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High Contrast Imaging and the Disk/Planet Connection

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Abstract. The Hubble Space Telescope's (HST) second generation instruments, NICMOS and STIS, have enabled the direct imaging of circumstellar debris disks and hot Jovian-mass exo-planets, which were previously beyond the reach of ground-based instrumental systems. Such contrast-challenged observations are extremely difficult from ground-based platforms, even with AO augmented systems, because of residual uncompensated effects of atmospheric turbidity. The resulting temporal instabilities in ground-based point spread functions (PSFs) set systemic detectability limits which are often under-appreciated, and overlooked, when instrumental performance is expressed with presumtively static metrics such as Strehl ratios. These limitations are greatly relaxed with space-based imaging, as unequivocally demonstrated by HST. HST repeatably achieves panchromatic Strehl ratios in excess of 98%, and does so with intrinsic stability in PSF structures routinely permitting removal of mid and high spatial frequency optical artifacts to a degree unchallenged from the ground. Coupled with coronagraphic optics to further reduce background instrumentally scattered and diffracted light, these capabilities have opened the door to new avenues of investigations requiring high-contrast imaging. As spectacular as the HST results have been, substantial improvements in high-contrast performance (perhaps three orders of magnitude in circumstellar light rejection) must be achieved in future space missions operating in the UV/optical domain. Such performance requirements must be baselined into mission/instrument concepts, design, and implementation to assure success.

1. Introduction

Imaging dust and debris that might agglomerate to form planets around young stars has been technologically challenging because of the very high intrinsic star-to-disk contrast ratios. Resolving structures on AU spatial scales is possible at UV to near-IR wavelengths for nearby planet-forming systems if imaging instrumentation with sufficient dynamic range is employed. Until very recently the large and nearly edge-on disk around β Pictoris remained the only such disk imaged, and the direct imaging of planetary companions even to nearby stars remains elusive. Resolved imaging in the close circumstellar environments of young stars directly provides the spatial distribution of dust and debris from which planets and planetary systems may evolve and with which they may interact, influencing their growth and evolution. Radial and azimuthal asymmetries in the dust distributions in the forms of rings, central holes, gaps, clumps, arcs, arclets, and other spatially confined features may implicate the existence of low-mass perturbers (i.e., planets). Multi-wavelength observations help to elucidate the scattering and physical properties of the constituent grains. Planets that have recently formed in such environments, in association with their young central stars, may be imaged in the near-IR due to their self-luminosity, if the light from the star itself can be sufficiently suppressed. The enabling technologies and instrumentation for doing so currently exist, having been demonstrated on the HST. While imaging terrestrial-like planets and older gas-giants around stars is beyond the current scope of capabilities, HST and its instruments provide a pathway for the development of future systems with which such observations will be realized.

2. Breaking the Low Contrast Paradigm

Today, HST provides a unique venue for high contrast imaging, with its second-generation coronagraphic systems, offering diffraction limited imaging in optical and near-infrared wavelengths with Strehl ratios panchromatically exceeding 98%. Of equal or perhaps even greater import, HST provides a highly stable platform resulting in a very high degree of temporal invariability in the structure of the PSF sampled by the instrument detectors. The repeatability of the PSF, particularly at spatial frequencies comparable to the size of the PSF itself, routinely permits self-subtractions of the underlying stellar components in high-contrast fields with an efficacy greatly exceeding the capabilities of ground-based AO systems. This capability is further augmented by HST's pointing control system which allows for highly precise intra-orbit field rotations about coronagraphically occulted targets, permitting ready discrimination between optical artifacts and features of celestial origin.

Differential (PSF-subtracted) coronagraphic imaging with HST/NICMOS consistently results in background rejections on the order of 10^6 per pixel at a distance of $1''$ from an occulted target in H-band, and 10^5 area-integrated over a $2''$-$3''$ radius annulus at 1.1μm. Similar contrast ratios are achievable at optical wavelengths with HST/STIS differential coronagraphy. With NICMOS, the non-destructive readouts of the HgCdTe detector in the coronagraphic channel results in a dynamic sampling range of 19.4 stellar magnitudes using the imaging strategy suggested by the NICMOS IDT (Schneider et al 1998) and does not limit the high-contrast imaging range achievable by the optical system.

