Target's, though the χ^2 values shown there is more variation within it than in the extended cloud. Our starting annulus, which we model as the source of particles, is typical centered at 90 au and between 15 and 20 au in width (see disc width and center posteriors in Table 2). It is only through the evolution, the continual creation and motion through the collisional lifetime, of particles that we see the most dense region form at 84.2 au.

The most sensitive regions were the arc itself and the inner edge of the disc. No result was able to produce an arc with the same intensity as the Target Disc: our best fits in the western arc have an average value 7.4 per cent higher than the average of the other quadrants, compared to 12 per cent increase seen in the Target Disc. Overall, our simulations are able to match the overall pattern with a 90° arc similar to the Target Disc.

Below we briefly describe the best-fitting result for each time-scale (corresponding to the assumed collisional lifetime of the particles), and include the simulated disc and χ^2 per pixel maps. The location of the planet is indicated by a white $\times$, and all maps are in the planet-centric frame.

3.2.1 Collisional time-scale of 3 kyr

The shortest time-scale we simulated was 3 kyr, translating to only six orbits of the proposed planet. The $2.6 M_J$ planet at 72.8 au creates a distinct $\sim 70^\circ$ arc, the most intense of any results (8.6 per cent compared to the Target Disc's 12.5 per cent). However there are significant mismatches on the inner edge, particularly in the south-west near the planet. As a result, the overall χ^2 values were the highest in all regions. Despite the high χ^2 values,

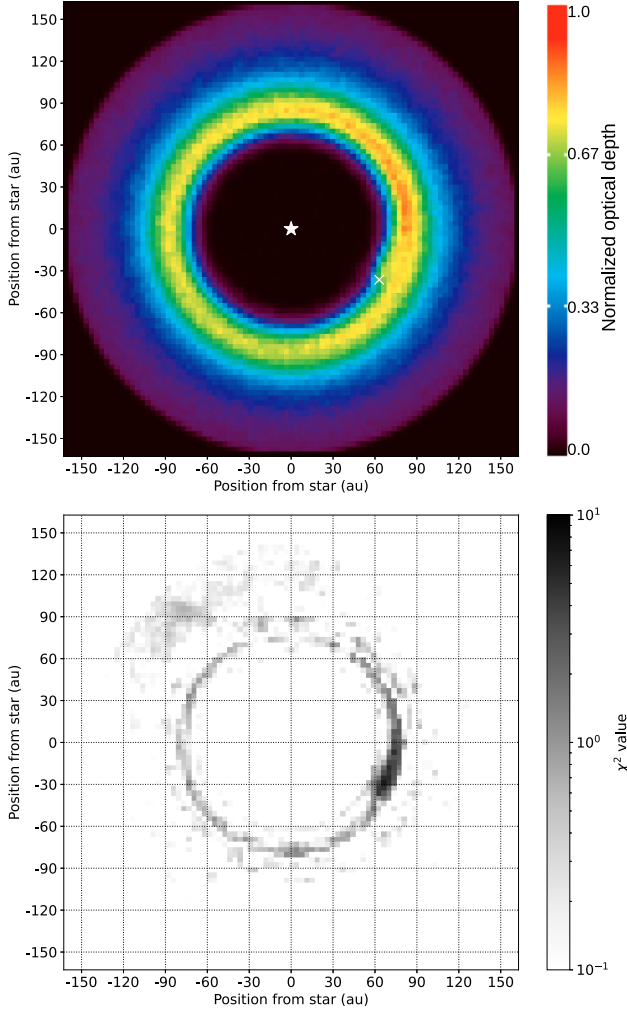


Figure 2. Best-fitting result for a particle lifespan of 3 kyr. The top image is the simulated optical depth map, with the white $\times$ marking the location of the planet. At the bottom is the χ^2 map when compared to the Target Map. Both the planet and particles orbit in the clockwise direction.

the intensity of the arc makes this a viable solution. The results are shown in Fig. 2.

3.2.2 Collisional time-scale of 4 kyr

The 4 kyr lifetime translates to about eight orbits of the proposed planet. The planet ($2.4 M_J$ at 73.6 au) is able to create a short arc while removing the larger mismatches seen at the 3 kyr result. A smaller tadpole-shaped region on the inner edge remains, but is significantly reduced. This keeps the χ^2 of the arc region relatively high. The results are shown in Fig. 3.

3.2.3 Collisional time-scale of 6 kyr

Our overall best fit occurs at the 6 kyr time-scale. A planet of $3.6 M_J$ at 70.1 au creates an arc of 90° . The arc is not as intense as our Target Map, with an arc that exceeds the parent average by 7.5 per cent, compared to 12 per cent of the Target Disc. This represents our single best overall result of this study, producing an arc of 90° , with the lowest overall χ^2 values. The results are shown in Fig. 4.

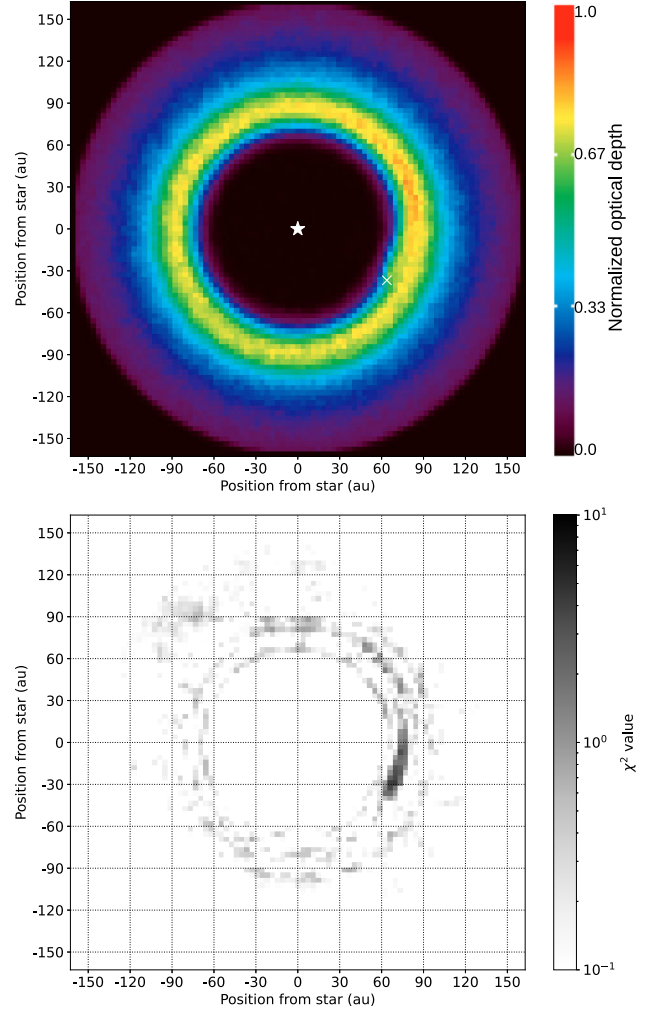


Figure 3. Best-fitting result for a particle lifespan of 4 kyr. Panels and symbols are identical to those described in Fig. 2.

