Extrasolar planet detection through spatially resolved observations

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Chapter 7

Outlook

This thesis has focused on optimizing the detection of faint planets primarily with the apodizing phase plate coronagraph (APP: Kenworthy et al. 2010) on the NaCo instrument (Lenzen et al. 2003; Rousset et al. 2003) at the Very Large Telescope (VLT). I begin this Chapter by discussing the current limitations of direct imaging and how new instruments, coronagraphs, and surveys which will yield significant results in the next five years. Then, I make predictions on the next 5-10 years with the potential for the direct detection of another Earth with future Extremely Large Telescopes (ELTs). Finally, I speculate on the long term outlook of the field of exoplanet research.

7.1 Current limitations and The Next Five Years

Significant advances in telescope optics and instruments have led to the discovery of the first few directly imaged exoplanets (HR8799 bcde (Marois et al. 2008, 2010), Fomalhaut b (Kalas et al. 2008), β Pic b (Lagrange et al. 2009, 2010), 2MASS1207 b (Chauvin et al. 2004), 1RXS J1609–2105 b (Lafrenière et al. 2008), HD 95086 b (Rameau et al. 2013a), HD 106906 b (Bailey et al. 2014), GJ 504 b (Kuzuhara et al. 2013), and GU Psc b (Naud et al. 2014).) However, unlike the other exoplanet detection techniques, direct imaging has not yielded many planet detections. There are a number of reasons why there are so few detections, outlined below:

- **Predicted methane:** Many of the first direct imaging surveys (discussed in the section 1.5) were performed in H (1.6μm) and Ks-band (2.18μm), explicitly to take advantage of the predictions from theoretical evolutionary models (e.g. COND: Baraffe et al. 2003) that cool planets would have strong methane absorption features and little cloud opacity. However, most of the direct imaging planets that have been observed so far are not similar to field brown dwarfs of similar effective temperature. These planets do not show the predicted methane absorption (e.g. HR 8799 bcd and 2M1207 b: Skemer et al. 2014) and in some cases are much redder than predicted (HD 95086 b: Galicher et al. 2014). This suggests that future direct imaging instruments and surveys should be focused on the thermal infrared (L'-band, 3.8 μm) and longer wavelengths, where the current detected planets appear the brightest.

- **Quasi-static speckles:** Nearly all of the current instruments used to detect planets have been designed for a wide range of science cases (NaCo at VLT, NIRC2 at Keck, STIS on HST). The ideal instrument designed for the direct imaging of exoplanets would have as few optical paths as possible, to limit the amount of aberrations in the final images, also known as quasi-static speckles. These speckles are similar in size and can be even brighter than a real companion signal. Many image processing algorithms have been designed to counter this limitation. However, in order to reach the faintest planets it is important to design the instrument from a systems level given the science goal of directly imaging exoplanets, and all choices of the design should reflect that.

- **Small number of planets:** Thus far, direct imaging planet searches are very resource intensive, requiring hundreds of stars to be observed to only discover one planet. As a result, there are few directly detected planets, and the stars which are best suited for finding these planets is not known. The properties of these planets and the frequency of planets is also difficult to assess statistically.

Fortunately, there are many exciting new instruments, coronagraphs, image processing algorithms, and direct imaging surveys being developed and implemented now. Based on the experience of many other direct imaging surveys, I am cautious about the exact number of planets that will be discovered with these new

