A Survey of Close, Young Stars with the Simultaneous Differential Imager (SDI) at the VLT and MMT

Beth A. Biller¹, Laird M. Close¹, Elena Masciadri², Rainer Lenzen², Wolfgang Brandner², Donald McCarthy¹, Thomas Henning², Eric Nielsen¹, and Markus Hartung³

¹Steward Observatory, University of Arizona, Tucson, AZ 85721
email: bbiller@as.arizona.edu

²Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

³European Southern Observatory, Alonso de Córdova 3107, Santiago 19, Chile

Abstract. We discuss the preliminary results of a survey of young (<300 Myr), close (<50 pc) stars with the Simultaneous Differential Extrasolar Planet Imager (SDI) implemented at the VLT and the MMT. SDI uses a double Wollaston prism and a quad filter to take 4 identical images simultaneously at 3 wavelengths surrounding the 1.62 \( \mu \text{m} \) methane bandhead found in the spectrum of cool brown dwarfs and gas giants. By performing a difference of images in these filters, speckle noise from the primary can be significantly attenuated, resulting in photon noise limited data. In our survey data, we achieved H band contrasts >25000 (5\( \sigma \) \( \Delta F_1(1.575 \mu m) \))>10 mag, \( \Delta H >11.5 \) mag for a T6 spectral type) at a separation of 0.5" from the primary star. With this degree of attenuation, we should be able to image (5\( \sigma \) detection) a 2-4 Jupiter mass planet at 5 AU around a 30 Myr star at 10 pc. We are currently completing our survey of young, nearby stars. We have obtained complete datasets for 35 stars in the southern sky (VLT) and 7 stars in the northern sky (MMT). We believe that our SDI images are the highest contrast astronomical images ever made from ground or space for methane rich companions.

Keywords. (stars:) planetary systems, instrumentation: adaptive optics

1. Introduction

Direct detection of extrasolar giant planets is extremely difficult. Giant gas planets seen in reflected light are >20 magnitudes fainter than their primary stars and likely lie within ~1" of their primary stars. The problem is slightly easier with younger, hotter planets – 100 Myr old extra-solar planets are \( 10^{4-7} \) times more self-luminous than old (5 Gyr) extra-solar planets, whereas their primary stars are only slightly (2-5 times) brighter at early ages. In theory, adaptive optics (AO) systems that are “photon noise limited” can detect an object up to \( 10^5 \) times fainter than its primary at separations >1". However, numerous surveys for extrasolar planets using large telescopes with AO systems have yielded useful limits but few confirmed giant planet candidates (Kaisler et al. 2003, Masciadri et al. 2005, Chauvin et al. 2005, Neuhäuser et al. 2005).

AO surveys for young extrasolar planets only address half of the difficulty of direct detection – the contrast limit problem. Beyond the contrast limit problem, all AO systems suffer from a limiting “speckle noise” floor (Racine et al. 1999). Within 1" of the primary star, the field is filled with speckles left over from instrumental features and residual atmospheric turbulence after adaptive optics correction. These speckles vary as a function of time and color. For photon noise limited data, the signal to noise S/N increases.
Figure 1. Age vs. Distance for our observed sample stars

as $t^{0.5}$, where $t$ is the exposure time. For speckle-noise limited data, the S/N does not increase with time past a specific speckle-noise floor (limiting contrasts to $\sim 10^3$ at 0.5$''$). This speckle-noise floor is considerably above the photon noise limit and makes planet detection very difficult. Interestingly, space telescopes such as HST also suffer from a similar limiting speckle-noise floor due to imperfect optics and “breathing” (Schneider et al. 2003). Direct detection of extrasolar giant planets requires special new instrumentation to suppress this speckle noise floor and produce photon noise limited images. The VLT, Keck, Subaru, and Gemini are all currently developing dedicated planet-finding cameras which exploit these new instrumental approaches for speckle suppression. The Simultaneous Differential Imager (SDI), which our team built and installed at the VLT and MMT (see Biller et al., this conference), is one of the first dedicated planet-finding optical devices to come online on a large telescope.