3.2.4 Collisional time-scale of 8 kyr

The 8 kyr time-scale produces an oversized arc, almost 180° in expanse. It does a good job at matching the arc itself, the best of any result. However, the arc is 180° extending into the northern quadrant. Due to a dearth in the southern side, the average value and overall χ^2 of the parent ring is among our best. The north-south dichotomy prevents this from being our best result. This planet has a mass of $3.6 M_J$ and semimajor axis of 69.5 au. The results are shown in Fig. 5.

3.2.5 Collisional time-scale of 10 kyr

The 10 kyr time-scale produces an inconsistent arc of about 120° . The arc is not well defined and not very intense. Here, the planet has a mass of $3.7 M_J$ and semimajor axis of 68.7 au. The results are shown in Fig. 6.

3.2.6 Collisional time-scale of 14 kyr

The best solution at the 14 kyr time-scale required a $11 M_J$ planet. As this is well above the limit set by Z. Wahhaj et al. (2013) (see Section 4.2) we instead looked at lower-mass solutions. A $4.6 M_J$

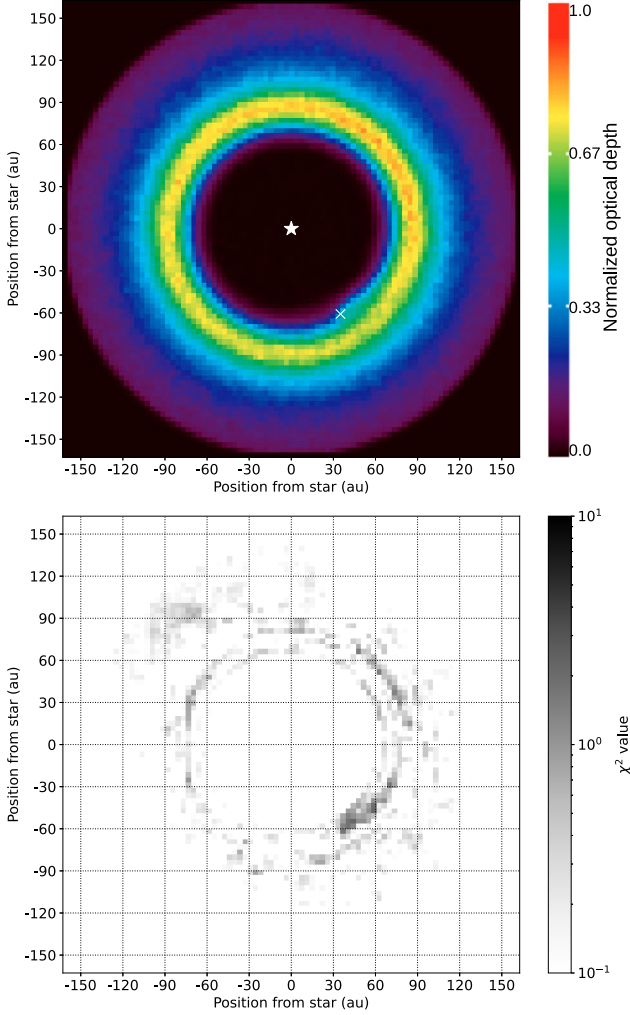


Figure 4. Best-fitting result for a particle lifespan of 6 kyr. Panels and symbols are identical to those described in Fig. 2.

at 53.8 au produces a thin 90° arc. The result is similar to the 10 kyr result. Though here, the eastern side of the disc is not fit as well as in other lifetimes. Overall, this has the second-worst χ^2 values of all our examined lifetimes. The results are shown in Fig. 7.

3.2.7 Collisional time-scale of 20 kyr

Our longest lifetime was 20 kyr. Like the 14 kyr run, the overall best result required an 11 M_J planet, which we rule out (Z. Wahhaj et al. 2013). Our best low-mass solution consists of a 3.8 M_J planet with a semimajor axis of 69.4 au. The result is a spotty 90° arc, and the far eastern side has a dearth of particles. The relative intensity of the arc (6.5 per cent greater than the rest of the parent disc) appears comparable to our best runs, but that is due to the low density on the eastern side. The results are shown in Fig. 8.

3.3 Relative particle density of arc to parent ring

To quantify the quality of our simulations, in particular the strength of the arc, we analysed and compared the particle counts

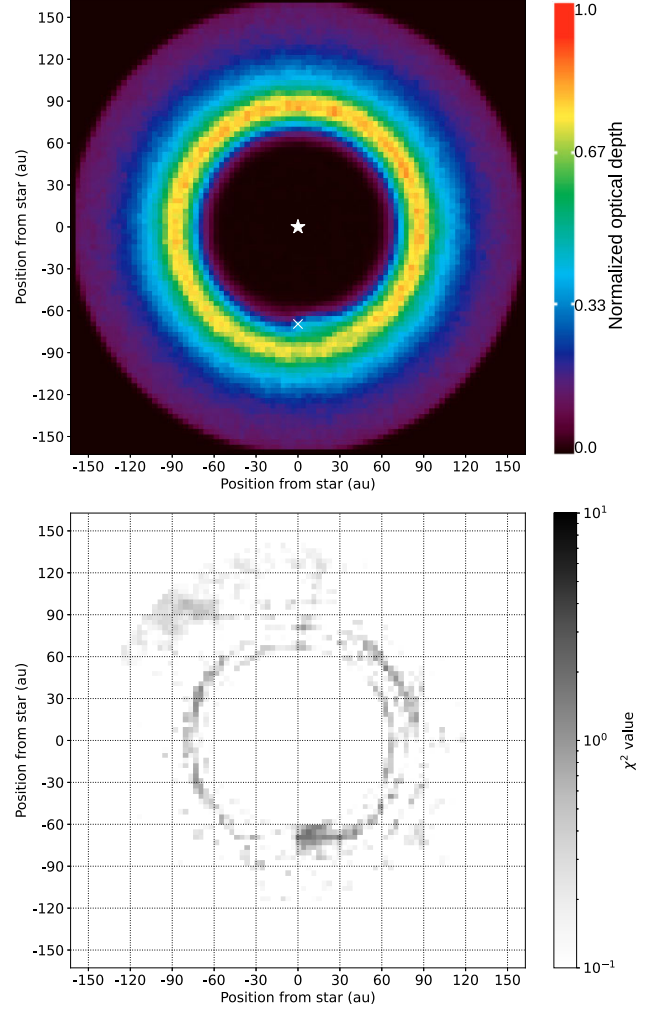


Figure 5. Best-fitting result for a particle lifespan of 8 kyr. Panels and symbols are identical to those described in Fig. 2.

in the regions of interest – the parent disc and the arc – between our simulations and the Target Disc.

