Science with CFHT's future high dynamic range AO system PUEO NUI

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ABSTRACT

Rethinking the efficient use of 4m-class telescopes in the dawning era of larger facilities is a timely but challenging debate. The extensive use of PUEO for imaging (and now spectroscopy) has kept CFHT at the forefront of scientific research with adaptive optics since its commissioning in 1996. Even though larger facilities are now starting to think about ways to implement high order AO systems, we believe the medium size of the CFHT and the excellent quality of the site on Mauna Kea is a perfect combination to reach the highest performances with a high order AO system.

The fields of application of high order adaptive optics are exciting: They include extremely high contrast imaging and coronography in the near-infrared and diffraction-limited imaging in the optical, with the corresponding gain in angular resolution. In this paper we present a quick description of a few specific astrophysical problems that would benefit from an upgraded AO system at the Canada-France-Hawaii Telescope.

More technical details about the upgrade of PUEO are presented by Lai et al. and Cuillandre et al. in these proceedings, see papers **4839-78** and **4839-31**.

Keywords: High contrast imaging, adaptive optics, science case, CFHT

1. INTRODUCTION

Many fields of high dynamic range astronomy have already been touched by CFHT's PUEO, from Solar System physics to Galactic and Extragalactic astronomy. An upgraded PUEO would give CFHT a resolution at 600nm that would rival Keck's, Gemini's, and VLT'S at 2μm. Observations in the optical will benefit from lower sky background and higher quantum efficiency, lower read-noise detectors than in the near-infrared. In the near-infrared, the new PUEO would successfully challenge HST / NICMOS. It would produce images with better angular resolution and comparable Strehl ratios. The NICMOS cameras NIC1 and NIC2 have field-of-views of only 11" and 19.2" respectively, with NIC2 being undersampled. KIR's corrected field-of-view behind PUEO is larger by a significant amount and correctly sampled.

In the following sections we describe a few scientific problems that would benefit from an upgraded AO system at the Canada-France-Hawaii Telescope

2. SOLAR SYSTEM

2.1. Asteroids

There are several distinct dynamical populations of asteroids, each of which has likely had a different collisional history. They are likely to have different compositions and structures. Past studies using adaptive optics have focused so far on the main belt asteroids (e.g., Ref. 1). But there are other populations, the near-Earth asteroids (NEA), the Trojans (at the Lagrangian points of Jupiter), the Trans-Neptunian objects (TNO) or the Kuiper Belt objects (KBO). *The problem is that these other populations are both faint and will have small primary/secondary angular separations.* However, as recently demonstrated[2] , there are many occurrences of KBOs passing sufficiently close to bright guide stars to make such observations possible on a nightly basis.

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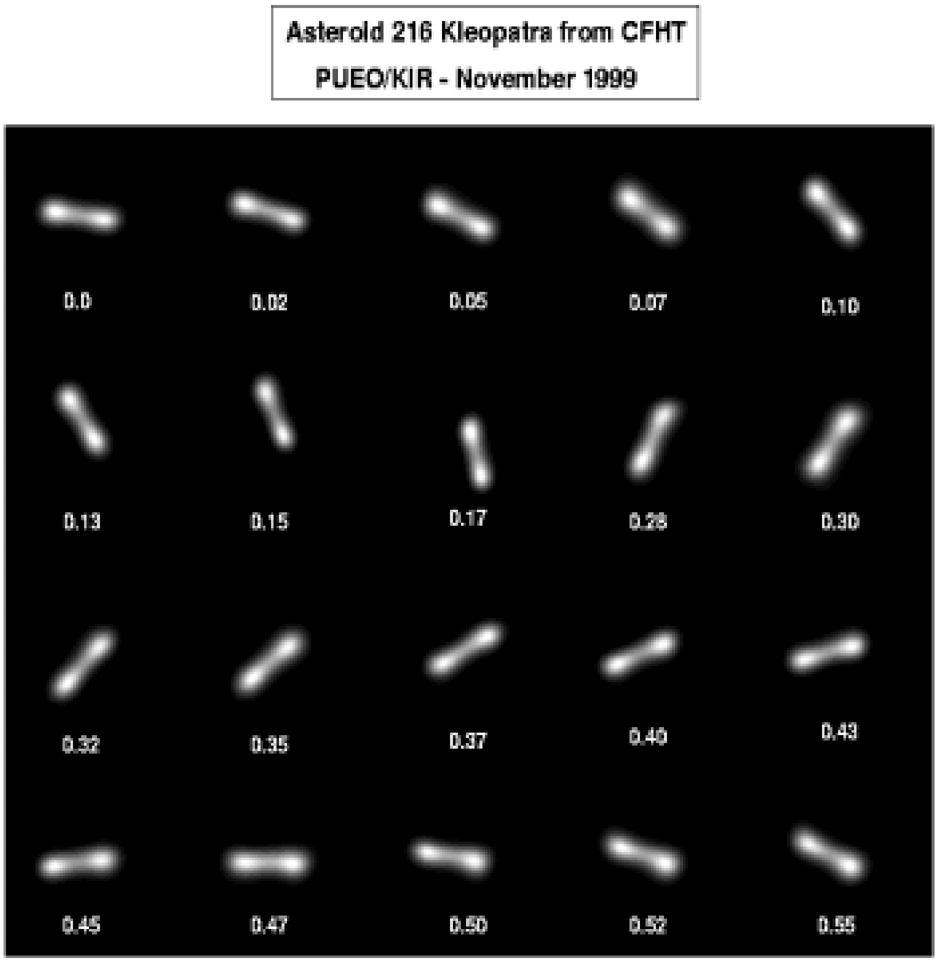

