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Contribution of the ESO Adaptive Optics Programme to Astronomy: a First Review

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Since 1988, the *Messenger* has kept its readers informed [1] of the steady progress being made in the ESO adaptive optics (AO) programme. The latest developments have been described in detail [2]. We simply recall here the main features. ComeOnPlus [3] is an adaptive system installed at the f/8.09 Cassegrain focus of the 3.6-m telescope at La Silla. It differs from the early prototype ComeOn in many ways: the deformable mirror has 52 actuators (instead of 19); a broader temporal bandpass (30 Hz) is available; modal control, which optimizes the efficiency of AO for a given observation, is implemented, and a user-friendly interface (ADONIS) using artificial intelligence to optimize the use of the system in real time is in preparation. The mechanical structure has been redesigned for high rigidity, and the optical train allows the installation of new elements, possibly provided by visitors, such as a coronograph, single-mode optical fiber pick-up, and in the future, spectroscopic capability or polarimetry.

In parallel, an agreement has been concluded between the Max-Planck-Institut für Extraterrestrische Physik in Garching and the Observatoire de Paris to install and operate a copy of the Sharp Infrared camera used at the NTT. This new camera, called Sharp II, is now on loan to ESO for Periods 52 and 53. ESO is planning to buy an upgraded version of the camera, with some new features, namely a Fabry-Perot spectrometer (resolution ca. 3,000), additional image scales and filters. This upgraded version will then permanently enhance the AO system.

Originally designed as a prototype system to evaluate the value of AO for the VLT, the first version of Come On was soon being used to obtain astronomical data, but was far from being user-friendly. Nevertheless the remarkable results obtained during technical runs in 1992 and 1993 and the unique availability of such a dedicated system on a large telescope encouraged ESO to take the risk of offering this "non-ESO standard" instrument to a broad community. To do so, a new staff member (M. Faucherre) was recruited and trained at La Silla to maintain, improve and operate the system, allowing visiting astronomers to use this new facility without special competence in exploiting adaptive optics. For the past eight months the ComeOnPlus/Sharp II configuration has been offered to visitors (see announcements for Periods 52 and 53), and the requests for observing time have steadily grown in number.

As a consequence, observing programmes of great diversity have benefited from 40 observing nights in Periods 51 and 52, broadly covering the fields of planetary, galactic, stellar and extragalactic astronomy. They all aim to exploit the near diffraction limited and high sensitivity imaging capability of AO, sometimes coupled to other functions such as coronography or spectrography. We present here some recent results in advance of forthcoming publications. They provide a good overview of the variety of fields currently covered by the astronomers using the AO system and demonstrate the worldwide leadership obtained in Europe, as no other group to date is able to present such applications of adaptive optics to frontier astronomical problems.

Solar System

The minor planets Ceres [4] and Pallas [5] were observed successfully. The axis of rotation of Ceres was determined, as well as the value of the ground thermal properties. Titan [5] was imaged in the 1.19–2.14 μm band (Fig. 1), a wavelength where the stratospheric haze is transparent and the low altitude clouds or even the ground may be observed. The ultimate purpose is to characterize the nature of Titan's ground and to test the current hypothesis of a global ocean. The tentative image obtained during Period 51 needs confirmation, and these infrared studies will complement Hubble Telescope observations in order to prepare for the Huyghens descent probe of the Cassini mission, planned to reach Titan in 2004. Examined in this band, Titan exhibits bright areas departing from circular symmetry. These may be caused by al-

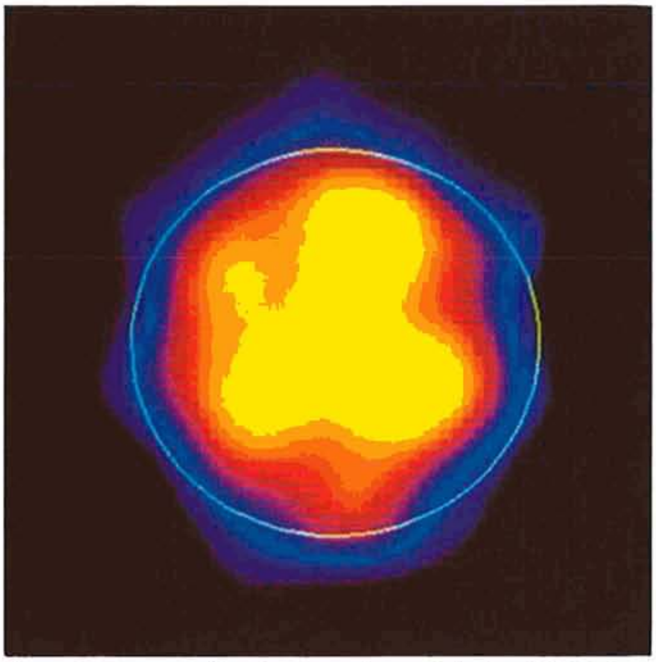


Figure 1: *Titan, satellite of Saturn, observed in the 1.96–2.14 μm band with adaptive optics/Sharp II. The PSF was determined on a star a few minutes before the observation and is 0.18″ wide.*

