Attenuation by the debris disk of the solar-like star HD 107146 of a distant occulted galaxy

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ABSTRACT

Observations of the debris disk around the solar-like star HD 107146 reveal the disk (nearly) transiting an extended background galaxy. By using out-of-transit observations to model the galaxy, we show it to be smooth and well modelable. When subtracting this model from the edge-of-transit observation, attenuation by dust of the debris disk in the line-of-sight can be seen. From this we calculate the column density of the dust. The results of this new way of detecting debris dust agree with previous work, however at increasing distance from the star we find an increasing column density, suggesting dust segregation.

Keywords

Stars: individual HD 107146 -- Techniques: high angular resolution -- Methods: data analysis -- Circumstellar matter -- occultations -- Galaxy: general

INTRODUCTION

In this research we are studying the debris disk around the young solar-like star HD 107146. Debris disks are circumstellar belts of dust, analogous to the Solar System's asteroid and Kuiper belt. Studying these disks can provide information on the formation and evolution processes of planetary systems, one of today's main subjects of research in astronomy. Particularly understanding debris disks around (young) solar-like stars, like in our case, might give us clues on the early history of our own solar system or the diversity of planet formation for host stars of the same spectral type. Due to improved observational techniques last decades, a few tens of resolved debris disk have been observed. These observations can be at infrared (IR) wavelengths, when observing the thermal radiation of mainly ~mm-sized particles, or at optical and near-IR wavelengths, when observing stellar light which is scattered by mainly ~µm-sized particles. However, in this research we apply a new technique to detect and characterize debris dust, called debris ring transit photometry (Zeegers et al. 2014). Here we make use of the rare occasion of a debris disk transiting an extended background galaxy, which currently is the case for HD 107146. By looking at the amount of background light that is blocked by the dust (instead of the amount of light that comes from the dust), we can directly measure the average optical depth of the debris disk along the line of sight. A similar method has also been used to detect dust in the case of two occulting galaxies (see for example Holwerda et al. 2007).

OBSERVATIONS

As mentioned before, we study the star HD 107146. This G2V star is at a distance of approximately 27.4 ± 0.4 pc from Earth (van Leeuwen 2007) and the age of the system is estimated to be between 80 and 320 Myr (Williams et al. 2004a, Moor et al. 2006, Roccatagliata et al. 2009). The ring-like debris disk is seen almost face-on with an inclination angle of 18.5 ± 2 ° (Schneider et al. 2014). HD 107146 has been observed with Hubble Space Telescope (HST) in optical (scattered) light using stellar coronagraphy techniques by the instruments HST/ACS in the I- and V-filter in 2004 (Ardila et al. 2004) and HST/STIS without filter in 2011 (Schneider et al. 2014). At the observations in 2004 the debris disk still out-of-transit, due to the large angular separation with the background galaxy. However, because of the proper motion of the star, in the 2011 image the debris disk is already at the edge-of-transit with the galaxy, i.e. the light of the debris disk is contaminated by the of the galaxy, hence the authors called it the Vermin Galaxy. The image of the 2011 observations can be seen in Figure 1.

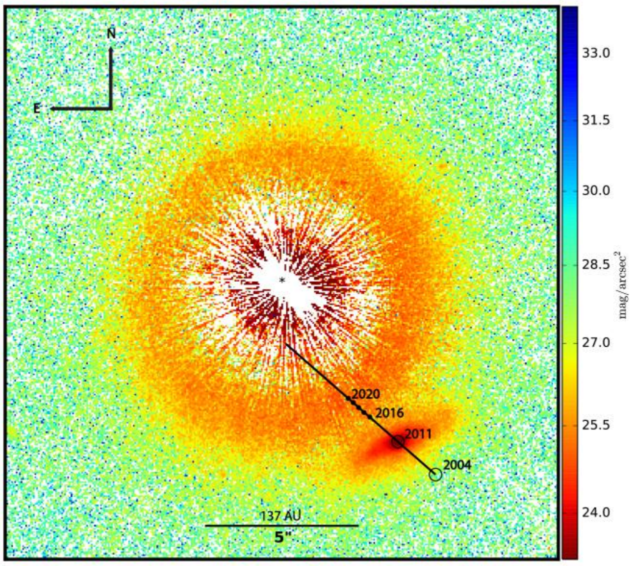

Figure 1: Image of HD 107146 taken in 2011 with HST/STIS PSF subtracted coronagraphy. The scale bar in au indicates the distance assuming a face-on orientation of the debris disk. The position of the Vermin Galaxy over the years is indicated, which changes due to the proper motion of the star.

