Pushing the Envelope: Unleashing the Potential of High Contrast Imaging with HST

Glenn Schneider & Elizabeth Stobie

Steward Observatory, University of Arizona, Tucson, AZ 85721

Abstract. The complement of HST instruments provides a unique avenue for obtaining diffraction limited optical/near-IR images with Strehl ratios unachievable with ground-based systems. Coupled with the much greater space-based stability of the telescope+instrument Point Spread Function, differential imaging by PSF subtraction enables very high contrast imaging. This is further enhanced, significantly, by the coronagraphic systems in the second generation instruments NICMOS and STIS. The high dynamic range of the non-destructive multiple-readout data formats provided by the NICMOS detectors and read-out electronics are complementary in allowing observers to take advantage of these imaging capabilities. Exploiting the very high levels of background rejection achievable with these instrumental systems, while preserving their intrinsic photometric and astrometric efficacy, required the development of a new suite of integrated analysis tools (the NICMOS/IDT's *IDP3* software). Here we discuss some of the significant scientific results obtained in the arena of extrasolar planet and disk imaging which has been advanced by the synthesis of these observing modes and analysis tools.

1. Introduction

The Hubble Space Telescope (HST) provides a unparalleled venue for high contrast imaging, coupling a highly stable Point Spread Function (PSF) with very high Strehl ratios (exceeding 98–99% in all spectral bands compared to, for example, $\sim 60\%$ in K-band achievable on current 10-meter ground-based adaptive optics systems). When augmented with coronagraphic optical systems as offered by NICMOS, STIS and (soon) ACS, and intra-orbit field rotations about occulted targets, new observational domains for the detection and spatially resolved imaging of substellar companions to nearby stars (including brown dwarfs and extrasolar planets) and circumstellar disks are opened. In H-band (1.6μm, with NICMOS) differential coronagraphic imaging ("self-subtracting" a coronagraphic stellar PSF under a change in field orientation) routinely results in per-pixel reductions in diffracted and instrumentally scattered background light of $\sim 10^{-6}$ compared to the peak of an unocculted PSF core at radial distances as close as 1" from occulted targets enabling the detection of very faint close-in companions. In the 2–3" region, corresponding to Kuiper belt distances for stars < 100 pc from the Earth, the background light scattered into an annulus bounded at those radii, after subtracting a well-matched reference PSF is

$\sim 10^{-5}$ of the 1.1μm total flux density of an occulted star thereby unveiling circumstellar disks hidden in the glare of the central stars. The very high dynamic range sampling afforded by the NICMOS non-destructive ("multiaccum") readout scheme and fast 16-bit A-to-D converters permits the full exploitation of these optical properties yielding unsaturated, quantization limited, Δmag=19.4 sampling in a single spacecraft orbit. For point sources these instrumental properties coupled with the systemic sensitivities allow probing the detection space in which extrasolar planets around young stars may be found. The higher spatial resolution of STIS broadband imaging (roughly a factor of 2 better than the longer wavelength NICMOS) offers more detailed morphologies, and further color information, about circumstellar disks discovered by NICMOS.

2. The Disk/Planet Connection

Current theories of star/disk/planet evolution suggest a presumed epoch of planet-building via the formation and agglomerative growth of embryonic bodies (Boss 2001). Subsequent accretion of gaseous atmospheres onto hot giant planets is postulated to be attendant with a significant decline in gas:dust ratios in the remnant protostellar environments. In these evolutionary epochs, likely 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. The existence of co-orbital, but unseen, planetary-mass bodies in these systems may be inferred as they influence the shape of the distribution of the dust (and hence morphologies of the disks) through dynamical interactions.

Newly formed planets will cool with time, and thus are more readily visible in the near-IR. A 10 Myr Jovian mass planet will have a luminosity of 10^{-6} solar, as compared to 10^{-9} solar at the age of the Sun (Burrows et al. 1997), and thus is readily detectable with NICMOS H-band differential coronagraphy if $\gtrsim 1"$ from its host star. Fortuitously, in the last few years regions of recent star formation at distances of < 100 pc from the Earth have been identified. Isolated stars of these ages were survey by NICMOS leading to the discovery of both substellar companions (subsequently confirmed as physically associated via common proper motions) and circumstellar debris disks.

3. New Capabilities Need New Tools - *IDP3*

To more readily deliver on the promise of the high contrast performance enabled by HST differential coronagraphy, an IDL based integrated suite of interactive analysis tools for high precision astrometry and photometry which operates on stacks of images was developed by the NICMOS IDT. Originally described by Lytle (1999), *IDP3* has grown into a generic quantitative engine for astronomical image analysis. *IDP3* performs stack oriented inter-image arithmetic (in an RPN-like manner) on masked or unmasked data, including addition, subtraction, multiplication, division, averaging, minimization, exclusive oring, and positive and negative value extraction. Clipped or unclipped medians and means through the stack may be taken. Application of image attributes such as flux scaling, bias offsetting, spatial resampling, positional offsetting, field rotation, geometrical distortion correction, and data padding are applied to each image individually prior to inter-image arithmetic. Operations may be interactively controlled in a GUI environment through menu pulldowns and control widgets (windows) or in a scripting-like mode via the execution of an ordered set of operations in an "image parameter file". Global execution control (such as sub-pixel interpolation, resampling and flux conservation methods, coordinate system definitions, preselection of default display annotations, formatting, overlays, etc.) may be pre-defined in a user-tunable "preferences" file, or updated "on the fly" for many operations. The end-result of the image stack operations may be extracted into a sub-array (a "region of interest") which may then be operated upon by photometric and astrometric tools such photometric extraction with array statistics, cross-sectional analysis, radial and encircled energy profiling, image centroiding, photocentric moment and 2D Gaussian fitting, noise analyses and others. Resulting images and tabular data from the set of analysis tools may be saved for exportation (or further processing) in a variety of data formats.