Scientific areas of inquiry enabled via PSF-subtracted coronagraphy include the search for and identification of young exo-solar planet and brown dwarf companions (with mass-equivalent detection limits of a few Jupiters at $1''$ for systems a few megayears old), and the direct spatially resolved imaging of circumstellar debris disks. Though the concern of this paper is in the arena of disk/planet imaging, it should be noted that the same capabilities can be applied to cosmological studies, such as in surveys for damped-Lyman alpha absorbers associated with host galaxies/quasars (e.g., Colbert & Malkin 2002).

3. HST Disk and Sub-Stellar Companion Detection

The detection of both debris disks and sub-stellar companions at small angular distances from their central stars are ultimately limited by the repeatability of the HST PSF. While atmospherics play no role in degrading the stability of the PSF, the varying near-Earth orbital thermal environment of HST drives very small changes in the metrology of the telescope assembly, resulting in fine-structure changes in the HST PSF (Schneider et al 2001a), particularly on multi-orbit timescales and with large pointing excursions with respect to the Sun.

In practice, debris disk systems with fractional flux density excesses (stellar light scattered by the disk itself) exceeding a few times 10^{-4} at $1''$, or an order of magnitude lower surface brightness at or beyond $\sim 2''$, are readily detectable with both NICMOS and STIS. Stars with known large far-IR (e.g., IRAS) and sub-millimeterer flux density excesses are prime candidates for harboring disks within the regime of detectability by with HST. The high dynamic sampling range afforded by the NICMOS multiaccum readout strategy (important when target surface brightness are unknown) and small size of the circular region obscured by its coronagraph ($0.''3$ radius) taken together are ideal for conducting disk discovery/imaging surveys. Once the geometry and approximate scattering efficiencies of disks found by NICMOS have been established, the higher (wavelength-dependent) spatial resolving power of STIS may be used advantageously for subsequent follow-up observations, despite the larger size and greater obscuring area of its tapered coronagraphic wedge. Such a strategy was employed successfuly for a number of NICMOS-revealed dusty disks in HST Cycle 7. We illustrate this for HR 4796A (Figure 1), which owing to its small size ($b/a = 0.''27/1.''05$; Schneider et al 1999), could easily have been obscured by the STIS wedge had it not first been imaged coronagraphically by NICMOS.

NICMOS detections of close companions are not limited by photon statistics but rather by the systematics imposed by small-scale structural variations in the HST+NICMOS PSF. These variations may be minimized by PSF self-subtractions using differentially oriented images spanning time intervals shorter than the thermal time constant of the telescope (in practice within single, ~ 50 minute, target visibility periods). On very moderate sub-orbit timescales (total integration time ~ 21 minutes) 5σ companion detection limits of ΔH = 10 @ $1''$, 12.5 @ $2''$, and 14 @ $3''$, are repeatably obtained from a single PSF-subtracted pair of observations (Figure 2). We illustrate this with an observation of a ΔH =13.2 object at $2.''5$ from TWA6 detected at $> 5\sigma$ significance, recently confirmed as a background object by a follow-up NICMOS Cycle 11 observation (Lowrance et al 2002). These data, with a differential astrometric precision of ~ 10 mas and photometric accuracy of ~ 0.1 magnitudes at a contrast ratio of $\sim$ 1:2x10^5, bespeak the performance levels routinely achieved by HST+NICMOS using this adopted two-orientation single-orbit observing strategy. For physical companions (i.e., those confirmed through common proper motions), expressing these luminosity ratios in terms of mass depends upon the age of the companion (which is presumed coeval with its primary). A hot young planet's bolometric luminosity will decline roughly as L $\sim$ $t^{-1.2}$ (Burrows et al 1997). At 10 Myr, thought sufficiently old for Jovian-like planets to form, these detection limits correspond to a 1 Jupiter-mass object at $2''$. Pushing into the sub-Jovian mass domain for hot gas giants is possible at ages of about 1 Myr, and suitable can-

