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Direct Imaging of Warm Extrasolar Planets

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Bruce Macintosh, Principal Investigator

1 Introduction

One of the most exciting scientific discoveries in the last decade of the twentieth century was the first detection of planets orbiting a star other than our own. By now more than 130 extrasolar planets have been discovered *indirectly*, by observing the gravitational effects of the planet on the radial velocity of its parent star. This technique has fundamental limitations: it is most sensitive to planets close to their star, and it determines only a planet's orbital period and a lower limit on the planet's mass. As a result, all the planetary systems found so far are very different from our own – they have giant Jupiter-sized planets orbiting close to their star, where the terrestrial planets are found in our solar system. Such systems have overturned the conventional paradigm of planet formation, but have no room in them for habitable Earth-like planets. (Figure 1.)

A powerful complement to radial velocity detections of extrasolar planets will be *direct imaging* - seeing photons from the planet itself. Such a detection would allow photometric measurements to determine the temperature and radius of a planet. Also, direct detection is most sensitive to planets in wide orbits, and hence more capable of seeing solar systems resembling our own, since a giant planet in a wide orbit does not preclude the presence of an Earth-like planet closer to the star.

Direct detection, however, is extremely challenging. Jupiter is roughly a billion times fainter than our sun. Two techniques allowed us to overcome this formidable contrast and attempt to see giant planets directly. The first is *adaptive optics* (AO) which allows giant earth-based telescopes, such as the 10 meter W.M. Keck telescope, to partially overcome the blurring effects of atmospheric turbulence. The second is looking for *young planets*: by searching in the infrared for companions to *young* stars, we can see thermal emission from planets that are still warm with the heat of their formation.

Together with a UCLA team that leads the field of young-star identification, we carried out a systematic near-infrared search for young planetary companions to ~200 young stars. We also carried out targeted high-sensitivity observations of selected stars surrounded by circumstellar dust rings. We developed advanced image processing techniques to allow detection of even fainter sources buried in the noisy halo of scattered starlight.

Even with these techniques, around most of our targets our search was only sensitive to planets in orbits significantly wider than our solar system (Figure 2.) (With some carefully selected targets – very young dusty stars in the solar neighborhood – we reach sensitivities sufficient to see solar systems like our own.) Although we discovered no unambiguous planets, we can significantly constrain the frequency of such planets in wide (>50 AU) orbits, which helps determine which models of planet formation remain plausible. Successful modeling of our observations has led us to the design of a next-generation AO system that will truly be capable of exploring solar systems resembling our own (section 3.)

1.1 Extrasolar planets

There are currently more than 100 extrasolar planets known (see Figure 1). Almost all have been detected through radial velocity measurements (Marcy & Butler 1998), studying via Doppler shifts the motion of the parent star induced by the gravitational tug of the orbiting planet. Since the acceleration due to the planet scales inversely with orbital radius squared, radial velocity techniques are primarily sensitive to planets orbiting close to stars. An additional limitation is imposed by time. A good radial-velocity measurement of an orbit requires the planet to complete at least one circuit around its parent star. Even Jupiter, the giant planet closest to our sun (5 AU), has an orbital period of 11 years. This is the fundamental reason why only one giant planet resembling Jupiter's orbit has yet been detected – since the discovery of the first extrasolar planet (Mayor & Queloz 1995), precision radial velocity searches have not been carried out for long enough except for a few stars where searches were begun in the early 1990s. In the next few years radial velocity searches may begin to discover more planets in Jupiter-like orbits, but they are unlikely ever to probe to wider separations. In addition, since radial velocity measurements are an indirect technique, they only indirectly measure properties of the planet itself, determining its orbital radius and period, and a lower limit on its mass in all but the rarest cases.

