Scientific Results from the MMT Natural Guide Star Adaptive Optics System

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ABSTRACT

The Natural Guide Star Adaptive Optics (NGS AO) system for the MMT Observatory is currently the only AO system in the world that uses a deformable secondary mirror to provide wavefront correction. This approach has unique advantages in terms of optical simplicity, high throughput and low emissivity. Here we present selected scientific results from the past year and a half of operation. Research with the AO system ranges from small scale structure around planetary nebulae, low mass stellar systems in the near IR, through to nulling interferometry in the mid infra-red.

Keywords: Adaptive optics, adaptive secondary mirror, scientific results

1. INTRODUCTION

1.1. THE AO SYSTEM

The AO system can be split into two main optical components - a deformable secondary mirror that produces the Cassegrain focus of the 6.5 meter monolithic mirror telescope (MMT), and an optical box that sits in front of the Cassegrain focus (known as the "top box") that contains reimaging optics that feed light to the wavefront sensor (WFS) camera. A tilted dichroic window on the science instrument reflects the visible light into the top box, whilst the infra-red science light passes on through to the instrument (see Figure 1).

By making the secondary mirror the wavefront correcting element of the system, the light entering the science instrument does not suffer the attenuation and extra thermal background that other AO systems introduce, and the physical design of the secondary mirror minimises ghost images and leads to a very smooth point spread function (PSF). More details can be found in Ref. 1 and the references therein.

Currently there are two instruments that are optimised for use on the AO system - BLINC/MIRAC3, a near to mid-infrared imager and nulling interferometer, and ARIES, a $1.2 - 2.5\mu m$ near infra-red imager and high spectral resolution long slit spectrograph.

1.2. OBSERVING RUNS

We currently operate during bright time with a single two week run per trimester, and we have labelled our observing runs[2] starting with our first engineering run on the telescope as Run 0, listed in Table 1.

The last three runs are notable in that we have lost a significant amount of time to unseasonably bad weather conditions, despite which we have obtained useful data for a wide range of scientific targets and programs. Currently the MMTAO system is oversubscribed by a factor of 50%, and as the system matures we expect this fraction to increase.

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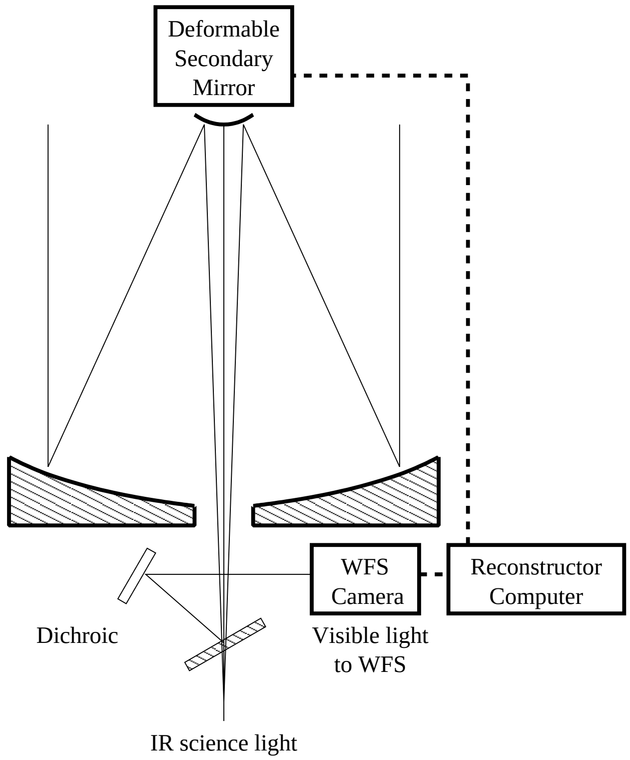

Figure 1. Cartoon of the MMT AO system. Light from the primary is reflected by the deformbale secondary to the Cassegrain $f/15$ focus, where a long pass dichroic reflects visible light through reimaging optics to the wavefront sensor camera. Sensing images from the camera are fed through a reconstructor computer and control system to control the deformable secondary mirror.

Table 1. The MMT NGS AO runs, divided into engineering time, scientific observing time, and losses due to weather.

