“Other” Debris Disks: Description & Similarities/Differences with β Pictoris through Scattered-Light Imaging

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OBSERVATIONAL MOTIVATION

CS "disks" are both the protoplanetary progenitors and the debris-strewn outcomes of planetary system formation processes. Spatially-resolved high-fidelity scattered-light imaging directly informs:

- system architecture / debris location: stellocentric & azimuthal
- surface brightness distribution ➔ particle/mass densities

Perturbations by (& locations/masses/orbits of) planets? Influences by other (intrinsic or extrinsic) forces?

Thermal emission in excess of stellar photospheric levels betrays the existence of CS material around many stars...

BUT, SEDs alone cannot uniquely inform upon the nature of these systems.

- breaks degeneracies in small particle properties and systemic geometries inferred from interpretation of thermal SEDs alone.
First 15 years of β Pic Imaging

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>LCO/du Pont 2.5m Coron</td>
</tr>
<tr>
<td>1986</td>
<td>ESO/La Silla 2.2m Coron</td>
</tr>
<tr>
<td>1991</td>
<td>LCO/du Pont 2.5m AOC</td>
</tr>
<tr>
<td>1991</td>
<td>ESO/La Silla 2.2m AB CCD</td>
</tr>
<tr>
<td>1993</td>
<td>UH 2.2m Coron</td>
</tr>
<tr>
<td>1995</td>
<td>HST 2.4m WFPC2</td>
</tr>
<tr>
<td>1996</td>
<td>ESO 3.6m ADONIS Coron</td>
</tr>
<tr>
<td>1997</td>
<td>2.4m STIS Coron (2000)</td>
</tr>
</tbody>
</table>

**BUT, NO OTHER LIGHT-SCATTERING DDs IMAGED**
IRAS found many “IR excess” stars indicative of CS dust…

- but (pre-HST) only one light-scattering disk (Beta Pictoris*)
- using most aggressive ground-based observing techniques

*prototypes are not necessarily good archetypes!

Imaging CS dust-scattered starlight in planet forming environments from the ground proved extremely challenging:

- seeing-limited Strehl ratios
- (posited) generally very high disk-to-star contrast

This contrast-limited problem was 1st engaged on the ground, and then (fruitfully) in space with HST CORONAGRAPHY, and now (EX)/AO-augmented, large ground-based telescopes with high-contrast imagers; E.g., NaCo, NICI, MagAO, GPI, SPHERE, SCExAO...
High-Contrast Imaging for DD Science Planned for HST

1st Generation (April 1990)

WFPC-1
0.1% reflective spot
d = 1.2” in FC8 (f/30)
14 λ/D @ 0.5μm

Lyot coronagraph
7.2 mas/pix, 3.2” FOV

Spherical Abberation

An ideal platform for high contrast imaging via coronagraphy:
- UVIS/nIR Wavelength coverage
- No atmospheric turbidity
- Panchromatic Strehl > 96%
- Platform (relative) stability
- Combined imaging modes

Observational Problem “simplified” from space.
High-Contrast Imaging for DD Science Planned for HST

SM1 (December 1993)

WFPC-2
High-contrast spot
eliminated

COSTAR(/FOC)
f/288 optical channel
not “fixed”

HST coronagraphy delayed until post-SM2 (NICMOS & STIS; 1997)
High-Contrast Imaging for DD Science Implemented for HST

2nd Generation

**NICMOS**
Lyot Coronagraph

$r = 0.3''$, $f/45$, 76 mas/pix

1.1–2.4 $\mu$m ($3.2 \lambda/D @ 1.1 \mu$m)

High-Contrast Imaging for DD Science Implemented for HST

2nd Generation

**NICMOS**
Lyot Coronagraph
r = 0.3”, f/45, 76 mas/pix
1.1–2.4 μm (3.2 λ/D @ 1.1 μm)
1997 – 1998

**STIS**
Occulting Wedges & Bars
Width: (0.3”*)0.6” - 3”, 50 mas/pix
Unfiltered (CCD broad response)
1997 – 2004
2009 – …

*new for cycle 22
High-Contrast Imaging for DD Science Implemented for HST

2nd Generation

**NICMOS**
Lyot Coronagraph
\[ r = 0.3'' \text{, f/45, 76 mas/pix} \]
\[ 1.1 \text{–} 2.4 \mu \text{m (3.2} \lambda/D @ 1.1 \mu \text{m)} \]

**STIS**
Occulting Wedges & Bars
Width: (0.3”*)0.6” – 3”, 50 mas/pix
Unfiltered (CCD broad response)
*new for cycle 22

3rd Generation

**ACS**
Aberrated-beam Coronagraph
\[ r = 0.9''/1.8'' \text{ masks, 25 mas/pix} \]
\[ \{21|42\} \lambda/D @ 0.5 \mu \text{m} \]
2002 – 2007
The HST Coronagraphic Suite: Symbiotic Capabilities

Spatially resolved imaging allows dynamical interpretation, but also...

