HST High-Contrast Imaging of Circumstellar Disks with Optical/Near-IR Coronagraphy

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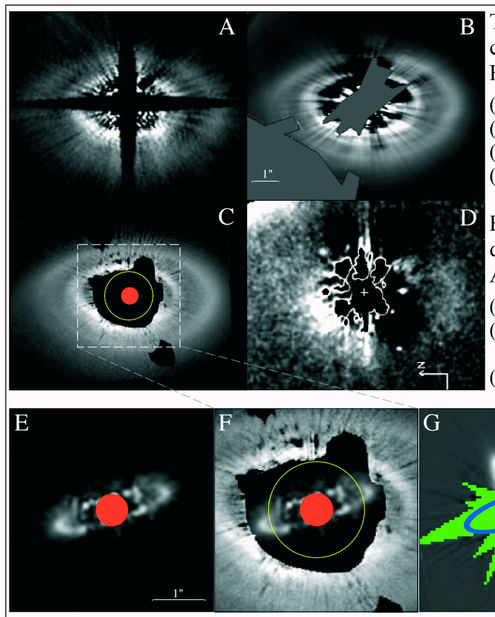
Introduction: Probing circumstellar environments with spatially resolved imaging of their constituent materials irradiated by, and scattering, central starlight has been observationally challenging. Both the intrinsically high contrast ratios and small spatial scales of such regions have rendered their study extremely difficult even with the most aggressive ground-based observing techniques. The *Hubble Space Telescope* (*HST*) uniquely provides high spatial resolution at optical and near-IR wavelengths, extreme image (point spread function) stability, and high contrast coronagraphic imagery. These technical attributes are simultaneously exploited to study the circumstellar environments of potentially planet-forming disks. High contrast images of circumstellar disks, provided by the enabling capabilities of *HST*, are being used to probe the posited evolutionary epochs of grain-growth, disk formation (and dissipation), and planet-building.



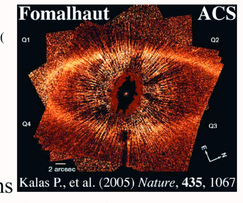
Top: 400 AU (4.0") radius circumstellar disk of the ~ 5 Myr Herbig AeBe star HD 141569A:
(A) NICMOS 1.1 μm [1]
(B) STIS 0.6 μm broadband [2]
(C) ACS 0.6 μm [3]
(D) ground-based 2.2 μm PALAO [4]

Bottom: 70 AU (1.05") radius debris ring around the ~ 8 Myr A0V star HR 4796A:
(E) NICMOS 1.1 μm [5]
(F) HR 4796A compared to inner region of HR 141569A at same angular scale
(G) STIS 0.6 μm broadband [6]

[1] Weinberger A. J., et al. (1999) *ApJL*, **525**, L53-L56.
[2] Schneider G. and Silverstone M., (2003) *ASPC*, **291**, 69-76.
[3] Clampin M., et al (2003) *AJ*, **126**, 385-392.
[4] Boccaletti A., et al. (2003) *ApJ*, **585**, 494-501.
[5] Schneider G., et al. (1999) *ApJL*, **513**, 127-131.
[6] Schneider G. (2001) *BAAS*, **904**, 911.

HST coronagraphic imagery of dusty circumstellar disks.

HST Capabilities: Direct and PSF-subtracted imagery of reflection nebulae and envelopes associated with younger sources are critically augmented with high-contrast coronagraphy in HST's NICMOS, STIS*, and ACS instruments which reveal detailed structures of, and within, both optically thick and thin circumstellar disks.



Kalas P., et al. (2005) *Nature*, **435**, 1067

*** STIS, unfortunately, is no longer functional. :-(**

Collectively, the HST coronagraphs:

- probe material as close as 0.3" from occulted stars,
- provide spatial resolutions of ~ 50 mas in the optical,
- enable panchromatic studies from λs ~ 0.4 to 2.0 μm,
- are sensitive to circumstellar material with scattering fractions of a few x 10^{-5} of the total starlight at a distance of ~ 1" from the central stars,
- are capable of imaging young co-orbital objects of ≳ 2 Jupiter masses in optically thin (e.g., debris) disks in the near-IR at distances ≥ 1" from their central stars.

