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Adaptive Optics Imaging of Faint Companions: Current & Future Prospects

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Abstract. I briefly describe how diffraction-limited imaging with adaptive optics (AO) can detect low mass companions (young massive brown dwarfs for example). I review how current curvature AO systems can already detect point sources 1 million times fainter at separations of 3 arcsec in median seeing (0.65 arcsec). I show real examples of very faint companion detections made with the University of Hawaii AO system located at CFHT on Mauna Kea around the young (2 Myr) nearby (132 pc) Herbig Ae/Be star MWC480. Moreover, I show that the four faint (H=18–19 mag) companions within 6 arcsec of MWC480 (H=7.0 mag) are unlikely to be physical since they are non-common proper motion objects. I point out that the current 8–10m class AO systems will detect even fainter companions at closer separations with 0.03–0.06 arcsec NIR imaging.

1. Introduction

Current curvature AO systems can already detect point sources almost 1 million times fainter at separations of 3 arcsec in median seeing (Close et al. 1998). In the near future AO on all 8–10m class telescopes will achieve these contrasts at only ~ 1 arcsec instead of 3, which will allow one to start probing giant planet masses at 10 AU around nearby low mass stars.

Based on these sensitivities and the Brown Dwarf atmospheric models of Burrows e al. (1997) detection limits with such an AO system (as CFHT) can be predicted. For example, current AO systems could detect a 5 Gyr old system at a distance of 3 pc consisting of an M4 primary and an 80 Jupiter mass companion at 8 AU (2.7 arcsec) separation. Another example would be that of a younger system ($\sim$1 Gyr) with a 10–80 Jupiter mass companion at respective separations 180–24 AU in orbit around a M1 star at 10 pc (in a 6 minute exposure at a 4m telescope with AO at J band). Future 8–10m class telescopes will be able to detect the same masses $\sim 2-3$ times closer than this.

The potential for current and future AO systems to detect these wide systems (with periods $>$ 50 years) is the perfect complement to the radial velocity or astrometric searches that require shorter periods for detection.

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2. Observational Procedure to Detect Faint Companions with AO & an Example Result with MWC480

1) Take both short unsaturated, and then deep saturated AO images of the target primary star. Make sure to dither (or jitter) the star around the science camera FOV.
2) Replace the saturated core of the image with the scaled unsaturated data. Median filter all the data to remove scattered light ghosts and flat field errors, as well as removing bad pixels and poorly corrected frames.
3) Use Fourier filtering to remove the large 1–2 arcsec uncompensated AO halo.
4) Search for diffraction-limited, round point sources in the final image.
5) One should then be able to detect objects of several (>4 M_J) Jupiter masses at 1–10 arcsec from a young central star in the near IR. Or in other words objects that are ~1 million times fainter at ~3 arcsec from the central star. A detailed account of this performance (AO sensitivity VS separation) is given in Close et al. (1998). See Figure 1 for detail on how sensitive a 3.35m AO system is at J band with 30% Strehl ratio (typical for 0.7 arcsec seeing - before AO correction).
6) Follow-up observations should be taken one year later to determine if these faint objects are both real and physically associated with the target star. *Only through confirming that the faint objects are common proper motion objects can one have some confidence that these are true physical companions.*

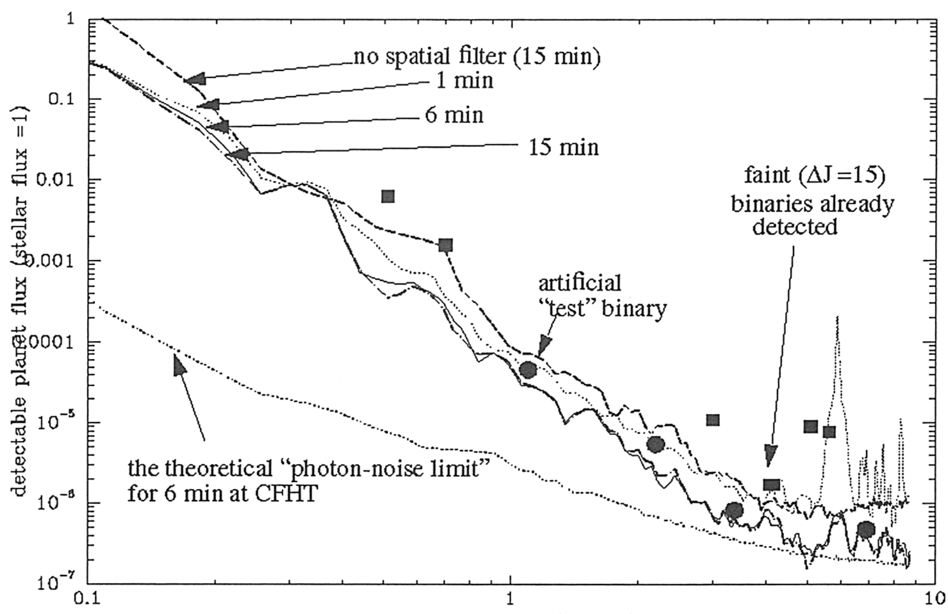

Figure 1. U of Hawaii's AO system's point source detection sensitivity at J to 3σ detections (6 min) of faint companions (called "planets") with the CFHT 3.35m telescope and a Strehl ratio of 30% at J.