Run number	Date	Division of time eng, sci, lost	Science output
0	2002 June	100, 0, 0	—
1	2002 November	100, 0 ,0	—
2	2003 January	50, 30, 20	1 paper
3	2003 May	50, 30, 20	1 paper
4	2003 October	40, 20, 40	Data taken
5	2004 Feb	30, 20, 50	Data taken
6	2004 May	20, 30, 50	Data taken, 2 papers

2. MIRAC3/BLINC

MIRAC3 is a mid-infrared camera system[3] with a Rockwell SiAs 128 x 128 array and a selection of narrow band and wide band filters covering 4 to 25 microns. The nominal pixel scale is 0.09 arcseconds per pixel. The MMT AO thermal performance excels for the mid-IR wavelengths, as the science light sees no additional optics in the beam train and thus only thermal contributions from the primary and secondary mirrors. The emissivity of the telescope at 11 microns has been measured to be approximately 7%.

The PSF FWHM for the 6.5m MMT is 0.32 arcsec for 10 microns, and the AO system provides an extremely stable PSF for the MIRAC3 camera, allowing accurate PSF subtraction and image deconvolution to be performed. Typically the Strehl ratio at 10 microns is $98\% \pm 2\%$. This has resulted in a paper on imaging of post asymptotic giant branch stars[4] and other high angular resolution investigations.

Initial images of evolved stars with extended dust shells are seen in Figure 2. Other scientific programs have included looking for extended structure around red giant stars by exploiting the stability of the telescope's point spread function with the MMT AO system.

An addition to the MIRAC3 camera system is the nulling interferometer BLINC.[5] This takes two separate elliptical regions of the 6.5m mirror and interferes these two beams to null out light from the central star whilst allowing light from circumstellar material to pass through to the detector. By taking data for diffrent position angles on the sky, a graph of achieved null depth versus position angle can be obtained and the geometry of dust surrounding the star mapped out.

In the most recent runs data were obtained of AB Auriga and the initial results are shown in Figures 3 and 4. This variation of depth of null as a function of position angle implies an inclined dust disk geometry, and further observations are needed to refine this result. Earlier nulling data on Vega has been published.[6]

3. ARIES

The ARIES near infrared imager and spectrograph[7] is optimised for use at the $f/15$ MMT AO focus. The imaging camera saw both first light and first science in Run 5. The instument consists of two halves, an imaging camera and a high spectral resolution spectrograph. The imaging section was completed in 2003, whilst assembly of the high resolution spectrograph continues in the laboratory. The imaging section has seen tremendous interest from the local astronomical community, and science data has been taken in the past two runs.

Two examples of imaging with ARIES are shown in Figure 5 and 6.

4. OTHER SCIENCE

The MMT AO system has observed and obtained data on other scientific targets and these are in the initial stages of reduction. Objects range from mid-IR imaging of Ceres, through imaging of Titan and Io, to stellar clusters and detection of quasar host galaxies at $z > 1$ redshifts.

5. CURRENT LIMITATIONS

We are developing a unique optical system and in the process we encounter new challenges that are not faced by other telescopes. In particular we do not have a test setup that allows off-telescope calibration of the capacitative sensors on the mirror. A test stand utilising a four phase imaging interferometer and a Hindle reference sphere appears to be the simplest and most efficient solution for off telescope testing and calibration of the deformable secondary mirror, and we are expecting to have a test stand by the end of the year. For more details, see the paper by Miller et al. in these proceedings.

Analysis of the tip-tilt wavefront residuals from the wavefront camera showed a significant frequency contribution of 20, 48 and 82 Hz, with a cumulative amplitude of 20 milliarcseconds or more depending on telescope and wind conditions. These vibrations are outside the AO loop bandwidth of 18 Hz, and as a result, are not corrected by the system. This reduces the Strehl ratio at the $f/15$ focus by one third at H band. Even so, in nights of good seeing we achieve up to 25% Strehl, and by shifting and stacking video frame rate data taken by an Indigo engineering array we have measured Strehls of 40%. We are currently investigating both passive and