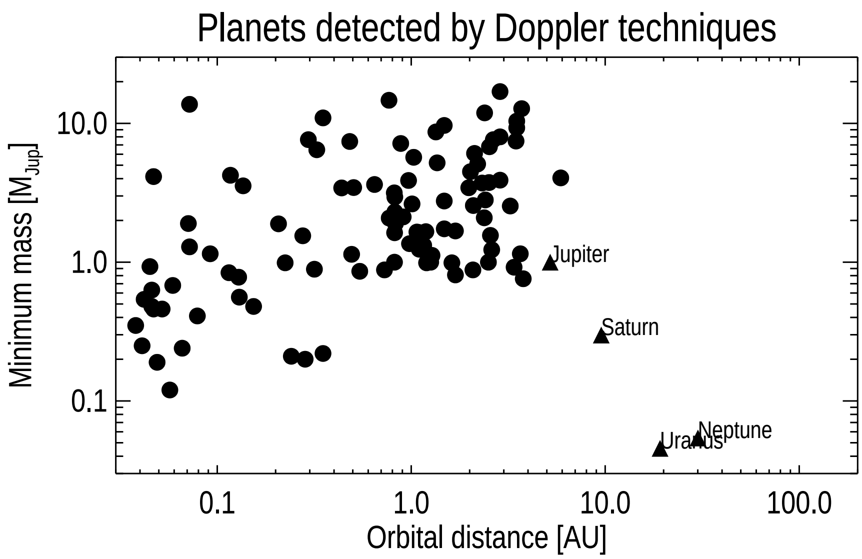

Figure 1: Known extrasolar planets as of 2004

The locations of the known extrasolar planets have been a considerable surprise to planetary formation theorists. The conventional paradigm of planet formation is that planets like Jupiter or Saturn form through accretion of material in a flattened disk surrounding the newly-formed sun. Particles in this disk collide and stick together into larger and larger "planetesimals". In the outer parts of the disk (r>5 AU) this process could take place quite rapidly, since it is cold enough that water ice – a solid that can be made out of very common elements – can form. It is thought that Jupiter could rapidly build up an earth-sized icy core, which would become large enough to begin to attract and hold gas directly from the protoplanetary disk – allowing it to accrete rapidly to large size. By contrast, in the inner solar system, without ice, solid material is rare enough that by the time the Earth reached its current size all the gas was gone. As a result, giant Jupiter-like planets were thought to only form *beyond* the 5 AU "ice line".

All extrasolar planets detected to date exist *inside* this boundary. The favored explanation now is that these planets still formed originally in wide orbits but then migrated inwards, either gradually spiraling in through tidal interactions with the disk (Lin 1996) or through gravitational scattering with other newly-formed planets. More exotic explanations include the suggestion that protoplanetary disks rapidly fragment (Boss 1997), forming planets directly rather than through classical accretion. By searching for more "conventional" planetary systems that resemble our own, we hope to shed light on the formation process and test the predictions of these competing theories.

1.2 Towards direct imaging

Direct detection of extrasolar planets would be an important and exciting complement to current techniques. Direct imaging would allow determination of the surface properties of an object – its temperature, radius, and composition. More importantly, by contrast to indirect techniques that are most sensitive to close planets, direct detection techniques are most sensitive to planets in wide orbits, probing a fundamentally different piece of planetary system parameter space. Our program will survey the region beyond the "ice line" to search for giant planets in solar systems that more closely resemble our own.

Unfortunately, direct detection is also extremely challenging: Jupiter is roughly a billion times fainter than our sun. Seen through even the best telescopes, stars are surrounded by a diffuse halo of light scattered by diffraction, atmospheric effects, and optical imperfections, limiting our ability to detect such faint companions. The combination of advanced adaptive optics and the selection of young stars as targets will make detection of planetary-mass companions possible.

Adaptive optics (AO) allows very large earth-based telescopes such as the 10 meter W.M. Keck telescope to partially overcome the effects of atmospheric turbulence. An adaptive optics system uses a fast wavefront sensor to measure the distortions in incoming light, and a rapidly-changing deformable mirror to correct these distortions. The most powerful astronomical AO system currently in use is the system on the 10-m W.M. Keck II telescope (jointly built by LLNL and the Keck Observatory, Wizinowich et al 2000). AO is imperfect, however; stars as seen by AO are usually still surrounded by a faint residual halo. AO can enhance the contrast between a faint companion and the stellar halo by a factor of a hundred or more, but even with AO we are currently limited to detecting only objects no more than a million times fainter than their parent star.

1.3 Search for young planets

The second key to detecting extrasolar planets with current technology is selecting for youth of the target stars and planets. When planets form, gravitational accretion releases considerable heat that only slowly leaks away; models predict that a Jupiter-mass (M_J) planet that is only 10 million years (Myr) old would have an effective temperature of 600 – 800 K. Advantageously, such planets do not radiate as black bodies; strong opacity induced by molecular species such as methane and water blanket the mid-infrared range and cause the planets to emit strongly in the near-infrared (Burrows et al 1997). A 1 M_J, 10 Myr planet is only 10^5 times dimmer than its star – detectable with current technology.