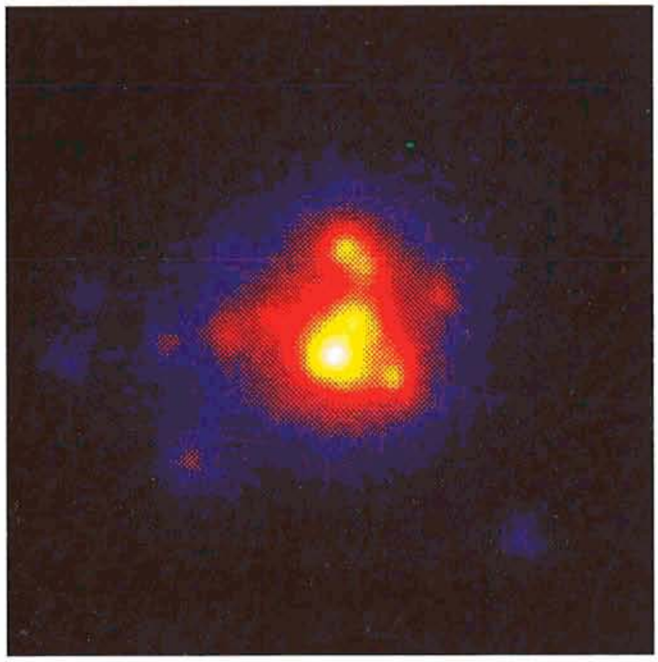


Figure 2: *An image of the multiple star Sanduleak −66°41 in the LMC, obtained in November 1993 with adaptive optics/Sharp II at 2.2 μm. The field is 6×6″, north is up, east left. The PSF is 0.30″ wide, as determined independently. This is a raw image, not yet upgraded by restoration methods. The picture shows mainly the brightest component in the previously resolved cluster. It is now resolved into several previously unknown components.*

bedo variations at the surface or by the low atmospheric cloud structure.

Stellar Astronomy

The detailed structure of massive stars was first examined with optical speckle interferometry, aiming to resolve assumed supermassive objects into multiple systems. One of the very massive stars, Sanduleak−66°41 in the Large Magellanic Cloud, was believed before 1988 to be over 120 times more massive than the Sun. However, observations conducted in 1988 [6] with the ESO 2.2-m resolved the assumed star into a tight cluster of six objects, and the mass of the most massive object was lowered to 90 $M_\odot$ [7]. Figure 2 shows how the AO observations, carried out in November 1993, again modify this result. The previous 90 $M_\odot$ object has been resolved again and the brightest component will again decrease in mass. Establishing the upper limit of massive stars is fundamental for theories of birth and evolution of stars, as well as for the determination of the cosmic scale.

Circumstellar Environment

The high resolution AO imaging of young stars has already led to the discovery of the disk surrounding the close binary ZCMa [8].

The evidence for a circumstellar disk and associated bipolar flow in the active object η Carinae [9] (Fig. 3) has been an object of interest. η Carinae was observed early in the AO programme (April 1991) and demonstrated the mapping capability of relatively extended objects (6×6″) when the central source is bright. New observations are planned in 1994 to determine with accuracy the relative position of the infrared core with regard to the multiple object discovered earlier in the visible by Weigelt with speckle interferometry. The infrared detailed core map confirms the bipolar structure observed at larger scale (30″) by the

