High-Contrast/High-Resolution Scattered Light Imaging of Circumstellar Disks

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Current theories of disk/planet evolution suggest a presumed epoch of planet-building via the formation and agglomerative growth of embryonic bodies, and the subsequent accretion of gaseous atmospheres onto hot giant planets, is attendant with a significant decline in the gas-to-dust ratios in the remnant protostellar environments.

In this critical phase of newly formed (or forming) extra-solar planetary systems, posited from a few megayears to a few tens of megayears, the circumstellar environments become dominated by a second-generation population of dust containing larger grains arising from the collisional erosion of planetesimals.
Direct (Scattered Light) Imaging of Dusty Debris

Observing scattered light from circumstellar debris has been observationally challenging because of the very high Star:Disk contrast ratios in such systems.

Until recently the large, and nearly edge-on disk around β Pictoris remained the only such disk imaged.

1984 - B.A. Smith & R.J. Terrile
6" radius coronagraphic mask, Las Campanas (discovery image)

1992 - 40 AU to 200 AU, ESO 2.2 m (BDL antibloom CCD)

1995 - Kalas & Jewitt, r-band, coronagraph 6.5" radius mask (10" obscuration), U. Hawaii, 2.2m, Mauna Kea.

1996 - Beuzit et al, J-band, ADONIS/coronagraph, ESO 3.6m, La Silla

13.1" x 13.1"
Direct (Scattered Light) Imaging of Dusty Debris

Resolved imaging ➔ spatial distribution of dust/debris.

- Asymmetries (radial & azimuthal):
  *May* implicate low-mass perturbers (planets) from:
  Rings, Central Holes, Gaps, Warps, Clumps, Arcs, Arclets

- Helps Elucidate the scattering & physical properties of the grains.
  Simultaneous Light Scattering & SED Modeling
**AU MIC: Large Dust Disk Around Nearby M-Star**

**β Pictoris**

AU MIC (GJ 803)
- Common Space Motion w/β Pic ("β Pic moving group")
- Likely coevol w/β Pic ~ 20 Myr
- Sub-mm (Kalas & Liu 2004 ApJ):
  - Dust Mass ~ 1/3 β Pic
  - Cold (40K) Dust
  - No Molecular Gas
  - Likely Inner Hole (r < 17 AU)

AU Mic (GJ 803)
- Kalas & Jewitt 1995 AJ 110 794
- Kalas, Liu, Matthews 2004 Science 303 1990
**TODAY HST Provides a Unique Venue for High Contrast Imaging**

- UV/Optical & Near-IR (<2.4 μm) Diffraction Limited Imaging
- > 98% Strehl Ratios @ all λs
- Highly *STABLE* PSF
- Coronagraphy: NICMOS STIS, ACS
- Intra-Orbit Field Rotation

**Background Rejection**

- 1.6 μm: ~10^{-6} pix^{-1} @ 1” ★
- 1.1 μm: ~10^{-5} in 2”–3” annulus

* w.r.t. central pixel

\[ F_{\text{central}}(H) = 11\% F_{\text{star}} \]

HST is a stepping stone for super-high contrast imaging

*B Background Rejection 10^{-9} to 10^{-10}

NIR High Dynamic Range Sampling
NICMOS/MA: Δmag=19.4 (6 × 4m)
Areas of Investigation in Planetary System Formation/Evolution Enabled With Today’s Capabilities on HST via PSF-Subtracted Coronagraphic Imaging

Young Extra-Solar Planet* & Brown Dwarf Companions

Circumstellar Disks

$\frac{f_{\text{disk}}}{f_\star} > \text{few} \times 10^{-4}$ at 1”
$\theta > 50 \text{ mas}$

* $< \text{few} \times 10^6 \text{ yr at 1”}$
**HST Imaging of β Pictoris Disk**

**HST/STIS Image Coronagraph**
Broadband 0.2-1.0 µm
Heap et al., 1999

**HST/NICMOS Image Coronagraph**
F110W (1.1 µm)
Smith et al., in prep.

**HST/WFPC-2 Image "Pyramid Edge" Imaging**
F555W (0.55 µm)
**Planet-Building Timeline**

- **HST Vis/NIR**
  - High Contrast: 10^6 yrs
  - TW Hydrae Assoc, Taurus, Ophiuchus star forming regions
  - β Pic Group
  - 10^7 yrs
  - Giant planets accrete gaseous atmospheres

- **Beyond HST Vis/UV**
  - 10^8 yrs
  - Tucanae Assoc, Pleiades
  - Era of heavy bombardment by comets
  - 10^9 yrs
  - α Persei, Sun
  - Current age of the Sun: 5x10^9 yrs.