**NICMOS**
- nIR (1.1 – 2.4 µm)
- W,M,N IR filters
- small IWA (r=0.3”)
- 2.0 µm Polarimetry
- F110W (1.1 µm)
  - 2 x 10 min (8° roll)
  - Weinberger et al. 1999

**ACS**
- Visible (0.4 – 0.9 µm)
- M,N,W VIS filters
- Two circular occulters
- Wide FOV
- Polarimetry
- F606W (0.61 µm)
  - 2 x 41 min (28° roll)
  - Clampin et al. 2003

**STIS**
- ~0.2 – 1.03 µm
- Unfiltered
- wedge-selectable IWA
- High photon efficiency
- Wide FOV
- 50CCD: 0.36 – 0.79 µm
  - 2 x 26 min (30° roll)
  - Schneider et al. 2001
Representative HST Debris Disk Discovery Images

**NICMOS**
- HR 4796A
  - Schneider et al 1999
- HD 181327
  - Schneider et al 2006
- HD 61005
  - Hines et al 2007
  - r(IWA) = 0.3"

**ACS**
- HD 15745
  - Kalas et al 2007a
- HD 107146
  - Ardila et al 2004
- HD 15115
  - Kalas et al 2007b

**STIS**
- HD 202628
  - Krist et al 2012
CURRENT CENSUS OF STARLIGHT-SCATTERING DEBRIS DISKS: Discovery Chronology

22 Light-Scattering DDs Since Beta Pic

<table>
<thead>
<tr>
<th>Number</th>
<th>Observations</th>
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<tr>
<td>6</td>
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<tr>
<td>5</td>
<td>ACS</td>
</tr>
<tr>
<td>4</td>
<td>STIS</td>
</tr>
<tr>
<td>3</td>
<td>NICMOS</td>
</tr>
<tr>
<td>2</td>
<td>ACS</td>
</tr>
<tr>
<td>1</td>
<td>NICMOS</td>
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<tr>
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</tr>
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</table>

First 15 years of β Pic Imaging

1984 - LCO/du Pont 2.5m Coron
1986 - ESO/La Silla 2.2m Coron
1991 - LCO/du Pont 2.5m AOC
1991 - ESO/La Silla 2.2m AB CCD
1993 - UH 2.2m Coron
1995 - HST 2.4m WFPC2
1996 - ESO 3.6m ADONIS Coron
1997 - 2.4m STIS Coron (2000)

Beta Pic: Smith & Terille 1994
HR4796: Schneider et al 1999
HD141569: Weinberger et al 1999
HD107146: Ardila et al 2004
AU Mic: Kalas et al 2004
Fomalhaut: Kalas et al 2005
HD32297: Schneider et al 2005
HD53143: Kalas et al 2006
HD139664: Kalas et al 2006
HD181327: Schreider et al 2006
HD15115: Kalas et al 2007b

HD15745: Kalas et al 2007a
HD61005: Hines et al 2007
HD207129: Krist et al 2010
HD92945: Golimowski et al 2011
HD202628: Krist et al 2012
HD79977: Thalmann et al 2012
HD30447: Soummer et al 2014
HD35841: Soummer et al 2014
HD141943: Soummer et al 2014
HD191089: Soummer et al 2014
HD202917: Soummer et al 2014

STIS (T Tau, H A/Be)+DD f.o.
ACS
NICMOS

2014
2013
2012
2011
2010
2009
2008
2007
2005
2003
2002
2001
2000
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
CURRENT CENSUS OF STARLIGHT-SCATTERING DEBRIS DISKS: Age vs. Spectral Type

F+G star disks well exampled Spanning > 2 dex in stellar ages
CURRENT CENSUS OF STARLIGHT-SCATTERING DEBRIS DISKS: Age vs. Spectral Type

A and early F-stars @ ~10 Myr
CURRENT CENSUS OF STARLIGHT-SCATTERING DEBRIS DISKS: Age vs. Spectral Type

Diagram showing the age vs. spectral type relationship for various stars, including
- HD207129
- HD202628
- HD53143
- HD92945
- HD107146
- HD139664
- HD15745
- HD202917
- HD35841
- HD30447
- HD141943
- HD181327
- HD191089
- HIP15115
- HIP79977
- β Pic
- HR4796
- HD141569
- HD32297