DEBRIS RING TRANSIT PHOTOMETRY

When detecting a debris disk in optical light, we observe light from the central star which is scattered by the dust. The fraction of scattered light depends on the albedo of these dust-particles. However, if a background object is present, we can make use of the physical size of the dust to block light, independent of the albedo (Zeegers et al. 2014). Since each dust particle will block part of the light from the background galaxy, we can measure the net contribution of all debris particles in front of the galaxy. Hence the average optical depth τ of the debris disk along the line of sight can be calculated. We do this by looking at the transmission T of the light from the galaxy through the

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debris disk, defined as $T = e^{-\tau}$. When looking at a region where the light-profile of the debris disk and the background galaxy overlap, the transmission can be determined as follows:

$$T' = \frac{<D + Ge^{-\tau}> - G'}{D'} \qquad (1)$$

where G' is the model of the Vermin Galaxy, D' the model of the debris disk and where G and D are the real (observed) values of the surface brightness of respectively the Vermin galaxy and the debris disk. The prime in T' denotes that we are calculating the transmission under the assumption that D' and G' are a perfect representation of D and G. The factor $< D + Ge^{-\tau} >$ corresponds with the surface brightness we measure in the image. When subtracting the expected amount of light from the galaxy (G'), the attenuation by the debris dust will become clear as the difference between the model and the detected light from the galaxy. When dividing this by the amount of light we expect to come from the debris disk (D'), we get the transmission, from which the average optical depth can be calculated. However, we are not just interested in the fraction of light that is attenuated, but even more in the amount of dust that blocks the light, i.e. the column density Σ of the debris disk at the line of sight. This can be calculated when the optical depth is known:

$$\Sigma = \frac{\tau}{\sigma} m_p = \frac{2}{3} \tau a \rho \qquad (2)$$

where σ is the effective cross section, m_p the mass of one particle, a the particle radius and ρ the mean solid density. Here we assume that $\lambda << a$ (where λ is the observed wavelength), which means the Mie theory says that the effective cross section σ is twice the geometrical cross section, i.e. $\sigma = 2\pi a^2$. We make this assumption since the smallest particles in the debris disk are a few ~µm (since smaller particles are quickly blown out of the system due to the radiation pressure), while the observations are at a central wavelength far smaller than ~µm. It is important to notice that in order to calculate the amount of dust we still need to make assumptions on the particle size and density, but not on the albedo of the dust particles. This is a huge advantage of our method, due to we are measuring attenuation instead of the scattering.

RESULTS

Determining the transmission

In Figure 1 we can see that the light-profile of the debris disk and the galaxy partially overlap in the outer regions of the debris disk. This means we can apply the debris ring transit photometry in this region, since we have a background light source. Therefore we can determine the transmission in the overlapping area, using Equation 1. However, in order to do this, we first need to obtain the models G' and D'.

Modeling the Vermin Galaxy with Imfit

Modeling the galaxy means finding a 2-dimensional light-profile that fits the observed light-profile of the Vermin galaxy as well as possible. To model the Vermin Galaxy we use the astronomical image-fitting program Imfit (Erwin 2015). This program uses χ^2-optimization to find the best fitting model. In order to model the Vermin Galaxy properly, we first analyze the out-of-transit 2004 observations (Ardila et al. 2004). At this point, the light of the galaxy is still unaffected by the debris disk, due to their large angular separation. Since these observations are taken in other filters than the 2011 observation, we cannot use them for photometric purposes, but we can use them to constrain model parameters for the 2011 model. It turns out that for the Vermin Galaxy a combination of an exponential light-profile for the disk and a Sérsic light-profile for the bulge leads to the best-fitting model. Empirically, this indicates that we are dealing with a spiral (late type) galaxy. Apart from some substructures in the inner parts of the galaxy (which are probably star-formation regions), the Vermin Galaxy turns out to be pretty smooth (i.e. without detailed structures that can be seen) and well-modelable. This means that when we subtract the model from the actual image, the light from the galaxy is almost completely removed (as can be seen in Figure 2). This is important for applying our method, thence Vermin Galaxy is an excellent candidate for performing debris ring transit photometry. Scaling the 2004 model to the 2011 observation, we can find the best-fitting 2011 model of the Vermin Galaxy. This model turns out to be similar to the 2004 model, except for some small differences due to the fact that the images were taken in different filters.

