Adaptive Optics with Laser Guide Stars - The ALFA system

Thomas Ott, Andreas Eckart, Wolfgang Hackenberg, Sebastian Rabien, Ric Davies, Stephan Anders

*Max-Planck Institut für extraterrestrische Physik, Postfach 1603,
D-85740 Garching, Germany*

Stefan Hippler, Markus Kasper

Max-Planck Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

Abstract. Adaptive optics will be essential for ground based interferometry with large apertures. In this contribution, we present the MPE/MPIA sodium laser guide star adaptive optics system ALFA, which has been installed at the Calar Alto 3.5-m telescope in southern Spain and is already openly available to the astronomical community. We discuss the current status of the adaptive optics system and the launched beam. We report on the performance level achieved with the adaptive optics system. We have begun to produce scientific results and mention one.

1. Introduction

Currently, all interferometry experiments are limited to small telescope apertures of the order of the Fried parameter r_0, which is about 10 cm at optical wavelengths. When using significantly larger apertures, atmospheric turbulence leads to images limited in angular resolution to the seeing-disk. The large-aperture interferometry envisioned by the Keck and VLT interferometers will only be usable when each separate telescope is equipped with an adaptive optics (AO) system. The classical design of using natural guide stars, however, is limited in sky coverage due to the fact that a suitable, bright guide star is needed to measure the wavefront within the isoplanatic patch, which is about 30” in the infrared K-band.

The use of laser guide stars (LGS) is a promising technique to circumvent the constraint of limited sky coverage. Since the up-link and down-link tip-tilt motions associated with a laser beacon are correlated, a natural tip-tilt reference star within the isokinetic patch is needed. This source can be comparatively faint, since the complete aperture of the telescope is available for sensing.

2. System overview

AO systems using an LGS have a slightly different design than AO systems using only natural guide stars. A separate tip-tilt sensor is needed as this cannot be determined from an LGS. The ALFA (Adaptive optics with Laser For Astronomy) system is a col-

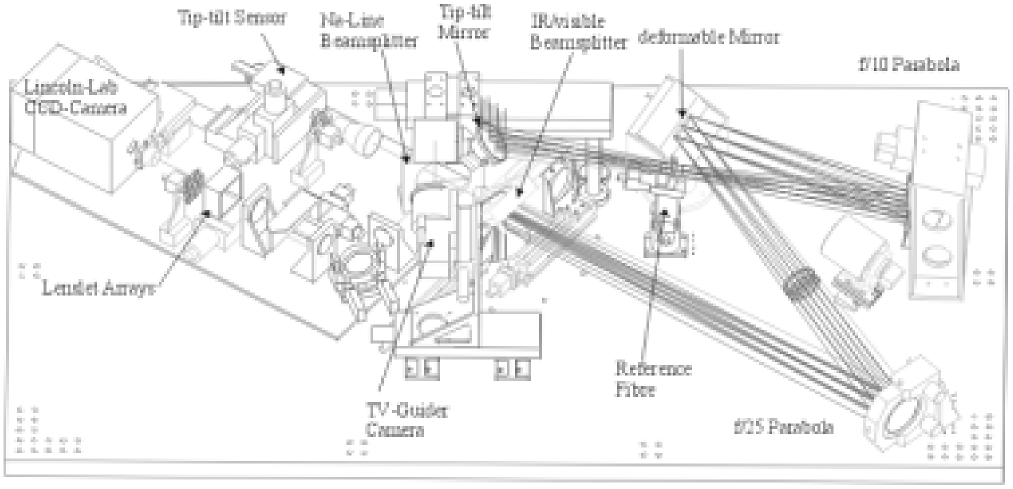


Figure 1. CAD view of the AO bench. A description of the beam path and the various elements can be found in the text.

laboration between the Max-Planck Institut für Astronomie (Heidelberg) responsible for the wavefront sensing and correction (adaptive optics), and the Max-Planck Institut für extraterrestrische Physik (Garching) which provides the laser guide star. It is installed at the German-Spanish Center for Astronomy on Calar Alto in southern Spain. Since summer semester 1998, it is openly available to the astronomical community.

2.1. The adaptive optics

The ALFA AO system utilizes a Shack-Hartmann sensor with several lenslet arrays which can be interchanged, normally providing 6 or 18 subapertures (arranged in a hexagonal pattern) which are sampled at rates of 25–1200 Hz. The centroids of the spots at the sensor are used to determine the coefficients for Zernike or Karhunen-Loeve modes, and these are then applied to a 97-actuator mirror. When correcting on a natural guide star, the wavefront sensor determines all the modes including tip and tilt. When using the LGS, a separate tracker is used to measure tip and tilt.