We compared the sum of the optical depths between 70 and 100 au for each quadrant. The western quadrant (where the arc of increased density resides) is compared to the average value of the other three quadrants. This provides a measure of how many more particles exist in the arc than not. For the Target Disc, this value is 11.9 per cent, whereas our best-fitting simulations show an increase of 7.4 per cent (for the 6 kyr result, see Fig. 4), and the 4 kyr result is very close (Fig. 3). The 8 kyr time-scale shows a lower 4.5 per cent increase in arc, but the arc itself is a good fit. This discrepancy is likely due to its arc extending into the southern quadrant thereby raising the average of the parent ring. The 10 and 14 kyr lifetimes are only 4.0 per cent and 3.5 per cent respectively, indicating the arc for those lifetimes are not as well defined. The 20 kyr result bucks this trend and increases to 6.3 per cent, but this appears to be due to a dearth of particles on the east side rather than a surplus on the west (see Fig. 8).

Overall, the best fits were for time-scales of 4 kyr, 6 kyr, and 8 kyr. The quality of fit as measured by χ^2 , and the relative intensity of the arc are both better matches for the shorter time-scales. The 6 kyr result is our best fit, with the 4 kyr producing a similar but

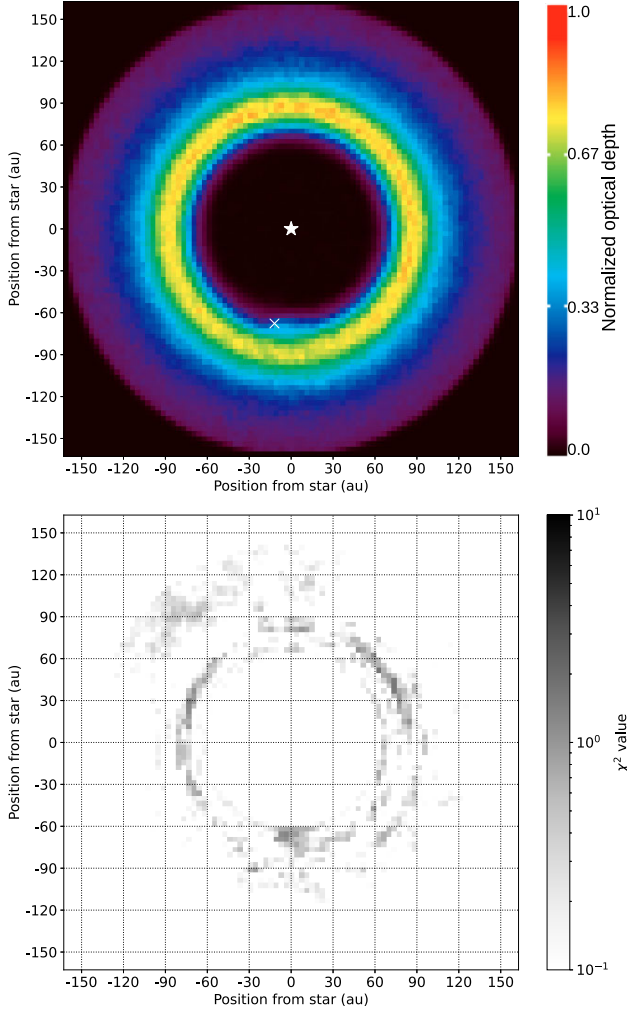


Figure 6. Best-Fitting result for a particle lifespan of 10 kyr. Panels and symbols are identical to those described in Fig. 2.

slightly shorter arc, and the 8 kyr producing an arc that is too long. Collisional lifetimes of 10 kyr and longer either do not produce a strong arc, or produce an arc but with a worse fit to the rest of the disc, or require a planet of significantly higher mass which we reject due to reasons in Section 4.2.

3.4 Simulated disc profile

To further test our best results, we examined the surface density profiles of the best-fit discs. Fig. 9 shows the normalized (peak value 1) mean optical depth profiles averaged radially over the entire disc. The inner edge slope is proportional to $a^{5.3}$ while the falloff outside the peak is proportional to $a^{-3.5}$. Our simulated inner edge is not as sharp as fig. 9 from C. C. Stark et al. (2014), with a value of 7.2 (rescaled and re-fitted after adjustment for updated *Gaia* distance). However, the outer side of our disc is better fitted, with our value of -3.4 compared to Stark's -3.8 . The 8 kyr result has a slightly better match on both the inner and outer sides of the disc.

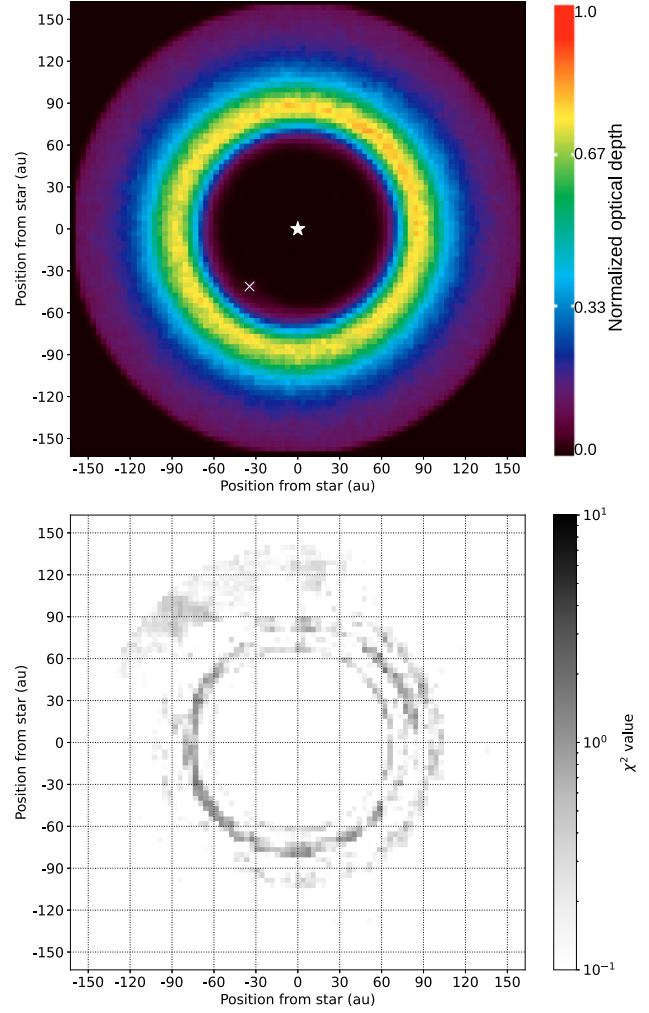


Figure 7. Best-fitting result for a particle lifespan of 14 kyr. Panels and symbols are identical to those described in Fig. 2.

3.5 Particle semimajor axis distribution evolution

The evolution of the particles' semimajor axis may provide insight into the mechanics at play. Fig. 10 shows the number of particles at four times during the simulation. Here, we show the 6 kyr result, but the outputs for the other time-scales show similar patterns. We examine only the first generation of particles, not a stack of continually generated particles.