**DISK EVOLUTION/DISSIPATION(?)**
- Rocky cores of giant planets form
- Terrestrial planets form
- Clearing of inner solar system, formation of a Kuiper cometary belt?
- Primary Dust (≤μm) Secondary Dust (≥μm)
- Locked to Gas Collisional erosion

Clearing Timescales: P-R drag few 10^6 yr
Rad. Pressure: ~ 10^4 yr
Cooling Curves for Substellar Objects

Evolution of M Dwarf Stars, Brown Dwarfs and Giant Planets (from Adam Burrows)

- Stars (Hydrogen burning)
- Brown Dwarfs (Deuterium burning)
- Planets
Cooling Curves for Substellar Objects

Evolution of M Dwarf Stars, Brown Dwarfs and Giant Planets (from Adam Burrows)

\[ \Delta H(50\%) = 9.7 \pm 0.3 + 2.1 \times \rho'' \]
NICMOS F160W (H-band) Coronagraphic Performance (G2V)

Radius (Pixels) from Hole Center

REDUCTION IN BACKGROUND FLUX FROM F160W PSF

w.r.t. central pixel

$F_{\text{central}}(H) = 11\% F_{\text{star}}$

- Unocculted PSF
- Coronagraph
- Coronagraph & PSF Subtraction

Coronagraphic Hole

$\text{Radius} = 0.3''$

$IW\lambda 1.6\mu m = 2.2 \lambda/D$

Background Reduction

Intensity (Azimuthal Average)

Radius (Arcsec) from Hole Center

0.3 0.45 0.6 0.75 0.9 1.05 1.2 1.35 1.5 1.65 1.8 1.95 2.1 2.25 2.4 2.55 2.7 2.85

0 0.075 0.15 0.225 0.3 0.375 0.45 0.525 0.6 0.675 0.75 0.825 0.9 0.975 1.05
HST PSF--Subtracted Coronagraphic Imaging of Circumstellar Disks
A Choice of Coronagraphs - The HST Arsenal

### Observation Details

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Wavelength (µm)</th>
<th>Total Integration</th>
<th># Orbits: Target/PSF</th>
<th>Diff. Orientation</th>
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<tr>
<td>NICMOS</td>
<td>1.1</td>
<td>1216s</td>
<td>1/0°</td>
<td>8°</td>
</tr>
<tr>
<td>STIS</td>
<td>0.5</td>
<td>3155s</td>
<td>2/1</td>
<td>30°</td>
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<tr>
<td>ACS</td>
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<td>4910s</td>
<td>2/1</td>
<td>28°</td>
</tr>
<tr>
<td>PALAO</td>
<td>2.2</td>
<td>1090s</td>
<td>2 NIGHTS</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Notes:**
- N/A indicates not applicable.
- All instruments are part of the Hubble Space Telescope (HST) arsenal.
- The table compares the observing details for different coronagraphs, including wavelength, total integration time, number of orbits, and differential orientation.
A Choice of Coronagraphs - The HST Arsenal

Obscured Areas Two-Orientation PSF-Subtracted Coronagraphic Images.
Red circle shows size of NICMOS 0.3" radius coronagraphic hole.

NICMOS

ACS

STIS

$r = 0.3"$

$r = 0.9"$

$w/2 = 0.25" - 1.25"$

$\text{PSF-Subtracted Rejection} / \text{arcsec}^{-2} @ 1" \text{ w.r.t. Total Stellar Flux:}$
- NICMOS (F110W for disk imaging) $\sim 20,000 / \text{Total Stellar Flux}$
  Largely Color Independent, Target-PSF $|J-H| < 0.3$
- STIS $\sim 3,000 / \text{Total T-Tauri Stellar Flux}$, may improve x10 for A *s
  Color Dependent, Large Variations, Target-PSF $|B-V| < 0.08$
- WFPC-2 $\sim 1,750$ (non-Coronagraphic) - Field/Color Dependence
NICMOS F110W (~ J-Band) Coronagraphic Performance (G2V)

Normalized* Radial Profiles (Azimuthal Median)

* w.r.t. central pixel
\[ F(F110W)_{\text{central}} = 23.3\% F_{\text{star}} \]
Mechanics: To Minimize Image Artifacts from Reference PSF Subtractions, Target & Reference PSFs Should Be:

- Obtained in the same (when possible) or adjacent visibility periods
- Of Similar Spectral Type (particularly for “wide” pass bands)
- At Least as Bright as the Target
Mechanics: To Minimize Image Artifacts from Reference PSF Subtractions, Target & Reference PSFs Should Be:

- Obtained at Two or More Spacecraft Roll Orientations

*TW HYDRAE*  *HD 141569A*
Terrestrial planets form in the inner solar system, with the formation of a Kuiper cometary belt? Clearing timescales: P-R drag few $10^6$ yrs. Rad. Pressure: $\sim 10^4$

Primary Dust ($\leq \mu$m) Locked to Gas
Secondary Dust ($\geq \mu$m) Collisional erosion

From: R. Webb
Observing young circumstellar disks with obscured central stars is not difficult.