Figure 1. PUEO H-band images of (216) Kleopatra. Although not part of a "pair" of asteroids itself, an impressive demonstration of the power of adaptive optics is shown in this series of frames of asteroid (216) Kleopatra. They were obtained in November 1999 during a four-hour period. They clearly show the asteroid to be elongated, with a rough 'dog-bone' shape. There is a solid 'bridge' of material between the two bright ends. IMage courtesy of Christophe Dumas (JPL) and W.J. Merline (SWRI).

Previous work with adaptive optics has made abundantly clear that the progress toward further understanding of these objects is limited by (1) requirements for the highest possible resolution, this is because all known moons are found relatively close to the primaries, thus we are probably missing a large fraction of them because they are too close, (2) requirements for very high contrast – this is because most known moons are much fainter than the primaries, so they are hard to detect, and we are probably missing many smaller moons, and (3) the amount of large telescope (plus AO) time available – there are clearly more objects than we can observe with the few nights available.

A new AO system such as proposed here would make a tremendous difference in the search for asteroid satellites, as both higher resolution and high dynamic range are the main goals of this upgrade. Many bodies in the Asteroid Main Belt could be resolved by CFHT. The linear resolution , for an asteroid at 1AU, is about 30km at K and 10km at R. The largest Asteroids are already resolved by PUEO (e.g. 216 Kleopatra[3]). Better resolution would allow to resolve a larger sample and better constrain their morphological parameters, namely their shape, spin, and mineralogical features at the surface. Solving these issues is important to understand the formation of these bodies, their dynamical history, and the history and evolution of our solar system.

2.2. Planets and their satellites

The higher image quality will permit the detection and study of fainter satellites of the main planets. PUEO in K-band was able to detect Puck and Portia, two faint (V$\sim$21) satellites of Uranus[4] . Also, planetary atmospheric features are observable from the ground on Neptune (e.g., Refs. 5, 6). Better images and more monitoring would permit to detect and better define the orbital parameters of many of these faint satellites. Finer details in the atmosphere of Titan, the volcanos on Io, the structure of rings and arcs, the clouds on Neptune and Uranus but also on smaller satellites, never studied before for lack of resolution, could be detected *and monitored* by an upgraded PUEO.

3. THE MASS-LUMINOSITY RELATION OF LOW-MASS STARS AND BROWN DWARFS

The IMF, the mass distribution of stars, is a fundamental indicator of the content of our Galaxy. A good knowledge of this distribution is mandatory if ones hopes to understand star formation on galactic scales. The