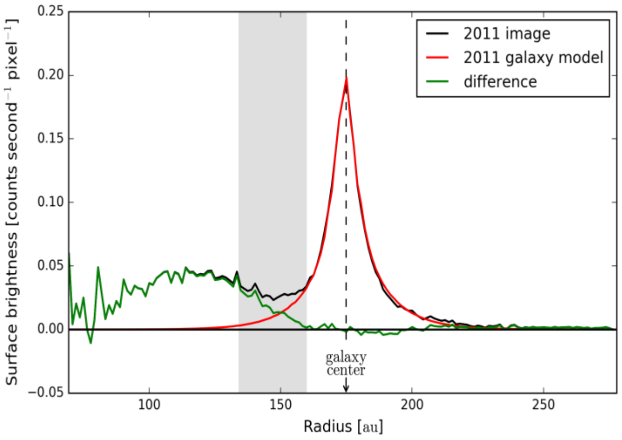

Figure 2: The average radial surface brightness profile of the image (at the angle where the galaxy is located) plotted against the de-projected distance to the star in au. In the figure the location of the center of the galaxy is indicated. In the gray region the image curve is above the curve of the model and the residual. This indicates the galaxy is already behind the debris disk in 2011. In this region we determined the column density of the debris disk.

Modeling the debris disk

D' is determined by looking at the difference between the radial SB profile of the disk (between radii that are not transiting the galaxy yet) at the angle where the galaxy is present and the average SB profile of the surrounding areas where no light of the galaxy is present. We find that the radial SB profile at the angle where the galaxy is located is a factor 1.15 higher, which means we have to multiply the average SB profile of the surrounding areas with this factor in order to get the debris disk model. This difference can probably be explained by the scattering efficiency which differs for different angles of the disk (Ardila et al. 2004).

Calculating the radial transmission profile

Now that we determined the models G' and D', the transmission can be calculated with Equation 1. We find