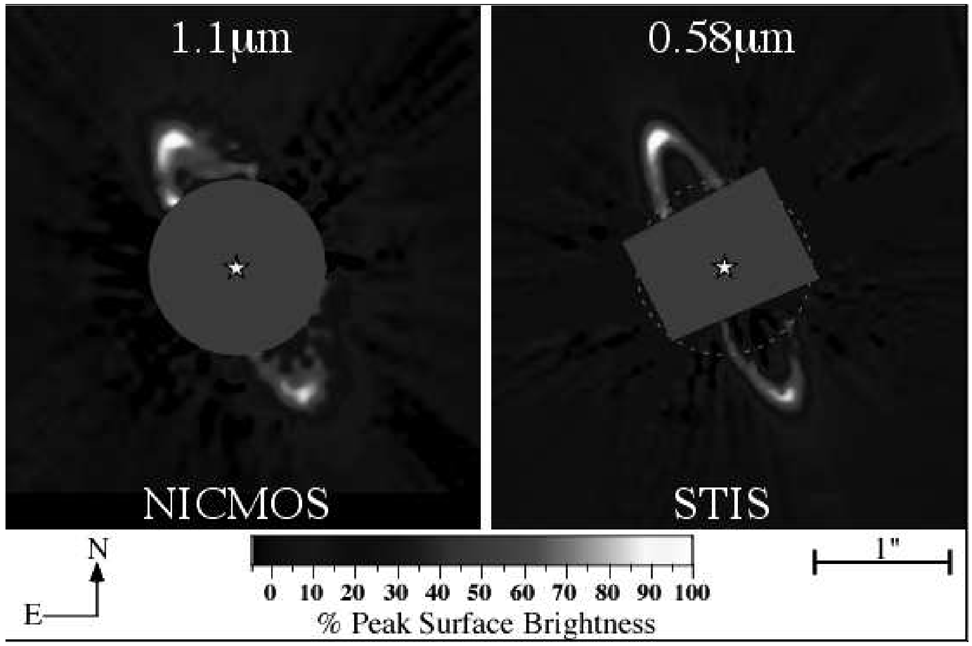

Figure 1. HST PSF-subtracted coronagraphic images of the ring-like debris disk circumscribing the $\sim$ 8 Myr old A0V star HR 4796A.

didates may be found among the members of the newly identified nearby young associations in the southern hemisphere.

The level of stability and repeatability of the HST PSF is also a pathway to securing spectra of young exo-solar giant planets (EGPs), once suitable candidates have been identified. Strong, broad, near-IR molecular absorption features (notably H_2O, CH_4, CO and H_2-H_2) are predicted in atmospheric models of hot (young) EGP spectra and albedos (Sudarsky et al 2000). NICMOS grism spectra of such objects at these ages (1 to 10 Myr with angular separations $> 1''$–$2''$) could be obtained by self-subtraction of the primary spectra with two-epoch observations acquired at diametrically opposed image orientation angles.

4. The Dust Disk/Planet Connection

Current theories of disk/planet evolution suggest an early epoch of planet-building via the formation and growth of planetary embryos followed by the accretion of gaseous atmospheres onto hot/giant planets (Boss 2001). Under this scenario, the circumstellar environments become increasingly dusty as the proto-stellar gas-to-dust ratios (presumed initially on the order of 100:1) in the circumstellar environments decline. In this critical phase of newly formed (or forming) exo-solar planetary systems, posited from a few megayrears to a few tens of megayears, the circumstellar environments become dominated by a second-generation population of dust with size distributions skewed toward larger (evolved) particles arising from the collisional erosion of planetesimals. The spatial distribution of such dust debris may be influenced by gravitational interactions (sculpting, dynamical resonances, etc.) of co-orbital planetary-mass

