High contrast imaging at 3-5 microns

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ABSTRACT

The 6.5 m MMT with its integrated deformable secondary, is an ideal platform for carrying out high contrast diffraction-limited imaging in the 3-5 micron wavelength regime. We have developed a dedicated camera for this purpose that can operate with high efficiency at both L' and M atmospheric windows. In addition we have demonstrated an approach to diffraction suppression, using a relatively simple apodizing phase plate (APP) that allows improved sensitivity to faint objects at several resolution elements away. These techniques are currently being used to search for Jupiter-like planets around nearby stars.

1. INTRODUCTION

Direct detection of extrasolar planets is crucial to advance our understanding of the formation and evolution of planetary systems. Although planet detection through its gravitational influence on its star has yielded important information about planets around other stars, many parameters of a planet are most easily derived from its spectral energy distribution (SED) including its temperature, size, and composition. For planets in orbit beyond approximately 5-10 AU, the length of time needed to detect a planet through indirect means also becomes prohibitive. Yet these are precisely the orbital radii where we see massive planets in our own solar system.

Initial success in the area of direct detection is just now occurring, although the detectable objects are still significantly different from what we think of as a typical solar system. Secondary eclipses of transiting hot Jupiters can begin to constrain the temperature and albedo of these objects. For younger stars (at wider separations) faint companions have been detected which are consistent with being planetary mass objects. However, these latter objects are unlikely to have been formed by either core accretion or gravitational instability suggesting that we are either seeing scattered planets or low mass objects that have formed by fragmentation.

Direct detection searches are typically focused on very young stars where giant planets are rapidly cooling and contracting. They are thus expected to be relatively bright in the near infrared. The H band is particularly attractive for detection of young hot gas giants due to methane absorption which creates an identifiable spectral feature, as well as the relative brightness of a young planet in H compared to the K band. The majority of the direct detection plans with large telescopes focus on this spectral region, utilizing techniques such as simultaneous spectral difference imaging, angular differential imaging and higher order adaptive optics to optimize the achievable contrast. Several observatories are currently designing ambitious near-infrared instruments to pursue the detection of young planets.

Although near-infrared sensitivity from the ground is better than at longer wavelengths, a significant contrast advantage can be achieved by looking for cool giant planets closer in wavelength to the peak of their expected SED. Giant planets have very nonthermal SEDs that depart significantly from simple Planck functions, requiring a knowledge of their spectral characteristics to choose an optimum wavelength for detection. Additionally, the sensitivity of a ground-based system is dominated by the spectral dependence of the atmospheric transparency and brightness, limiting possible detection to discrete spectral windows.