Simultaneous Differential Imaging is an instrumental method which can be used to calibrate and remove the “speckle noise” in AO images, while also isolating the planetary light from the starlight. This method was pioneered by Racine et al. (1999), Marois et al. (2000), Marois et al. (2002), and Marois et al. (2005). It exploits the fact that all cool ($T_{\text{eff}} < 1200$ K) extra-solar giant planets have strong CH$_4$ (methane) absorption redwards of 1.62 $\mu$m in the H band infrared atmospheric window (Burrows et al. 2001, Burrows et al. 2003). Our SDI device obtains four images of a star simultaneously through three slightly different narrowband filters (sampling both inside and outside of the CH$_4$ features). These images are then differenced. This subtracts out the halo and speckles from the bright star to reveal any massive extrasolar planets orbiting that star. Since a massive planetary companion will be brightest in one filter and absorbed in the rest, while the star is bright in all three, a difference can be chosen which subtracts out the star’s light and reveals the light from the companion. Thus, SDI also helps eliminate the large contrast difference between the star and substellar companions (Close et al. 2005; Lenzen et al. 2004; Lenzen et al. 2005) The SDI device has already produced a number of important scientific results: the discovery of AB Dor C (Close et al. 2005) which is the tightest (0.16$''$) low mass companion detected by direct imaging, detailed surface maps of Titan (Hartung et al. 2004), the discovery of $\epsilon$ Indi Ba-Bb, the nearest binary brown dwarf (McCaughean et al. 2005), and evidence of orbital motion for Gl 86B, the first known white dwarf companion to an exoplanet host star (Mugrauer and Neuh"auser 2005).

2. The SDI survey

We are currently completing a survey with the SDI device of $\sim 50$ young ($<300$ Myr), nearby ($<50$ pc) stars. Stars were chosen based on strong lithium absorption features (our best targets have Li equivalent widths of $>100$ mA from the Li 6707 Å line, corresponding
3. An Example Dataset

A fully reduced dataset from the VLT SDI device as well as the same dataset reduced in a standard AO manner is presented in Fig. 2. This is 40 minutes of data for AB Dor A, a 70
Figure 3.

Top: Case A, Middle: Case B, Bottom: Case C. Left: ∆F1 (5σ attenuation in magnitudes in the 1.575 µm F1 filter) vs. Separation for 40 minutes of VLT SDI data for each example star. The top curve is the AO PSF. The next curve is the “classical AO PSF” unsharp masked. The third curve down is 40 minutes of SDI data taken at two different position angles and subtracted (0° data -33° data). The last curve is the theoretical contrast limit due to photon-noise. For each case, at star-companion separations >0.5", we are photon-noise limited and achieve H band star to planet contrasts >25000 (5σ ∆F1(1.575µm)>10 mag, ∆H>11.5 mag for a T6 spectral type)

Right: Minimum Detectable Planet Mass vs. Separation – using the models of Burrows et al. (2003) and primary star properties from the literature, we can convert our ∆F1 values into a minimum detectable planet mass for each object. Objects above the 1400 K methane cutoff line (horizontal dashed line) are not detected with the SDI device. For details, see Nielsen et al. 2005 (this conference).
Table 1. Properties of Example SDI Survey Stars and Comparison Stars

| Case | Spectral Type | Age   | Distance | H   | V   | Exposure Time | ΔF1^1 | ΔH^1 |
|------|---------------|-------|----------|-----|-----|---------------|-------|------|
| A    | K2V           | 30 Myr | 45.5 pc  | 7.1 | 9.1 | 40 min        | 10.5  | 12   |
| B    | K1V           | 70 Myr | 15 pc    | 4.8 | 6.9 | 40 min        | 10.5  | 12   |
| C    | M3V           | 30 Myr | 24 pc    | 7.1 | 12.2| 40 min        | 10    | 11.5 |
| 10 late K-M stars^2 | K-M | 0-1 Gyr | 10-50 pc | 6.4-8.7 | 8-12 | 10-25 min | 8.61 | 10.31 |
| Gl 86^3 | K1V | 10 Gyr | 10.9 pc | 4.2 | 6.2 | 80 min        | 12.8  | 14.3 |

^1 5σ at 0.5"  ^2 Masciadri et al. IAUC 200  ^3 Mugrauer & Neuhäuser 2005

Myr K1V star at a distance of 14.98 pc (V=6.88). Simulated planets have been added at separations of 0.55, 0.85, and 1.35" from the primary, with ΔF1 = 10 mag (attenuation in magnitudes in the F1 1.575 µm filter) fainter than the primary. These planets are scaled from unsaturated images of the star taken right before the dataset (and have fluxes and photon noise in each filter appropriate for a T6 object). In the SDI reduction, the simulated planets are detected with S/N > 10 past 0.7". In comparison, none of the simulated planets are detected in the standard AO data reduction and numerous bright super speckles remain in the field.