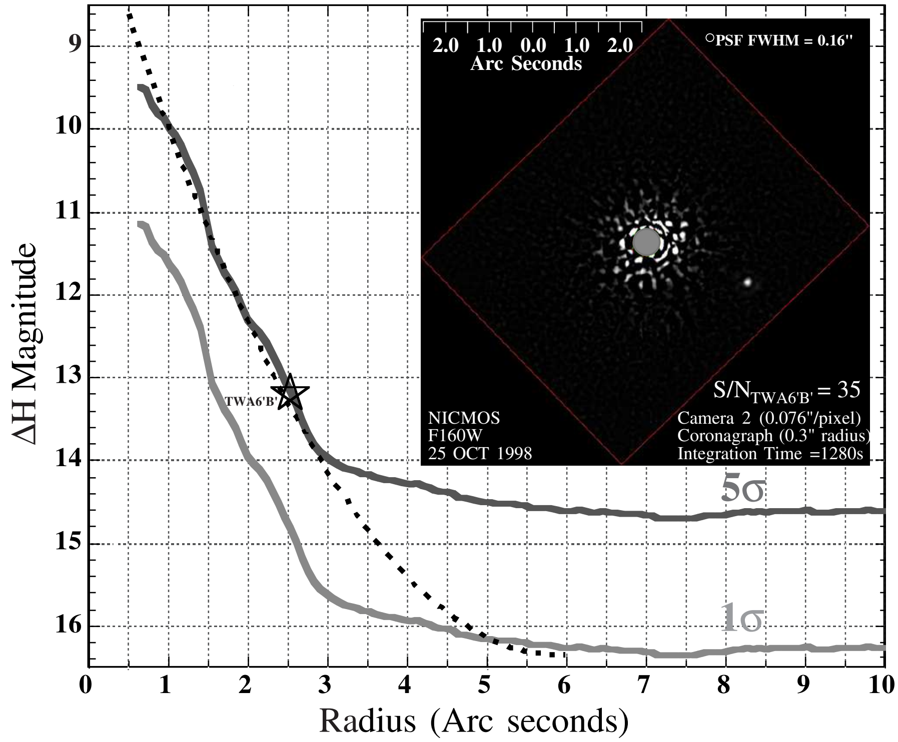

Figure 2. NICMOS H-band azimuthally averaged detection limits for close companions to M & K stars with 2-roll coronagraphic PSF subtraction (21 minute total integration time). Dotted line: Median 5σ detection limit from fifty GTO program targets. Solid lines: 5 and 1 σ detection limits for TWA6 (H=6.9, read noise limited at $> 3''$) field. Inset image: TWA6 after high spatial frequency filtering with H=20.1 unresolved object at $2.''5$ (statistical S/N = 35).

bodies. In Figure 3 we present two additional examples of dusty circumstellar disks detected by NICMOS and later imaged at higher spatially resolution with STIS. Their brightness anisotropies and complex morphologies are suggestive of such dynamical interactions and may implicate the existence of unseen planetary mass companions. High spatial resolution coupled with high levels of background light rejection enable intra-disk differential photometric mapping of the circumstellar environments, even in disks of intrinsically small angular sizes. We illustrate this for HR 4796A in Figure 4, where the STIS image of the disk (Figure 1, right) has been projected onto a “face-on” geometry (while conserving the flux density per unit area). Spatially resolved photometry of the ring indicates flux densities on the northeast side (left side in Figure 4) which are $\sim 20\%$ greater than at corresponding azimuths (reflected about the ring minor axis) on the souththwest side. Such a brightness anisotropy may result from an unequal spatial distribution of particles which may have been perturbed into (or out of) azimuthal sectors by resonances with one or more undetected planets. Photometry across the ring indicates a steeper inner truncation than an outer fall-off, which may also have implications for dynamical confinement mechanisms. Additionally, directionally preferential scattering, symmetric about the ring minor