Legend:
- High-Mass (F&A) Stars
- Dearth of Older Stars
- Death of Low-Mass
- Late K & M Stars
- Dearth of Low-Mass
CURRENT CENSUS OF STARLIGHT-SCATTERING DEBRIS DISKS: Imaging Data

DISCOVERY
vs.
FOLLOW-UP

improving upon:
• Image artifacts
• Sensitivity
• SNR
• Stellocentric range
IWA and OWA

* Spectral range
* i (and p) vs. p*i
STARLIGHT-SCATTERING DEBRIS DISKS: (yet unimproved) Discovery Imaging

HD 207129    Krist et al 2010

HST/ACS

TWO-ROLL PSF SEPARATION*/“SELF-SUBTRACTION” (*Heap et al 2000)

HD 202628    Krist et al 2012

STIS

HD 79977                                            Thalmann et al 2012

LOCALLY OPTIMIZED COMBINATION OF IMAGES

(b)

Subaru/HiCAIO H-band

HST/NICMOS

SOUMMER et al 2014

PRINCIPAL COMPONENT ANALYSIS/KARHUNEN–LOEYES IMAGE PROJECTION:
STARLIGHT-SCATTERING DEBRIS DISKS: HST/STIS Post-Discovery Follow-up Imaging

β Pic
HD 139664
HR 4796
1"

AU Mic
Fomalhaut
5"
Kalas et al 2013
HD 141569

HD 15115
HD 32297
HD 107146

HD 61005
HD 15745
HD 181327

HD 92945
HD 53143
other DDs: Schneider et al 2014
A WHIRLWIND REVIEW
THROUGH THE MENAGERIE
OF HIGH-FIDELITY
SCATTERED-LIGHT IMAGES OF
“OTHER”
CIRCUMSTELLAR DEBRIS SYSTEMS

HR 4796
Fomalhaut
AU Mic
HD 61005
HD 32297
HD 15115
HD 181327
HD 107146
HD 53154
HD 92945
HD 139664
HR 4796A – 1st DD Imaged Following Beta Pic

- 8 ± 3 Myr (Stauffer 1995), A0V (“Vega-like”) star
- TW Hya Association member (Webb et al 1999), d = 72.8 ± 1.7 pc
- Large amount of CS dust inferred from IRAS excess:
  - \( \frac{L_{\text{disk}}}{L_*} = 5 \times 10^{-3} \) (Jura 1991), \textit{TWICE that of } \( \beta \) Pictoris.
  - \( T_{\text{dust}} = 110K \rightarrow \text{lack of material @ } r < 40 \text{AU, and to be bound at } r > 40 \text{AU } \rightarrow > 3 \mu \text{m grains (Jura 1995)} \)

HST/NICMOS Reveals a “Compact” Ring-Like Disk

**GEOMETRY/MORPHOLOGY**

- \( PA = 26.8 \)
- \( i = 73.1 \) (\( PA = 26.8^\circ \))
- \( r = 1.05'' \) (~76.4 AU)
- Ring width < 14 AU
  - “abrupt” truncation
  - “clear” @ \( r < 50 \text{ AU} \)


NIR scattered flux in good agreement with visible absorption & mid-IR re-radiation.
HR 4796A – Post-Discovery Imaging Follow-Ups

• HST/STIS (Broadband Optical High-Resolution Imaging)
  “STIS imaging of the HR 4796A Circumstellar Debris Ring”

• HST/NICMOS (Multiband Diagnostic Photometry)
  “Complex Organic Materials in the Circumstellar Disk of HR 4796A”

• Subaru/HiCIAO (AO188/H-band; ADI + LOCI)
  “The Extended Outer Regions of the Debris Ring Around HR 4796A”

• VLT/NaCO (L’-band; ADI & Sparse Aperture Masking)
  “An Insight into the Surroundings of HR 4796”

• Gemini/GPI (K-band Integral Field Polarimetry; p*i and ADI/KLIP i)
  “Polarimetry with the Gemini Planet Imager: Methods, Performance at 1st Light, and the Circumstellar Ring around HR 4796A”

• Gemini/NICI (JHKs + CH4L/S 4% wide filters @ 1.6µm)
  “The Gemini NICI planet-finding campaign: The offset ring of HR 4796A”
HR 4796A – STIS High-Resolution Optical Imaging

- Improved upon nIR Discovery Imaging Fidelity
- Better Enabled Dynamical Interpretation of Debris Structure
- Provided Optical Dust Scattering Efficiency (vis-nIR colors)

HR 4796A – Debris Ring Dynamics

Radial SB profile of ring (sharp inner and outer slopes) consistent with dynamical confinement of debris by yet unseen co-orbiting planet-mass companion(s).