The very youngest stars, though, are not ideal targets for such a search in that they are relatively distant – the ~2 Myr stars in the stellar nursery in the Taurus region are ~130 parsecs away. Since planets cool slowly during their first 10-20 Myr, it is better to look for stars that are slightly older than Taurus but significantly closer. Unfortunately, stars generally remain in their nurseries for only a few million years; 10 Myr nearby stars are not located in convenient easy-to-identify clusters like Taurus but must be picked out from amidst their middle-aged counterparts using diagnostics such as X-ray emission or motion.

2 Results

2.1 Observations of young stars

Our UCLA collaborators are one of the leading groups in identifying such young field stars. (Zuckerman et al 2001, Zuckerman and Song 2004a, 2004b). They have identified ~200 new young stars, generally with ages of 5-20 Myr and distances less than 60 parsecs. Access to such a large sample is crucial to companion searches such as ours; while the frequency of planets in wide orbits around other stars is of course unknown, experiences in both radial velocity searches and direct imaging searches indicate that detectable planetary and brown dwarf companions are sufficiently rare (1 to 5% of stars having such companions) that one must survey 100-200 stars for our sample to be statistically comparable to the close-in detections.

During the course of the project we carried out observations of ~120 young stars using the Keck AO system. Initial analysis of the data by graduate student Denise Kaisler revealed a few candidate companions, though none appears to have a high probability of being a true planet (Kaisler et al. 2003.) We have also observed a large number of binary and dusty stars (e.g. Kaisler et al 2004.) A more detailed analysis is now being carried out by postdoctoral researchers at LLNL and UCLA and will be reported in a future publication. Figure 2 shows our sensitivity (expressed as detectable companion mass as a function of orbital radius) for a typical target.

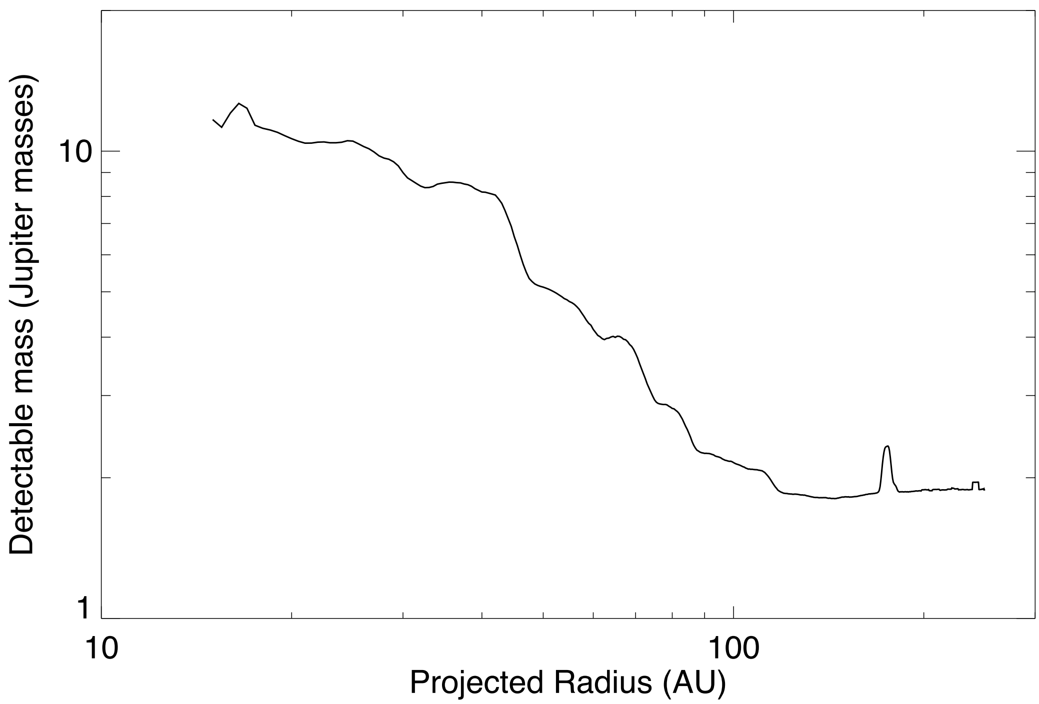

Figure 2: Sensitivity (expressed as detectable companion mass as a function of radius) for a typical target in our survey (d=50 parsecs, age=30 million years.)

