Searching for, Finding, and Imaging Young Extrasolar Planets with HST/NICMOS

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ABSTRACT

Imaging discovery and subsequent characterization of extrasolar planet (EP) mass companions to stars has been observationally challenging due to the severe planet-to-star contrast ratios. Since the detection of the extrasolar giant planet (EGP) companion to 51 Peg [1], continuing discoveries of 1 – 10 Jupiter mass companions by *indirect* methods have revealed an unanticipated diversity in mass ranges, dynamical properties, and primary-star characteristics. The past decade has seen an explosion of indirect detections of EGP companions to solar-like stars through radial velocity surveys [2] and more recently, in much smaller numbers, via photometric transits [e.g., 3], microlensing [4] and astrometry [5]. These methods are contributing enormously to this effort, and predicate the *Kepler* mission's hopes of transit-detection of lower mass (i.e., terrestrial) planets. Yet, the *direct* detection of a bona fide EGP by imaging (and spectroscopy) remained elusive as recently developed technical capabilities (i.e., space-based with HST/NICMOS and complementary ground-based adaptive optics observations at longer-wavelength) were to be demonstrated.

Today, *young* EGPs, still thermally emissive from their residual heat of formation can, *and now have*, been imaged in the near-IR at sub-arcsecond distances from their primaries using aggressive state-of-the art observing techniques such as differential coronagraphy with HST/NICMOS [6, 7] and AO augmented longer wavelength imaging at the largest ground-based telescopes [e.g., 8]. *We illustrate with the very recently confirmed EGP image of 2M1207b*. The observational parameter spaces enabled by these techniques probe for young Jovian mass planets at tens to hundreds of AUs from host stars within ~ 100 pc of the Earth. With the recent identification of very young (5 – 50 Myr) and "nearby" (≤ 70 pc) stellar associations [9], the hunt for EGPs using both space and ground based facilities is underway with vigor.
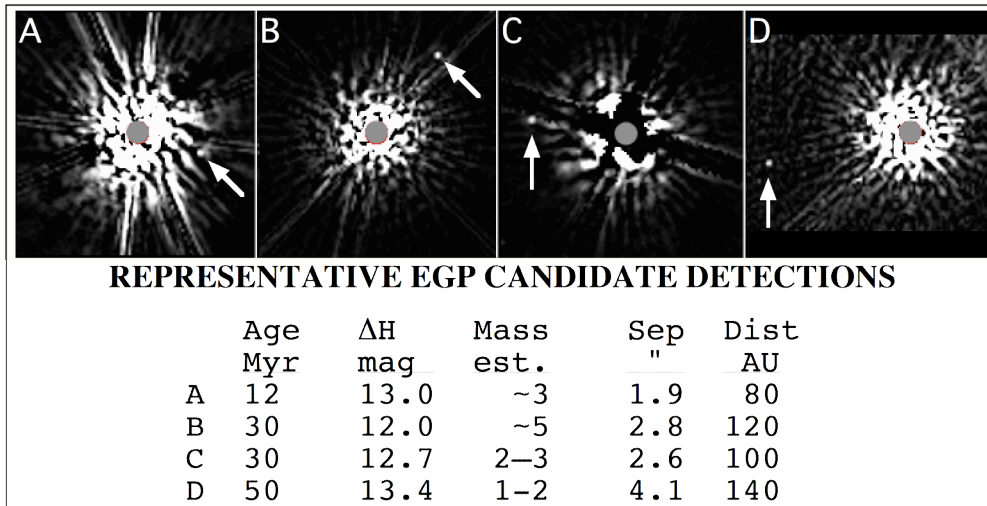
THE GO/10176 SURVEY

Predicated on the success of NICMOS IDT's HST cycle 7 substellar companion surveys (GTO/7226 and 7227), we are using HST/NICMOS coronagraphy in conducting a 116-target imaging survey to identify candidate EGP companions to stars of spectral types A through late M in our currently executing HST/GO program 10176. Our targets were carefully selected based on their ages and distances. We focus on selected members of the *closest, youngest stellar groups:*