Analogous to Shepherding in Saturnian Ring System?  
→ but, see Lagrange et al. A&A 546 A38 (2012)  
vis-à-vis uncertainty regarding an outer planet, with M-star companion @ 560 AU
HR 4796A – Debris Ring Dynamics

Radial SB profile of ring (sharp inner and outer slopes) consistent with dynamical confinement of debris by yet unseen co-orbiting planet-mass companion(s).

HR 4796A: Sharp outer fall-off, SB(r) ~ r^-8
Beta Pic: Smooth SB(r) ~ r^-3.6

see: Thebault & Wu (2008) “Outer Edges of Debris Disks” (development & longevity)
HR 4796A – Debris Ring Dynamics

- Center of Ring Offset from Position of Star by $1.4 \pm 0.4$ AU

- Ansal Brightness Asymmetry $\sim 2x > 1/r^2$ Differential

Cause (?):
- Inhomogeneous grain population
- Non-uniform spatial destruction of homogeneous population

$T_{\text{orbit}} = 350$ yr, Age $\sim 8$ Myr
“expectation” $\rightarrow$ well-mixed azimuthally, if not perturbed

![Graph showing slice flux vs. distance from star in arcseconds.](graph.jpg)
HR 4796A – Optical + nIR Colors Constrain Composition (scattering efficiency and phase angle dependency with $\lambda$)


STIS (Optical) + NICMOS (nIR filter-band) Imaging Photometry
HR 4796A – Optical + nIR Colors Constrain Composition (scattering efficiency and phase angle dependency with $\lambda$)


<table>
<thead>
<tr>
<th>Filter</th>
<th>Scaling$^a$</th>
<th>Flux Density (mJy)</th>
<th>Total Disk Flux Density (mJy)</th>
<th>NE : SW Ratio</th>
<th>$g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>STIS 50CCD</td>
<td>0.705</td>
<td>5.5 ± 0.2</td>
<td>9.4 ± 0.8</td>
<td>0.74 ± 0.07</td>
<td>0.16 ± 0.06</td>
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<tr>
<td>F110W</td>
<td>0.78 ± 0.03</td>
<td>5.2 ± 0.3</td>
<td>8.1 ± 0.6</td>
<td>0.9 ± 0.08</td>
<td>0.06 ± 0.07</td>
</tr>
<tr>
<td>F160W</td>
<td>...$^b$</td>
<td>3.7 ± 0.5</td>
<td>5.7 ± 0.9</td>
<td>1.0 ± 0.1</td>
<td>0.0 ± 0.06</td>
</tr>
<tr>
<td>F171M</td>
<td>0.819 ± 0.007</td>
<td>2.8 ± 0.1</td>
<td>4.8 ± 0.5</td>
<td>0.62 ± 0.08</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>F180M</td>
<td>0.79 ± 0.01</td>
<td>2.9 ± 0.1</td>
<td>4.7 ± 0.3</td>
<td>0.71 ± 0.07</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>F204M</td>
<td>0.79 ± 0.02</td>
<td>2.5 ± 0.1</td>
<td>4.2 ± 0.2</td>
<td>1.02 ± 0.09</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>F222M</td>
<td>0.79 ± 0.03</td>
<td>2.1 ± 0.1</td>
<td>3.5 ± 0.2</td>
<td>1.0 ± 0.1</td>
<td>0.1 ± 0.1</td>
</tr>
</tbody>
</table>

Best fit suggestive of radiationally evolved complex organic polymers; i.e., tholins, as found on the small icy bodies in our own solar system (e.g., 5145 Pholus) and in the atmosphere of Titan.
HR 4796A – Other Debris System (sub)-Structures?


“Streamers”: exo-ring material detected beyond the ansae.

Seen also in HD 61005 ground-based ADI processing by Buenzli et al A&A 524 (2010).

Questioned by Milli et al A&A 545 A111 (2012) potential w.r.t. ADI artifacts.

Left: Subaru/HiCIAO, H-band, 2600 s, ADI: 260 rots over 23°, LOCI: 10000 with footprints

Middle: HST/STIS, Vis. Broadband, 260s, PSF-template subtraction, 2 rots 18° combined

Right: VLT/SPHERE (ESO PR # 1417; H-band/ADI+PCA) – see talk by Mouillet Wed. Noon
HR 4796A – Other Debris System (sub)-Structures?

Intra-Ring “Gap”? – artifact or further evidence of a co-orbiting planet?