. Although we have limited sensitivity on solar-system-like scales (5-40 AU), we can exclude wide-orbit planetary companions at a statistically significant level.

2.2 Observations of dusty stars

Several young and/or nearby stars are surrounded by circumstellar rings of dust, analogous to dust associated with the Kuiper Belt in our solar system, showing clear structure that indicates gravitational perturbation by an unseen object. These dust rings take a wide variety of shapes, ranging from well-defined rings with very high optical depths, through clumpy or broken rings such as that surrounding Epsilon Eridani, to pairs of asymmetric clumps such as seen in mm and sub-mm imaging of Vega. Kuchner and Hohlman (2003) produced a taxonomy of potential dust structures generated by the gravity of a varying range of unseen planetary companions; if true, these models indicate that certain dust geometries may be signposts of relatively high-mass - and hence potentially directly detectable - extrasolar planets. We have observed several such stars: the older nearby stars Vega and Epsilon Eridani, the very young star HR4796 with its massive dust ring, and the young nearby star GJ803, which is the young star closest to the sun and the perfect target for such observations.

Figure 3 shows our observations of Epsilon Eridani. We obtained a series of long-exposure (1-2 hour per position) wide-field images of four fields offset from the star itself to search for companions located in the circumstellar dust ring. Several candidate companions were identified and followed up to determine their true nature; all proved to be background objects (Macintosh et al 2003).

For more recent observations, we developed a new strategy of imaging in the thermal infrared, where AO Strehl ratio is highest and warm planets are significantly brighter. Figure

4 shows four hours of Keck AO 3.8 micron observations of the young dusty star HR4796. Although no planets are seen, a narrow elliptical dust ring surrounding the star can be detected. This ring has never before been seen by adaptive optics, and comparison of our long-wavelength observations to short-wavelength Hubble data will help determine the size and properties of the interstellar dust.