4. Contrast Limits and Planet Detectability

To determine the range of star-planet contrasts achievable in our SDI young stars survey, we consider three example cases which span the space of our target stars: case A – a high quality dataset (observed with seeing of ~0.5"), case B – AB Dor A, a young solar analogue, and case C, a faint young M star. Properties of each example star (distance, age, spectral type, etc.) are presented in Table 1.

ΔF1 (5σ attenuation in magnitudes in the 1.575 µm F1 filter) vs. separation from the primary is presented for each of the example cases in Fig. 3. For these datasets, we achieved H band star to planet contrasts >25000 (5σ ΔF1(1.575µm)>10 mag, ΔH>11.5 mag for a T6 spectral type) at a separation of 0.5" from the primary star – approaching the photon-noise limit in 40 minutes of data.

Using the models of Burrows et al. (2003) and adopting values for the primary star’s age (from the Li 6707 Å line), distance, and spectral type from the literature, we can convert our measured attenuations for each object into a minimum detectable mass (see Nielsen et al. 2005, this conference). Minimum detectable mass vs. separation for each of the examples is also presented in Fig. 3. Although we achieve similar contrast limits for our example cases (with slightly higher contrasts for brighter targets as one might expect), the mass and separation of objects detectable around each varies strongly with age and distance. Even though case A was our best quality data, we are more likely to detect planets for case B and C, simply because these two objects are closer to the sun, and hence, we can resolve the inner ~20 AU around the star. For case C, we can detect (>5σ) a 3-5 M_J planet at 6 AU from the primary. ΔF1 and ΔH (for a methane object) for each survey case as well as for other comparison objects from independent studies with the VLT SDI device are shown in Table 1 – it is clear that the achievable contrast varies according to the magnitude of the object and total exposure time.

To determine what sort of objects we can realistically detect with this level of contrast, we inserted and then attempted to retrieve simulated T6 dwarf planets to the case B dataset with a variety of separations and ΔF1 contrasts. ΔF1 contrasts were translated into planet masses using the models of Burrows et al. 2003. In Fig. 2 we plot minimum
detectable planet mass (for a $5\sigma$ detection) vs. separation. For this particular star (case B: K1V, 70 Myr, 15 pc), we can detect a $5 \, M_{Jup}$ planet 12 AU from the star. In this particular case we were able to detect a real non-methane companion (AB Dor C) at 3 different epochs and separations from 0.15” to 0.2” even though $\Delta H > 5$ mag (Close et al. this conference and Nielsen et al. 2005).

5. Conclusions

The novel SDI device at the VLT and MMT has been fully commissioned and is currently achieving attenuations of $>25000$ ($\Delta H > 11.5$ for a T6 spectral type object, $\Delta F_1(1.575 \mu m) > 10$) at 0.5”. With these contrasts, we can detect a wide range of substellar objects. For instance, for AB Dor A (a 70 Myr K1V star 15 pc away) we can detect ($>5 \sigma$) a $5 \, M_{Jup}$ planet 12 AU from the star. For a younger closer star (30 Myr age at 10 pc), we can detect a 2-4 $M_{Jup}$ planet at 5 AU.

We have currently observed 42 of the youngest (<300 Myr), nearest (<50 pc) stars as part of a survey of young, nearby stars. We have received time at the VLT for followup observations of 8 tentative candidates found as part of the survey. With a total sample size of ~50 stars, we will be able to place strong constraints on the frequency and semimajor axis distribution of massive extrasolar planets $>5$ AU from their primaries. From scaling laws derived from the distribution of known radial velocity planets (Marcy et al. 2003, Lineweaver and Grether 2003, Burrows et al. 2003), we expect to detect ~4 planets for our total sample (see Nielsen et al., this conference). Whether or not we detect planets, our survey will begin to measure the true distribution young massive extrasolar planets $>5$ AU from their primaries and will provide valuable constraints for theories of planet formation and migration.

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