The semimajor axis plots includes 4 vertical lines. The black indicates the semimajor axis of the best-fit planet. The blue, red, green, and yellow lines indicate the locations of the 3:2, 2:1, 3:1, and 4:1 resonances of a $\beta = 0.5$ particle with the planet. At the beginning of the simulation, there is a peak of particles at the 2:1 resonance, but this quickly migrates to show a dearth and peak just before and after respectively of the 2:1 line. A second smaller peak appears just above the 3:1 line, and another potential small bump may exist near the 4:1. This suggests that orbital resonances could play a role in the structure and stability of the system, as they do with planetary interactions (D. Fabrycky & S. Tremaine 2007; J. H. Steffen & J. A. Hwang 2015).

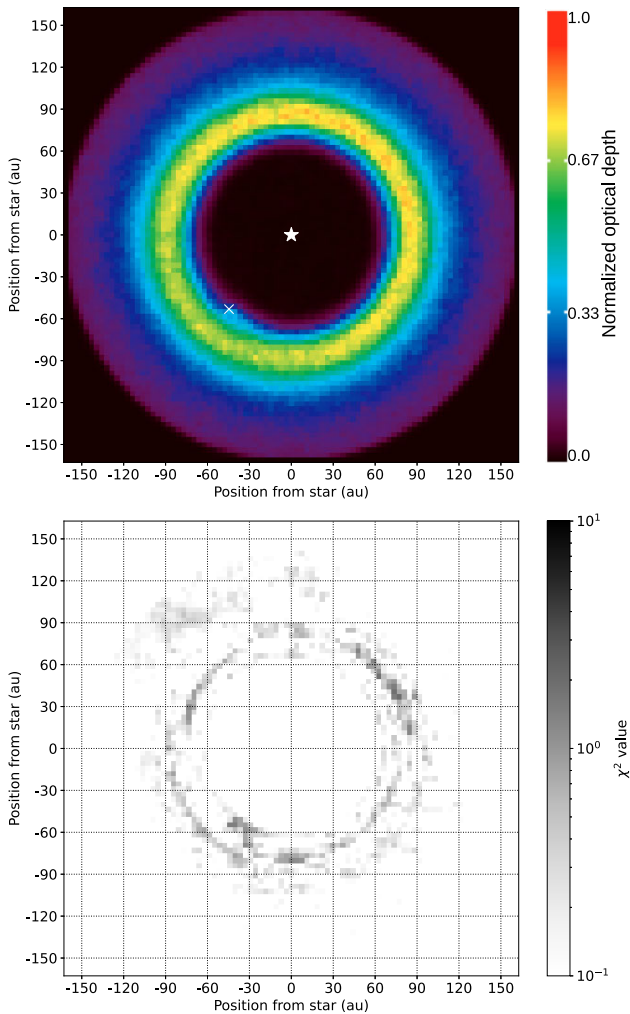


Figure 8. Best-fitting result for a particle lifespan of 20 kyr. Panels and symbols are identical to those described in Fig. 2.

3.6 Scale height

The scale height H of HD 181327 has been reported as 4–8 au (G. Schneider et al. 2006; C. C. Stark et al. 2014; J. Milli et al. 2024) within the parent ring. We measure the height of the disc in our model using the standard deviation of the vertical positions within the parent ring (74 to 94 au). For the 6 kyr result, we find a height of 11.1 au, somewhat larger than observed values. Our planet-based models tend to produce values at or above of previous estimates, though our most refined models (Section 3.8.3) do produce scale heights within the range of previous observations.

3.7 Behaviour of larger particles

Our results thus far have illustrated the behaviour of small ($\beta \approx 0.5$) particles (particle radii of 1–2 μm for mean grain density of 2 g cm^{-3}). Such small particles are observable in the visible bandpass of STIS, but would less prominent or invisible at longer wavelengths. The fact that observations at different wavelengths are sensitive to different particle sizes may provide an explanation of why observations of HD 181327 in the infrared by J. Milli et al. (2024) and at millimeter wavelengths by S. Marino et al. (2016)

both indicated an axisymmetric disc without a pronounced arc such as reported by C. C. Stark et al. (2014).

We next briefly examine how larger particles behave under the same conditions. We took the best-fit planetary parameters from our 6 kyr and 20 kyr collision lifetime results (Table 2) and applied them to an identically structured initial disc, but composed of larger particles with $\beta = 0.0001$ to 0.1 (corresponding to grain sizes of 7 mm to 7 μm , respectively).

These larger particles require some changes to the initial simulation parameters. They are less affected by radiation pressure and as a consequence, instead of being put on a parabolic orbit, a $\beta = 0.1$ released with identical orbital speed as the planet will be immediately put on an $e \approx 0.1$ orbit. As before, a random ejection ‘kick’ is added. However, a $\beta = 0.1$ particle is on the order of 100 $\times$ more massive than a $\beta = 0.5$ particle. Given our ‘typical’ ejection kick for the best-fitting run of a $\beta = 0.5$ particle, what is a reasonable value for the ejection kick of a more massive particle under identical circumstances?

The ejection velocity scaling of asteroid collisions is a non-trivial topic and beyond the purview of this paper. Such values can be stated in terms of total mass ejected given a particular velocity (K. R. Housen & K. A. Holsapple 2011; R. Hyodo & H. Genda 2020). For our purposes, we need a sense of how the speeds of different masses of individual particles compare for a given collision. A. Nakamura & A. Fujiwara (1991) performed low-speed (up to 100 m s^{-1}) experiments and found $v \propto m^{-1/6}$, but our collision speeds are an order of magnitude higher. If that relationship held, then we could expect a $\beta = 0.1$ particle to have roughly 45 per cent the ejection speed of a $\beta = 0.5$ for an equivalent collision event.

To account for many possibilities and give the best chance of success for replicating the Target Map with large particles, we tried several different ejection kicks, and applied them to our best-fitting 6 and 20 kyr simulations. The ejection kicks we tried were 70, 250, 625, and 1250 m s^{-1} , which correspond to ~ 5 per cent, 25 per cent, 50 per cent, and 100 per cent respectively of the typical kick values found in the posteriors and best-fits (per Table 2).

Regardless of ejection speed (even implausible ones) and for all particle lifetime scenarios, when our previous best-fitting results are applied to large particles, a matching arc of the Target Disc is not recreated. There are significant deviations in the inner edge and extended cloud as well. In the best-case of these scenarios (50 per cent kick for 6 kyr), the average χ^2 per pixel values for entire disc, parent ring, and the arc region are 0.59, 0.50, and 0.49, respectively, all at least $4\times$ above the values in Table 2. The result is shown in Fig. 11. The disc is nearly axisymmetric, and is a much better match to the ALMA image from S. Marino et al. (2016) (no asymmetry) than the Target Disc. For HD 181327, the planet that is capable of creating a 90° high-density arc using $\beta \approx 0.5$ particles does not create the same pattern with particles of $\beta \leq 0.1$. This supports the premise that the arc observed by C. C. Stark et al. (2014) is the result of $\beta \approx 0.5$ particles, observable to STIS in the visible spectrum but not observable in longer wavelengths.