In Fig. 1, the optical layout of the AO system is shown: The light enters from the top, is reflected by the tip/tilt mirror to an off-axis f/10 parabola which collimates the beam. The next optical element is the deformable mirror which applies the modes measured by the wavefront sensor. After reflection, the beam is focused by a f/25 parabola. An optical/infrared beam splitter reflects the infrared light to the science camera and passes the optical light on to the wavefront sensor. An additional beam splitter is used to reflect only the sodium line onto the Shack-Hartmann sensor. All the other light is passed to the tip-tilt tracker camera. When using a natural guide star, this beamsplitter is replaced by a mirror, since in this case all modes (including tip-tilt) are determined by the wavefront sensor.

An interchangeable lenslet array makes it possible to correct using reference sources of various brightnesses and enables the system to adjust for different atmospheric conditions. The CCD camera uses 64x64 pixels which can be read out at frequencies of 25–1200 Hz. When using the laser guide star, mostly a 5×5 lenslet array is used, and the CCD detector is read out at frequencies of 50–200 Hz.

2.2. The Laser

The optical bench for the laser is installed in the coudé lab, where an Ar^+ laser with 25 W multiline output power pumps a dye ring laser with a single line output power of 4.25 W tuned to the Na D_2 line. The lasers are continuous-wave to avoid difficulties of synchronization with the AO and saturation of the sodium layer. The output beam passes a quaterwave–plate for control of the polarization state and is pre-expanded to a diameter of 1–2 cm. It is then fed along the coudé path via several steerable mirrors and directed into a launch telescope, which expands the beam by a factor of 16. It also provides beam steering and focusing capabilities.

The laser is focused at a naturally occurring Na layer in the upper atmosphere at a height of 90 km. The fluorescent backscatter of these atoms is then used as the reference source for the AO system. In order to efficiently excite the Na atoms, the frequency of the laser must be kept very accurately and with a low bandwidth at the Na D_2 line, and the laser light should be circular polarized.

A CCD camera mounted behind the secondary mirror of the 3.5m telescope watches the night sky for aircraft passing its field of view of 20°. Whenever an object is detected, an alarm is issued and the outgoing laser beam is shut off by means of a cooled shutter in the coudé lab.

Progress on optimizing the entire system has been hampered by poor weather, but important milestones include closing the loop on the laser beacon (September 1997), and then using it to enhance image resolution (December 1997) with 6 subapertures sampled at a rate of 60 Hz. In the following months, both laser brightness and spot size were significantly improved. To date, the laser can easily be used for wavefront reconstruction with the 5×5 lenslet array at frame rates of 50–200 Hz, allowing diffraction limited imaging in K-band.