Group/Association	Approximate Age (Myr)	Representative Distance (pc)
TW Hydrae	8	60
β Pictoris	12	35
Tucana/Horologium	30	45
AB Doradus	50	20

Ages of these young nearby stellar groups are well determined with multiple indicators: location on M_k vs. V – K color-magnitude diagrams, Li 6708 Å line strength, X-ray emission, galactic space (UVW) motion, stellar rotation, emission lines, etc. Our target ensemble is about an order of magnitude younger than target stars observed in previous NICMOS programs with the similar science goals (i.e., imaging of brown dwarfs; e.g. [12, 13]), and thus, through target selection, is sensitive to much lower mass objects than previous NICMOS coronagraphic companion surveys.

GO/10176 is a single color, single epoch, survey that is yielding high-probability EGP companion *candidates*. We illustrate with four EGP candidate detections (below), from representative targets, with two-orientation recombined PSF-subtracted differences images.

REPRESENTATIVE EGP CANDIDATE DETECTIONS

	Age Myr	ΔH mag	Mass est.	Sep "	Dist AU
A	12	13.0	~3	1.9	80
B	30	12.0	~5	2.8	120
C	30	12.7	2—3	2.6	100
D	50	13.4	1-2	4.1	140

NICMOS CORONAGRAPHY

The ability to detect faint point sources (e.g., planetary mass companions to stars) near much brighter objects is instrumentally enhanced by reducing the brightness putative primary. To enable such observations, HST has provided unique resources for high contrast imaging with its panchromatic complement of coronagraphically augmented imagers: NICMOS (near-IR), ACS (UV/Optical) and, until recently, STIS (broadband Optical). Imaging *young* substellar (brown dwarf and planetary mass) companions, which decline in brightness with age, in thermal emission in the near-IR significantly improves planet-to-star contrast ratios and detectabilities over scattered light imaging at optical/UV wavelengths. The HST/NICMOS coronagraphic system (in camera 2, with a pixel scale of ~ 76 max pixel^{-1}) is optimized for high-contrast point-source detections in H-band (1.6 μm) at $\rho > 0.3$". H-band coronagraphy routinely achieves per-pixel stellar-light rejection approaching a factor of a million when compared to the peak stellar intensity (or ~ 10^{-7} compared to the total stellar flux) at 1" from the occulted star in PSF-subtracted, differentially oriented, images [10]. The coronagraph itself provides a reduction in the instrumentally scattered and diffracted background by factors of ~ 10 to 4 from the edge of the coronagraphic hole to a radius of ~ 1". The unocculted wings of the target PSF remain fixed on the detector when the spacecraft/telescope is rotated about the target in the coronagraph. At these radial distances, the stability of the HST+NICMOS optical system is such that starlight in
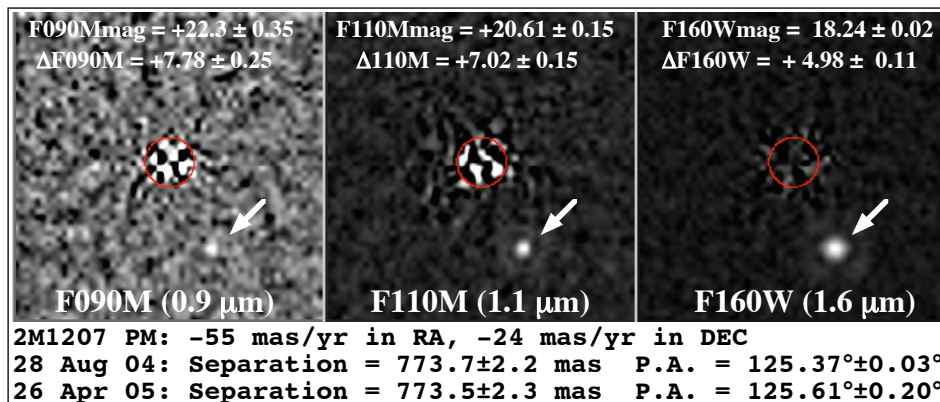
the unocculted wings of the target PSF is additionally reduced by a factor of ~ 50 in H-band self-subtractions of differentially rotated coronagraphic images acquired on orbit time scales.