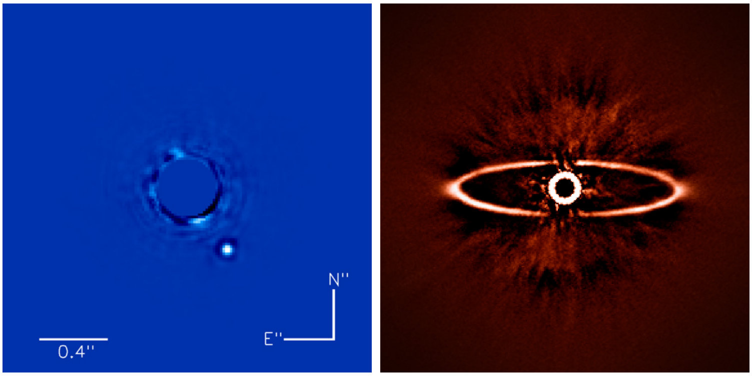

Figure 7.1 Left: GPI detection of the planet beta Pictoris b from the GPI first light press release. Right: SPHERE detection of a dust ring around the star HR 4796A from the SPHERE first light ESO press release.

instruments and surveys. I predict, at a minimum, a dozen new directly imaged planets will be discovered in the next five years, detailed below:

- **Instruments:** Two dedicated exoplanet imagers have recently gone online, making the next few years particularly exciting. The Gemini Planet Imager (GPI: Macintosh et al. 2006) at the Gemini telescope and Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE: Beuzit et al. 2008) at the VLT. Figure 7.1 shows the first light data from GPI and SPHERE, which re-detect a planet and disk with much higher signal-to-noise than before and in less time. In addition, the Subaru Coronagraphic Extreme-AO (SCExAO) system (Guyon et al. 2011) at the Subaru telescope is an instrument currently being used for exoplanet direct imaging. The Large Binocular Telescope Interferometer (LBTI: Hinz et al. 2014; Skemer et al. 2014 is very recently in operation. This combines the two 8.4 meter mirrors at the LBT in order obtain the equivalent baseline of 22.8 meter telescope. All of these instruments are remarkably sensitive to lower mass planets (down to 1 Jupiter mass), closer to the star ($> 0.''1$). This increased sensitivity allows us to image – for the first time – planets similar in mass and orbital distance to our own outer Solar System planets. Rather than obtaining broadband images, some of these instruments obtain integral field spectroscopy (IFS) data. Instead of a single image, a data cube is obtained, each frame of which corresponds to a different wavelength. IFS data are extremely powerful, they allow us to detect and characterize planets through spectral analysis (see Konopacky et al. (2013)).

- **Coronagraphs:** There are several new coronagraphic optics which will allow us to probe for fainter planets and closer to the star. Many of the latest coronagraph designs achieve high throughput at small inner working angles. For example, the Vector Vortex coronagraph (Mawet et al. 2005) has been demonstrated in on sky performance to reach deep sensitivity limits at extremely small angular separations (>0.″09). However, these optics are susceptible to tip-tilt vibrations and pointing errors (discussed in 1.4). Pupil plane coronagraphs modify the amplitude (Pueyo et al. 2011) and the phase (Kenworthy et al. 2010) of the wavefronts from the star and planet. One such optic is the vector Apodizing Phase Plate (vAPP: Otten et al. 2014), which has been developed at the Leiden Observatory. The vAPP takes advantage of the design of the standard APP coronagraph (Kenworthy et al. 2010), which modifies the pupil-plane phase in order to create a dark hole on one side of a point source PSF. Most of the work in this thesis takes advantage of the APP coronagraph at NaCo/VLT. The vAPP deals with the most important problem with the APP: one can only search for planets on one side of a star at a time. In order to solve this problem, the vAPP uses a circular polarization to beam-split and create two PSFs with the dark hole on different sides of the star. Thus, the vAPP has all the advantages of the APP (no tip-tilt error, works in the pupil-plane, single optic, see Section 1.4.3) without the dark hole being only on one side. These new coronagraphs will be installed and in operation on several telescopes within the year.

- **Image Processing Algorithms:** Current image processing algorithms typically use the data itself as the reference to create a model stellar PSF to subtract away from each image (ADI: Marois et al. 2006, LOCI: Lafrenière et al. 2007 , PCA: Amara & Quanz 2012, Soummer et al. 2012). However, at small angles, basic ADI results in significant self-subtraction that can hide planets. By observing different stars on the same night with the same observing strategy, we can use the other datasets to create reference PSFs to subtract the stellar PSF in our data (Mawet et al. 2012). This prevents self subtraction in small inner working angles, as an exoplanet is very unlikely to be in the same location in two datasets. By compiling a library of reference PSFs, we can also reanalyze large databases of archival data from telescopes, much of which was never published since no planets were detected.