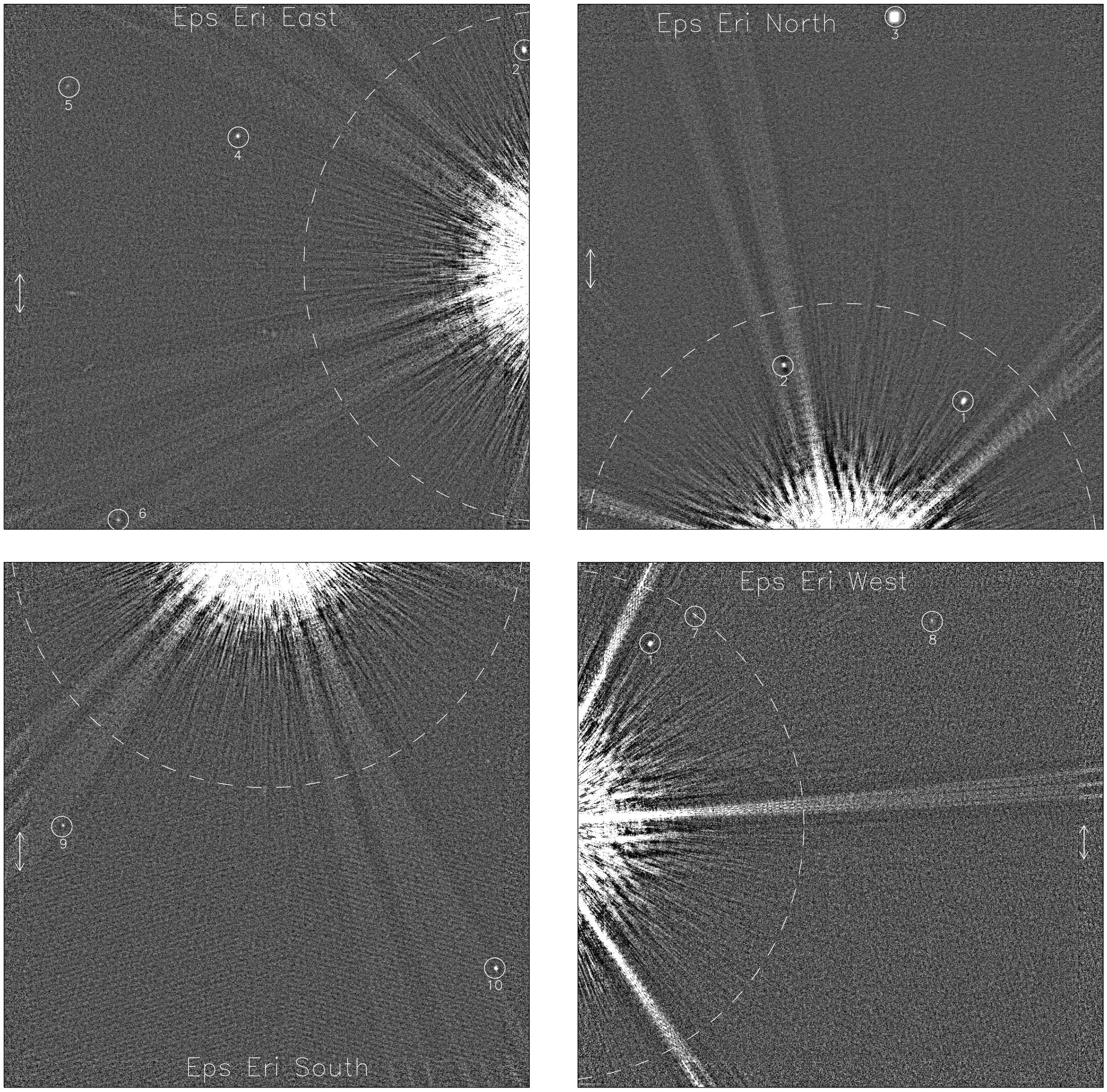

Figure 3 a-d: Deep Keck AO 2.1 μm images of Epsilon Eridani, offset 24" E (a, upper left), N (b, upper right), S (c, lower left) and W (d, lower right) from the star. The dashed line indicates a radius of 20 arcseconds from the primary star, and the arrow a length of 3". Candidate companions (all now known to be background objects) have been circled

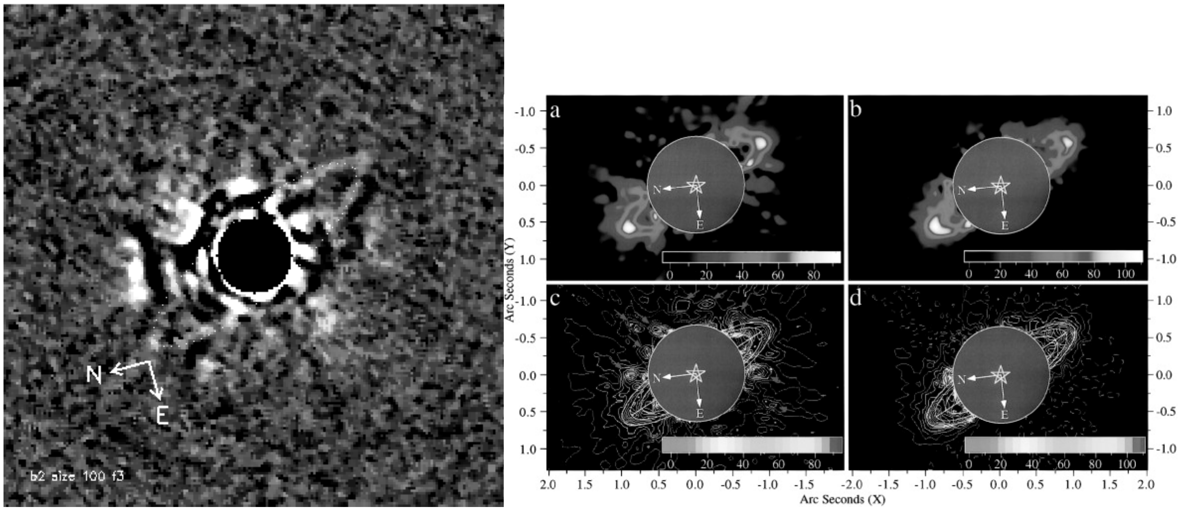

Figure 4: Left: Close-up of a Keck observatory 3.8 micron adaptive optics image of the young star HR4796 showing a tilted dust ring (most clearly visible at ~2:00). The star is masked out by a occulting spot, and the image has been processed to highlight the ring, which results in white/black artifacts close to the star. Right: Hubble-space-telescope near-infrared images of the dust ring from Schneider et al 1997. The narrow dust ring could be confined by an unseen body such as an extrasolar planet.