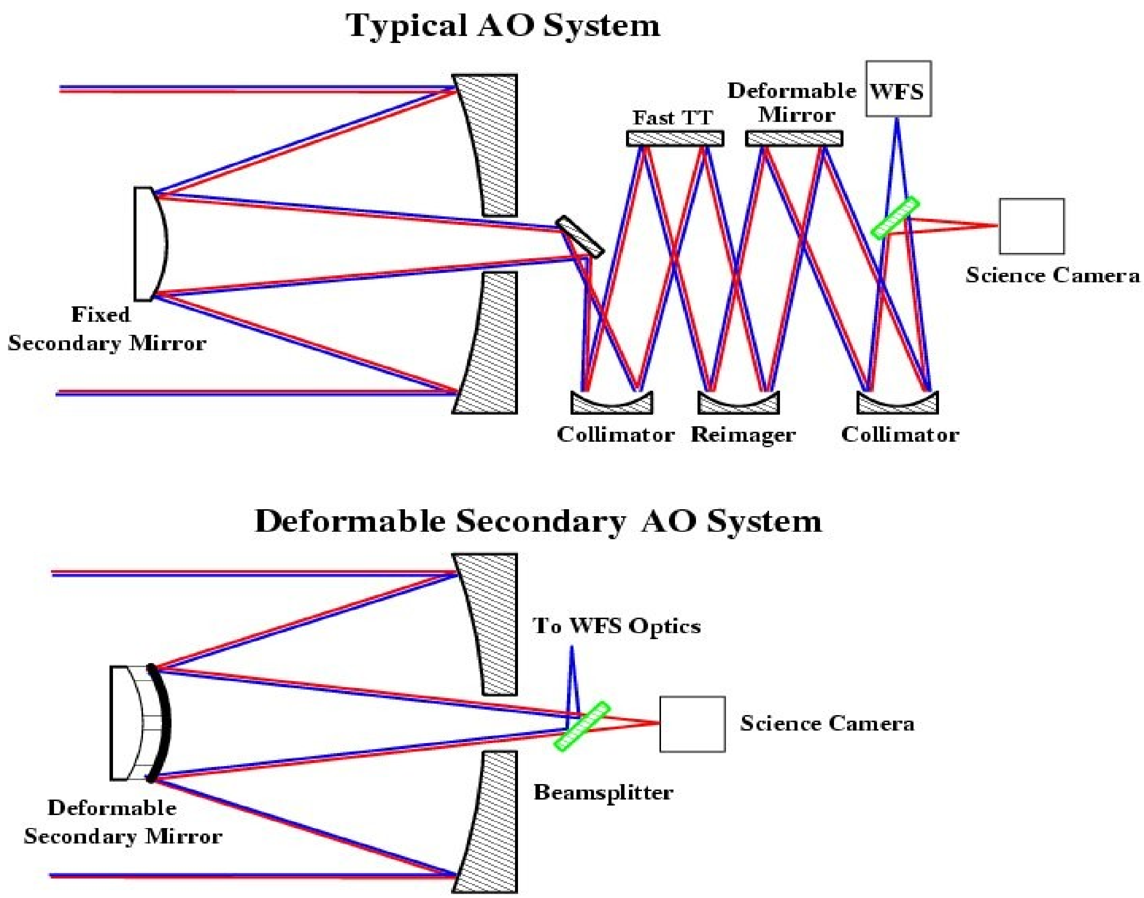

Fig. 1. Schematic representation of conventional and deformable secondary AO systems. The deformable secondary system provides fewer warm, IR emitting surfaces for lower background IR observations.

It has long been known that Jupiter's SED displays an anomalous peak at approximately 4-5 μm[1]. This is due to the lack of absorption features in this spectral region which allows the observation of thermal emission from much deeper in the planet's atmosphere, at a higher brightness temperature than at other wavelengths. A similar, broader peak can be seen in T type brown dwarfs and is an expected generic feature for objects with effective temperatures below approximately 1200 K, ([2][3][4]). The anomalous flux appears in the L' and M bands for hotter object (>800 K) and narrows to a feature which is well matched to the M band window for cooler objects. Even though models are still uncertain, they appear to be more reliable for older systems where the thermal IR advantage is largest.

2. The MMT AO System

To make use of this expected contrast enhancement it is necessary to detect the relatively faint planet flux in the presence of background from the sky as well as any warm optics in the system. The relatively small expected separations require diffraction-limited performance, which in turn requires an adaptive optics system to correct for atmospheric turbulence. Typical AO systems add 5-10 warm surfaces. For wavelengths longward of approximately 2 μm the infrared glow from the warm optics can dominate the background and, thus, the noise. For planet detection at longer wavelengths an optimum system is one which is integrated into the telescope itself, such as the deformable secondary mirror or a cryogenic corrector.

The MMT Adaptive Optics (AO) system makes use of the world's first deformable secondary mirror ([5][6]), allowing integration of the AO into the telescope itself. The deformable secondary is undersized to form the stop of the system, and an provide an effective aperture of 6.35 m diameter. The secondary undersizing is a proven technique to provide efficient baffling of warm background radiation from the telescope structure. Infrared light encounters only two warm reflecting surfaces, the primary and secondary mirror before entering the cryogenically cooled camera which eliminates background contributions from these optics (see Figure 1). The result is an infrared optimized system which is also capable of diffraction-limited imaging (a full width at half maximum of 0.13 arcseconds at L' and 0.16 arcseconds at M band). Compared to conventional adaptive optics systems this results in improved sensitivity. Lloyd-Hart [7] shows that for typical parameters expected at the MMT, observations with an optimized system can achieve the same signal in one third to one half of the integration time that would otherwise be needed using a conventional adaptive optics system at L' and M bands.

Atmospheric turbulence is sensed using visible light reflected from the entrance window of the cryostat. The telescope pupil is imaged onto a CCD-based Shack Hartmann wavefront sensor operating at 550 Hz. The resulting slopes are reconstructed to measure and correct the first 56 Zernike modes of the turbulent wavefront. The system typically delivers Strehls of approximately 25% at H band in median seeing [8]. Scaled to M band this is a Strehl of 85%.