In 1997 we discovered MWC480 to have four faint "companions" located at distances of 4–6 arcsec with magnitudes of 17.67, 18.80, 19.24, & 19.37 at

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H (since MWC480 has H$\sim$7.0 these are all extremely faint companions). At MWC480's distance of 132 pc and age of $\sim$ 2 Gyr, these companions could be planetary companions of mass $\sim 5 - 10$ Jupiters (Burrows et al. 1999) *-if they are physically associated with the young Herbig Ae/Be star MWC480.* If they are physical then these faint objects should share MWC480's proper motion (of 6.25 mas/yr east and 28.3 mas/yr south) on the sky from Hipparcos data.

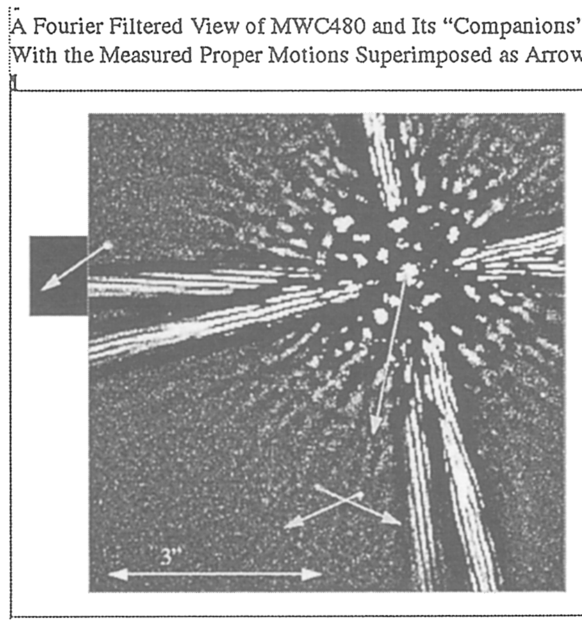

Figure 2. The Fourier filtered image of MWC480 at H with proper motions superimposed. These proper motions are magnified by 100x w.r.t. the image scale. The accuracy of these AO proper motion measurements are 0.005 arcsec/yr. The H magnitude of the companions shown are (from left to right) H=17.67, H=19.37, and H=19.24 (MWC4380 has H=7.0). Therefore, these companions range from 20,000 to 100,000 times fainter - yet are easily detected inside of 4 arcsec from the primary star with AO. The proper motion of MWC480 is depicted with the big arrow which equals 6.25 mas/yr proper motion east and 28.3 mas/yr south. The proper motions of all the other nearby stars are smaller than that of MWC480 and are also in different directions. Therefore, none of these faint companions are true physical companions, and so are likely just background faint M or K type stars. Note the H=18.80 companion is hidden by the northern spider arm in this image and so there was no accurate proper motion measured for this source. (East is to the left, north is up)

Follow up AO observations in 1998 and 1999 with the CFHT PUEO curvature AO system (Rigaut et al. 1998) suggested in fact that these faint stars appear to have systematically less proper motion based on 2.25 years of observation (5 different epochs). As is clear from Fig. 2, none of these companions

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are common proper motion and so they are likely just background stars (which is possible since MWC480 is near the galactic plane). Hence, we can likely reject the hypothesis that these are physically associated with MWC480. This is an excellent example of the sensitivity (measuring 0.01 arcsec/yr proper motions of objects 100,000 times fainter) that will become commonplace with AO in binary star research.

3. The Future: High Spatial & Low Spectral Resolution with AO

Future science with AO will commonly detect close companions (within 1 arcsec) that are a million times fainter than the primary. Moreover, such contrasts will allow one to take spectra of these extremely faint companions with a low resolution spectrograph. I estimate that an 8m telescope with a good AO system will be able to produce an $R \sim 30$ spectrum of a 5 Jupiter mass planet around a M primary star at 10 AU ($D = 10$ pc) in about 5 hours of exposure time to get $S/N = 5$. The combination of high spatial resolutions (on the 0.03–0.06 arcsec scale) and spectral techniques will become common. For a complete review of AO techniques present and future see Close (2000) and the references within. In short, we are in a very exciting time for AO, right now we are witnessing the change from space-based high resolution imaging to ground-based AO observations on 8-10m telescopes in the near IR. This will revolutionize binary star research in the NIR.

4. Conclusions

The case of MWC480 shows how important it is to use proper motion to confirm physical association with faint companions. However, it is clear that AO is a powerful direct imaging technique to detect massive planets and brown dwarfs. In particular, the potential for AO systems to detect wide systems (with periods > 50 years) is the perfect complement to the radial velocity or astrometric searches that require shorter periods for detection. The use of current and future 8-10m class AO systems will allow 0.03–0.06 arcsec images to be commonplace, and so the nature of binary star research in the NIR will be vastly improved forever.

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