High Spatial Resolution Imaging of a Dynamically Perturbed Circumstellar Debris Disk

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HD 61005

- G3/G5 V
- 35 pc
- 40 - 120 Myr

\[ T_\ast = 5500 \text{ K} \]
\[ L_\ast = 0.6 \, L_\odot \]

- Argus member? (Desidera et al. 2011)

\[ L_{\text{IR}}/L_\ast = 3 \times 10^{-3} \]

Hillenbrand et al. (FEPS; 2008), Rocctagliata et al. (2009)

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**ISM Interaction?**

- blue colors $\rightarrow$ small grains
- interaction with cold, dense cloud?
  - stripping of bound grains
  - deflection of unbound grains
- Limit on Na I absorption below that expected for CNM cloud column density (Maness et al. 2009)
• warm, low-density cloud?

• typical values for density and velocity are insufficient for stripping grains

• secular perturbations by gas forces may play a role
ISM Interaction?

- can approximate gross morphology, but not yet asymmetries
- collision time on order steady-state relaxation time
- no perturbations from planets

Figure 15. Comparison between the ACS Stokes I image (top), the NICMOS 1.1 µm image (middle), and a promising neutral gas model (bottom), taken from Figure 12 (top row, third column). This comparison shows that the simple model presented here is only a very rough representation of the data. Still, the gross swept, asymmetric morphology is clearly present in the model image.

Figure 16. Ratio of the radiation pressure force to gravity ($\beta$) for astrophysical silicate grains (left) and water ice (right) for the HD61005 system. The horizontal dotted line indicates the ratio above which grains launched by parent bodies on circular orbits become unbound. Thus silicate and ice grains in a conventional debris disk surrounding a solar type star are likely to remain bound to the star. On the other hand, the weak radiation field ($\beta < 1$) implies that radiation pressure alone does not impede interstellar grains from entering the system. Thus if the astrosphere surrounding HD 61005 is smaller than the disk, interstellar sandblasting could potentially erode the HD 61005 disk grains.

Maness et al. (2009)
Recent Observations

(a) [Image of a debris disk with annular and streamer features]

(b) [Image with overlay of a curved slit] Buenzli et al. (2011)
AO Roll Subtraction

Original  Filtered  Subtracted
Eccentric Perturber?

- Secular perturbations from a planet on an eccentric orbit can cause offset.
- Deprojected offset is 18 AU for circle of radius 70 AU.
- Can relative inclination be responsible for apparent “swept” structure?
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*Fomalhaut* Stapelfeldt et al. (2004)

also e.g. Holland et al. (2003)
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Figure 15. Comparison between the ACS Stokes $I$ image (top), the NICMOS $1.1 \mu m$ image (middle), and a promising neutral gas model (bottom), taken from Figure 12 (top row, third column). This comparison shows that the simple model presented here is only a very rough representation of the data. Still, the gross swept, asymmetric morphology is clearly present in the model image.

6. SUMMARY

The morphology and polarization structure of HD 61005 in the HST/ACS data (Figures 1–3) strongly suggests that HD 61005 is a debris disk undergoing significant erosion by the ambient ISM. The physical mechanism responsible for this erosion remains uncertain. Previous work has suggested that HD 61005 may be interacting with an unusually dense cloud. However, our high-resolution optical spectrum argues against this idea, instead suggesting an ambient ISM density typical of local interstellar clouds. Thus, the evolutionary state of HD 61005 may represent a commonplace, intermittent stage of debris disk evolution driven by interaction with typical, low-density gas.

With this motivation, we considered the effects of secular perturbations to grain orbits induced by ram pressure in warm, tenuous clouds. This mechanism can significantly distort grain orbits within a typical cloud crossing time and generate structures that very roughly reproduce the HD 61005 images. Future work that incorporates additional, more detailed physics may improve the agreement between the observations and interstellar gas drag models. The theoretical effects of interstellar sandblasting for solar-type stars should also be investigated in greater detail.

Regardless of the interpretation for HD 61005, we expect interstellar gas drag is important at some level in shaping the structure and evolution of planetary debris disks. The frequency with which this effect is important strongly depends on the typical sizes, shapes, velocities, and filling factors of warm interstellar clouds, which have poorly constrained global properties at present. Nevertheless, some morphological features common to nearby resolved debris disks (e.g., brightness asymmetries, warps, and bow structures) can in principle be produced in this way. A larger sample of spatially resolved debris disks at a wide range of wavelengths and more detailed theoretical work will help eliminate some of these remaining ambiguities.

We wish to thank Jay Anderson and Vera Platais for providing the astrometric software used to test for companion-ship. We also thank Carl Heiles, Gaspard Duchene, Seth Redfield, and Marshall Perrin for useful conversations that helped shape the ideas discussed in this paper. H.M. is funded by the GRFP at NSF and the GOPF at UC Berkeley. Support for this work was provided by NASA through grant number GO-10847.
• We have resolved scattered light from the HD 61005 debris disk with Keck II adaptive optics

• Single perturber can produce a morphology consistent with an offset and ‘swept’ wings

• Secular perturbation timescale must be less than collision time (~5000 yr) – degeneracy in $M_p, a_p, e_p$

• Scattered-light contribution from grains with similar $\beta$

• Test hypothesis with direct detection planet search using next-generation instruments (e.g. GPI)
The inference that the F606W ACS images trace predominantly submicron-sized grains is also consistent with the images of HD 61005 (Section 3.1.2), also showing potentially erode the HD 61005 disk grains. The morphology and polarization structure of HD 61005 is currently under debate (Debes et al. 2007), though on a much larger scale than HD 61005 disk is comparable to the [F606W] color of the AU Mic and HD 15115 debris disks, for example, have been suggested to show blue optical to near-infrared scattered light at larger radial distances, indicating changes in the disk color at projected radii within 200 AU. The approximate size spectrum for HD 32297 shows a bowed disk structure, which is consistent with ISM interaction (Debes et al. 2009). The global [F606W] color of the HD 61005 disk is comparable to the [F606W] color at 200 AU, which is a large number of grains at increasingly small sizes, consistent with greater detail.