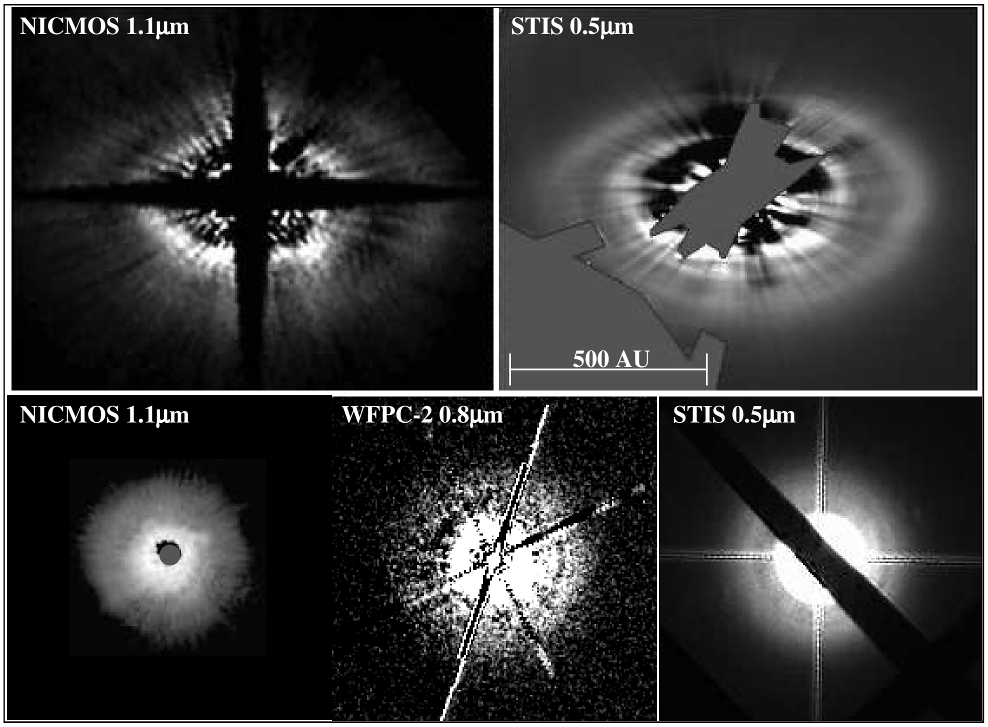

Figure 3. Top: HD 141569A ($\sim$ 5 Myr Herbig Ae/Be star) exhibits a 400 AU radius disk with a broad, partially filled, asymmetric gap (Weinberger et al 1999; Mouillet et al 2001) containing a spiral "arclet". Bottom: TW Hya (K7), an "old" classical T-Tauri (pre-main sequence) star of similar age has a pole-on circularly symmetric disk (Weinberger et al 2001). A break in its surface brightness profile at 120 AU is also seen at lower S/N by HST/WFPC-2 (Krist et al 2000) and an arc-like depression is noted in both optical images (Schneider et al 2001b). Both disks are shown at the same physical scale.

axis, is seen in an increase in efficiency of $\sim$ 36% in the "forward" direction. The direction-dependent scattering properties of the disk grains, coupled with color information, can put strong constraints on the particle size distribution.

The panchromatic high-contrast imaging capabilities of NICMOS and STIS in concert can yield very useful photometric information on the disk particle properties. In the case of HR 4796A, though only very broad colors have been thus-far obtained (*F160W* and *F110W* with NICMOS, and *50CCD* with STIS), it is quite apparent that the grains are intrinsically very red (see Figure 4, right panel). These colors are consistent with an evolved population of particles with characteristic sizes of at least a few microns, not primordial ISM grains. These colors are also consistent with laboratory irradiation experiments on a variety of organics (Andronico et al 1987) to study reddening of D and P type asteroids (as a function of distance from the Sun). Indeed, it is of interest (though perhaps anecdotal) to note that the HR 4796A disk color indices are similar to the intrinsic colors of the brightest trans-Neptunian objects in our solar system (Barucci et al 2001), when corrected for the color of the Sun ([V]-[J] = +1.07).