Figure 5 and Figure 6 show our observations of GJ803. To distinguish true companions from speckle artifacts we used a variety of image processing techniques. One of the most powerful was to take advantage of the sidereal rotation of the sky. Making a series of observations with the science camera fixed relative to the telescope causes the field of view to rotate on a telescope like Keck. True planetary companions will appear to rotate in successive images, while artifacts internal to the telescope or camera/AO system will be fixed. Properly combining images in a sequence will therefore significantly enhance sensitivity (Figure 5.) Calculating our sensitivity using models of extrasolar planets, we would have been able to detect 1-2 Jupiter-mass planets at solar-system-like separations (5-10 AU) – the first direct imaging observations that could have detected a solar system like our own. A paper on these observations (Macintosh et al. 2005) is being submitted to the Astrophysical Journal.

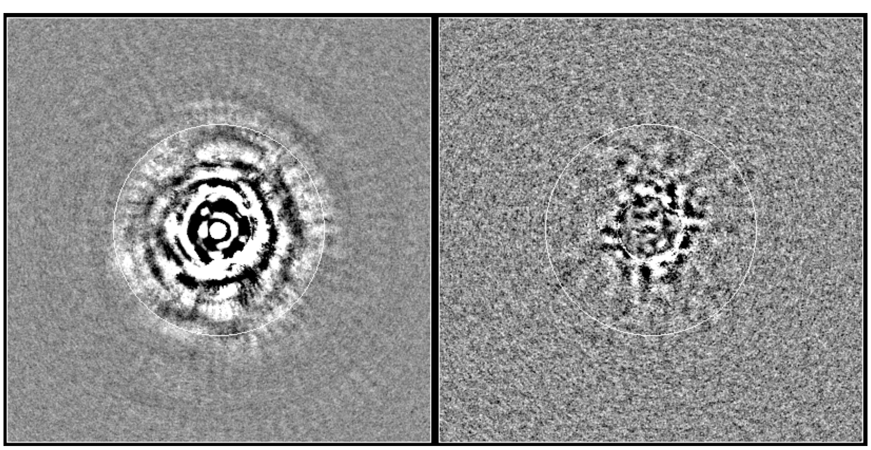

Figure 5: Deep 3.8 micron images of GJ803 obtained as a series of short exposures in a stationary-pupil mode. The images have been high-pass filtered to highlight point-source

companions. The left-hand image has been combined with conventional techniques. The right image has been processed taking advantage of field rotation to distinguish artifacts (which will remain fixed) from true companions (which will rotate with the parallactic angle) using an algorithm developed by Christian Marois (Marois 2004.)

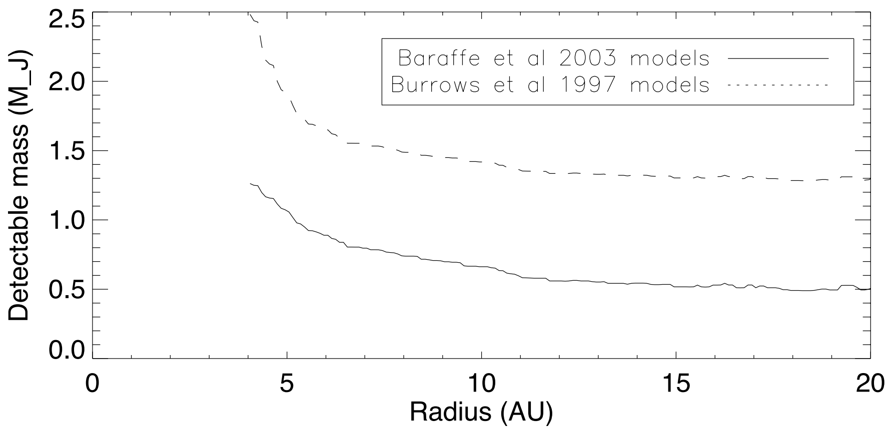

Figure 6: Detectable planet masses (evaluated at the 6-sigma level using a robust detection algorithm) as a function of radius for GJ803 (12 Myr, 10 pc) from our 2004A observations. Curves are given for both Burrows et al 1997 and Baraffe et al 2003 planet models.