Disk systems with unembedded, or only marginally obscured central stars are much more observationally challenging and require PSF-subtracted coronagraphy.
cTTs (K7V)
Age: 1.3+/-0.3 Myr

Beckwith et al 1990:
Dust inferred from
1.3mm continuum

Koerner, Sargent &
Beckwith 1993:
$^{13}$CO(2->1) emission,
Keplerian rotation.

Stapelfeldt et al 1997:
WFPC-2 imaging,
flared inclined disk.
cTTs (K7V)
Age: 1.3 +/- 0.3 Myr

Beckwith et al 1990:
Dust inferred from 1.3mm continuum

Koerner, Sargent & Beckwith 1993:
$^{13}$CO(2->1) emission, Keplerian rotation.

Stapelfeldt et al 1997:
WFPC-2 imaging, flared inclined disk.
GM AUR F110W (top) & F160W (bottom) NICMOS Imaging

Linear Display Range in $\mu$Jy / pixel

-1 to +10

-0.5 to +2.0

-0.2 to +0.5

-0.05 to +0.1
GM AUR F110W & F160W Surface Brightness

Flux Density Beyond Inner Radius (r) [µJy]

Surface Brightness [µJy/sq-arcsec]

F110W = 302.12 * r^{-2.94} (R= 0.972)

F160W = 775.29 * r^{-3.53} (R= 0.984)
GM AUR F110W & F160W Front/Back Scattering

Flux Density 1x13 pixels (µJy) vs. Radial Distance (Arc Seconds)

- MINOR AXIS F110W
- MINOR AXIS F160W
- MAJOR AXIS F110W
- MAJOR AXIS F160W

Points of Interest:
- P1
- P2
Circumstellar Dust Inferred from Spectral Energy Distribution

**GM AUR (cTTS)**

SED & Spatial Dust Distribution Simultaneously Constrain Disk Models
Model as Passively Heated Disks to Determine:
Geometry: Orientation, Inclination, Size
Physical Characteristics: Disk Mass, Scale Height, Envelope Infall Rate

Dependency of Grain Properties ($\lambda$ Dependent):
Dust Lane Width, Scattered Light Pattern, long-$\lambda$ SED slope
(Disk dust opacity, $\kappa \sim \lambda^{-1}$, shallower than ISM grains, as in other disks)

Simultaneously Model Scattered Light & SED:
-Envelope: Tereby, Shu & Cassen (84) Rotational Collapse Geometry
  Curved Bipolar Evacuated Cavity (Whitney & Hartmann 93)
- Dust Model & Grain Parameters per Wood (00)
- Adopted Flared Disk Structure (300 AU radius, 1000 AU envelope)

$$\rho_d = \rho_0 (R_*/\omega)^\alpha \exp \left[ -\frac{1}{2} \left( \frac{z}{h(\omega)} \right)^2 \right]$$

$\rho_0$ = disk density extrapolated to stellar surface
$\omega$ = radial coordinate in disk midplane
$h = \text{scale height increasing with radius} = h_0 (\omega / R_*)^{\beta}$
$\Rightarrow \beta = 1.25; \alpha = 2.25; \text{surface density } \Sigma \sim 1/\omega$ (D’Alessio et al 99)
- Monte Carlo scattered light modeling (Whitney & Hartmann 92)
GM AUR Model Fitting Results

OBSERVED   50° Model   55 ° Model                Residuals

LOS Inclination = 52.5°        PA Major Axis = 328.5°
Disk Mass = 0.04 $M_{\text{sun}}$        Infall Rate = 1.5x10^{-7} $M_{\text{sun}}$/year
Envelope Mass = 0.001 $M_{\text{sun}}$        Scale Height = 0.008$R_*$ (z=8AU @ r=100 AU)
Ground-Based AO and Dual-Beam Polarimetry of cTTS Circumstellar Disks
GM Aur: Coronagraphy & Dual Beam Polarimetry

HST/NICMOS  Hokupa’a/Gemini N.

Duvert et al. 2000
Lk Ca 15 Dual Imaging Polarimetry with Gemini/Hokupa`a
More Results from Dual Imaging Polarimetry with Gemini/Hokupa`a

Young CTTS in Rho Ophiuchus

Resolved disk around a WTTS in Rho Ophiuchus

Optically Thick Lane

D. Potter, U. Arizona
Space/AO/Long $\lambda$ Imaging of HK Tau

- Scattering from larger (> 1 $\mu$m; evolved; non-ISM grains)

- Likely stratified (larger grains deeper; longer $\lambda$ observations)
Space/AO Imaging of HV Tau

Stapelfeldt et al 2003

HST/WFPC2

0.5–0.8 μm

1"

Keck/AO

0.2"

3.8 μm

4.7 μm

Keck/AO

Courtesy of G. Duchene
Nebular Environments of T Tau Stars: Surface Brightness Scales with $H_2$ Flux

See Grady et al poster (this conference)
LGS + AO Dual Channel Imaging Polarimetry
Lick/Shane 3m + IRCAL (J, H, Ks)
Intermediate Mass HAeBe Stars with T Tau-like envelopes

Perrin et al. 2004 Science 303 1345
Examples of Dusty Disks with Radial and Hemispheric Brightness Anisotropies and Complex Morphologies, Possibly Indicative of Dynamical Interactions with Unseen Planetary Mass Companions, Spatially Resolved and Imaged Around Young (< 10 Myr) Stars by HST.

