

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

2MASSWJ 1207-334-393254b (2M1207b): A Common Proper Motion Companion of Planetary Mass to a Young Brown Dwarf

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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 EP 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, *an 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.

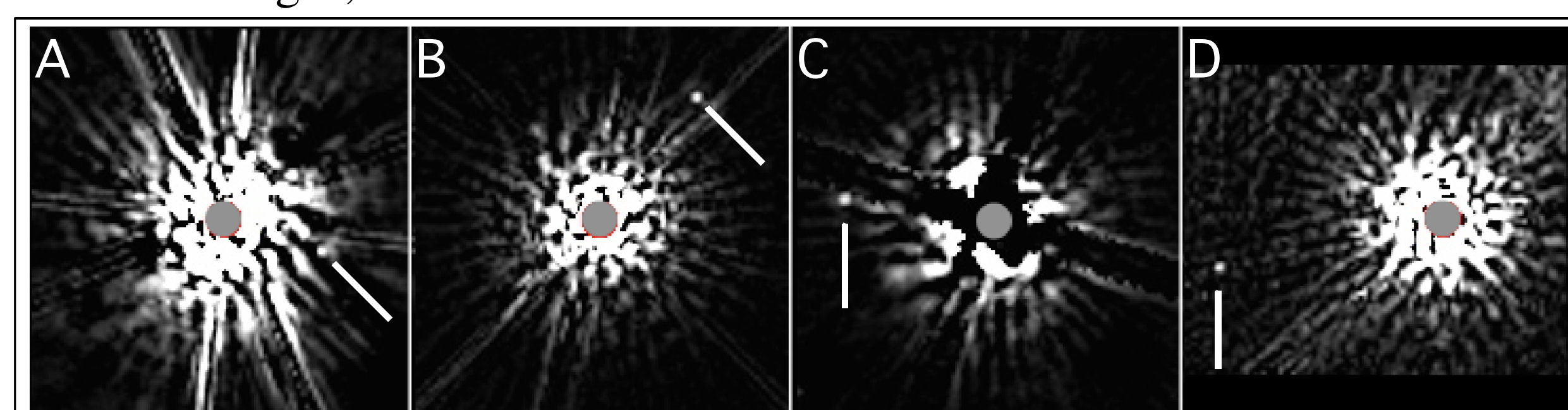
THE GO/10176 SURVEY

Predicated on the success of HST substellar companion surveys executed by the NICMOS IDT (GTO/7226 and 7227) in Cycle 7, 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*:

- A) TW Hydrae Association (d ~ 60 pc, age ~ 8 Myrs)
- B) β Pictoris moving group (d ~ 35 pc, age ~ 12 Myrs)
- C) Tucana/HorA group (d ~ 45 pc, age ~ 30 Myrs)
- D) AB Doradus group (d ~ 20 pc, age ~ 50 Myrs)

Ages of these young nearby stellar groups are well determined using multiple indicators such as location on *Mk* versus *V-K* color-magnitude diagrams, Li 6708 Å line strength, X-ray emission, Galactic space motion (UVW), stellar rotation, emission lines, etc. Our target ensemble is about an order of magnitude younger than target stars observed through 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 searches.

The GO/10176 survey is a single color, single epoch survey which is yielding high-probability EGP planetary candidates. EGP candidate detections for four representative targets in our survey, from two-orientation recombined PSF-subtracted differences images, are illustrated below.



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

Companion masses are *estimated* based upon presumptions of companionship and coevolution from theoretical cooling models of EGPs given H-band flux densities established from the NICMOS observations, and astrometrically determined distances for the target stars. Candidate *minimum* distances (in AU) from primaries (projection onto sky based upon stellar parallax).