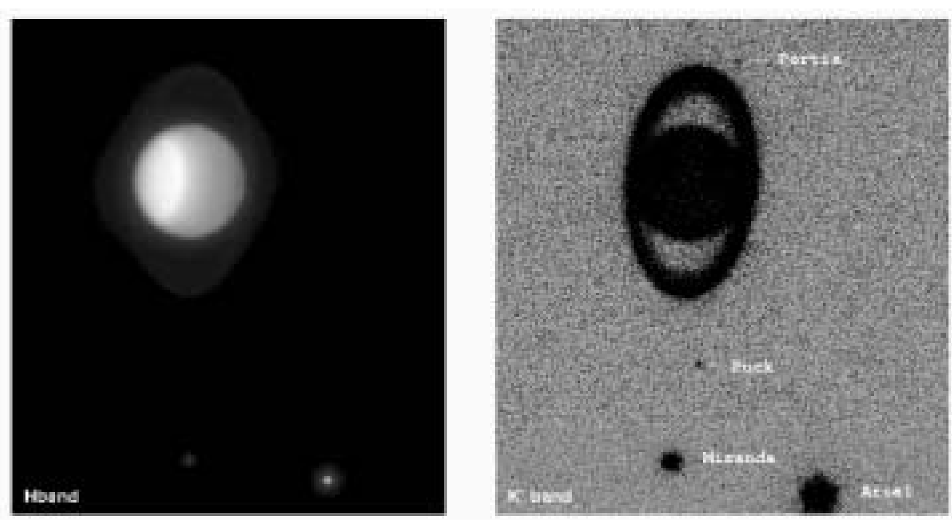

Figure 2. Left Panel: H-band image of Uranus showing structure in the upper atmosphere near the polae of the planet. **Right Panel:** Deep PUEO K-band image showing faint satellites of Uranus. This is the first image of Portia ever obtained from the ground. The satellite is only 110km in diameter. Image courtesy of Christophe Dumas (JPL).

IMF is fairly well known for solar-like or more massive stars[7] . However, the lower main-sequence and the substellar part of this distribution remain poorly known, both observationally and theoretically. Unfortunately, that's where most of the stars are found, at least in young open clusters like the Pleiades[8] . Their role elsewhere in the Galaxy remains poorly known. Are they numerous enough to be dynamically important in clusters or at larger scales? The best way to accurately estimate the mass of a star is to resolve the orbits in binary systems, knowing both the radial velocity and the visual orbital parameters. Spectacular advances were made in recent years, partly based on work with PUEO, and masses can now be estimated to an accuracy of ~0.5-1% for the best cases (e.g., Refs. 9, 10). But the road to a full characterization of the mass-luminosity relation, down to planetary sized bodies, is still long. An upgraded PUEO would allow to find fainter objects closer to bright stars because of improved contrast and finer PSF. Low-mass objects are intrinsically very red and observations in the optical are not optimal, but the gain in resolution would allow to follow the orbits of closer systems at critical points in their orbits, hence increase the size of the sample. There are more than 1000 nearby bright stars that need to be looked at!

4. THE EVOLUTION AND DISSIPATION OF YOUNG ACCRETION DISKS

Our understanding of the planet formation process will benefit from better observations of accretion disks around young stars as they evolve toward the main sequence. HST observations of HD 141569 give a perfect example of what can be expected from the gain in resolution by going to shorter wavelengths with AO. Coronographic images of the disk surrounding the Herbig Ae star HD 141569 were obtained at 1.6 μm with HST/NICMOS[11] and at 0.7 microns with HST/STIS[12] . The NIR image shows the presence of the dust disk around the star, and clear suggestions of asymmetry. However, the scattering cross section of the dust located the disk is almost 10 times larger at 700nm than it is at 2.2 microns. This fact, coupled to a diffraction-limited PSF that is 10 times finer (in surface) allows to probe the dust disk of HD 141569 with unprecedented details in the visible domain. Arcs and rings of scattered light can be seen. They are suggestive of gaps in the disk, but dynamical models are needed to confirm this suggestion. Surveys, with or without coronographs of young stars with an upgraded PUEO would allow to understand in great details how the disks evolve. Imaging gaps, finding their positions and their widths, will provide useful clues to understand not only the evolution of disks but also the formation of planets, from the coagulation of small grains into planetesimals to the possible migration of giant planets.