Grain Properties: Scattered-light imagery of circumstellar disks directly provides the spatial distribution of the constituent grains, which cannot be uniquely inferred from (longer-wavelength) spectral energy distributions (SEDs) alone. This information can be used to break the degeneracies in disk geometries and compositions intrinsic to SED-driven models of disk properties. Together, spatially resolved imagery and SEDs of evolved circumstellar disks, inform on their global structures and on the distribution and physical properties of the circumstellar grains (e.g., Schneider et al 2003, *AJ*, **125**, 1467).

Disk Structures & Planetary Dynamics: Asymmetries (e.g., warps, gaps, arc, spirals, rings, axial anisotropies, etc.) in the spatial distributions of dusty debris in evolved disks provide evidence for unseen co-orbital planetary-mass companions through their dynamical interactions with the disk grains.

This work is based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with program 10177. Support for program 10177 was provided by NASA through a grant from the Space Telescope Science Institute.

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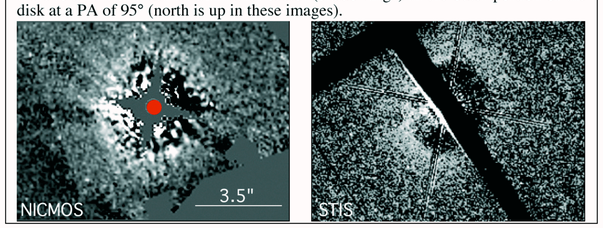
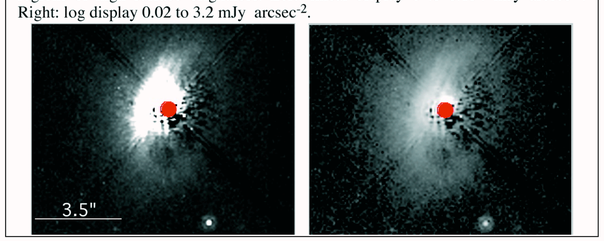
HST/GO 10177 Survey: We are conducting a highly sensitive HST/NICMOS coronagraphic survey to provide critically needed circumstellar disk imagery. Our sample of 52 stars spans spectral types A-M, crossing the evolutionary epochs of planet building. Our disk targets fall into two broad categories segregated, primarily, by age. Below, we present recent examples of protoplanetary and debris disk images from our HST/GO 10177 survey program obtained with NICMOS PSF-subtracted coronagraphy.

Young Stellar Object (YSO) Sample. A < 10 Myr sample of 26 optically-thick YSO disk candidates:18 T Tauri (d < 150 pc) stars of spectral types G-M, with millimeter continuum excesses and/or intrinsically high optical polarizations; 8 A-F (d < 200 pc), including 4 Herbig AeBe stars with thermal IR and/or millimeter emission well above their photospheric levels. Several of these YSO disks were previously detected with HST in the optical: (WFPC-2: GO Tau, DoAr 25, Sz 82, Haro 6-33; STIS: AA Tau, DM Tau, DL Tau), with possible detections about three others (CW Tau, CY Tau, RNO 91) and two (LK Ca 15 and HD 169142) with ground based differential polarimetry in the near-IR.

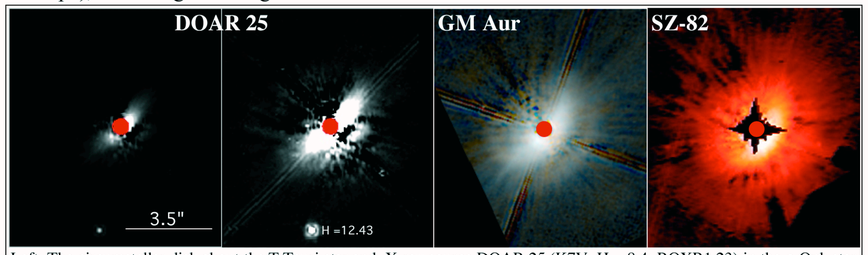
DM Tauri: A faint disk (peak surface brightness ~ 17 μJy arcsec^{-2}) seen around DM Tau (K5, H=9.8) at 1.6 μm with NICMOS (left) was also detected in the optical with STIS (right) as previously reported by Grady. The disk appears to be inclined appx 37° from the line-of-sight. The interior of the disk, to a distance of ~ 1.8" (240 AU), appears relatively dark (cleared?), though with a brightening toward east. A "bright" ring, at ~ 320 AU, is hemispherically asymmetric in surface brightness, and there is a hint of a darker azimuthal sector (shadowing?) in the outer portion of the disk at a PA of 95° (north is up in these images).