- **Optimizing chances of finding planets:** The primary targets for directly imaging exoplanets are young, as they are still self-luminous, making them brighter in the infrared. However, determining the age of a star is challenging. Stellar associations are often the targets of direct imaging surveys because the age of the stars are typically well constrained. Thus, one possible way to discover many new planets is to focus on discovering new stellar members of known, young associations. Large direct imaging surveys are resource intensive, requiring many nights of telescope time to observe hundreds of stars, often resulting in only one new planet detection. One other possibility to discover new planets is to focus on the types of stars which have already been found to harbor planets. In our Holey Debris Disks survey (Meshkat et al. 2015), two new planets (HD 106906 b: Bailey et al. 2014, HD 95086 b: Rameau et al. 2013b) were discovered out of our list of only fifteen stars. Given the typically low rate of detection in imaging surveys (<2%), this survey shows that Holey Debris Disks are effective signposts for planet formation. Focusing future direct imaging surveys on Holey Debris Disks targets and discovering new stars with Holey Debris Disks will likely yield a higher planet detection rate.

- **Surveys:** There are several ongoing direct imaging surveys which are expected to be completed in the next few years. The Strategic Explorations of Exoplanets and Disks with Subaru (SEEDS) survey has already published a subset of results (Janson et al. 2013; Brandt et al. 2014), including one planet detection GJ 504 b (Kuzuhara et al. 2013). The complete survey of nearly 400 stars is expected to published soon, which will be the largest number of stars observed in one survey to date. The new second generation imagers GPI and SPHERE both have ongoing very large surveys of stars. Over the next few years, dozens of planets are predicted to be discovered and confirmed with proper motion. The LEECH survey is unique from the previous three surveys in that images will be obtained in L'-band (3.8μm) rather than H-band (1.6μm). This 100 night survey using the LBTI is expected to be completed in the next few years.

One of the most important events that will happen in the next 5 years is the launch of the *James Webb Space Telescope* (JWST). While it almost certainly will not be used for direct imaging surveys (simply due to the vast amount of hours such a survey will require), it will provide the much needed sensitivity necessary to characterize the already discovered direct imaging planets and to perhaps even to see the rocky surfaces of tidally heated exomoons (Peters & Turner 2013). It is important that many planet candidates are detected in the next few years in order to provide the target list for JWST.

7.2 The Long Term

There is a limit to the sensitivity that can be achieved with current ground based telescopes, and as a result, the number of planets that can be detected through direct imaging is limited. At some point in the next 5 years, all the planets which can be directly imaged may well be discovered (from the ground) and subsequently characterized with the JWST. In order to reach fainter planets at smaller inner working angles, we need ELTs sized telescopes. The planned ELTs (the European Extremely Large Telescope, the Giant Magellan Telescope, and the Thirty Meter Telescope) will have the resolving power of a 24 to 40 meter primary mirror at visible and NIR wavelengths. This will give us unprecedented sensitivity at very small angular separations. A study of the planned European Extremely Large Telescope instrument METIS suggests that it will be possible to detect the first nearby super Earth with its increased sensitivity and inner working angle (Quanz et al. 2015). Additionally, by combining high dispersion spectroscopy with high contrast imaging at the European Extremely Large Telescope, it may be possible to detect and characterize nearby rocky planets (Snellen et al. 2015).

It is hard to predict the longer term beyond the ELT generation of telescopes, but it is very likely that Earth-sized planets will be directly imaged in reflected light within 20 years. It is my sincere hope that as we begin to characterize Earth-twins and perhaps even measure bio-markers, we as a species will collectively reflect on the importance of habitable worlds like our own.

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