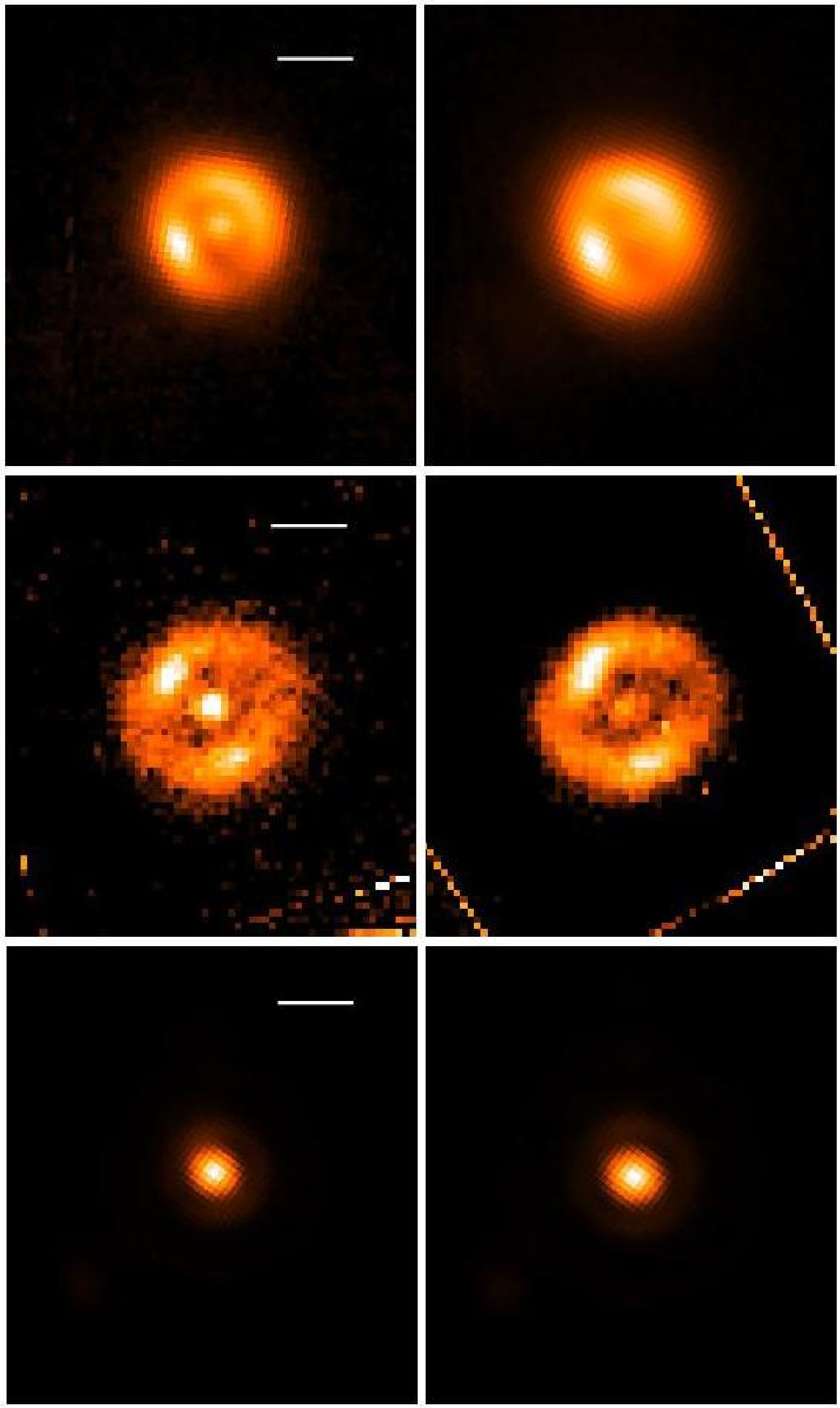

Figure 2. Images of planetary nebulae taken at $9.8\mu m$ and $11.7\mu m$ using MIRAC3. The white bar in the corner of each image is 1 arcsecond in length. Images courtesy of Benjamin D. Oppenheimer.