HD 141569A (Herbig Ae/Be) ~ 5 Myr

A 400 AU radius disk, with a broad, partially filled asymmetric gap containing a “spiral” arclet.
Examples of Dusty Disks with Radial and Hemispheric Brightness Anisotropies and Complex Morphologies, Possibly Indicative of Dynamical Interactions with Unseen Planetary Mass Companions, Spatially Resolved and Imaged Around Young (< 10 Myr) Stars by HST.

TW Hya
K7Ve eTTs
“Old” PMS Star

Near pole-on, near circularly symmetric disk with a break in its surface brightness profile at 120 AU (2”).
Examples of Dusty Disks with Radial and Hemispheric Brightness Anisotropies and Complex Morphologies, Possibly Indicative of Dynamical Interactions with Unseen Planetary Mass Companions, Spatially Resolved and Imaged Around Young (< 10 Myr) Stars by HST.

TW Hya
K7Ve cTTs
“Old” PMS Star

and, possibly, a radially and azimuthally confined arc-like depression.

Near pole-on, near circularly symmetric disk with a break in its surface brightness profile at 120 AU (2”).
Examples of Dusty Disks with Radial and Hemispheric Brightness Anisotropies and Complex Morphologies, Possibly Indicative of Dynamical Interactions with Unseen Planetary Mass Companions, Spatially Resolved and Imaged Around Young (< 10 Myr) Stars by HST.

HR 4796A (A0V), ~ 8 Myr
A 70AU radius ring, ~ 12 AU wide ring of red material, exhibiting strong forward scattering and ansally asymmetric hemispheric flux densities.
Terrestrial planets form Clearing of inner solar system, formation of a Kuiper cometary belt?

10^8 yrs Era of heavy bombarment by comets

10^9 yrs Current age of the Sun: 5x10^9 yrs.

α Persei

10^7 yrs Giant planets accrete gaseous atmospheres

β Pic Group

10^6 yrs Collapsing protostar forms proto-planetary disk

TW Hydrae Assoc

Tucanae Assoc

Pleiades

Hyades

Sun

Rocky cores of giant planets form

Terrestrial planets form

Primary Dust (≤ μm) Secondary Dust (≥μm)

Locked to Gas Collisional erosion

Clearing Timescales: P-R drag few 10^6
Rad. Pressure: ~ 10^4

From: R. Webb
HD 141569A

Herbig Ae/Be Star (B9V, H = 6.9)

d = 100 pc, Age ~ 5 Myr, Mass ~ 2.3 M\textsubscript{sun}

$L_{\text{IR}} / L_\star = 8.4 \times 10^{-3}$ (few x \(\beta\) Pic, HR 4796A)

Hierarchical Triple with 2 M-Dwarf Companions
HD 141569A - Thermal IR Disk Detection / Imaging

Silverstone 1999

HD 141569             PSF STAR

12.5 17.9 20.8

0.26" FWHM

0.37" FWHM

0.43" FWHM
HD 141569A - NICMOS Coronagraphic Imaging

Disk Radius = 400 AU
Gap Radius = 245 AU
Gap Width ~ 40 AU

1.1 μm NICMOS Coronagraphic Image

Also observed by Augereau et al. at 1.6 μm

Scattering by cold dust is OUTSIDE region of thermal emission.
**HD 141569A - Circumstellar Disk & “Gap”**

Flux Density = 8±2mJy (r > 0.6")
SB @ 190 AU = 0.3 mJy arcsec^{-2}
ω ~ 0.3 @ < 190AU, 0.4 @ > 190AU

Inclination to LOS = 51°±3°

Intrinsic Scattering Function results in Brightness Anisotropy in ratio 1.5±0.2:1 in direction of forward scattering.

Gap partially cleared of material (by an unseen planetary companion?).

Hierarchical triple system
d_A(BC) = 8.3””, d_BC = 1.3”

M2V/M4V companions may influence disk dynamics.

**HD 141569A - “Embedded” Planet Detection Limits**

3σ Point Source Detection Limits

\[
\text{Mass of Planet to Clear Gap: } M/M_* \sim c(\Delta a/a^3) \text{ where } c \sim 0.1 \text{ (Lissauer 1993)}
\]

For \( \Delta a = 50 \text{ AU, } a = 240 \text{ AU} \Rightarrow M = 0.9 \text{ M}_{\text{jup}}, \text{ below detection threshold.}

In gap (83% area observed) F110W detection limit = 20.3 \( \sim 2 \text{ M}_{\text{jup}} \) @ 5 Myr

**Gap Width:** Radius implies planetary mass of \( \sim 0.9 \text{ M}_{\text{jup}} \) -- UNDETECTABLE

Mass of Planet to Clear Gap: \( M/M_* \sim c(\Delta a/a^3) \) where \( c \sim 0.1 \) (Lissauer 1993) for \( \Delta a = 50 \text{ AU, } a = 240 \text{ AU} \Rightarrow M = 0.9 \text{ M}_{\text{jup}}, \text{ below detection threshold.}

At 240 AU with \( M = 2.3 \text{Msun, } P = 2500 \text{ yr} \Rightarrow 2000 \text{ orbits (at 5 Myr).}

*Gaseous* disk gap clearing in \( \sim 300 \text{ orbits (Bryden et al 1999), 0.8 Myr.} \)
HD 141569 (A, BC) - Dynamical Sculpting by Companions?