3.8 Further tests and a refined disc model

3.8.1 Combining particles of different sizes / ejection speeds

Thus far, we have examined simulations of particles with a narrow range of particle sizes, focusing on discs comprised of particles with β values from 0.4 to 0.6. These particles were given a specific ‘kick’ of a particular magnitude but in a random direc-

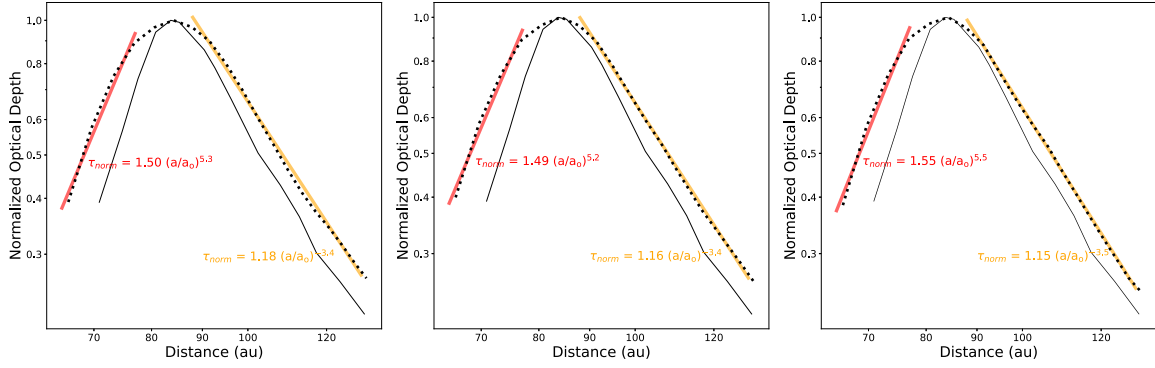


Figure 9. Normalized mean optical depth profiles of the discs. On the left is the 4 kyr best-fitting result, the middle is the 6 kyr best-fit, and the right is the 8 kyr result. The dotted line is our simulated result (see Table 2), with the best-fitting lines for our data overlaid for comparison. The slopes of the optical depth from 90 to 130 au closely match the slopes found in C. C. Stark et al. (2014), which we recreate here with the solid line. The inner slope is still steep but less than those from Stark.

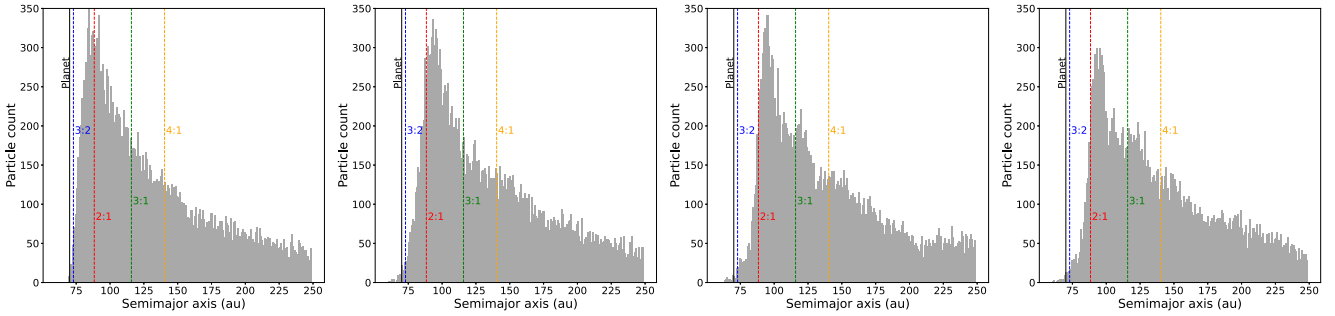


Figure 10. Evolution of newly created particles' semimajor axis at 0 yr, 2 kyr, 4 kyr, and 6 kyr from left to right. The solid line indicates the position of the planet, and the dotted vertical lines indicate the locations of the 3:2, 2:1, 3:1, and 4:1 resonances (for $\beta = 0.5$).

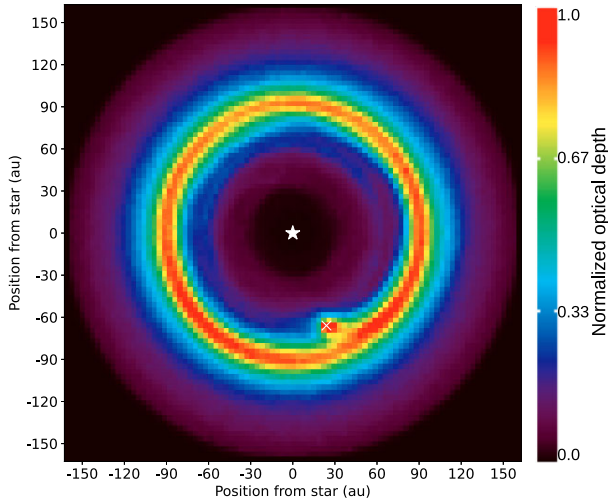


Figure 11. Disc of large ($\beta \leq 0.1$) grains under the influence of the best-fitting planet on a 6 kyr time-scale (see Table 2). The planetary configuration that drives small ($\beta \sim 0.5$) particles into a high-density arc does not drive large particles into an arc. Panels and symbols are identical to those described in Fig. 2.

tion. Here, we seek to take our previous results and apply them to a more realistic disc.

Our initial models were based on the hypothesis that particles with $0.4 < \beta < 0.6$ dominate the reflected light. To verify this hypothesis, we simulated additional discs consisting of a full range of particle sizes. Our new disc was based on the best-fitting parameters from our 6 kyr run, but using particles of β 0.05 to 0.8. We refer to this improved disc model as our ‘refined’ disc.

The particle size distribution of HD 181327 has a Dohnanyi-like distribution with a size index near -3.5 (J. Lebreton et al. 2012; S. Marino et al. 2016; J. Milli et al. 2024). Our reconstructions of the Target Disc assume equal albedo for all particle sizes and an amount of reflected light proportional to their radius squared. We thereby account for the particles total relative scattering ability.

The ejection speed values for the new disc are also adjusted for different particle sizes, as it was in Section 3.7. Particles of different β values had their kick values scaled per the $v \propto m^{-1/6}$ law used previously. Further, instead of using a static speed for each particle size segment, every particle was given its own unique kick value, informed from our previous results. We experimented with various distributions for these kicks. The distribution that gave us the best result has a mean speed of $3/4 \times$ the best result (see Table 2) uniformly distributed over ± 50 per cent of this value. For example, in this new simulation, the ejection speeds of each $\beta \sim 0.5$ particle (previous best-fitting kick of $\sim 1.2 \text{ km s}^{-1}$) is within the range of $0.9 \pm 0.45 \text{ km s}^{-1}$. The speeds for each β value are scaled accordingly.