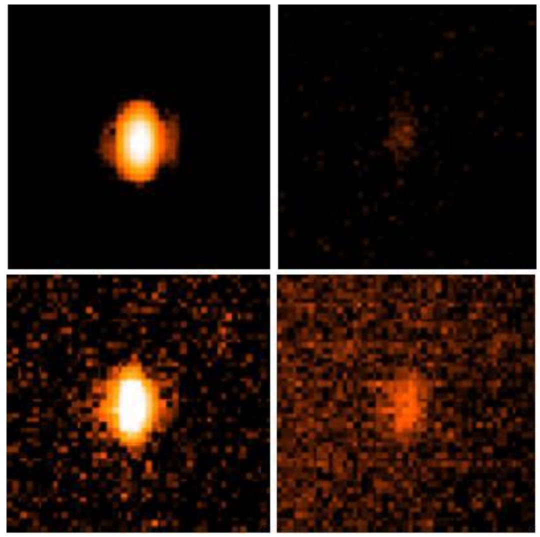

Figure 3. Nulling images of AB Auriga and a calibrator using BLINC/MIRAC3 taken during 2004 Feb. The upper row shows constructive interference and the best nulled image for a calibration star. The lower row shows constructive interference and the best null obtained for AB Auriga. The residual flux in the lower right-hand image indicates the presence of extended material around the star. Data courtesy of W. Liu and P. Hinz.

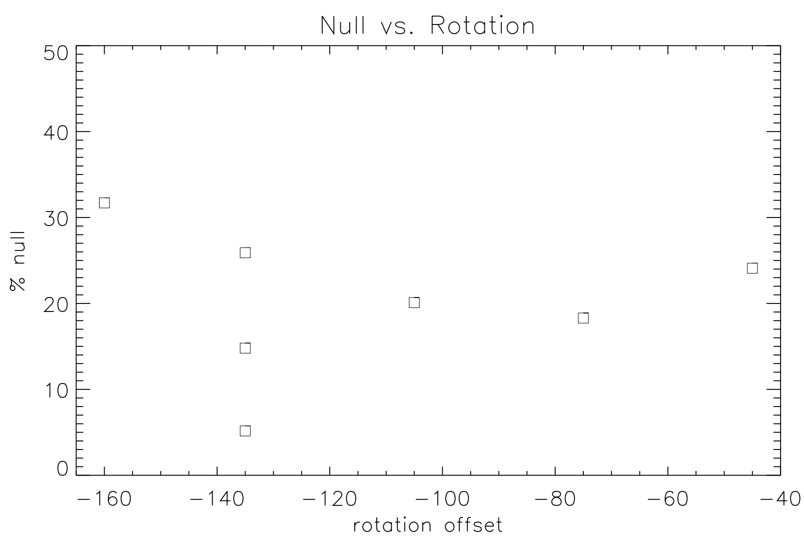

Figure 4.

The depth of the null obtained as a function of rotator angle on AB Auriga. The calibrator nulls are represented by the bottom two points at the -135 position. The science object is represented by all the other points, and the sinusiodal variation of the null as a function of position angle is indicative of resolved emission from an inclined disk. Typical error bars are ± 3%. Data courtesy of W. Liu and P. Hinz.