FOLLOW-UP OBSERVATIONS

PROPER MOTIONS: The companion status of the candidate EGPs identified in imaging surveys such as GO/10176 must be confirmed through second-epoch differential proper motion (PM) observations. All but the most challenging observations may be carried out with HST/NICMOS in "2-gyro" mode (where a small loss of detection sensitivity results from inter-orbit instabilities in the HST/NICMOS coronagraphic PSF) but with reduced observing efficiency. Less demanding PM observations may conducted, in some cases, with suitably instrumented AO-augmented large ground-based telescopes [14, 8, 15] (e.g., Keck, VLT).

MULTI-COLOR IMAGING: EGP companions may be characterized via multi-wavelength (filter photometric) color-diagnostic imaging observations using broad and medium bandwidth filters available with NICMOS coronagraphy. Companion candidates with less severe image contrasts may be imaged with two-orientation PSF subtraction, without coronagraphy, using NICMOS camera 1's shorter wavelength diagnostic filters and higher spatial resolution. We illustrate with the EGP companion to the young, 25 $M_{jupiter}$, brown dwarf 2MASSWJ 1207-334-393254 (2M1207; M8.5V).

2M1207: Originally on the GO/10176 survey list, a 0.77" distant EGP companion candidate to 2M1207, with modest image contrasts ($\Delta_{mag} < 5$) at wavelengths longer than ~ H-band, was identified in VLT observations [16] executed before the NICMOS coronagraphic survey observations were scheduled. NICMOS was then used to establish the candidate's common proper motion (2.6 σ at the time of the NICMOS observation on 28 Aug 2004 and subsequently confirmed with follow-up observations in April 2005 at ~ 10 σ). Shorter wavelength color diagnostic information (as suggested above) [17] that could not be obtained from the ground was obtained at both epochs to inform on its physical nature.


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2M1207 PM: -55 mas/yr in RA, -24 mas/yr in DEC
28 Aug 04: Separation = 773.7±2.2 mas   P.A. = 125.37°±0.03°
26 Apr 05: Separation = 773.5±2.3 mas   P.A. = 125.61°±0.20°
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28 August 2004 NICMOS camera 1 images of 2M1207's then-EGP candidate. Later NICMOS observations, obtained on 26 April 2005, *unequivocally demonstrated 2M1207A/b as common proper motion pair*. Based upon its near-IR colors and flux densities (including 1.45 μm H_2O absorption band), 2M1207b is likely an EGP of ~ 2 – 5 Jupiter masses. With confirmation of its physical association to 2M1207 now established, *its status as a gravitationally bound companion of planetary mass has been secured*.

DETECTION LIMITS & UNCERTAINTIES

SINGLE ORBIT observations that roll the telescope about the target axis (technically unfeasible with the soon to be implemented 2-gyro guiding mode) are highly efficient and permit optimal self-subtraction of the underlying coronagraphic point-spread function. Such observations yield total integration times of, typically, $\sim$ 1300s. Highly repeatable point source detection limits in companion angular separation (ρ, in arcseconds) and ΔH magnitude (relative to their primaries), have been established from extensive experience with NICMOS coronagraphy [11]: $\Delta H(S/N=25) = 8.1\pm0.3 + 2.1 \times \rho"$, or $\Delta H(P=50\%) = 9.7\pm0.3 + 2.1 \times \rho"$, where P=50% is the 50% probability of close-companion detection.

ASTROMETRIC AND PHOTOMETRIC calibration observations, taken as part of the target acquisition process, also provide contemporaneous flat-field corrections for the coronagraphic field and unoccluted (unsaturated) target images to anchor differential position measures [4]. For companion candidates with $\rho \sim 2"$, and $\Delta H = 13$, astrometric measures with positional uncertainties of $\sim$ 10 mas are obtained, permitting confirmation/rejection of candidates by common proper motions on short time scales.