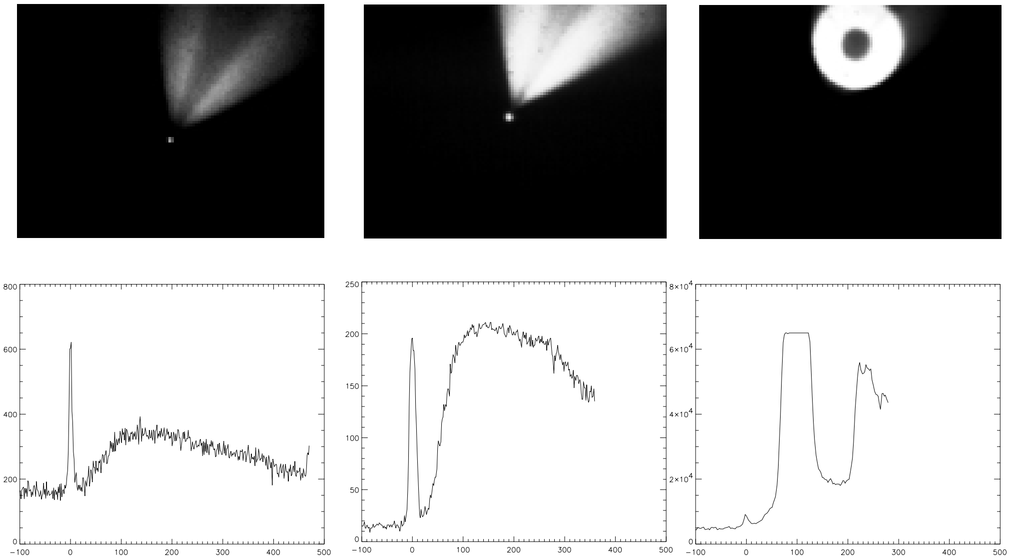
2.3. Performance

For seeing of around 1”, K-band Strehls in excess of 60% can be reached for the brightest natural guide stars ($m_V < 6$), while values in the range 25–50% can be attained for stars with $m_V > 8$. When using the LGS, strehl ratios of $\sim$10% can be reached with long exposures. The brightness limit for the tip-tilt tracker camera reference source is $m_V < 14.5$ within about 60”. The performance can be translated to other wavebands, and we have achieved a J-band Strehl of 12% on SAO 56114 (m_V=7.0), and a resolution better than 0.10”, close to the diffraction limit of 0.07” FWHM.

The LGS brightness depends strongly on atmospheric conditions (Fig. 2). For excellent transmission, the resulting sodium beacon has a magnitude at zenith of about $m_V = 9$–10. This brightness decreases as transmission gets poorer due to high altitude humidity or a large amount of aerosols in the lower atmosphere. Most of the light is then lost in the Rayleigh cone. The angular size of the LGS depends on seeing, for median values of 1” an LGS spot size of 1.5” can be achieved.

3. Scientific results: Integral Field Spectroscopy

The potential for spectroscopy at diffraction limited scales represents an exciting aspect of adaptive optics. However, the inherent difficulties also make it a special challenge. Standard techniques with a longslit may no longer be feasible, since in order to make the most of the benefits of minimizing both background and contamination from ex-



A B C

Figure 2. TV guider images showing the transmission of the lower atmosphere and the resulting laser beacon brightness. (A) Excellent transmission where only a small amount of light is lost in the Rayleigh cone. (B) Medium transmission, the Rayleigh cone is brighter than the laser beacon. (C) A thin layer of clouds blocking most of the upgoing light

tended sources, the slit must be extremely narrow. Accurately positioning a target on such a slit can be very time consuming, and for faint sources this becomes impractical. The alternative method of integral field spectroscopy which involves re-ordering a 2-dimensional field into a longslit, dispersing it, and then reconstructing a datacube (2 spatial and 1 spectral axes), opens considerable opportunities in this area.

During August 1998, the MPE 3D imaging spectrometer (Weitzel et al. 1996), which simultaneously obtains H- or K-band spectra of an entire 16×16 pixel field, was used with ALFA. In order to facilitate this, an aperture interchange module (*AIM*, Anders et al. 1998a) has been built as an interface to allow the pixel scale to be changed between 0.25” and 0.07” per pixel, as well as providing the ability for efficient sky observations with minimal overhead. Although the field of view is small (1.2”), this is ideally matched for observations at the diffraction limit of 3.5m telescopes.

Here we present some of the first spectroscopy at diffraction limited scales (see Anders et al. 1998b), of HEI 7, a binary listed in the WDS Catalog. The primary, more commonly known as HD 197443, is itself a photometric/spectroscopic binary (denoted AB) with a period of about 6 hrs and has not been resolved. A third member of the system (denoted C) was suspected from variations in the time of minimum in the primary pair, and its orbit was first calculated by Hershey (1975) from changes in parallax of the primary with respect to a set of reference stars (later confirmed by observation). The data yielded both the parameters of the AB-C 30.5 yr orbit as well as the absolute parallax, which sets the distance as 24 pc (ie the current projected separation is only 6 AU).