Thus, the observation that HD 61005 is globally brighter at optical wavelengths than near-infrared wavelengths, likely reflecting the larger number of grains at increasingly small sizes. The above ratio image indicates that the disk appears predominantly blue with no appreciable color gradient. The middle panel displays the NICMOS image convolved with the ACS PSF. The right panel shows a masked ratio image with a Dohnanyi size spectrum convolved with the NICMOS off-spot PSF. The left panel displays the ACS image binned to the NICMOS pixel resolution and processed to compute the grain color. Scattered light images provide the background.

The theoretical effects of interstellar gas drag are important at some level in shaping the structure and evolution of planetary debris disks. The frequency with which this effect is important strongly depends on the type of debris disk evolution driven by interaction with typical, low-density tenuous clouds. This mechanism can significantly distort grain location in the disk. Assuming a steep size spectrum (e.g., Dohnanyi), a large wavelength, this product largely determines the surface brightness at a particular location in the disk. The global [F606W] color of the HD 61005 disk is comparable to the [F110W] color of the HD 32297 and HD 15115 debris disks, for example, have been suggested to show blue optical to near-infrared scattered light at larger radial distances, indicating changes in the disk color at projected radii within 200 AU. The approximate size spectrum for HD 32297 shows a bowed disk structure, which is consistent with ISM interaction (Debes et al. 2009). The global [F606W] color of the HD 61005 disk is comparable to the [F606W] color at 200 AU, which is a large number of grains at increasingly small sizes, consistent with greater detail.

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The morphology and polarization structure of HD 61005 suggest that the dust grains are eroding due to radiation pressure from the central star. This erosion is similar to that observed in other debris disks, such as HD 32297 and HD 15115. The eroded grains in HD 61005 are likely composed of water ice and astronomical silicates, consistent with the observation that the F606W ACS images trace the predominate grain scattering cross section.

The development of these disks may be influenced by the presence of interstellar material. This can potentially erode the HD 61005 disk grains, although this affects a relatively small number of grains. The observations indicate that the HD 61005 disk is globally brighter at optical wavelengths than its surrounding dust disk, possibly due to the presence of a steep size spectrum of grains.

The theoretical effects of interstellar gas drag models on the interstellar medium are important at some level in shaping the debris disk evolution. A larger sample of spatially resolved debris disks at a wide range of wavelengths and more detailed theoretical work will help eliminate some of these remaining ambiguities.

We wish to thank Jay Anderson and Vera Platais for providing the HST/ACS data (Figures 13–15). This comparison shows that the simple model presented here is only a very rough representation of the data. Still, the gross features of the grain color at projected radii within ~20 AU, the approximate peak for water ice and astronomical silicates at 0.6 µm, are visible.

Figure 16. The large polarization contrast between the HD 61005 disk and the background field, and Marshall Perrin for useful conversations that helped shape the ideas discussed in this paper. H.M. is funded by the NSF and the GOPF at UC Berkeley. Support for this work was provided by the National Aeronautics and Space Administration through grant NNX09AB89G issued through the Astrobiology Joint Program Office at NASA and the Gordon and Betty Moore Foundation. We also thank Carl Heiles, Gaspard Duchene, Seth Redhead, and the anonymous referee for helpful comments that improved the paper.

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The disk appears predominantly blue with no appreciable color gradient. Values less than unity represent grains that preferentially scatter blue light.

The grain size distribution (Strubbe & Chiang 2007) is strongly peaked near $a \sim 2 \mu m$. The plots illustrate that the grain scattering cross section is a function of grain size. The large polarization structure to HD 61005 (Section 3.1) is potentially eroded by the ambient ISM. The physical mechanism responsible for this erosion remains uncertain. Previous work has suggested that very roughly reproduce the HD 61005 images. Furthermore, the gas drag models presented in the paper provide the astrometric software used to test for companion-stars that very roughly reproduce the HD 61005 images. For more detailed theoretical work will significantly aid in differentiating the disk warps, and bow structures) can in principle be produced in this range of wavelengths and more detailed theoretical work will help eliminate some of these remaining ambiguities.

Regardless of the interpretation for HD 61005, we expect the disk surrounding a solar type star are likely to remain bound to the star. On the other hand, the weak radiation field (Dohnanyi 1969) may improve the agreement between the observations and interstellar gas drag models. The theoretical effects of interstellar gas drag is important at some level in shaping the structures that very roughly reproduce the HD 61005 images. Furthermore, the gas drag models presented in the paper provide the astrometric software used to test for companion-stars that very roughly reproduce the HD 61005 images. For more detailed theoretical work will significantly aid in differentiating the disk warps, and bow structures) can in principle be produced in this range of wavelengths and more detailed theoretical work will help eliminate some of these remaining ambiguities.

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