GO Tauri (K5V, H=9.8). NICMOS PSF-subtracted cornonagraphy shows that the morphology of the GO Tau disk is similar to GM Tau, but slightly more inclined. The disk also exhibits a much stronger brightness asymmetry along the minor axis. The dark zone in the GO Tau disk extends to ~ 2.4" (290 AU). The disk semimajor axis is ~ 4.5" (540 AU). Striated structures (above the disk midplane) are seen the regions of high surface brightness. Left: linear display 0 to 0.134 mJy arcsec^{-2}. Right: log display 0.02 to 3.2 mJy arcsec^{-2}.

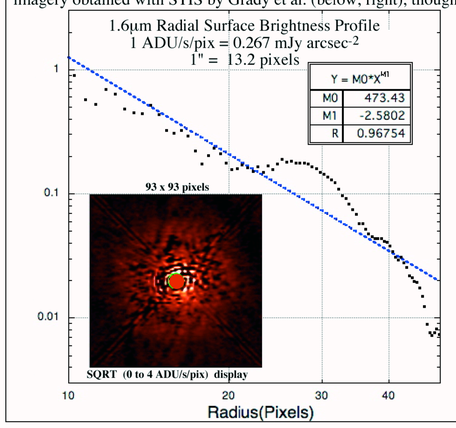


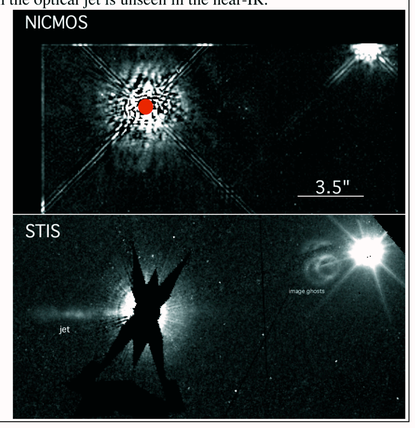
More Disks Are Coming... Stay Tuned!



Left: The circumstellar disk about the T Tauri star and X-ray source DOAR 25 (K7V, H = 8.4; ROXR1 23) in the ρ Oph star forming region was imaged with NICMOS 1.6μm PSF-subtracted coronagraphy. The r = 2.7" DOAR 25 disk, (left: 0 to 5.3 mJy arcsec^{-2}; adjacent: 0 to 0.53 mJy arcsec^{-2}), is similar to the less-inclined GM Aur disk (middle right; NICMOS 1.1 and 1.6 μm two color image; Schneider et al 2003). The dark DOAR disk mid-plane, 0.7" from the star and the "lower" scattering surface of the disk are seen below and to the right of the star. Right: A strikingly similar morphology is seen in the disk of the weak-lined T-Tauri star SZ-82 (IM Lup) in the NICMOS 1.6μm PSF-subtracted coronagraphic image.

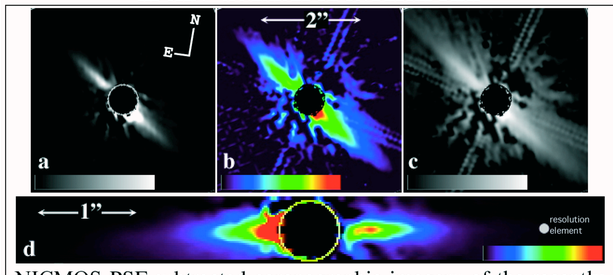
DL Tau (GV:e; H = 8.68) appears to have a nearly circularly symmetric scattered light disk at extending to r ~ 3.5" as seen in NICMOS PSF-subtracted 1.6 μm coronagraphic images. This morphology generally agrees with earlier corongraphic imagery obtained with STIS by Grady et al. (below, right), though the optical jet is unseen in the near-IR.