NICMOS CORONAGRAPHY

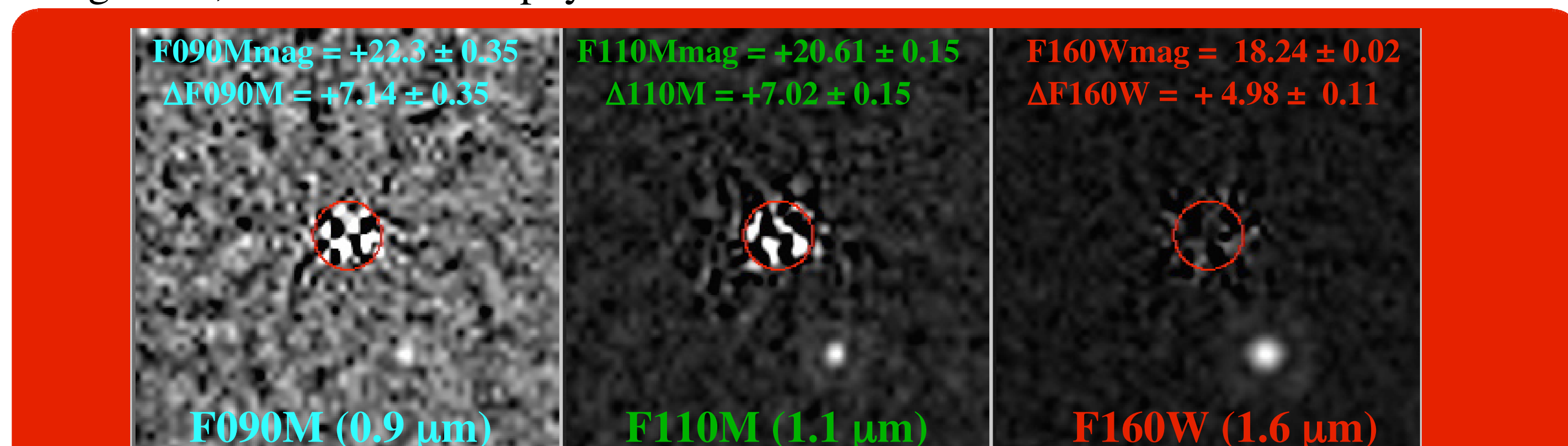
The ability to detect faint point sources near bright objects (e.g., planetary mass companions to stars) is instrumentally enhanced by reducing the brightness of the central star. To enable such observations, HST has provided unique resources for high contrast imaging with its panchromatic complement 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 μ m) 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 rolled) 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 be carried, in some cases, with suitably instrumented AO-augmented large ground-based telescopes [14,8,15] (e.g., Keck, VLT).

MULTI-COLOR IMAGING: Physical characterization of companions via subsequent multi-wavelength (filter photometric) color-diagnostic observations may be conducted with broad and medium bandwidth filters available with NICMOS coronagraphy. Companion candidates with less severe image contrasts, such as the EGP companion to the young brown dwarf 2MASSWJ 1207-334-393254 (2M1207; M8.5V), may be imaged via two-orientation PSF subtraction without coronagraphy using NICMOS camera 1's shorter wavelength diagnostic filters and higher spatial resolution.

2M1207: Originally on the GO/10176 survey list, an EGP companion candidate to 2M1207 with modest image contrasts at longer wavelengths was identified in a VLT observation [16] executed before the NICMOS observation was scheduled. NICMOS was then used to establish the candidate's common proper motion (2.6 σ at the time of the NICMOS observation; 28 Aug 2004) and to obtain shorter wavelength color diagnostic information (as suggested above) [17], which could not be obtained from the ground, to inform on its physical nature.



28 August 2004 NICMOS camera 1 images of 2M1207's then-EGP candidate. Second epoch NICMOS observations were obtained on 26 April 2005, *unequivocally demonstrating 2M1207b is a common proper motion companion.* Based upon its near-IR colors and flux densities (now also at 1.45 μ m), 2M1207b is likely an EGP of ~ 2 – 5 Jupiter masses. With confirmation of its physical association to 2M1207 established, *its status as a gravitationally bound companion of planetary mass has been secured.*

2M1207 PM: -55 mas/yr in RA, -24 mas/yr in DEC
 28 Aug 04: Separation = 773.7 \pm 2.2 mas P.A. = 125.37 \pm 0.10 $^\circ$
 26 Apr 05: Separation = 773.5 \pm 2.3 mas P.A. = 125.61 \pm 0.22 $^\circ$