- Density of Scatters: Equal at 200 AU and 360 AU. If non-coplaner companions can excite vertical velocities in disk.

- Circular 50 AU-wide Gap @ 250 AU
  Continual clearing to remove P-R and RP driven transiting particles.

- Gap circularity implies dynamical stability on long time-scales.

- If co-planer Lindblad resonances from 1053AU distant CoM (BC) 
  (9:1) @ 243 AU, (8:1) @ 263AU closest to gap.
Knowing the Flux Density, Orientation, Size, etc.,
Allowed Planning an Effective Follow-up...
Global structure better described by “concentric ring” morphology.

“Gap” broader and partially filled.

“Spiral arclett” structure seen in disk gap.
HAeBe Disk Brightness Correlates with PAH Flux

See Grady et al poster (this conference)
**TW Hydrae**

- K7Ve (Rucinski & Krautter, 1983)
- Distance: 56±7 pc (Hipparchos)
- Age: ~ 6 Myr
- Hα and UV Excesses
  - Isolated Classical T-Tauri Star
- Member TW Hya Association
  - (TWA ~ 10 Myr, 60 pc)
- Long Wavelength Excesses
  - \( \tau \sim L_{\text{disk}}/L_{\text{star}} \sim 0.3 \) (IRAS)
  - CO emission (Zuckerman et al. 1995)
**TW Hydrae - NICMOS Coronagraphic Imaging**

“Face-On”, Optically Thick, 190 AU radius Flared Disk

- Gray scattering:
  \[ F_{110W} - F_{160W} = \sim 0.96 \text{ mag (same as star)} \]

![Image](image-url)
TW Hydrae

Also seen in HST Optical Band-Passes

And, Subsequently Observed from the Ground:

e.g., Trilling et al 2001 (CoCo); Apai et al 2004 (NACO)
**TW Hydrae - NIR Surface Brightness Profile**

Flux density Power Law: $r^{-2.6 \pm 0.1}$ @ 35 AU < $r$ < 135 AU

Break @ 100 AU
TW Hydrae - Surface Brightness Profile

“Zone 2-3 Break” may implicate sculpting by grains

Surface Brightness (mag arcsec^{-2})

Zone 1 2 3 4

NICMOS- Weinberger et al. 1999
WFPC-2 - Krist et al. 2000

F160W
F110W
F814W
F606W
50CCD (uncalibrated)
TW Hydrae - Optical Surface Brightness Profile


STIS
TW Hydrae - Azimuthal Brightness Variation

$r = 70 - 88 \text{ AU}$

“warp” in disk?

**TW Hydrae - Optical Asymmetries?**

Hemispheric? Azimuthally confined arc-like depression?
TW Hydrae - NICMOS Companion Detection Limits

**Axes:**
- **Y-axis:** Absolute Magnitude
- **X-axis:** Radius (AU)

**Markers:**
- 1 Mjup
- 3 Mjup
- 7 Mjup
- 10 Mjup
**TW Hydrae - Mid-IR (8—13 µm) Spectrum**

(Spatially Unresolved @ 11.7 & 17.9 µm)

Peak: Amorphous (~9.6 µm) & Crystaline (~11.2 µm) Silicates.

Keck I LWS $\Delta \lambda/\lambda \sim 120$

TW Hydrae - SED Model from All Spectral Bands

ala Chaing et al. (2001)

Surface grains < 2µm
Interior grains < 12mm

Grain Size Distribution
\[ \frac{dN}{dr} \text{ (interior)} \sim r^{-1} \]
\[ \frac{dN}{dr} \text{ (surface)} \sim r^{-3.5} \]

Dust Surface Mass Density
\[ 10 \left( \frac{r}{\text{AU}} \right)^{-1} \text{ cm}^{-2} \]

Disk Radii:
Inner = 0.05 AU
Outer = 200 AU
$\lambda$ dependent scattering $\rightarrow$ >1μm grains to large radii.

Inner disk *possibly* bluer then outer $\rightarrow$ smaller gains near star.
TW Hydrae - VLT/NACO Polarimetric Differential Imaging

Apai et al. 2004

Polarized Disk Emission at $0.1'' < r < 0.4''$
**TW Hydrae - Summary**

TTS surrounded by Optically Thick dust disk.