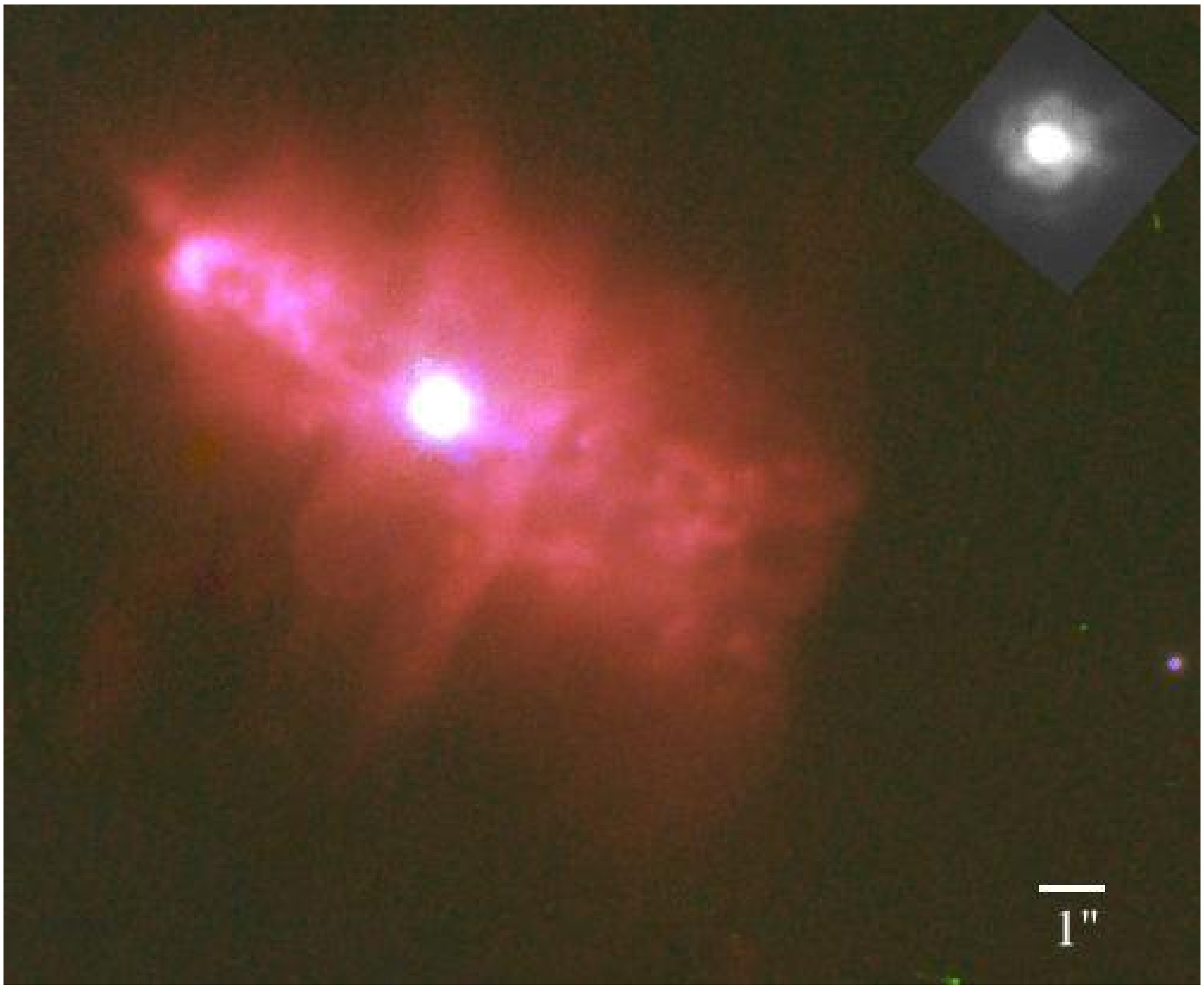

Figure 5. The planetary nebula IC 2149, imaged by the ARIES near-infrared imager The central star has been allowed to saturate in order to bring out details in the surrounding nebula, which is several thousand times fainter. The inset is a narrow band continuum image of the central bright region magnified by a factor of two. The contrast has been adjusted so that details in the inner dusty shell around the central star can be seen. The image has a spatial resolution of ~ 0.1". This is comparable to the resolution of the WFPC2 instrument on HST at optical wavelengths, and two and a half times better than that of NICMOS on HST at $2\mu m$.