“...this feature could be due to noise. However, it seems to be at the same position as that pointed by Thalmann et al. (2011) in their data as well as Schneider et al. (2009) data as well as, in L’-data obtained at Keck by Marois & McIntosh (priv. comm.)” – Legrange et al 2012 (pA39)

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**HR 4796A**

- **HST/STIS**
  - Vis. Broadband
  - 216 s
  - PSF-subtraction
  - 2 rots combined

- **Subaru/HiCIAO**
  - H-band 2600 s
  - ADI: 260 rots
  - 23°
  - LOCI: 10000 ftpt.
  - Thalmann et al. 2011

- **VLT/NaCo**
  - L’-band 2600 s
  - SAM+ADI
PUZZLING RESULTS!

(1) Relatively isotropic TOTAL intensity phase function
   \[\rightarrow\] small particle Rayleigh scattering. BUT:
(2) Counter-indicated by p*I not peaking at the ring ansae
(3) VERY strong (> 9x) minor-axis opposed w. side brighter p*i asymmetry
   \[\rightarrow\] speculation the disk is optically **thick** / self-shadowed on w. side
All Images
Same Angular Scale

NICMOS F110W

HR 4796A (Schneider et al 1999)

ACS F606W CORON 1.8

HD 141569 (Clampin et al 2003)

ACS F606W CORON 1.8

HD 107146 (Ardila et al 2004/05)

ACS F606W CORON 3.0
(multiple rolls)

FOMALHAUT
(Kalas et al 2005)

* DDs are not only about inner working angle!
COMPARISON TO FOMALHAUT (A3V, 7.7 pc, ~ 200 Myr)

Fomalhaut is 10x closer than HR 4796, and its r = 140 AU debris ring is ~ 2x larger with a very similar steep inner edge, radial profile, and large stellocentric offset.

HST/ACS

Angular scale: r(Fomalhaut) = 19\textquoteleft\textquoteleft (141 AU)
COMPARISON TO FOMALHAUT (A3V, 7.7 pc, ~ 200 Myr)

Only light-scattering DD other than β Pic for which a planet is directly imaged.

Structure postulated as arising from dynamical interactions with now-imaged and possibly other (additional) planet(s).

Fomalhaut b (confirmed):

Follow-up/combined 2010/2012 HST/STIS observations

Photometry (brightness)
→ Dwarf planet with dust ring?

Highly eccentric (“ring-crossing”) orbit:
  \[ e = 0.8 \pm 0.1 \]
  \[ a = 177 \pm 68 \text{ AU} \]
  \[ q = 32 \pm 24 \text{ AU} \]

→ Posited interaction with Speculative “Fom c”


See talks Wed: Kalas 10:30 AM
Faramaz 11:45 AM
COMPARISON TO FOMALHAUT (A3V, 7.7 pc, ~ 200 Myr)


Angular scale: $r(\text{Fomalhaut}) = 19^\prime$ (141 AU)

HST/STIS follow-up observations

Material beyond main-belt (NE) ansa

morphological similarities to HR 4796A

Intra-ring (3° wide) azimuthal “gap”*

*material scattered by planet crossing? giant impact scenario? nodal+apsidal alignment?
AU Mic

A very Near-by (9.9 pc), ~ 12 Myr, Low-Mass (0.31 M\(_{\text{sun}}\), M1Ve) Star Hosting Member of β Pic moving group, likely coeval with Beta Pic

An Edge-On Debris Disk, with a significant out-of-plane “bump” @ 13 AU, and a one-side warp “opposite” the “bump”.
AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

UH 2.2m + Coronagraph R-band Discovery Image (Kalas et al. 2004)

M-star disk imaged from 50 – 210 AU from AU Mic

Scaling the stellar brightness of β Pic to AU Mic, the AU Mic disk is ~11x brighter than β Pic’s at constant angular radii.

Radial SB power law index “similar” to β Pic, but...
AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

Keck II AO/NIRC2 H-band (Liu 2004):
Edge-on disk imaged to IWD = 15 AU the along mid-plane

Suggested break in radial SB profile @ r = 35 AU

Radial & Vertical ➔ substructure in the disk @ r < 50 AU with some asymmetries
AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/ACS F606W image (Krist et al 2005):
Detects the disk (degraded) to IWD ~ 10 AU the along mid-plane
AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/ACS F435W/F606W/F814W imaging (Krist et al 2005):

"BVI" photometry of the disk suggests the disk grains are blue relative to the star. Posited small grain retention compared to neutral/red grains around early type stars. Modeling suggests the inner disk is clear of material at r < 12 AU.
AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/ACS F606W POLARIMETRY
In addition to optical colors, helps constrain grain properties

~40% P% (@ 80 AU) – 5% P% (@ 20 AU) ⊥ to mid-plane.
Declining P% with smaller stellocentric distance
in indicative of small optically thin grains

Model: “Hole” interior to ~ 45 AU collision-dominated birth ring
depleted x300 of µm size grains

AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/STIS image (Schneider et al AJ 148 59 2014) ± 50 AU
Resolves the disk to IWD = 5 AU the along mid-plane

Linear Display 0 – 15 counts/s/pixel

Significant surface brightness asymmetries are seen in the inner disk
AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/STIS image (Schneider et al 2014) ± 100 AU
Defines the morphological (photometric) mid-plane

Log10 Display [-1] to [+3] {dex} counts/s/pixel
AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/STIS image (Schneider et al 2014) ± 100 AU
Defines the morphological (photometric) mid-plane

SW side warp below the >50 AU isophotal mid-plane opposite NE “bump”

4x vertical (z) expansion in image scale
AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

\[ Y = M_0 \times e^{M_1 \times x} \]

<table>
<thead>
<tr>
<th></th>
<th>M0</th>
<th>M1</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>NORTHEAST</td>
<td>2.3981</td>
<td>0.065261</td>
<td>0.98614</td>
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<tr>
<td>SOUTHWEST</td>
<td>3.0727</td>
<td>-0.069258</td>
<td>0.97048</td>
</tr>
</tbody>
</table>

Krist et al. 2005
AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/STIS image (Schneider et al 2014) ± 200 AU

Low SB flux
SNR ~ 2-3 resel\(^{-1}\)

radial outer “gap”
Low SB flux
SNR ~ 2-3 resel\(^{-1}\)

The outer disk
HD 61005 ("the moth"); G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My

HST/NICMOS 1.1μm (Hines et al ApJL 671 165 2007)

~ 90 Myr, 35 pc, G8V

3-component debris system
- highly inclined debris ring
- "skirt" of material on one-side of the disk plane with high SB ‘forward’ edge
- material in disk plane beyond the ring

Exo-ring material: “blown back” by Interaction with (cold, dense) ISM cloud?

→ ISM “wind”
→ bow shock
HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)

HST/ACS 0.61µm Imaging Polarimetry

Exo-ring material: or embedded in low-density cloud secularly perturbing dust grain orbits

Optical (ACS) + nIR (NICMOS) color + POLARIMETRY suggest blue, sub-micron, grains, with no strong color gradient with stellocentric distance.
HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)


Resolving the Nearly-Edge on Ring and Central Hole

* Technical note: Angular Differential Imaging
  + enhances local surface brightness gradients (@ high/mid spatial frequencies)
  - does not preserve total flux, insensitive to diffuse shallow-gradient SB flux
HD 61005 ("the moth"; G8V @ 34.5 pc, $V = 8.22$, $B-V = +0.72$, ~ 90 My)

VLT/NaCo H-band/LOCI* (Buenzli et al. 2010)
Resolving the Nearly-Edge on Ring and Central Hole

* Locally Optimized Combination of Images
HD 61005 ("the moth"); G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My

HST/STIS Broadband Optical  (Schneider et al. 2014)
Resolving the Nearly-Edge on Ring and Central Hole

i \sim 85^\circ
r \sim 63 \text{ AU}
r_{\text{in}} \sim 40 \text{ AU}
HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)

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HST/STIS Broadband Optical  (Schneider et al. 2014)

Resolving the Nearly-Edge on Ring and Central Hole

exo-ansal & edge-brightened “skirt” of material
HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)

HST/STIS Broadband Optical  (Schneider et al. 2014)

The full (detectable) extent of the debris system

\[ f_{\text{disk}} = 4.46 \text{ mJy} \quad f_{\text{disk}} : f_{\text{star}} = 0.245\% \]
HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)

HST/STIS Broadband Optical (Schneider et al. 2014)

The full (detectable) extent of the debris system

\[ f_{\text{disk}} = 4.46 \text{ mJy} \quad \frac{f_{\text{disk}}}{f_{\text{star}}} = 0.245\% \]
HD 32297

An ~ 10 Myr A0 star @ 112 pc with a r ~ 1300 AU, Nearly, Edge-On Debris Structure

Exhibiting a large z-height of scattering grains on one side (only) of the Disk-Plane

(postulated to be interacting with the ISM)

with also extreme minor-axis mirrored SB asymmetries,

and out-of-plane structure
HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

HST/NICMOS 1.1 μm Discovery Image (Schneider et al. 2005)

nearly edge-on  ~2x SB asymmetry  hint of “curvature”
                   @ 0.3”–0.5”  wrt. linear mid-plane

$F_{\text{disk}}/F_\star (1.1 \mu\text{m}) = 0.36\% \pm 0.04\%$
HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

The Large Scale Environment
UH 2.2 m R-Band Image
(Kalas ApJ 635 169 2005)

HST/NICMOS 1.1 µm

HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

The Large Scale Environment
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**HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)**