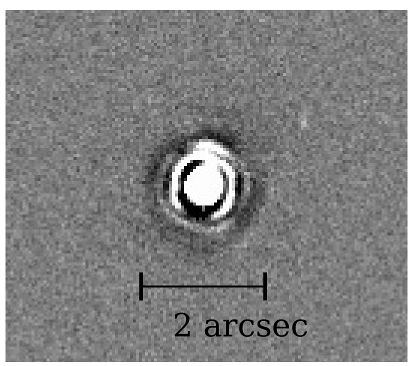

Fig. 2. Representative image using direct imaging at L'. The star is a relatively young star at 17 pc. A chance background star (upper right) allows us to confirm that we have sensitivity to detect a 5 MJ planet in an hour's observation. The object is L'=16.1 and corresponds to a contrast of 8.3 mag. The object is 1.9 arcsec away but could be seen with this dataset as close as ~0.5 arcsec, using PSF subtraction.

3. **CLIO 3-5 MICRON CAMERA**

The use of 3-5 μm detection to search for gas giant planets is being carried out currently with the 6.5 m MMT, making use of an adaptive secondary and a camera, called Clio, built for this purpose ([9][10]). Initial estimates of sensitivity can be found in [11] and [12]. In

Figure 2 we show an example of observations that can reach interesting levels of photometric sensitivity at L' and M bands as well as probing the 10-40 AU region of typical targets. Contrast estimates as a function of separation are shown in Figure 4.

Clio is designed for obtaining high spatial resolution images with optimum efficiency at L' and M band. The favorable contrast for planets at M band is at least partially offset by the high background in this atmospheric window. Our initial estimates of the relative sensitivity in these two bands suggests the L' band magnitude limit is approximately 2 magnitudes better than the M band limit, consistent with the higher background at M band compared to L'. This is a good match to the expected colors for giant planets. For example, models of giant planets ([2][3]) predict that a planet will be roughly 2 magnitudes brighter in M band versus L' for an effective temperature around 350 K. The coincidence of these two factors, a fainter L' limiting magnitude and a red L'-M color for a typical planet, provides favorable conditions for confirmation of any substellar companion. While common proper motion will still be important to verify physical association, confirmation via color is a strong secondary indicator that an object is indeed a planetary mass object.

High efficiency observations with Clio are aided by an Indium Antimonide (InSb) detector, from Indigo Systems, Inc. which has a high well depth compared to more typical astronomical InSb detectors. This feature allows efficient use in the M band where high backgrounds can typically swamp detectors with lower well depths. The detector has a a measured well depth of 3 million photo-electrons[10].

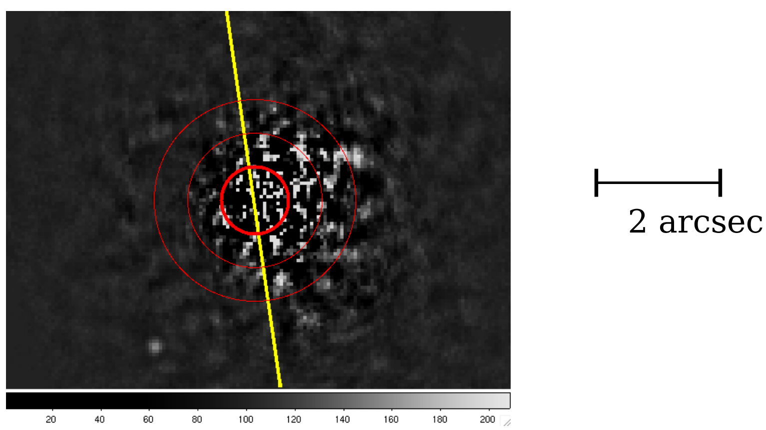

Fig. 3. Image of Procyon with APP coronagraphy at M band. The image shows how the APP approach can reduce diffraction on the left side of the image. The vertical yellow line marks the two sides of the diffraction pattern. Despite PSF subtraction, the right side of the image has worse noise characteristics. The inner red circle marks 0.5” radius, corresponding to 3 λ/D. Concentric circles mark 1.0 and 1.5 arcsec. The plate is sky limited outside of approximately 1 arcsec. Procyon B can be seen to the lower left at a contrast of 11.2 mag.

4. APODIZING PHASE PLATE

A significant improvement to direct imaging at small angular separations can be achieved by suppressing the diffraction pattern. A range of solutions are available for this. We have developed an apodizing phase plate (APP) approach([13],[14]) to create a 180 degree region about the star where diffraction is suppressed via a phase plate inserted at a pupil location in the optics. Compared to other coronagraphic approaches this has several advantages. The plate creates a dark region on one side of the star, independent of the star's location on the detector. This is an important feature that allows the use of standard nodding techniques for the IR observations. In addition the phase plate only modifies the wavefront phase, it does not block any of the light. This results in a high throughput device, which is important to not compromise background-limited sensitivities at larger separations. Finally, it is relatively straightforward to implement, involving a device that can be manufactured and installed into an existing camera.