Disk must be flared given scattered light radius and thermal SED.

“Break” in Surf. Brightness @ ~ 95AU *may* be due to dynamical effects.

No Companions found to 10—2 $M_{\text{jup}}$ @ 40—100 AU limit.

Disk Mass: ~ few $10^2$ Earth Masses of Condensed Silicates & Ices.

Dust mass few times > “typical” Taurus & Ophiuchus TTS Disks.

Good evidence for grain growth within the disk.
Terrestrial planets form via clearing of inner solar system, formation of a Kuiper cometary belt?

Primary Dust ($\leq \mu$m) Locked to Gas
Secondary Dust ($\geq \mu$m) Collisional erosion

Clearing Timescales: P-R drag few $10^6$
Rad. Pressure: $\sim 10^4$

From: R. Webb
HR 4796A - Observational Chronology

1991 - Jura (ApJ, 383, L79) inferred presence of large amount of circumstellar dust from IRAS excess. Estimated $\tau_{\text{dust}} = L_{\text{disk}}/L_{\text{star}} = 5 \times 10^{-3}$ ($\sim 2x \beta$ Pictoris).

1995 - Jura et al. (ApJ, 445, 451) noted earlier 110K estimate of dust temperature indicated lack of material at $<40$ AU. Required grains $>3 \mu$m to be bound gravitationally at $40 < r < 200$ AU. No close companions with $M_\star > 0.125 M_{\odot}$ seen (speckle).

1998 - Koerner et al. (ApJ, 503, L83) and Jayawardhana et al. (ApJ, 503, 79) independently image mid-IR disk. Inner depleted region evident in high resolution $20.8 \mu$m image reproduced with a model suggesting: $i = 72^\circ (+6^\circ, -9^\circ)$, PA $= 28^\circ \pm 6^\circ$, $R_{\text{in}} \sim 55$ AU, $R_{\text{out}} \sim 80$ AU -> Kuiper belt-like dust ring.

1999 - Schneider et al. (ApJ, 513, L127) report on morphology and photometry of well-resolved NIR images in two NIR colors (1.1 and 1.6 $\mu$m) of a narrowly confined ring-like circumstellar disk, with characteristic properties predicted by Koerner et al, from $\sim 0.1''$ resolution NICMOS coronagraphy obtained contemporaneously with 1998 mid-IR images.
NICMOS Observations of the HR 4796A Circumstellar Debris Ring

**GEOMETRY**
- \( PA = 26.8^\circ \pm 0.6^\circ \)
- \( i = 73.1^\circ \pm 1.2^\circ \)
- \( a = 1.05'' \pm 0.02'' \)

**MORPHOLOGY**
- \( r = 70 \) AU
- width < 14 AU
- “abrupt” truncation
- “clear” @ \( r < 50 \) AU

**FLUX DENSITY**
- \( 12.8 \pm 1.0 \) mJy @ 1.1\( \mu \)m
- \( 12.5 \pm 2.0 \) mJy @ 1.6\( \mu \)m
- \( H(F160W) = 12.35 \pm 0.16 \)
- \( J(F110W) = 12.92 \pm 0.08 \)
- \( T_{\text{dust}} \sim \frac{L_{\text{disk}}}{L_*} \)
- \( 1.4 \pm 0.2 \times 10^{-3} \) @ 1.1\( \mu \)m
- \( 2.4 \pm 0.5 \times 10^{-3} \) @ 1.6\( \mu \)m

NIR scattered flux in good agreement with visible absorption & mid-IR re-radiation.
**NICMOS Observations of the HR 4796A Circumstellar Debris Ring**

**Anisotropies**

NE ansa ~ 15% brighter than SW ansa.
NICMOS Observations of the HR 4796A Circumstellar Debris Ring

**Anisotropies**
NE ansa ~ 15% brighter than SW ansa.

**Suggestion of preferential (forward) scattering to SE.**

**Implications**
Possible dynamical confinement of particles by one or more unseen bodies.

**Mean particle size > few µm. debris origin, not I.S. dust.**
HR 4796A - OSCIR Thermal IR Imaging

1999 - Telesco et al. (A&A):
- Indicate comparable sizes of 10.8 and 18.2 μm emitting regions.
- Confirm central hole is largely cleared (τ_{central zone} ≤ 3% of main part of the disk).
- Inward fall-off from the ring is shallower at 18.2 μm then in near-IR.
- Brightness asymmetry in OSCIR images (similar to NICMOS) possibly suggesting the existence of a gravitational perturber (Wyatt, et al 2000).

Top: OSCIR 18.2μm  
Bottom: NICMOS 1.1 μm

Star-subtracted scans along the disk major axis.
Models for different grain sizes (Telesco, et al. 1999)
HR 4796A - Observational Chronology

1999 - Greaves et al. obtain JCMT/SCUBA 450 and 850 μm flux excess measures of 0.18 and 0.019 Jy, respectively, and estimate total gas mass < 1–7 Earth masses.