NICMOS GRISM SPECTROPHOTOMETRY
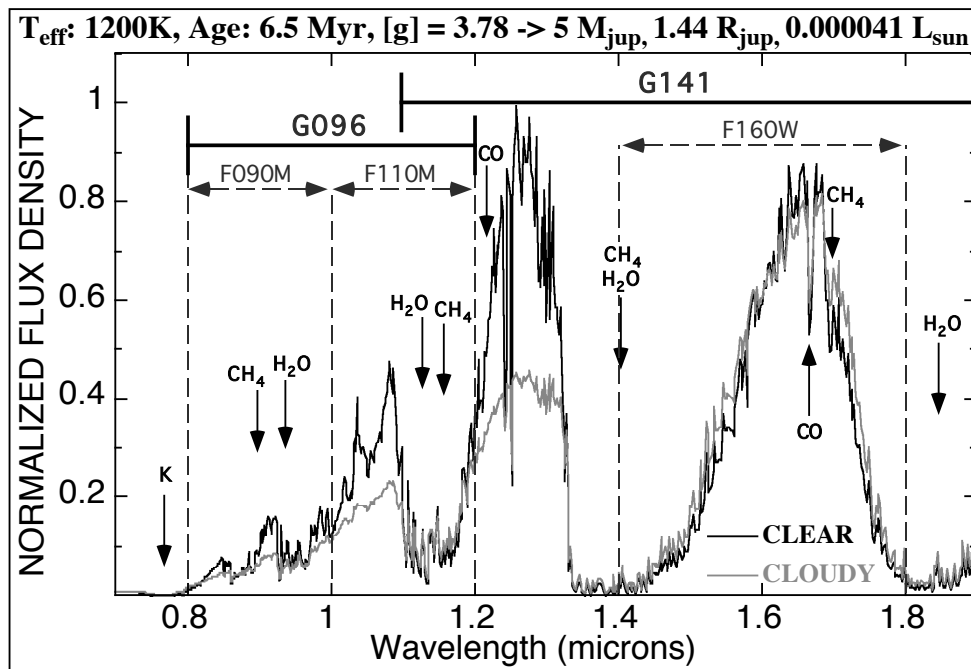
Representative theoretical spectra of a 2M1207B-like analog (courtesy of A. Burrows). Model spectra with both a cloud-free atmosphere (black line) and with additional opacity due to clouds of fosterites (gray line), further suppressing the emergent flux, are shown. The NICMOS filter bands used to observationally establish the photometric flux densities and color indices of 2M1207B from our first epoch Cycle 13 observations are shown in relation to the two grism bands, G096 and G141. The F090M and F110M filter bands are non-overlapping and completely tile the G096 grism wavelengths. F160W is fully contained within G141 bandpass.

For candidates with separations & contrast ratios similar to 2M1207, the physical properties of its EGP companion may be probed with NICMOS grism spectrophotometry. Using the target

primary as its own spectral template for two-orientation high-contrast image subtraction, the grism field may be oriented to place the EGP "above" and "below" the primary (at two observational epochs) and two independent spectra of the EGP will emerge from a difference image. While currently untested, this method of obtaining high contrast 0.8 – 1.2 μm (G096) and 1.1 – 1.9 μm (G141) EGP spectra will be attempted in GO/10538 (to be executed in HST Cycle 14). Diagnostic spectra at these wavelengths (shorter than appx 1.6 μm) are unfeasible with ground-based facilities. The "short" wavelength near-IR spectrum we hope to obtain will serve to test and improve upon current models of young EGPs, which predict flux suppression by molecular absorption in their atmospheres [e.g., 18, 19], and further constrain the still uncertain mass estimation for 2M1207B.

HST CYCLE 14 & BEYOND

The continued utility and efficacy of NICMOS direct, coronagraphic, and spectrophotometric imaging for EGP detection and characterization were recently demonstrated in on-orbit testing of HST's 2-gyro guiding mode [20] (though with a loss of efficiency due to restrictive scheduling for some observations).

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