For observations at 3-5 µm, the sky sets the background noise for typical nearby stars, unlike NIR observations where the scattered light sets the noise floor and thus the detection threshold. Because of this difference, the use of a coronagraph at 3-5 µm is needed, not to reduce the photon noise from the star, but to reduce confusion noise associated with static or slowly changing aberrations in the optical system. Because of this difference, a crucial criteria for any 3-5 µm coronagraph is that it not reduce the throughput of the optical system. An apodizing phase plate coronagraph does not attenuate the beam, it simply modifies the phase of the light as a function of position in the pupil plane. This modifies the diffraction of the light in the image plane. By modifying the phase (but not the amplitude) of the light beam, the phase pattern can only suppress the light on one side of the image. The effect is to create a dark "D" shaped hole to one side of the diffraction pattern. An advantage of the APP approach to coronagraphy, compared to most other designs, is that the dark "D" hole appears in the star image **no matter what its location is on the detector**. Most coronagraphs depend on focal plane optics that require precise alignment of the star image with the optic to work as designed. Effects such as vibration of the telescope can easily degrade their performance. This position independence of the APP's suppression also means that periodic beam switching and dithering - a necessity for IR observations - can be carried out in a way that is identical to standard imaging.

We have begun exploring the apodizing phase plate approach to coronagraphic suppression with Clio and the MMT AO system. Successful on-sky demonstrations of a phase plate approach ([15],[16]) confirms that the APP approach is a simple, straightforward way to achieve good sensitivity at small separations. We are currently carrying out a survey on the MMT to look for super-Jupiters at closer separations than has been possible with standard imaging at either H band or M band. The comparison of the Clio sensitivity for direct imaging and with the APP is shown in Fig. 4.

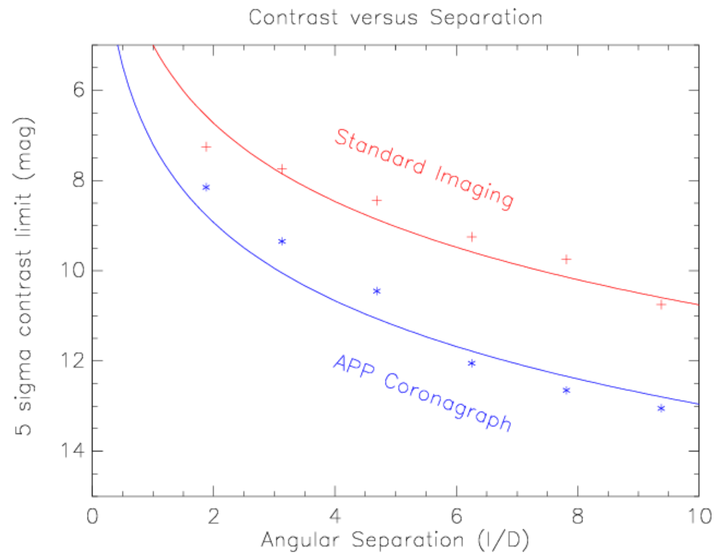

Fig. 4. Contrast limits from approximately one hour observations at M band on the MMT. The top data shows limits for direct imaging while the bottom limit is for APP observations. The data points are measured sensitivities and the lines show a 1/(λ/D) sensitivity curve.

5. THE LARGE BINOCULAR TELESCOPE INTERFEROMETER

The MMT observations are limited by the sky background at relatively small angular separations. This noise floor can be significantly reduced by simply using a larger aperture telescope. In fact, it is expected that exoplanet observations in L' and M band will be of increasing interest for larger apertures since much of the interesting search space for target stars are simply limited by sky and telescope background, not noise from the star's scattered light. A significant sensitivity increase is possible through use of the Large Binocular Telescope.

The Large Binocular Telescope is a common mount design interferometer with 8.4 m apertures on a 14.4 m baseline. The common mount design negates the need for long delay lines. Only three warm mirrors, primary, secondary and Nasmyth flat, are used to direct the beams toward the central instrument platform. This is especially important for thermal infrared (>3 µm) observations where telescope emissivity can be the dominant source of noise. The deformable elements of the AO systems of the LBT are integrated into the secondary mirrors of the telescope, which form the aperture stop of the telescope to optimize infrared performance. These several unique aspects of the LBT allow for efficient high sensitivity beam combination that is well matched to the goals of thermal infrared detection of extrasolar planets.