DETECTION LIMITS & UNCERTAINTIES

SINGLE ORBIT observations which roll the telescope about the target axis (unfortunately, technically unfeasible with HST's soon to be implemented two-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, ~ 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]:

$$\Delta H(S/N=25) = 8.1 \pm 0.3 + 2.1 \times \rho''$$

or

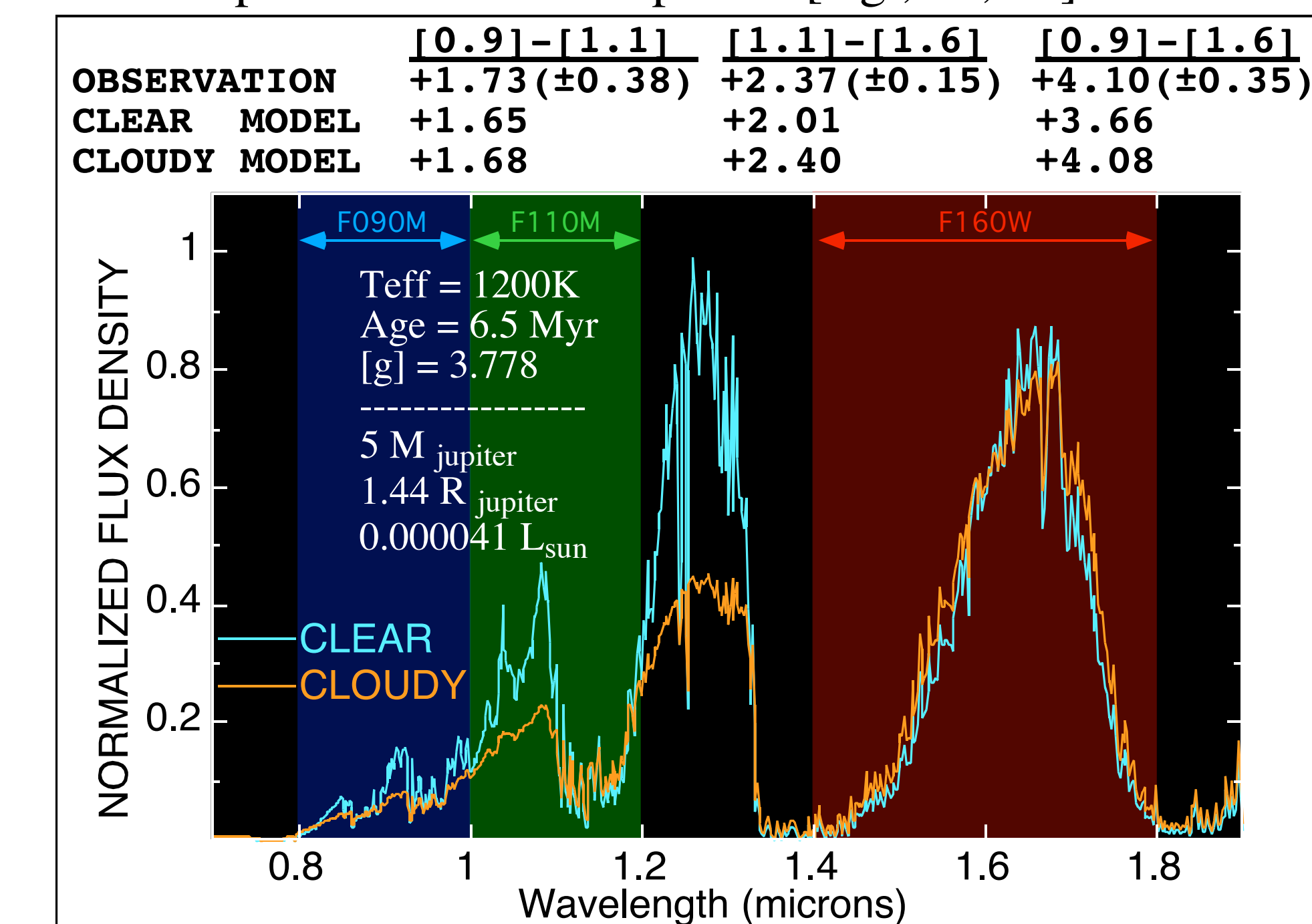
$$\Delta H(P=50\%) = 9.7 \pm 0.3 + 2.1 \times \rho''$$

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 unocculted (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 ~ 10 mas are obtained, permitting confirmation/rejection of candidates by common proper motions on short time scales.

NICMOS GRISM SPECTROPHOTOMETRY

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 μ m (G096) and 1.1 – 1.9 μ m (G141) EGP spectra will be attempted in GO/10538 to be executed in HST Cycle 14. Diagnostic spectra at these wavelengths are unfeasible with ground-based facilities. The "short" wavelength near-IR spectrum will 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].



NICMOS camera 1 photometric color indices (Δ_{mag} ; brackets indicate λ_{cent}) of 2M1207"b", in anticipation of spectrophotometry to be obtained, are compared to theoretical EGP models with "clear" and "cloudy" atmospheres (A. Burrows).

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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