1999 - Augereau et al. re-reduce K' observations of Mouillet et al. 1997 and find excess in agreement with Schneider et al at ~1" in low S/N image showing extension in NE/SW directions. They estimate a lower limit for dust mass of ~ 4 Earth masses.

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Schneider et al. (1999)  Augereau et al. (1999)
HR 4796A - Kenyon & Wood (2000) Dynamical Evolutionary Model

Produces observed dust distribution in 10 Myr with initial 10-20M_{MMSN}

Monte Carlo runs constrain geometry & $\tau_{\text{dust}}$
Assumes: isotropic scattering
$\omega = 0.3$ (Augereau et al, 1999)
Adjust to obtain $\tau = 1.5 \times 10^{-3}$

CONCLUSIONS:
• Planet formation at 70 AU in 10 Myr possible with initial disk mass = 10—20M_{MMSN}
• Dust production associated with planet formation is then confined to a ring with $\Delta a = 7—15$ AU.
• Optical depth in ring satisfies constraints on scattered light at 1—2 $\mu$m and on thermal emission at 10—100 $\mu$m if the dust size distribution is $N \sim r_i^q$ with $q \geq 3$ for $r_i \leq 1$ m.
• Models with disk masses smaller than 10M_{MMSN} fail to produce planets and an observable dusty ring in 10 Myr.
HR 4796A - Has an M-Dwarf Companion

HR 4796B (late M)
Likely PMS Star
Hβ, Hγ, Ca H&K emission
J-H = 0.75

... which could help to truncate the outer portion of the disk
HR 4796A - Augereau et al. (1999) Physical Model

Two-component model reproduces all then-available observations: "the full spectral energy distribution from the mid-infrared to the millimeter wavelengths, resolved scattered light and thermal emission observations".

a) cold amorphous (Si and H2O ice) grains > 10 \( \mu m \) in size (cut-off in size by radiation pressure), with porosity ~ 0.6, peaking at 70 AU.

b) hot dust at ~ 9 AU of "comet-like" composition (crystalline Si and H2O), porosity ~ 0.97.

Collisions are common in both populations. Bodies as large as a few meters are required.

Model gives rise to a minimum mass of a few \( M_{\text{Earth}} \) with gas:dust < 1.

Simulated disk at 20.8 \( \mu m \). assuming grain properties and surface density derived from the SED fitting and a \( \beta \) Pic like vertical structure, with 0.14" pixels like observations by Koerner et al. (1998) and convolved 10m telescope PSF.

Simulated images of the cold annulus peaked at 70 AU in scattered light at 1.1 \( \mu m \) (with 0.076" pixels as in NICMOS) for two asymmetry factors considered assuming a Henyey-Greenstein phase function (The inner hot dust not observable has not been added). The NICMOS observation suggests \( |\alpha| < 0.15 \). The flux density predicted in the region outside \( r > 0.65" \) is 5.2mJy, in good agreement with the 7.5±0.5mJy observed with HST.

Full SED fitting with two dust populations.
Additional processing recovered ring flux closer in and suggested somewhat higher inclination (~76°).

“Clumpiness” due to residuals in PSF subtraction, not attributed to structure of ring.

Here Be Dragons!

Schneider et al 2000 ASP Con Ser 219 499
HR 4796A RING GEOMETRY
(Least-Squares Isophotal Ellipse Fit)
**HR 4796A RING GEOMETRY**
(Least-Squares Isophotal Ellipse Fit)

- **Ansal Separation (Peaks)** = 2.107" ± 0.0045"
- **Major Axis of BFE** = 2.114" ± 0.0055"
- **P. A. of Major Axis (E of N)** = 27.06° ± 0.18°
- **Major:Minor Axial Length** = (3.9658 ± 0.034) : 1
- **Inclination of Pole to LOS** = 75.73° ± 0.12°
- **Photocentric Offset from BFE(Y)** = −0.0159" ± 0.0048"
- **Photocentric Offset from BFE(X)** = +0.0031" ± 0.0028"
HR 4796A Circumstellar Debris Ring - WIDTH

Distance (Arc Seconds)

0.197'
HR 4796A Circumstellar Debris Ring - WIDTH

NE ANSA CROSS-SECTIONAL PROFILE

WIDTH AT NE ANSA

FWHM: 12.3 ± 0.7 AU
8.7% D_{ring}

1−e^{-1}: 7.7 ± 10.1 AU
12.5% D_{ring}

Measured = 0.197"
PSF point source = 0.070"
FWHM ring = 0.184"

1−e^{-1} = 0.265"

20% inner:outer fall-off asymmetry

Distance (Arc Seconds)

Brightness (Normalized to NE Ansa)
RING GEOMETRY - Least-Squares Isophotal Ellipse Fit

Ansal Separation (Peaks) = 2.107" ± 0.0045"
Major Axis of BFE = 2.114" ± 0.0055"
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“FACE-ON” PROJECTION - With Flux Conservation
Spatially Resolved Relative PHOTOMETRY of the Ring