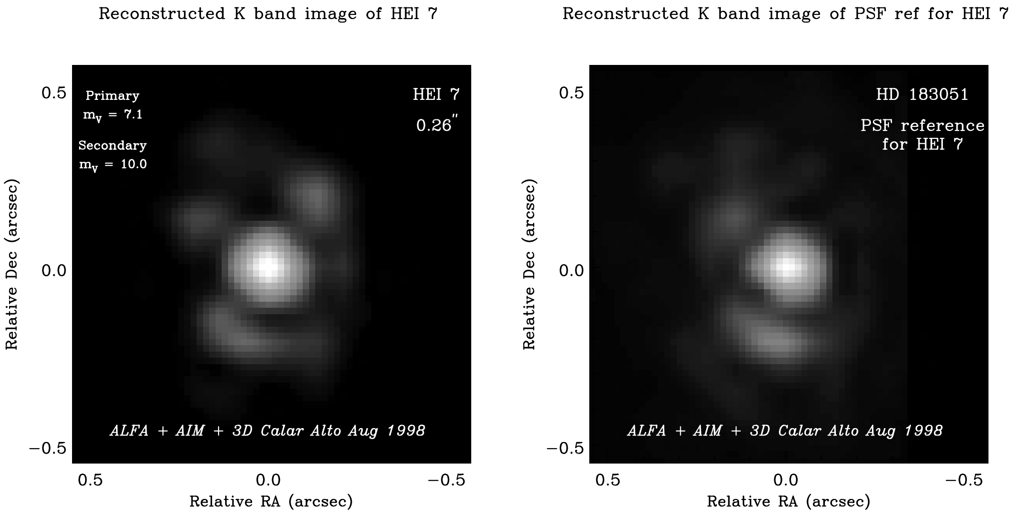


Figure 3. Reconstructed K-band images of the PSF reference HD 183051 (right) and the binary HEI 7 (left). North is left and East is top, rotated 15° counterclockwise. Parts of the first diffraction ring can be seen; the extra blob to the top right in HEI 7 is the companion.

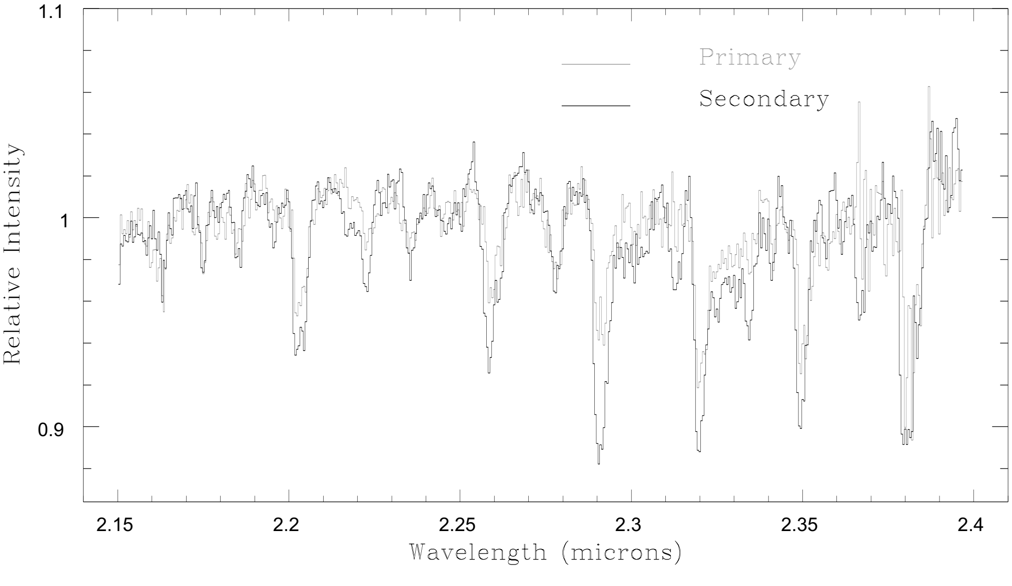


Figure 4. Smoothed K-band spectra of the two components of HEI 7. All the features show the expected depth, based on spectral type classifications (K0 V and K5 V) of the two stars. In particular the ^{12}CO bandheads at 2.29, 2.32, 2.35, and 2.38μm vary by almost a factor of 2, while the Mg line at 2.28μm is the same for the two types. Other prominent lines include Na (2.21μm) and Ca (2.26μm).

A PSF reference (HD 183051, right in Fig. 3) with the same m_V=7.1 as the primary component of HEI 7 was observed 10 minutes before the binary using the same adaptive optics parameters. The difference between this and the reconstructed K-band image of HEI 7 is clear: the secondary can be seen to the top right (south east) at a radial separation of 0.26" and about a factor 15 fainter (m_V=10.0).

Spectra of the two components are shown in Fig. 4. The primary (AB) component has the expected absorption features for a K0 V star; the differences between this and the secondary (C) are expected from its spectral type of K5 V (estimated from colors). In particular the ^{12}CO bandheads are almost a factor of 2 deeper, while the Mg line has a similar equivalent width. The depths of the Na (2.21μm) and Ca (2.26μm) lines also show some variation. These spectra, then, are from two separate objects and not simply the same one extracted at different points. This example clearly demonstrates the feasibility of diffraction limited spectroscopy, although the technique remains difficult.

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