ADAPTIVE OPTICS IN THE NEAR-IR

Daniel Rouan
Département Spatial, Observatoire de Paris-Meudon
92195 MEUDON Cedex, France

ABSTRACT
After a review of the astrophysical programs that should take advantage of the advent of Adaptive Optics, two existing AO systems using different solutions are presented with their characteristics. The present performances, 0.1 arc-sec FWHM images currently obtained are illustrated by astrophysical results recently obtained. The limit in sky coverage of this technique, due to the scarcity of bright enough reference stars is shown, and prospects on present and future evolutions are mentioned.

1- Astronomy with Adaptive Optics

Among the various high angular resolution techniques, the adaptive optics approach, first proposed by Babcock [1], is gaining more and more support in the community since it represents one of the most desired improvement in astronomy [10] and appears now to be fully proven after the success of the first experiment ComeOn [14,7,12]. It will certainly become a standard facility on most of the large telescopes in the world [8,2].

Roughly speaking, Adaptive Optics opens the field of 0.1 arc-sec astronomy in the near-infrared and 0.2 arc-sec in the visible. Almost any area in Astrophysics should benefit from this instrumental breakthrough: here follows a few examples, from solar system to distant galaxies, of programs that should be adressed soon:

- Detection of the rings in Uranus and Great Brown Spot in Neptune, study of Titan
- Asteroïds: rotation (through thermal effects), shape, binarity
- Interstellar Medium: very small scale structure of molecular clouds (H_2, PAH etc.)
- Young Stellar Objects: disks around T Tauri, Ae/Be stars, binarity, dense very young clusters
- Proto Planetary Nebulae: disks and binarity in bipolar nebulae, grain condensation radius
- Missing mass: brown dwarfs in binary systems
- Globular clusters: mass in central region
- Nearby galaxies: galactic center, nuclear region, core of elliptic
- AGN and starburst nuclei: structure of the active region, Seyfert nucleus, BRL and NRL
- Gravitational lensing: multi-images mirages, arcs
- Primordial galaxies: small pixels increase the contrast against sky background

Fig.2-a gives an example of a recent result obtained with the ComeOn experiment on the post-AGB bipolar nebula *Frosty Leo.*

2 - Principles, advantages, existing systems

An adaptive optics (AO) system aims to correct in real-time the images distorded by atmosphere by sensing the wavefront from a nearby reference source - or in a few cases the source itself - and actionning, through a servo-loop, a deformable optics, generally a mirror (Fig. -a). An AO system working with a large number of corrected modes provides images that can be diffraction-limited (Fig. 2-b). In fact the number of cells to correct on the wavefront surface is typically the surface of the telescope divided by the surface of one coherent cell, i.e. $(D/r_o)^2$ where D is the telescope diameter and r_o the Fried parameter. Because r_o increases with wavelength (as $\lambda^{6/5}$), the number of sub-pupils to correct decreases and the characteristic time constant increases with wavelength, both conditions that make the situation much easier in the infrared than in the visible. Adaptive optics provides five definite advantages over other high angular resolution techniques: *i)* it restores a good approximation of the initial, unperturbed, transfer function of the optical system, whereas the transfer function for speckle interferometry is strongly attenuated in the middle to high spatial frequency range; *ii)* It allows long integration times in the imaging channel and hence extends the sensitivity of imaging towards the faint to very faint fluxes regime; *iii)* it provides a strongly enhanced contrast, so that the signal to noise ratio per pixel is largely increased, while background is proportionally reduced; *iv)* it allows real-time assessment of the data quality; *v)* it generates a small quantity of data as compared to short exposure methods.

Today, only two astronomy-dedicated instruments have reached a degree of maturity and performances that has lead to successful observations on large telescope: the ComeOn experiment from Meudon/ESO/ONERA and the IFA-Hawaii AO system:

• *Come-On* was the first successful astronomical adaptive optics experiment and, up to now, the one that produced published results of astrophysical interest [12,9,15]. This experiment was developed as a collaborative program of ESO and several french institutes (Observatoire de Paris, ONERA) and companies (Laserdot, LEP); it was recently upgraded to become *Come-On+*. The Come-On system [14] is installed at the f/8 focus of the ESO 3.60m telescope in La Silla (Chili). The deformable mirror

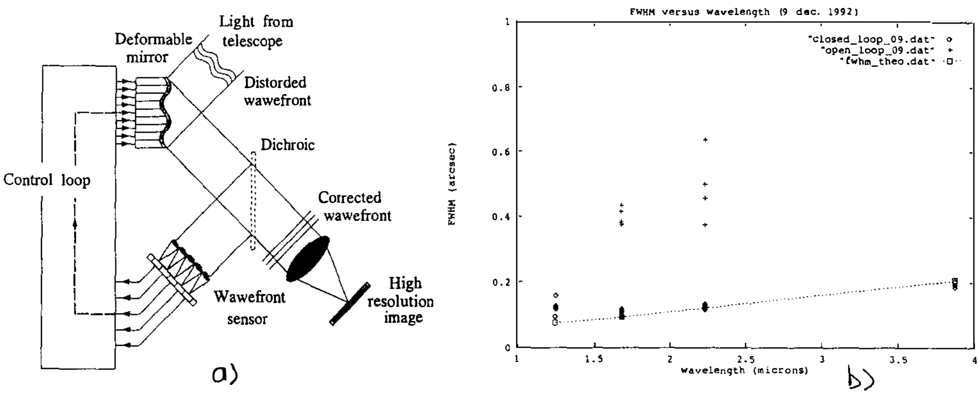

Figure 1: a) Principle of Adaptive Optics; b) FWHM of images obtained with ComeOn.