“FACE-ON” PROJECTION - With Flux Conservation
Surface Brightness Anisotropies

NW:SE ("Left/Right")

Front/Back

Angle from Major Axis (Degrees)

Brightness Ratio (Percent)

N-Sigma

(\%SW - \%NE) : SIGMA (\%SW/\%NE)

NE % FRONT:BACK
SW % FRONT:BACK
MEAN FRONT:BACK
1 + 0.73*\text{COS}(\theta)

\text{SIGMA}(\text{Front/Back})
\text{SIGMA}(\text{Front/Back})
\text{SIGMA}(\text{Front/Back})
**Broad Colors of the HR 4796A Debris Ring**

\[
\begin{align*}
[50\text{CCD}]-[F110W] &= 0.55 \pm 0.09 \\
[50\text{CCD}]-[F160W] &= 1.14^{+0.20}_{-0.17}
\end{align*}
\]

**Intrinsically red grains**

- Consistent with collisionally evolved population of particle sizes > few microns
- Not primordial ISM grains
- Similar intrinsic colors to TNOs in our solar system: \([V]-[J]=+1.07^*\)
- Consistent with laboratory* irradiation experiments of organics to study reddening of D & P type asteroids with distance from Sun.

HR 4796A SUMMARY

★ Ring geometry/astrometry defined by NICMOS improved by higher resolution STIS observations ($i = 2.6^\circ$ larger than original NICMOS solution).

★ Spatially resolved photometry of ring with ±2% uncertainty at ansae (1"), and ±6—8% uncertainty at 0.5".

★ Characteristic width ~ 10% of 70 AU radius ring.

★ “Left/Right” brightness anisotropy or ~20% along at least 50° wide diametrically opposed arcs centered on ansae.

★ “Front/Back” brightness anisotropy, roughly symmetric in both L/R “hemispheres”, increasing with longitudinal distance from ansae to 35% difference at 30° from ansae.

★ Ring is uniformly RED from “V” to H with 1:1.7:2.9 spectral reflectance in CCD50 (“V”):F110W(1.1µm):F160W(H).
Brightness Anisotropies, “Confinement” & Color Consistent with Dynamical Interactions of Evolved (non-ISM) Grains with Co-Orbital Unseen Planet-Mass Bodies
Today we have only a handful of Spatially Resolved Images of Dusty Circumstellar Disks. Many more are needed.
HST Cycle 13 - 52 Target Disk Imaging Survey

Solar Systems in formation:
A NICMOS Coronagraphic Survey of
Protoplanetary and Debris Disks

Glenn Schneider (PI), Murray Silverstone, Karl Stapelfeldt, Deborah Padgett, Carol Grady, Dean C. Hines, Angela S. Cotera, Francois Menard, Bringfried Stecklum, Thomas K. Henning, Sebastian Wolf, Mark Clampin, David Wilner, John Krist, Jinyoung Serena Kim, Caer-Eve McCabe

26 optically thick, < 10 Myr, YSO Disk Candidates (18 G–M T Tau stars, d <150pc), 8 A-F stars (4 HAeBe) with IR/mm excesses.

26 optically thin, > 10 Myr Dust-Dominated Debris Disk Candidates (A0–K2 IR excess Main sequence stars, d < 150 pc) with \( L_{ir}/L_* > 3 \times 10^{-4} \).
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Inner Regions of Evolved Disks

Cannot yet be probed in scattered light. Yet, as inferred from mid-IR:

An inner tenuous component of warm zodi-like dust may be confined within a few AU of HR 4796A.

12–20 µm thermal emission is contained completely within the large inner “hole” of HD 141569A.
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What evolutionary and dynamical interactions may be going on between unseen planets and unseen dust which will shape these systems?

Requires “Super-High” contrast and resolution.
Scattered-light imaging and spectroscopy of collisionally evolved circumstellar debris and co-orbital bodies will play a pivotal role in furthering our understanding of the formation and evolution of extrasolar planetary systems.

**Extrasolar Planet Imaging & Spectroscopy:**
*(Hot Jovian) few \( \times \) 10^6 yr at 1″*

**Disk Imaging & Spectroscopy:**
\( f_{\text{disk}}/f_\star > \text{few} \times 10^{-4} \)
\( \theta > 50 \text{ mas} \)
To study physical processes acting on sub-AU scales and time scales comparable to the age of our solar system will require a 3—4 orders of magnitude improvement in instrumental stray light rejection (i.e., image contrast) over performance currently obtainable with HST.

**Extrasolar Planet Imaging & Spectroscopy:**
(Hot Jovian) few x 10^6 yr at 1”  (Terrestrial) > 10^9 yr (solar age) at 1”

**Disk Imaging & Spectroscopy:**
\[ \frac{f_{\text{disk}}}{f_\star} > \text{few} \times 10^{-4} \leq 10^{-6} \]
\( \theta > 50 \text{ mas} \rightarrow \text{a few mas} \)
(sub-AU at 200pc)