4. Coronagraphic Imaging of Planets and Disks

The basic strategy for both disk and companion detection is to subtract an "identical" coronagraphic reference PSF from that of a target of interest. For companion detection, the target serves as its own reference. When a field is rotated about the target, optical artifacts (as well as the PSF of an occulted star) remain fixed in the frame of the detector while real objects rotate about the occulted target. Upon properly registered subtraction the background diffracted and scattered light from the occulted target will be largely nulled and two independent images (of opposite parity) of any companions will emerge separated by the amount of the field rotation. Disk imaging, however, relies on subtracting well-matched PSF stars. Image subtraction is imperfect because the HST+NICMOS PSF does not repeat identically, though it is MUCH more stable then any ground-based AO augmented PSF. Primarily, the HST focal plane undergoes very small inter-orbit axial displacements arising from thermal instabilities in the telescope structure (Schneider, 2001a). By obtaining coronagraphic target and reference images as close together in time as practical (shorter than the thermal time constant of the telescope) the non-repeatability effects are greatly reduced. The nature of HST often precludes obtaining a disk target and its reference PSF in the same visibility period. In such cases we apply a suite of reference PSFs obtained at different HST thermal/optical phase spaces to gain confidence that any features we may see are not artifacts of a single ill-chosen PSF. The inexact repetition of the PSF is the dominant systematic effect in reducing the residual background and ultimately sets the system sensitivity and object detectability. Image subtraction in *IDP3* is done to minimize the variance in masked annuli of interest in the background by adjusting the centering of the target and reference stars (and to a very small, constrained, degree the flux scaling due to correspondingly small calibration uncertainties), while demanding the median background remains zero. If a companion is suspected this is done locally in restricted regions around the companion, rather than seeking a global optimization.

5. Direct Detection of Planets by Imaging

A companion candidate to TWA6 is seen at an angular separation of $2\farcs54$, corresponding to a projected distance of 140 AU (Schneider et al. 2001b). Some theories suggest it may difficult to form giant planets at such a large distance, but they may be excited into large apastron eccentric orbits by perturbative interactions with terrestrial planets in their inner solar systems. TWA6B is 5x10^{-6} fainter than TWA6 (ΔH=13.2), and if physically associated has a H_{abs}=16.6. This implicates a mass of $\sim$ 2 Jupiters and a temperature of 800K based upon cooling models of Burrows et al (1997). The object was unseen in a follow-up NICMOS 0.9μm observation suggesting a very red color (I-H>3). Low resolution optical spectroscopy with STIS was unable to produce a meaningful spectrum because of the very low flux levels at wavelengths $<$ 1μm, but limits on colors extracted in the R and I photometric bands, when combined with the NICMOS measures match well with a synthetic spectrum of a 10 Myr 2 Jupiter mass object (Sudarsky et al. 2000). Confirmation of companionship via common proper motions with the Keck AO system has been attempted, but repeatable observations have been difficult. Such ground-based confirmation must await a longer temporal baseline, or the soon-anticipated return of NICMOS to service.

6. Inference of Planets by Their Effects on Disks

Our NICMOS survey and STIS follow-up observations of nearby IR-excess stars found a number of scattered light disks exhibiting complex morphologies (rings, central holes, gaps, arclets, etc.) possibly implicating the existence of planetary-mass perturbers. The color lever provided by the two instruments helps elucidate the scattering and physical properties of the dust grains. For example, HST images of the HR 4796A disk (Schneider et al. 1999) confirmed models of thermal IR emission (Koerner et al 1998; Jayawhardana et al. 1998) by showing a 10 AU wide ansally asymmetric ring of material 70 AU from the star, possibly implicating dynamical confinement of dust by one or more unseen co-orbital bodies. Its very red color and significant forward scattering suggest large (i.e., collisionally reprocessed) grains of non-primordial origin.

References

Burrows, A., et al. 1997, ApJ, 491, 856

Boss, A., 2001, Proc. IAU Symp. 202, in press

Jayawardhana, R., et al. 1998, ApJ, 503, L79

Jura, M. 1991, ApJ, 383, L79

Lytle, D., et al. 1999, ASP Conf Ser 172, 445

Koerner, et al. 1998, ApJ, 533, L37

Schneider, G. et al. 1999, ApJ, 513, L127

Schneider, G. et al. 2001a, AJ, 121, 525

Schneider, G. et al. 2001b, LNP, in press

Sudarsky, D., et al. 2000, ApJ, 538, 885