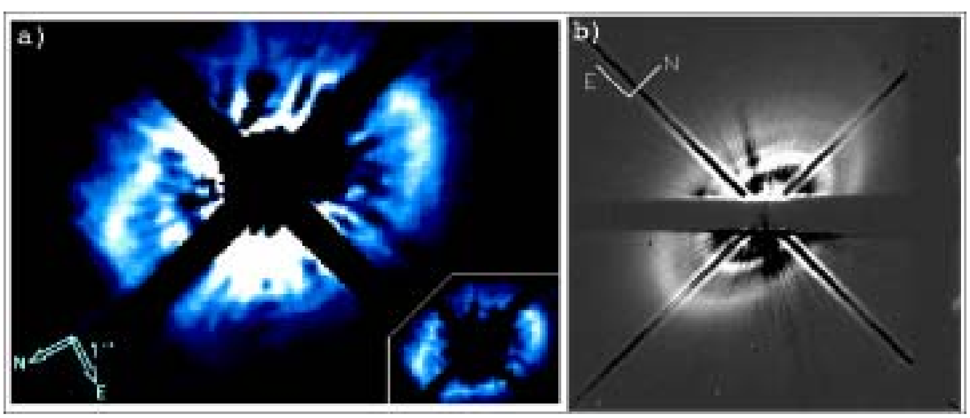

Figure 3. Left Panel: HST/NICMOS + coronograph 1.6 micron image of the circumstellar disk around HD 141569. This is the disk discovery image. Important residuals from the PSF subtraction are evident and limit the dynamic range close to the mask. Image from Ref. 11. **Right Panel:** HST/STIS + coronograph 0.7micron image of the disk around HD 141569. The improved resolution leads to a much better view of the disk structure. Image from Ref. 12.

5. THE MORE SPECULATIVE EXTRASOLAR PLANET DIRECT DETECTION

The detection of extrasolar planets is a popular topic these days. About 90 hot and massive (Jupiter-like) planets are now known to orbit solar-like stars. These objects are more massive than the Earth and likely not bearing life. However, the search as only begun recently and there is no doubt that, as the time span increases and the sensitivity of the instruments improves, lighter Earth-like planets will be discovered around very nearby stars. The planets known today are all orbiting nearby stars and they do so at distances less than a few AU. See Fig.4. In the most favorable cases, they are separated visually by 0.5arcsec or more from their parent star (e.g., Eps Eri b). *Angular resolution is therefore not the only limitative factor to "resolve" the planet from the central star. It is the glare from the central star itself that drowns the signal of the planet and forbids its direct detection... so far!* PUEO's very best images today can reach Strehl ratios of 70% or so, with representative average around 45% at K-band. This means in practice that about half the energy contained in the light-beam reaching the detector remains in the uncorrected seeing halo at 2.2 microns. The interest of a higher order AO system to look for extrasolar planets lies in the progressive suppression of this unwanted seeing halo. Figure 5 shows radial cuts of PUEO NUI's expected PSFs in K and R bands. In the K-band, the increase in dynamic range provided by an upgraded PUEO is maximum for small separations. It is about a factor of 10 between 0.3"