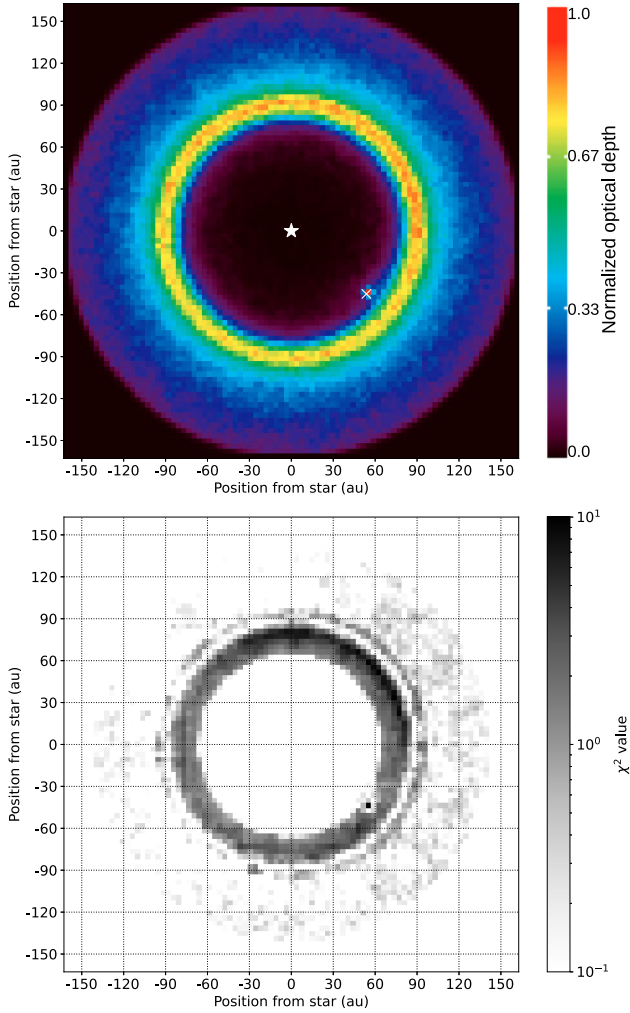


Figure 12. Best-fitting result for a particle lifespan of 6 kyr, but using particles of all sizes ($\beta = 0.05$ to 0.8). The top image is the simulated optical depth map, with the white $\times$ marking the location of the planet. At the bottom is the χ^2 map when compared to the Target Map. The refined disc has a mismatch on the inner edge, but otherwise produces a good match to the Target Disc.

3.8.2 Assessment of the refined model

Our refined model includes a variety of particles of different sizes and ejection speeds, and is shown in Fig. 12. This scenario creates an arc of increased density with an overall strength (7.4 per cent) equal to our earlier model (per Table 3). However, there are some differences to our previous models. While the parent and extended discs remain a good match to the Target Disc, the χ^2 map indicates a lower-quality fit around the inner edges of the parent disc when compared to the $\beta \approx 0.5$ simulations (see Fig. 4). We also find the resulting parent ring is narrower than the Target Disc. From these results, we conclude that our model is relatively insensitive to the precise ejected velocity distribution adopted.

3.8.3 Evolution of the refined disc grains

The dust size distribution created by ongoing collisions within the parent disc is expected to create more small particles than

large ones; however, in our model, the light reflected from our model disc is dominated by the particles that remain in orbit. To demonstrate this, we examined the time evolution of the grain distribution. Fig. 13 shows the proportion of light scattered from the grains at the start of the simulation compared to the steady-state disc. Newly created grains on hyperbolic orbits initially dominate the scattering, but these grains move outside of 150 au within a few hundred years. The few particles that are not lost accrue and become the dominant source of light.

To further analyse the behaviour of the grains, Fig. 14 shows the time evolution of a single generation of particles for different values of β . The smallest particles are initially the most numerous, but they are lost quickly to radiation pressure. The mid-sized particles ($\beta = 0.4$ – 0.6) are partially lost, but those retained on bound orbits become the largest overall contributor to the scattered light. The last plot of this Figure is the stacked result, representing the steady-state of particles across all ages up to their collisional lifetime. In the steady-state, $\beta = 0.4$ – 0.6 particles with eccentricities of 0.2 – 0.3 dominate the scattering.

The specific particles in the arc are always changing, and their resonance properties are difficult to determine, but similar arcs have also been seen by J.-C. Liou & H. A. Zook (1999) in models of Kuiper belt dust trapping by the giant planets. J.-C. Liou & H. A. Zook (1999) models use relatively gentle ejection speeds, placing dust on $e = 0.1$ and $i = 10^\circ$ orbits, which may account for the differences seen. Arcs like those found here (asymmetrical with respect to the planet) have been seen in S. F. Dermott et al. (1994) in models of the Earth’s dust ring, related to trapping of inspiraling asteroid dust near 1:1 resonances; however the grains in our ring are well outside the 1:1 resonant zone.

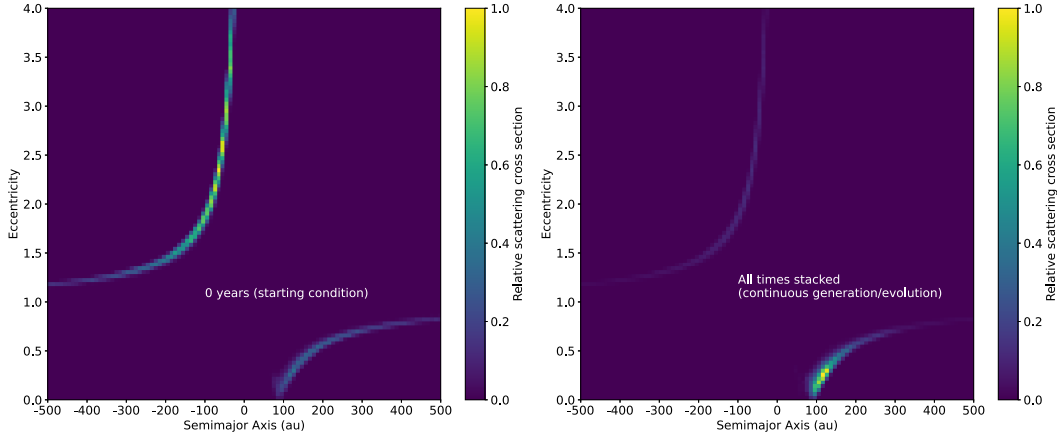
The particles in the region of the arc have perihelia concentrated at 81–84 au, and median eccentricities ranging from 0.14 for $\beta \approx 0.1$ particles and up to 0.45 for $\beta \approx 0.7$. Fig. 15 shows the semimajor axis distribution of the particles in the refined disc at 6 kyr, which is broader for the refined disc compared to our earlier results. Instead of the distribution peaking near the 2:1 period ratio (see Fig. 10), the distribution peaks between the 3:1 and 4:1 resonances. The 2:1 shows less than half the number of particles as the 3:1, and there are very few near the 3:2. This trend applies for all bound particle types, not just the $\beta = 0.4$ – 0.6 grains. This suggests that the revised velocity-kick has distributed the particles more broadly, resulting in more of the inner edge particles being spread out across the disc. While the particle distribution changes as it ages and has various over and underdensities throughout its circumference during its lifetime, starting around 3 kyr the primary arc (western quadrant) becomes apparent and holds its position with respect to the planet. The individual grains in the arc themselves are not stationary with respect to the planet, and move from perihelia within the parent ring to the more diffuse outer disc and back.