The LBT Interferometer is planned for the central instrument platform of the LBT (see Figure 5). The instrument consists of a cooled optical train, called the Universal Beam Combiner (UBC) that combines the individual focal planes of each side to a common, central focal plane[17]. The UBC feeds a Nulling and Imaging Camera (NIC) that can carry out observations in the 3-5 and 8-13 µm atmospheric windows .

The MMT performance can be used as a baseline for expected performance of the LBTI. Since observations with the MMT outside of ~1” are background-limited for typical targets, the advantage of larger apertures improves both the inner working angle (IWA) and the limiting planet mass detectable.

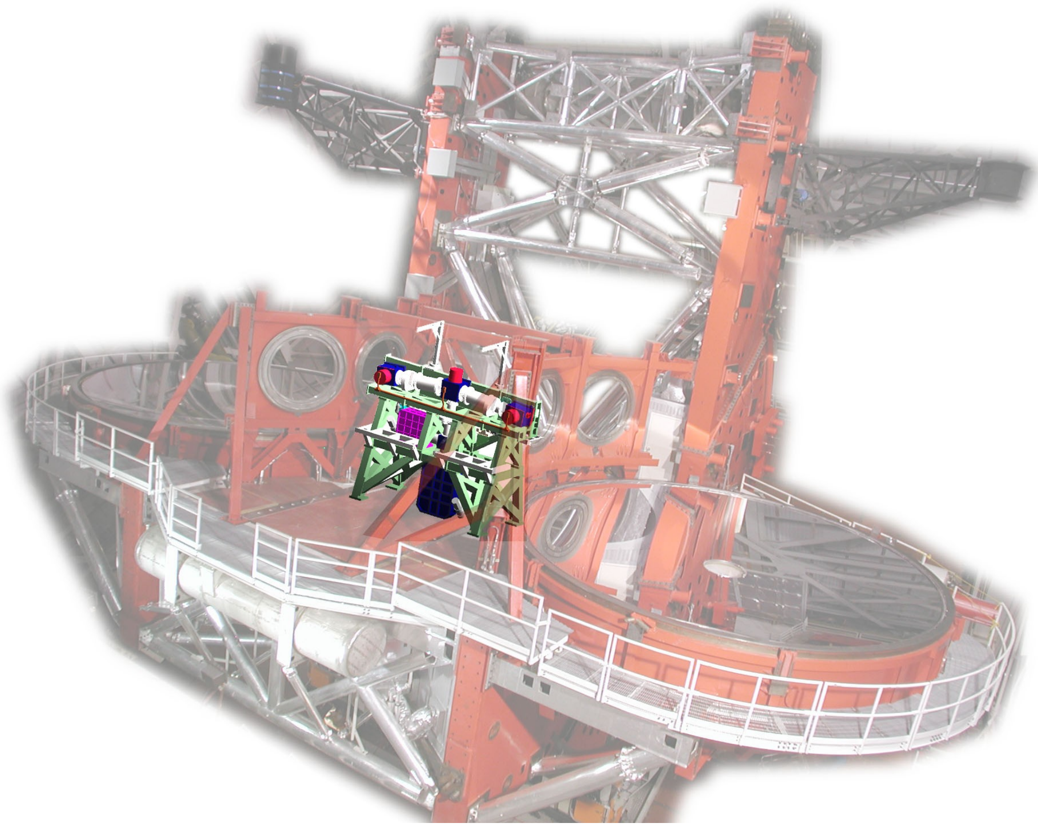

Fig. 5. The LBT Interferometer at the central instrument platform of the LBT. The common mount design of the LBT and deformable mirrors integrated into the secondary mirrors make the system uniquely sensitive for infrared observations of extrasolar systems.

The scaling to LBTI assumes the same background, and similar Strehl for the images so that the limiting magnitude is simply scaled with the collecting area of the telescope.

From current observations with the MMT we know we are limited to 3-5 M_J planets and above outside of 10-20 AU. The LBT will push this limit to below 2 M_J for a significant sample of stars and separations of approximately 3 AU. The best targets for such searches will be a combination of the very nearest (<6 pc) as well as stars slightly further away that have good indications of youth (<1 Gyr).

6. **REFERENCES**

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