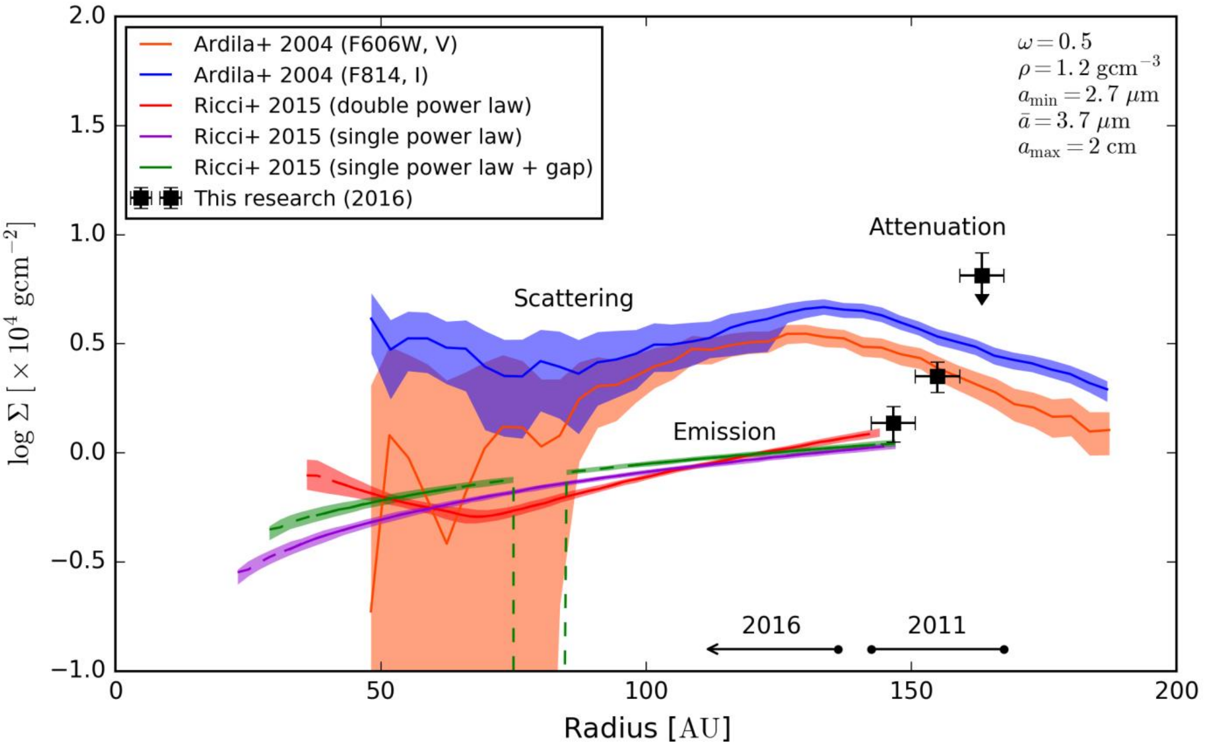

Figure 3: The radial column density profile of the HD 107146 debris disk, as determined by this research, Ardila et al (2004) (under our assumptions) and Ricci et al. (2015). The results are determined by looking at different physical processes, respectively: attenuation, scattering and thermal emission by dust. Our assumptions are shown in the right top corner. The radius is the de-projected distance to the star in au. Our measurements (from the 2011 data) are in the regions between ~142-151 au, ~151-159 au and ~159-167 au. The 2016 region indicates where we could determine the column density with this method when we did measurements right now (in 2016).

that $0 < T' < 1$ in the region where the light of the debris disk and the galaxy seem to overlap (indicated as the gray region in Figure 2), hence we can conclude that there is attenuation by dust here. This means that the outer regions of the debris disk are indeed already in front of the debris disk. Therefore it is possible to perform debris ring transit photometry with the Vermin Galaxy in the 2011 observations. Since the signal of the attenuation by dust at individual data points in the outer regions of the disk is quite weak compared to the noise, the signal in certain regions is binned in order to increase the accuracy of the transmission measurements. Hence, the average transmission was determined between the radii ~142-151 au, ~151-159 au and ~159-167 au from the star over an extension of 10°. From now on we shall only work with these average transmission values to determine the average column density. At radii further away from the star than these regions, we cannot well determine the transmission anymore. Close to the center of the galaxy, the calculation of the transmission is too much affected by the substructures in the galaxy (i.e. over- and underdensities in the galaxy model). At even larger radii than the galaxy center, the measured flux from the debris disk fades away, which means it gets too close to the background noise to calculate the transmission well. At radii closer to the star we find $T' \approx 1$, since there is no more background light from the galaxy present. As a result we will see no attenuation by dust, hence here we cannot apply our method anymore.

Determining the column density

Using Equation 2, the calculated average transmissions can be converted into average column densities. In order to do so, assumptions on the particle radius and particle density have to be made. We choose to assume the grain size distribution and mean solid density which Ricci et al. (2015) used in their analysis of the debris disk. They assumed a particle distribution $n(a) \sim a^{-q}$ where a is the radius of the particle and q the power law index. This distribution is valid between a specified minimal and maximal grain size (a_{min} and a_{max} respectively). In their paper it was assumed that $a_{min} = 2.7\ \mu\mathrm{m}$, $a_{max} = 2\ \mathrm{cm}$. and $q = 3.25 \pm 0.09$. For our assumptions we will use the average particle size $\bar{a}$ of the distribution described above. Assuming $\bar{a} = 3.7\ \mu\mathrm{m}$ and $\rho = 1.2\ \mathrm{g\,cm^{-3}}$ we can calculate the column density from the average transmissions using Equation 2. The result is plotted in Figure 3. To compare our column density with previous research we also plotted the column density determined by Ricci et al. (2015). Furthermore, we converted $\tau\omega$ (optical depth · albedo) calculated by Ardila et al. (2004, 2005) into a column density using Equation 2. We did this by using the mentioned assumptions on the particle radius and mean solid density and by assuming an albedo ω = 0.5, another assumption by Ricci et al. (2015). The resulting column density is also plotted in Figure 3.