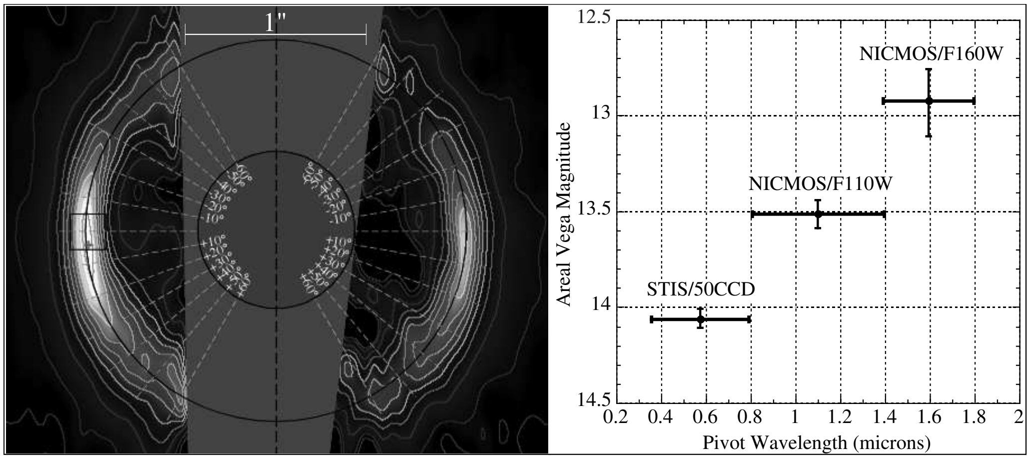

Figure 4. Left: Surface brightness isophotes of a "face-on" projection of the HR 4796A ring with a spatial resolution of $\sim$ 70 mas (4 AU at the 57 pc distance of HR 4796A). Right: NICMOS and STIS broad-band photometry of the HR 4796A ring indicate very red, and thus non-primordial, disk grains.

5. Moving Beyond HST into the Super-High Contrast Regime

While HST differential (PSF-subtracted) coronagraphy and spectroscopy (e.g., via grism imaging with NICMOS) permits the ready detection of young (few Myr) Jupiters at $> 1''$ from their primaries, and disks with scattering fractions of $\sim 10^{-4}$ at comparable distances, these capabilities are just a stepping stone to the "super" high contrast imaging which would be required for solar (few x 10^9 yr) age systems. For solar type (and age) stars, straylight/background rejections on the order of 10^9–10^{10} must be achieved to image zodiacal dust and planetary companions, and improvements in spatial resolution to a few mas (e.g., sub-AU at 200 pc) is highly desirable. Achieving this at least three-order of magnitude improvement in background light rejection over HST requires overcoming a number of significant technological challenges. Optical configurations which might lead to these levels of performance need not be limited to optimized coronagraphs. Polarimetric nulling, nulling interferometry, space-based systems with active wavefront correction, interferometric arrays, and station-keeping occulters warrant consideration.

Moving from the near-IR to the UV/short-wavelength optical is significantly advantageous simply from the purview of the smaller, and much better centrally contained, PSF as well as the commensurate improvement in spatial resolution with decreasing wavelength. The contrast advantage obtained in the near-IR for imaging young thermally emissive planets is not important for older systems whose planets (and dust debris) would be detected primarily by reflected light. The adoption of any such systems present a number of technology challenges which must be stringently controlled and addressed to enable success. These include micro-roughness of optical surfaces, particulate/contamination control, stray light management and control, pupil apodization (and shaping), metrological tolerancing and stability, wavefront/mirror sensing and control, and pointing control authority. Deficiencies in any of these areas would preclude achieving super-high contrast ratios of at least 10^9, critical for exo-planetary system imaging at evolved ages.

6. Summary

Optical imaging and spectroscopy of collisionally evolved circumstellar debris and co-orbital bodies will play a pivotal role in furthering our understanding of the formation, evolution, and maturation of exo-solar planetary systems. SIRTF, with its leap in mid and far-IR sensitivity over precursor survey missions, will undoubtedly discover a multitude of candidate systems to be subsequently imaged at higher spatial resolution and at other wavelengths. As a pathfinder, HST has shown how high contrast and high spatial resolution can elucidate the nature of such systems. With care and forethought, the legacy of Hubble in giving our first look at planetary systems in formation can be turned into a harvest to be reaped. To study physical processes acting over sub-AU spatial scales and timescales comparable to the age of our solar system will require a 3–4 order of magnitude improvement in instrumental stray light rejection over HST. Such an improvement is obtainable with a UV/optical 4–8 meter class space-based telescope with instrumentation optimized for high-contrast imaging, but requirements to achieve these levels of performance must be incorporated in the end-to-end design of the system at the outset.

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