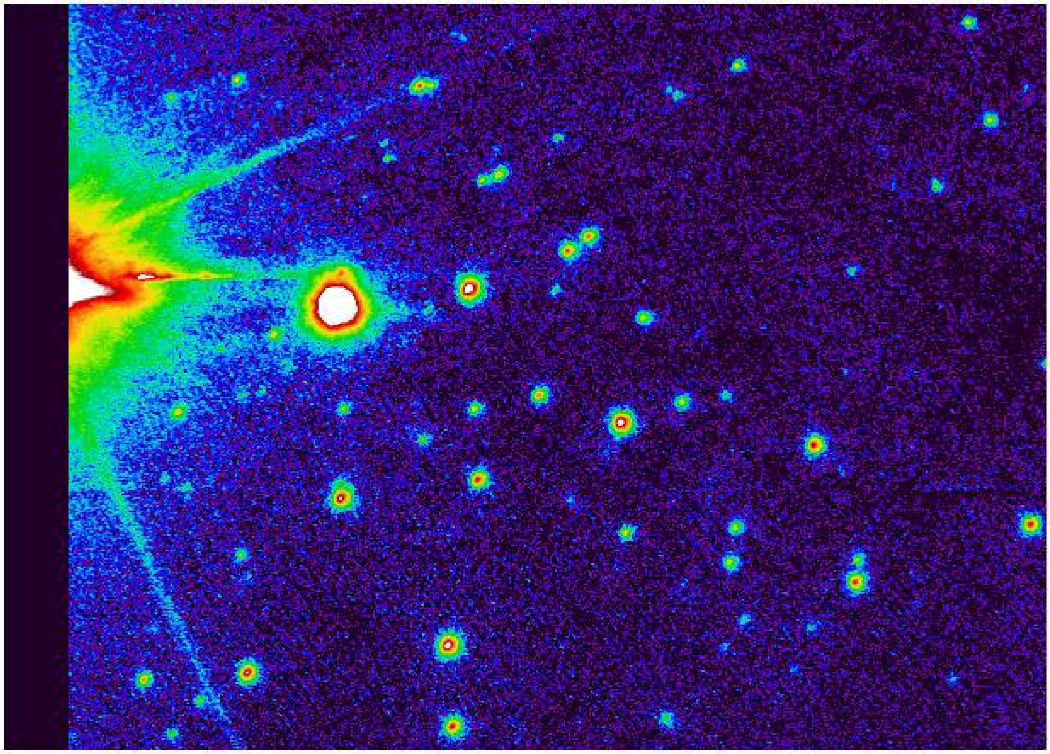

Figure 6. A single 30 second image of the cluster W51 in K_s band taken with the ARIES imager. This image shows a section of the whole image, approximately 10 by 15 arcseconds in size. The guide star is sitting off to the left of the array. Image courtesy Mike Meyer and Julia Greissl.

active damping methods, and also feed forward systems that utilise high rate readouts from accelerometers in order to reduce this unwanted contribution to the system.

As mentioned earlier, a recalibration of the higher order mirror modes will help minimise the wavefront residual in the system, and a new test stand is expected this Fall 2004 for off-the-telescope calibration purposes.

Another area of improvement is the wavefront sensor camera. By increasing the number of subapertures, increasing the readout speed, and using a camera with lower read noise, we expect to improve the sensitivity of the AO system by a magnitude or so.

With these improvements we expect to reach the current Natural Guide Star limits of the MMT NGS AO system, where we are limited by the number of naturally occuring guide stars available on the celestial sphere. Recent work by others in our group is showing promising results from using a Rayleigh laser beacon as an artificial laser guide star, potentially opening up the whole sky to astronomers at the MMT in the near future. Watch this space!

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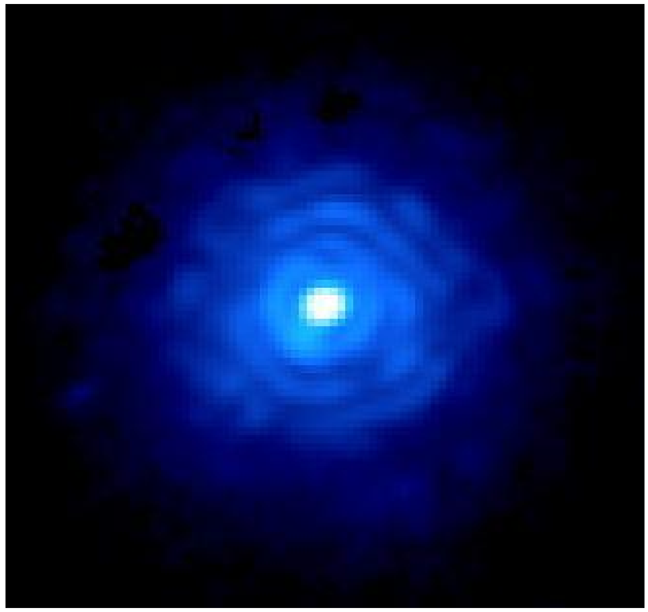

Figure 7. A logarithmically scaled image of the PSF of the MMT AO system. A 5th magnitude star was observed with a video camera and H-band filter. The tip and tilt components of the stack of resultant images is removed before combination. Four diffraction rings can be seen, along with the uncorrected seeing-limited halo. The peak value is approximately 20,000 counts, lowering to 20 counts in the edge of the halo. The dark patches in the upper left corner are detector artifacts.

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