3.8.4 Scale height of the refined disc

The scale height of our refined disc parent ring (74 au to 94 au) is found to be 7.6 au, as estimated from the standard deviation of the vertical positions of particles within the parent disc. Thus, unlike our initial model value (11.1 au), our refined model has a scale height consistent with the analysis from previous studies (G. Schneider et al. 2006; C. C. Stark et al. 2014; J. Milli et al. 2024). The reason for the difference between our refined disc and the previous is likely the lower ‘kick’ speed and distribution. Our

Table 3. Average optical depth per pixel in each quadrant of the parent disc.

Quadrant	Target Disc	3 kyr	4 kyr	6 kyr	8 kyr	10 kyr	14 kyr	20 kyr
West	0.738	0.735	0.709	0.712	0.711	0.703	0.704	0.700
North	0.681	0.680	0.665	0.686	0.700	0.695	0.685	0.679
East	0.641	0.652	0.639	0.644	0.661	0.653	0.673	0.622
South	0.657	0.697	0.678	0.660	0.681	0.680	0.682	0.674
Increase of West arc compared to other quadrants	11.86%	8.65%	7.35%	7.43%	4.51%	4.04%	3.47%	6.30%

**Figure 13.** Heat map of semimajor axis versus eccentricity, at the beginning of the simulation and after 6 kyr. The left panel shows the distribution of newly created particles (with ejection kick included). These are primarily on hyperbolic orbits and quickly move outside of 150 au. The right panel shows the stacked result, representing the ongoing distribution of particles of various ages. Particles that are not initially lost build up in numbers and become the dominant source of scattered light, concentrated with eccentricities of 0.2 to 0.3.

refined model used kick speeds of $0.45\text{--}1.35\text{ km s}^{-1}$, while the original used a static 1.2 km s^{-1} .

4 OTHER CONSIDERATIONS

4.1 Model limitations

Our simulated model has several limitations. First, it presumes a single type of particle. The composition of the debris disc of HD 181327 includes many dust species (carbon-, iron-, silicon-based) along with water ice (J. Lebreton et al. 2012 and C. Xie et al. 2025). We have also assumed that particles of all sizes have the same albedo. However, depending on the distribution and albedo of these various species, different grain sizes may contribute to the brightness profile differently.

Secondly, our simulations use ejection ‘kicks’ to simulate the ejected debris from a collision. The magnitude of these kicks is $\sim 1\text{ km s}^{-1}$, corresponding to the relative velocity of two particles of $e \approx 0.3$. This is in mild tension with the usual assumption that $e \sim i \sim H$, since the scale height H of HD 181327 has been measured to be $\lesssim 0.1$. However, our speed distribution (1) has a scale height $H \approx 0.1$ [Section 3.8.4, which is of the same order as the measured values from G. Schneider et al. (2006) and C. C. Stark et al. (2014)], (2) contains a distribution of eccentricities peaking between 0.2–0.3 (see Fig 14), and (3) the appearance of the observed disc is well reproduced by our model.

We note that while collision speeds of this magnitude are plausible within our model, the resultant speed of ejected debris is more difficult to determine. Our refined model from Section 3.8.1

requires a mean ejection speed of less than 1 km s^{-1} , which reduces this tension. Particles with $\beta > 0.5$ and with low ejection speed are naturally lost (immediately put on $e \approx 1$ or $e > 1$ trajectories). Only grains with sufficient ejection speeds in the proper direction remain bound and thus they contribute disproportionately. This accumulation means that each generation of grains needs only a small fraction with high ejection speeds. The ejection speed of debris is a complex topic beyond the scope of this paper, but if ejecta speeds of this magnitude can exist (by whatever mechanism) in modest quantities, then a planetary explanation for the arc observed by C. C. Stark et al. (2014) is viable.

4.2 Detection limits of planet masses

There have been previous estimates and limits placed on the mass and orbital distance of a potential planet within the HD 181327 system. As part of the Gemini NICI planet-finding campaign (using direct imaging), Z. Wahhaj et al. (2013) estimated that a 4.0 M_J planet in HD 181327 would be detectable at $1.0''$ from the central star and a 2.6 M_J planet at 2.0 arcsec . Interpolating from their limits, the detectability of our best-fitting planetary distance (70 au , or 1.4 arcsec) would be $\sim 3.5\text{ M}_J$. This suggests that our predicted planet must have a mass lower than 3.5 M_J , otherwise the Gemini NICI campaign would have observed it. This informed the results we used throughout Section 3. Our MultiNest results suggest that more massive planets could induce the arc, but because of the Gemini NICI results, we focused on solutions that were near or below the limits set by Z. Wahhaj et al. (2013).