The Large Scale Environment
UH 2.2 m R-Band Image
(Kalas ApJ 635 169 2005)

VLT/NACO K-band / LOCI
HD 32297 (A0V @ 112 pc, $V = 8.13$, $B-V = +0.20$, $\sim 12$ My)

The Large Scale Environment
UH 2.2 m R-Band Image
(Kalas ApJ 635 169 2005)

Keck II AO/NIRC2
K-band/LOCI


5'' (560 AU)
HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

The Large Scale Environment
UH 2.2 m R-Band Image
(Kalas ApJ 635 169 2005)

see talk by Rodigas 5PM

LBT/LMIRcam L-band'/ ADI

5" (560 AU)
HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)
HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

HST/STIS 6R-PSFTSC (Schneider et al 2014)
HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

Debris System Structure and Asymmetries

23.2” (2600 AU)

Log10 display from [-3] to [+2.13] dex counts/sec/pixel
HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

Debris System Structure and Asymmetries

23.2” (2600 AU)

Sqrt display from 0 to 1 counts/sec/pixel
HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

Debris System Structure and Asymmetries

23.2” (2600 AU)

Linear from -0.01 to +0.2 counts/sec/pixel.
HD 15115 (aka {BLUE/GREY} “Needle”)

An ~ 12 Myr, 45 pc distant F2 star (BPMG) with

Nearly edge-on, r ~ 320 AU debris structure

Highly asymmetric (w.r.t. all axes)

Complex sub-structures

ISM/exo-stellar interaction?
HD 15115 (F2 @ 45.2 pc, V = 6.80, B-V = +0.35, BPMG, ~ 12 My)

HST/ACS F606W Discovery Image (Kalas et al. 2007)

“Extreme” E/W stellocentric asymmetry extent along disk major axis
→ Posited dynamical perturbation from nearby comoving M-star HIP 12545
**HD 15115 (F2 @ 45.2 pc, V = 6.80, B-V = +0.35, BPMG, ~ 12 My)**

KECK II/NIRC2 H-band Confirmation Image (Kalas et al. 2007)

V-H color @ 2.0” < r < 3.3” suggest blue VIS-to-nIR scattering “may indicate grain properties similar to AU Mic”

Debes et al 2008: V-1.1μm-H color gradients in disk; red @ r = 1
**HD 15115 (F2 @ 45.2 pc, V = 6.80, B-V = +0.35, BPMG, ~ 12 My)**

**KECK II/NIRC2 H-band Confirmation Image (Kalas et al. 2007)**

**LBT/AO+PICES Ks (shown), LBTI+LMIRcam L’ ADI + LOCI (Rodigas et al. 2012)**

**0.8” ≤ r ≤ 2.5”**

\[
\log_{10} [-2.5] \text{ to } [+1.0] \text{ mJy arcsec}^{-2}
\]

Ks – L’ color is grey from 1.10 – 1.45 AU

1-10 μm grains on W side, 3-10 μm grains on E side

→ Supports ISM interaction scenario, agreement with Debes et al 2009
HD 15115 (F2 @ 45.2 pc, V = 6.80, B-V = +0.35, BPMG, ~ 12 My)

HST/STIS F606W 6R-PSFTFC Image (Schneider et al. 2014)

Mazoyer et al 2014/Poster
A&A, accepted 03SEP14
HD 15115 (F2 @ 45.2 pc, V = 6.80, B-V = +0.35, BPMG, ~ 12 My)

HST/STIS F606W 6R-PSFTFC Image (Schneider et al. 2014)

“Extreme” E/W stellocentric asymmetry extent along disk major axis
→ Possible ISM interaction?
HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

HST/NICMOS 1.1μm Discovery Image (Schneider et al 2005)

W/D Narrow, Asymmetric, Intermediate-Inclination Centrally-Cleared Debris Ring

Very steep inner And steep outer “truncation”

Stellocentric Ring-Offset

Asymmetric, Low-SB Extended Diffuse Outer Halo

Postulated Recent Collisional Dust Replenishment
HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

HST/NICMOS 1.1µm LAPLACE Reprocessed (Schneider et al 2011)

Successive Improvements in Resolving the Debris Ring
HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

Successive Improvements in Resolving the Debris Ring

HST/NICMOS 1.1µm PCA/KLIP (Soummer et al 2012)
**HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)**

HST/STIS Broadband Optical (Schneider et al 2014)

Flux Density: 7.81 mJy (± few%)

\( f_{\text{disk}}/f_{\text{star}}:\)
0.17±0.015%

PA = 102° ± 4°

i = 30.1° ± 1.2° from face-on

\( D_{\text{ring}} = 177.7 \text{ AU} \)