3 Future work

Although for ideal targets such as GJ803 we could have detected 1-2 Jupiter-mass planets at 5-10 AU separations, for a more typical target we are only sensitive to massive planets (5-10 M_J) in wide orbits (50+ AU). While the presence or absence of such objects places important constraints on planet formation models, our survey does not reach the more compelling goal of being able to image solar systems resembling our own. It is now possible to design and construct next-generation "Extreme" adaptive optics systems designed specifically for planet detection and capable of much greater sensitivity.

During our survey we have carefully modeled the performance of the telescope and adaptive optics system we use. These models show that for the planet-detection mission current AO systems are limited both by their low Strehl ratio (~0.5 in the near-infrared) and by residual static wavefront errors in the AO system, camera, and telescope.

The Strehl ratio (S) of an optical system refers to the ratio of the peak intensity of the image of a point source to the theoretical maximum for a system of that aperture. More broadly, it is a measure of what fraction of the light is properly concentrated into a diffraction-limited core. The Keck AO system, with S ~0.4-0.6, has 60 to 40% of the light remaining in a broad diffuse halo (Figure 7). The sensitivity to planets goes roughly as S/(1-S).

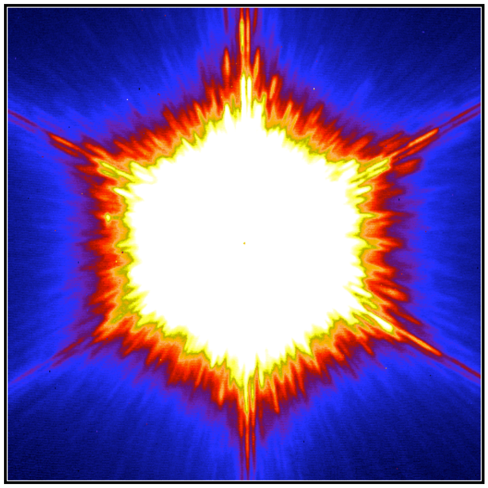

Figure 7: Keck AO image of a young star. The star is surrounded by a halo of scattered light with a complex pattern caused by the hexagonal shape of the segmented Keck primary mirror and residual optical errors in the telescope and AO system.

The Strehl ratio of current AO systems is limited by their small (~200) number of degrees of freedom, which is in turn set by the available deformable mirror technology and the need to operate with dim laser guide stars. Deformable mirrors are now available with 1024 actuators with 4096 actuators possible soon. A dedicated “Extreme” AO system (ExAO) designed specifically for planet detection could achieve S~0.95, an enormous increase in sensitivity over current AO.

Based on our Keck AO observations and work funded by the NSF Center for Adaptive Optics, we have designed such a next-generation system (Macintosh et al 2004a, 2004b.) We developed several innovative concepts, including a spatially-filtered wavefront sensor (Poyneer and Macintosh 2004) which may be applicable to a wide range of AO problems including laser beam control.

Our group was selected by the Gemini Observatory to carry out a detailed conceptual design of an ExAO planet-finder, with the design study completed in March 2005. If our team is selected for construction of the full system, it would be complete by 2009 and capable of detecting planets ~100 times fainter than those we can currently see with Keck AO (Figure 8.)

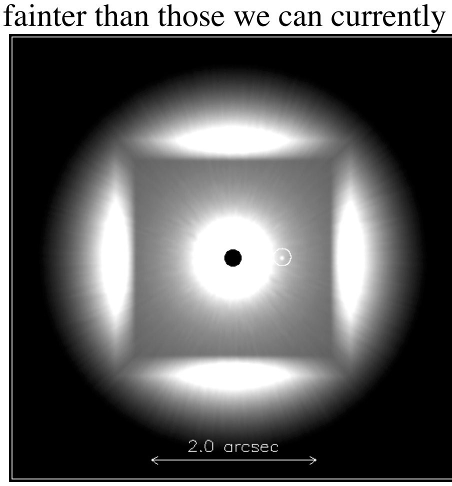

Figure 8: Simulated 450 second ExAO integration showing an extrasolar planet (circled) in a 5 AU orbit around a solar-type star at 10 pc. The star is located behind an occulting spot; residual scattered light from the star leaks out to form the bright region in the

center. The square "dark hole" region, 2.6" on a side, is produced by the combination of high-order AO with an advanced wavefront sensor design (Poyneer and Macintosh 2004.)

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