DISCUSSION

Figure 3 shows the result of three different kind of observations: Ricci et al. (2015) looks at thermal emission of dust at millimeter wavelengths, where Ardila et al. (2004) looks at scattered light in the optical, while this research looks at attenuation by the dust at a broad wavelength approximately centered around the optical V-band wavelength. As can be seen in Figure 2 our results of the column density closest to the star is in accordance with previous research of Ricci et al. (2015), although our results are not sensitive enough to rule out their different models. The fact that our result agrees with this previous result under their assumed particle distribution is very interesting, since we use a completely different method.

For the observations farther from the star the column density increases more rapidly than both other methods expect. Our middlemost observation seems to agree with Ardila et al. (2004), but our outermost point overestimates the column density compared to the other results. The latter could suggest that we are looking at smaller particles compared to the observations of Ardila et al. (2004): particles which scatter ineffectively, but are effective absorbers. Since we look at attenuation by the dust, as Ardila et al. (2004) looks at scattered light, this could be a possible explanation for this difference in observed column density. However, for the determination of the outermost point, overdensities in the Vermin Galaxy could also explain higher values for the column density. Hence, we conservatively regard this outermost point as an upper limit for the column density.

A possible explanation for our observation that the column density increases with distance (assuming a constant particle size) might be dust segregation: a particle size distribution where the particle size decreases with increasing distance (see e.g. Wyatt 2006). Ricci et al. (2015) found that the mm-particles distribution only extends to ~150 au, based on the observations of the continuum emission of the particles. Furthermore, Ricci et al. (2015) calculated the blown-out grain sizes due to radiation pressure to be between $a_{min} = 1.7\,\mu$m and $a_{min} = 2.7\,\mu$m. Therefore, a particle distribution with sizes between these values and $a_{max}\sim$mm with decreasing particle size for increasing distance might be an explanation of our observations. Another possible explanation for the increase in the column density at this distance from HD 107146 could be a period of a higher dust production rate in the (near) past, caused by a collisions between ~km or larger sized objects. Such an explanation has been investigated for example in the case of the (possible) exoplanet Fomalhaut b (see e.g. Kalas et al. 2008).

CONCLUSION

From our research we can conclude the following:

1. From out-of-transit data we conclude that the Vermin Galaxy is a distant, smooth spiral galaxy that can be modeled well. Therefore, this galaxy is an excellent object to perform debris ring transit photometry. This gives us an unique opportunity to directly measure the optical depth of a debris disk around the young solar-like star HD107146.
2. Already in the image made by the HST/STIS in 2011 attenuation caused by dust in the debris disk can be detected.
3. Our measured column density at a distance between ~142-151 au from HD 107146 agrees with previous work by Ricci et al. (2015) and between ~151-159 au with previous work by Ardila et al. (2004), however our results are not sensitive enough to arbitrate between the different models used by Ricci et al. (2015).
4. We find an increasing column density in the outer regions of the debris disk assuming a constant particle size. This could be explained by a particle distribution where particle sizes decrease with increasing distance from HD 107146 or a higher dust production rate in the past.

FUTURE RESEARCH

Already at this moment (2016) and in the near future the Vermin Galaxy will be occulted by larger parts of the debris disk (see Figure 1). Therefore, near-future observations by HST may be our best chance to map the dust in these parts of the HD 107146 debris disk directly using this method. In this case our 2004 and 2011 models of the Vermin Galaxy are directly useful as calibration data, since the galaxy itself will be occulted for the coming decades.

ROLE OF THE STUDENTS

Dennis Vaendel and Lennart van Sluijs were undergraduate students working under the supervision of dr. Benne Holwerda and dr. Matthew Kenworthy at Leiden University when the research in this report was performed as part of their bachelor research project. The topic was proposed by the supervisors. The processed (2011) image was provided by dr. Glenn Schneider at The University of Arizona. The processing of the results as well formulation of the conclusions and the writing were done by the students.

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