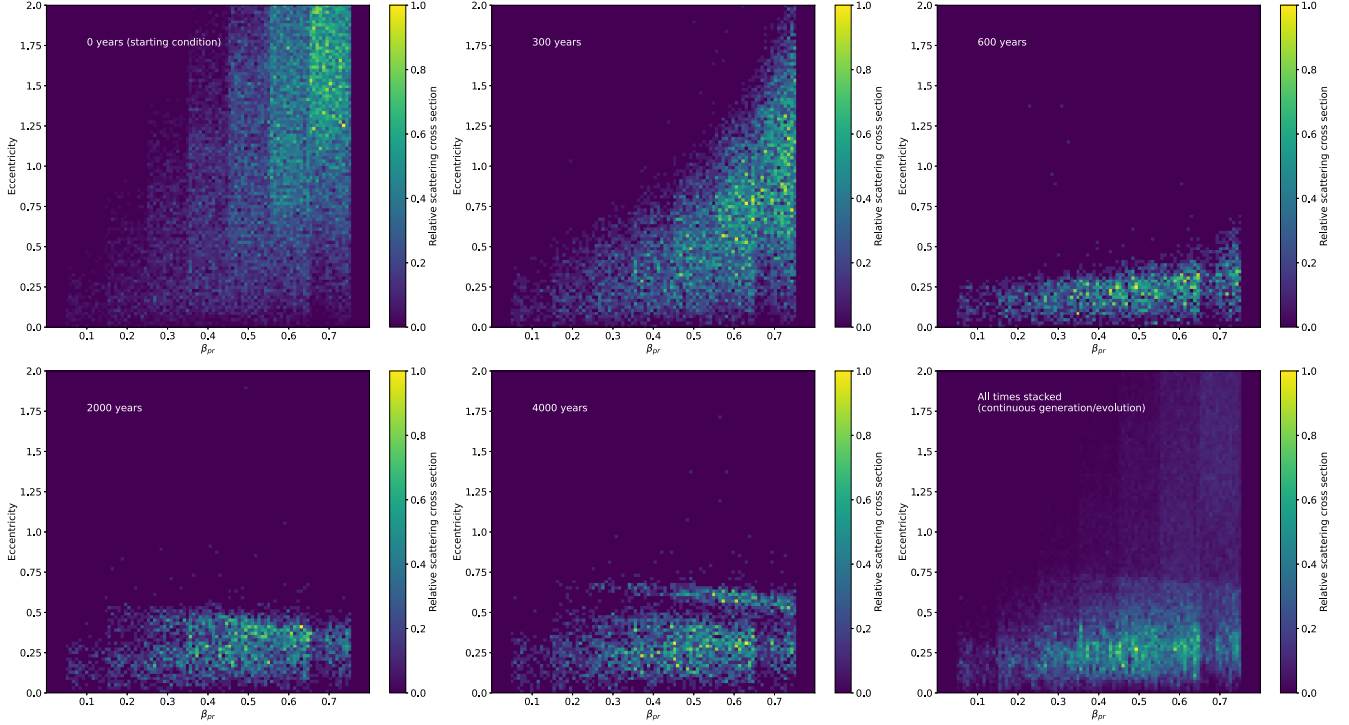


Figure 14. Heat map of the time evolution of a single generation of particles. The maps display the scattering cross-section within 150 au of the star. On the top row are snapshot of the distributions at ages of 0, 300, and 600 yr, respectively. The high- β high- e particles that initially contribute the most scattering cross-section are lost quickly. On the bottom row, the particle ages are 2000 and 4000 yr. The final panel (bottom-right) shows the stacked (all times representing the steady state generation and evolution of particles), and demonstrates the most dominant particles to the scattered light are $\beta = 0.4$ – 0.6 with $e = 0.2$ – 0.4 . Note that the vertical striations are artefacts of how we combined particles of different β values in our simulations.

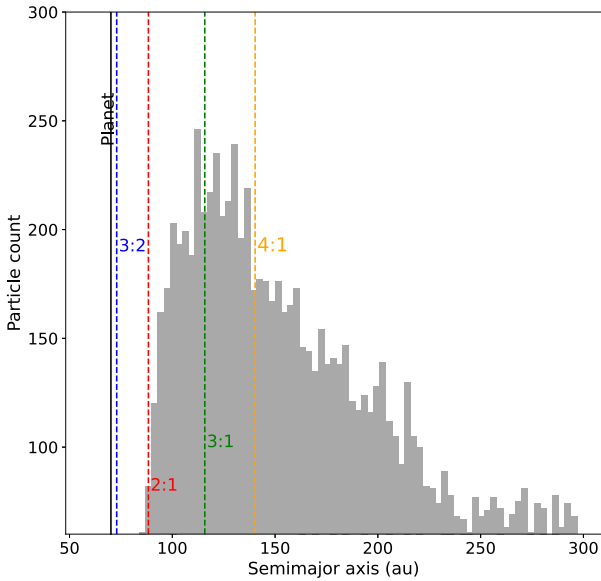


Figure 15. Semimajor axis distribution of the particles in the refined disc after 6 kyr. The solid vertical line indicates the position of the planet, and the dashed vertical lines indicate the locations of the 3:2, 2:1, 3:1, and 4:1 resonances (for $\beta = 0.5$).

In another study, T. J. Rodigas et al. (2014) through dynamical N -body simulations made predictions for shepherding planets in the interior of several debris discs. For HD 181327, they found

the planet could have a mass no larger than $15 M_J$ and must be at least 35 au from the star, and our results are consistent with these limits.

Our simulations point to a planet with a semimajor axis of ≈ 70 au and a range of possible masses, 2.0 to $4.0 M_J$. Our posteriors are inside the limits set by T. J. Rodigas et al. (2014) and Z. Wahhaj et al. (2013), though our upper uncertainties exceed these limits. Most of our best-fit masses are near the Wahhaj limit, but a few have planetary masses as low as $1.6 M_J$ that are also capable of producing a similar arc. Thus our results adhere to the pre-established detection limits.

4.3 Longer time-scales and particle lifetime scaling

Our refined disc model has focused on using the best-fit result from the 6 kyr result from Section 3.2 (Fig. 4). As an experiment, we permitted this run to run out to 20 kyr. This resulted in the loss of the arc, with a very axisymmetric parent ring.

We note that particles of different sizes have different lifetimes. Work by P. Thébault & J. C. Augereau (2007) indicate that there is a sharp minimum lifetime at approximately $10\times$ the blowout radius ($\beta \sim 0.05$). Per equation (7) from P. Thébault & J. C. Augereau (2007) a $\beta = 0.1$ particle has a lifetime $\sim 25\times$ less than a $\beta = 0.5$ particle. Further, grains contribute less to the scattering the larger they become ($\propto s^{-1.5}$). Combining these two effects, we expect that regardless of the exact lifetime, large particles will have a small impact on the disc profile.

4.4 Rotation direction

The motion of orbits in our simulations shown in Section 3 is in the clockwise direction, consistent with analysis by S. Marino et al. (2016). The disc and arc are very symmetric across the positive diagonal, so we expected the direction of rotation to play a minimal roll in our results. For confirmation, we also ran simulations in the counter-clockwise direction. We find that we get statistically identical results (near-identical posteriors). If the disc actually rotates in the counter-clockwise direction our results would still stand, but the simulated maps in Section 3.2 and location of the simulated planet (the $\times$ symbol) would be flipped across the positive diagonal.

5 SUMMARY

The primary goal of this study was to determine whether a planet could be the cause of the asymmetry in the HD 181327 debris disc reported by C. C. Stark et al. (2014), and if so to parametrize such a planet. We find that a planet can indeed create an arc similar to that observed. We summarize the relevant requirements and results below.

- (i) Grains are produced throughout the disc from an exo-Kuiper belt, with approximate limits of 80 to 100 au.
- (ii) The likely lifetime of micron-sized grains is somewhere between 4 and 8 kyr.
- (iii) Contributing grains are initially released on moderate-eccentricity orbits, requiring ejection speeds near 1 km s^{-1} in a retrograde direction relative to the planet, the result of energetic collision processes.
- (iv) The majority of grains are released with low speeds and put on high eccentricity orbits. These are either lost quickly or on such large orbits that they do not often contribute to the arc.
- (v) The planet has a mass of $2\text{--}4M_J$ and semimajor axis of 68–73 au.
- (vi) Only grains with $\beta \approx 0.5$ are quickly driven to the requisite pattern. This may explain why the arc is reported at visible wavelengths but is not at longer wavelengths.

The structure of the HD 181327 disc as observed by C. C. Stark et al. (2014) is reproducible by the presence of a giant planet within the system. Our simulations are able to produce a debris disc very similar to the disc of HD 181327 with a range of planetary masses and time-scales. These simulations are premised on the existence of ongoing collisions [as indicated by C. Xie et al. (2025)] with adequate energy to create and eject grains of sufficient speed and moderate eccentricities in modest quantities. While the bound grains are relatively few in number for each generation, their accrual enables them to dominate the light scattering over the unbound grains. This hypothesis can explain the absence of structure seen at longer wavelengths, as larger particles do not take on the same distinct arc as smaller particles. We encourage further observations of the system to corroborate or refute the planet hypothesis.

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DATA AVAILABILITY

This paper is based on the work of C. C. Stark et al. (2014), and all source data comes directly from that work. No new data were generated in support of this research.

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