\( W/D(SW) = 0.131 \)
HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

Data: HST/STIS Broadband Optical (Schneider et al 2014)

Multiple-Roll Residual Removal (Stark et al 2014)

+ Radially Adaptive Iterative Azimuthal Filtering (Schneider et al in prep)
HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

HST/ACS 0.61µm co-Discovery Deep Image (Schneider et al 2005)
HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

HST/STIS Optical Broadband Deep Image (Schneider et al 2014)
HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

A: Log display - ring and diffuse asymmetric halo  
B & C: Linear display - narrow width, sharpness, SB asymmetries.
HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

Inner “hole”, peak, and exo-ring radial “surface density” profiles

Stellocentric position uncertainty: 4.4 mas RMS
HD 181327 (F6V @ 51.8 pc, \( V = 7.03, \) B-V = +0.48, 12-20 My)

Radial & Azimuthal SB asymmetries

* w.r.t. azimuth of peak SB along the ring
HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)


Inconsistent with empirically determined scattering phase function (not well-represented with H-G SPF) assuming an unpretured disk → unseen planet

Consistent with:

- Recent catastrophic disruption of body with $>1\% M_{\text{Pluto}}$
- Disk “warping” with strong ISM interaction
A VERY QUICK LOOK AT SOME

“OTHER” (WELL-RESOLVED)

LIGHT-SCATTERING DEBRIS SYSTEMS
HD 107146 (G2V @ 27.5 pc, V = 7.07, B-V = +0.63, 80-200 My)

HST/ACS V (shown) & I Discovery Imaging
Ardila et al. 2004/05

HST/STIS Broadband Optical
Schneider et al. 2014

Broad ("Featureless"), Axisymmetric,
Centrally-Cleared Ring-Like DD
HD 107146 (G2V @ 27.5 pc, V = 7.07, B-V = +0.63, 80-200 My)

F_{disk} = 0.40 \text{ mJy},
F_{disk}/F_{star} = 0.0077 \pm 0.0004\%,
\text{r}_{\text{ring}} = 100 \text{ AU}
HD 107146 (G2V @ 27.5 pc, V = 7.07, B-V = +0.63, 80-200 My)

WARNING for FUTURE OBSERVERS

APRIL 2011
HD 53154 (G9V @ 18.3 pc, V = 6.82, B-V = +0.80, 1000 ± 300My)

HST/ACS 0.61 μm
Kalas et al 2006
Discovery Image

suggested ~ 45° incl.
But...
HD 92945 (K1V @ 21.4 pc, V = 8.59, B-V = +0.89, 80/150 - 300My)

**HST/ACS**
Krist et al 2011
Discovery Imaging

**HST/STIS**
Schneider et al 2014
Broadband Optical

**Krist et al 2011**
Scattered-Light Model

\[ F_{\text{disk}} = 0.143 \text{ mJy} \]
\[ F_{\text{disk}}/F_{\text{star}} \sim 0.0051\% \]
\[ r_{\text{ring}} = 59 \text{ AU} \]
\[ IWD_{\text{LIMIT}} = 50 \text{ AU} \]
HD 139664 (F5V @ 17.4 pc, V = 4.64, B-V = +0.40, 100-1000 My)

HST/STIS
Schneider et al 2014
Broadband Optical

HST/ACS
Kalas et al 2006
0.6 µm Discovery Imaging

F_{disk} = 0.26 mJy
F_{disk}/F_{star} \sim 0.0005\%
IWD_{LIMIT} = 23 AU
CONCLUDING REMARKS (Philosophical Comments)

1) The Beta Pictoris Debris Disk is a Prototype, *NOT* an Archetype

2) Circumstellar Debris Disks are Incredibly Diverse

3) There is NO such thing as a “Symmetric” Circumstellar Debris Disk

4) Circumstellar Debris Disks & Planets are Inexorably Linked

5) Circumstellar Debris Disks CANNOT be considered in Isolation

6) The (EX)/AO era is upon us – exploit symbiotic & unique capabilities

7) They are not “DISKS”! → Exoplanetary Debris Systems
1) The Beta Pictoris Debris System is a Prototype, \textit{NOT} an Archetype

2) Exoplanetary Debris Systems are Incredibly Diverse

3) There is NO such thing as a \textit{“Symmetric”} Exoplanetary Debris System

4) Exoplanetary Debris Systems \& Planets are Inexorably Linked

5) Exoplanetary Debris Systems CANNOT be considered in Isolation

6) The (EX)/AO era is upon us – exploit symbiotic \& unique capabilities

7) They are not \textit{“DISKS”}! \rightarrow Exoplanetary Debris Systems