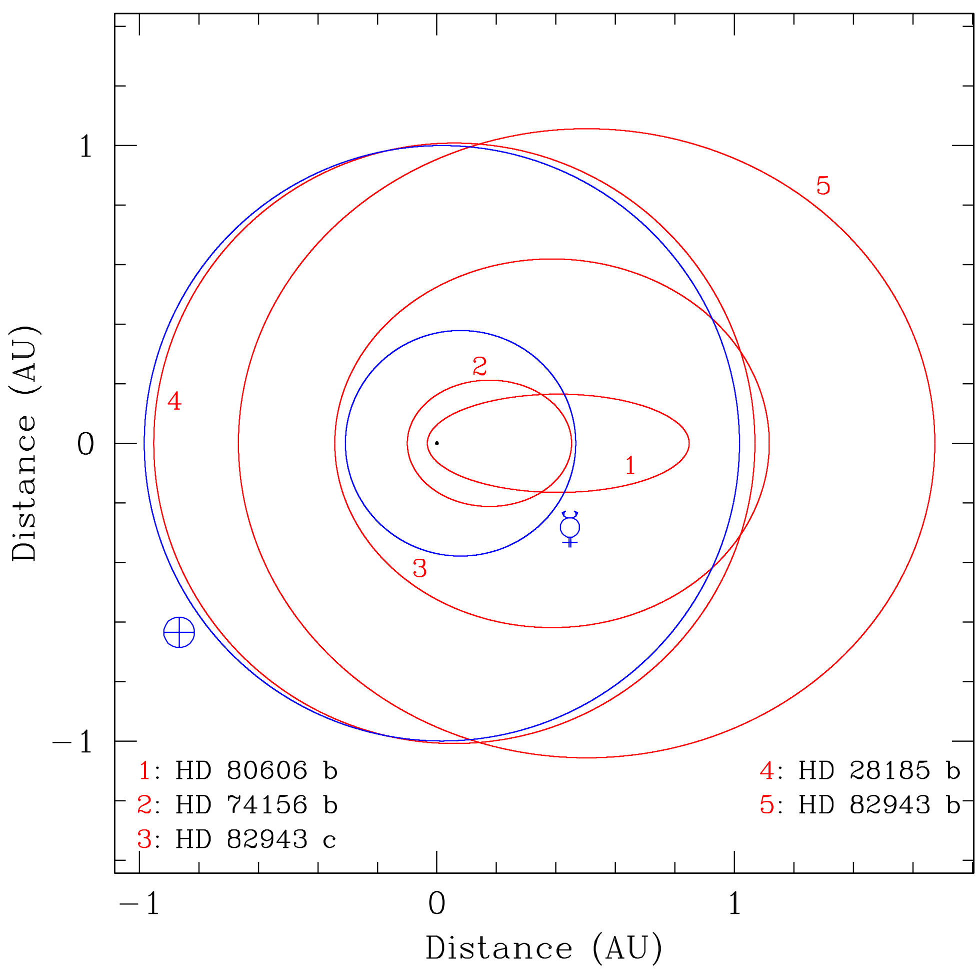

Figure 4. Orbital plot of newly discovered Jupiter-like planets compared to the Sun-Earth system. The images shows that orbits larger than 1AU are often found. These could be easily resolved by CFHT if located at d < 10pc. In this volume, there are several hundreds of stars that can be looked at for planets with adaptive optics. Image courtesy of Stéphane Udry, Observatoire de Genève, Switzerland.

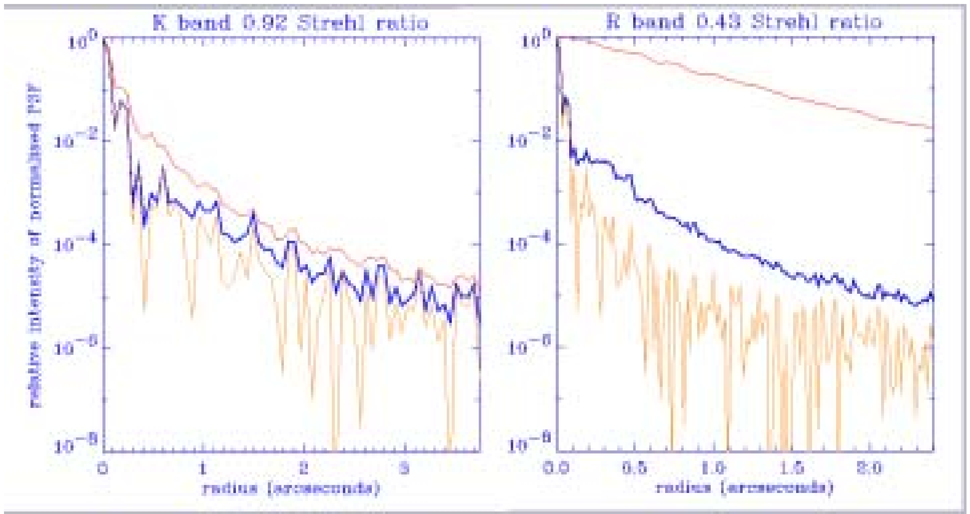

Figure 5. Radial cuts of PSFs in K- and R- bands, left and right panel respectively. The lowest curve shows the diffraction pattern of the CFHT, the middle one is PUEO NUI with 104 electrodes, the upper one is the current 19 electrode PUEO. The increase in dynamic range provided by the upgrade is the ratio of the latter two curves.

and 0.7". The more stable PSF of an upgraded PUEO also means that coronographs can be used efficiently, further increasing the dynamic range achievable. In the R-band, the gain is about 1000 everywhere with respect to the current PUEO!

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