is a continuous facesheet mirror with 52 stacked piezoelectric actuators. A separate two-axis tip-tilt mirror compensates for the wavefront tilt. Both mirrors are driven by a digital control loop using fast computers. A Shack-Hartmann wavefront sensor (WFS) uses 52 subapertures on a 8×8 square grid to measure the slopes of the wavefront. The WFS, working in the visible, benefits from the high sensitivity of the detector, an Electron Bombarded CCD working essentially in a photon-noise limited regime. The corrected image is recorded on one of the two available IR cameras, one developed in Meudon (2.5-5μm) and one in MPE-Garching (1-2.5 μm) with a 0.05 arcsec pixel size on the sky. The present performances are such that the critical threshold of 0.1 arc sec is now currently crossed in normal seeing conditions (Fig.-b).

• The AO system developed at IFA-Hawaii by Roddier and co-workers, is based on the "curvature" appproach where the wavefront sensing is done by measuring its curvatures rather than the slopes and the correction achieved thanks to a bimorph mirror where curvatures are localy created through piezo effect [13)]. The main advantage of this approach is the excellent sensitivity of the wavefront sensor which uses fast, high quantum efficiency, photon-counting monodetectors (avalanche photo-diodes), the drawback is the degree of correction limited to $\approx$ 20 modes.

3 - Limits and prospects

The deformable mirror can no longer be considered as a hard technological point and systems with several hundred actuators have been successfully produced. Moreover, the number of actuators is not really the problem in astronomy where full correction represents a rare case because of the scarcity of bright reference stars that it supposes [13)].

Sensing the wavefront is the real problem, due to the requirement that a sufficiently bright and nearby reference star must lie in the vicinity of the studied object: *i)* sufficiently nearby because of the anisoplanetism (wavefront perturbations are less correlated at increasing angular distances, the turbulent layer being at a finite altitude), *ii)* sufficiently bright because the best correction implies a large number of sub-pupils and a large temporal bandpass (30-100 Hz) requiring a fast rate of wavefront sensing (typically 5 to 10 times the aimed bandpass).

With the present systems, one roughly evaluates as 10 %, the probability to find a star (mR $<$ 17.5) at $b = 30^o$ when $\approx$ 15 modes are corrected. Hopefully, this drawback will be no longer actual once artificial laser sources are practically usable [4),5)], however severe difficulties, among which the impossibility to directly measure the wavefront tip-tilt [11)] and the light pollution by laser shot, make

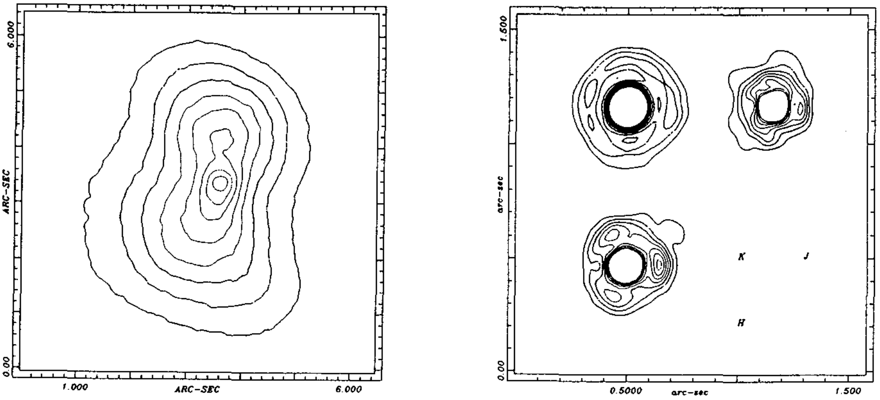

Figure 2: a) The Frosty Leo Nebulae at 2.2 μm is an envelope of gas and dust recently ejected by a post-AGB star; the off-center star location indicates that binarity is at the origin of the bipolarity; b) Stellar image in J, H and K showing distinctly the Airy pattern. All images from ComeOn.

this approach still far from routine.

In given circumstances, the AO system may not provide full correction, either because the reference source is too faint or too far or because one operates at too short a wavelength. It can be shown that the highest modes (or spatial frequencies) in the correction are the most affected by this situation and that even a degradation of the image can arise because of the noise introduced by those modes. The system may then be fine-tuned to provide the optimum, though limited, resolution: the highest spatial frequencies are attenuated by filtering the highest Zernike modes of the mirror. This method, known as the "modal control", has been shown to be very powerful[6]. The complexity of this optimization procedure will require some artificial intelligence to be integrated in future AO systems [3].

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