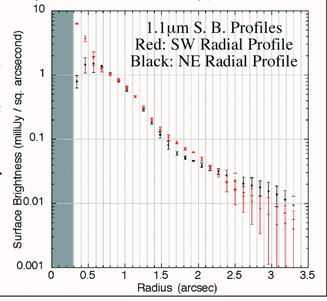
Debris Disk Candidate Sample. A > 10 Myr sample of 26 optically thin dust-dominated debris disk candidates (d < 150 pc), A0–K2 main sequence stars, with IRAS far-IR excesses (thermal emission > stellar photospheric level, $L_{IR} / L_* > 3 \times 10^{-4}$) unconfused by background nebulosity at $b > 10°$. Our selection criteria were predicated, in part, by results from earlier NICMOS disk surveys, and were designed to maximize the likelihood of imaging spatially resolved circumstellar disks.

HD 32297 - A NEAR EDGE ON DEBRIS DISK



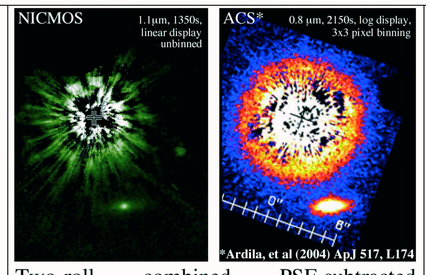
NICMOS PSF-subtracted coronagraphic imagery of the recently discovered circumstellar disk of **HD 32297*** (A0V) (possibly of comparable age to HR 4796A and β Pictoris, ~ 10 My).

Radial surface brightness asymmetries along NE and SW "halves" of the HD 32297 disk major axis may implicate the existence of a planetary perturber modifying the azimuthal distribution of circumstellar scattering grains. (Region in gray obscured by the NICMOS coronagraph.)

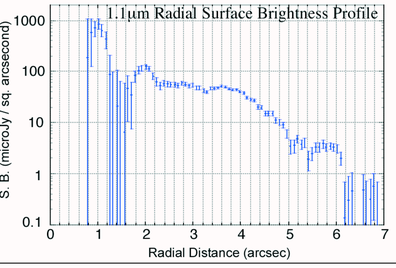


***Schneider G., et al. (2005) ApJ, 639, L227**

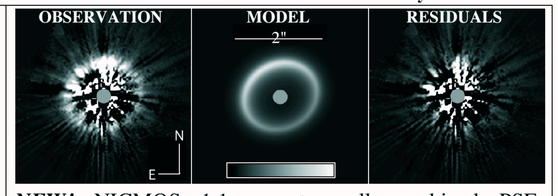
HD 107146 - A NEAR FACE ON DEBRIS DISK



Two-roll combined PSF-subtracted coronagraphic images of a near face-on debris disk, r ~ 150 AU, about the Sun-like star **HD 107146** (G2, J = 5.9, d = 28.5 pc).

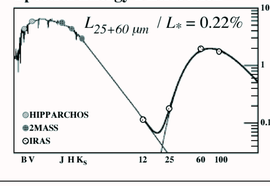


86 AU RADIUS DEBRIS DISK ABOUT AN ~ 10 Myr F-STAR



NEW! NICMOS 1.1 μm two-roll combined PSF-subtracted coronagraphic image of an 86 AU radius debris ring about an ~ 10 Myr old F-star. Seventy percent of the scattered starlight ($f_{scat} / f_* = 0.17\% \pm 0.015\%$ at 1.2" ≤ 5") is confined in a 36 AU wide annulus. The bilaterally symmetric ring, with a peak surface brightness of 1.75 ± 0.14 mJy/sq. arcsec on the disk minor axis, is well represented by a Henyey-Greenstein scattering function with $g = 0.30 \pm 0.03$. No photocentric offset is seen in the ring relative to the position of the central star.

Spectral Energy Distribution



Axial & Median S. B. Profiles