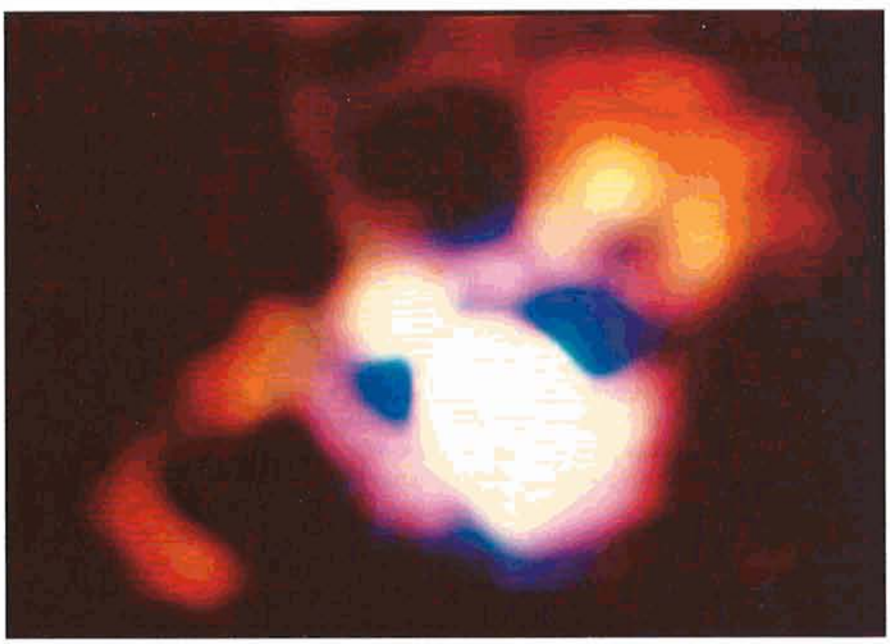
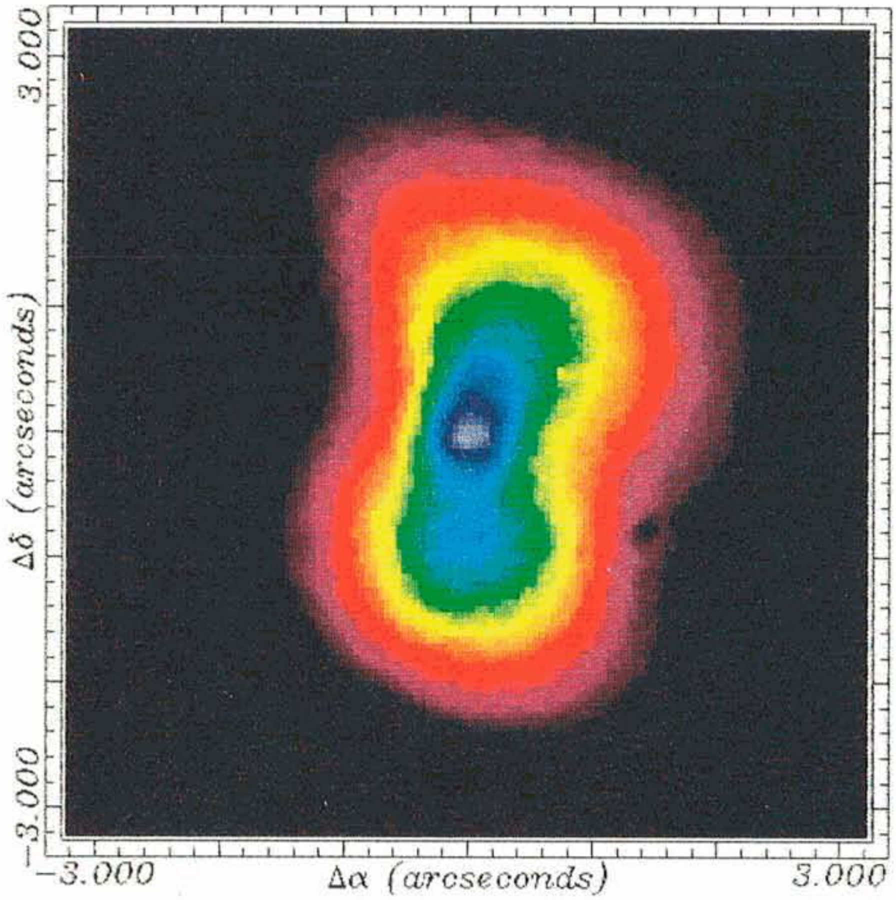


Figure 3: *The centre of the η Carinae nebula observed in January 1991 with adaptive optics/Circus camera. The image size is 4×5″, east is up and north to the right. The colour map is a composite of L′(3.6 μm) and M (5 μm) bands where colours represent colour temperature (blue is hot, red is colder). The dust temperature is determined with a resolution of 0.26″ to be 300–350 K, decreasing away from the central heating source. The positioning accuracy of L′ and M maps is 30 milliarcsec, after correction for instrumental flexure.*

Figure 4: *The Frosty Leo nebula (post AGB star) observed in the K′ infrared band with adaptive optics/Sharp II. The field is 6×6″, north is up and east is left. The PSF was determined to be 0.3″ wide, despite 1.5″ seeing due to relatively poor observing conditions. The nebula main axis is tilted by −14° with regard to the north-south direction. The narrowing of the isophotes near the equatorial plane is an indication of the disk embedding the central object. The nebula is asymmetric and the suspected presence of an unseen companion, the obvious central object, is on an orbit 0.25″ away from the exact centre. Exposure time 300 s.*



HST and gives hints on sporadic ejection of matter which may be related to the ultrabright event of 1843.

An object of particular interest is the evolved post Asymptotic Giant Branch bipolar source Frosty Leo (Fig. 4), where evidence for a disk seen edge-on was previously complemented by the demonstration of the dust-to-gas relative velocity. Adaptive optics imaging of this source in April 1993 allows us to identify and precisely locate the central star [10]. Its excentric position, relative to the accurately positioned nebula isophotes, strongly suggests that a binary system is at the origin of the disk and bipolar structure. In addition, knowing from previous measurements the propagation velocity of the ejected shell (10 km/s), it is possible to derive the position of the emitting object from the isophote centroid position. It is remarkable that the positions of these centroids regularly move and give hints on what could be the orbit of the emitter. This orbit fits with the current position of the observed star and a companion mass (ca. 6 $M_{\odot}$) may then be derived.

Many current programmes deal with bipolar flows and jets, circumstellar disks around young or evolved stars, etc., where the superior resolution of AO becomes extremely valuable.

Star Clusters

The possibility to resolve rich fields of stars with 0.1″ resolution has two advantages: by reducing the background and concentrating the energy, it increases the sensitivity and by sharpening the image it reduces confusion.

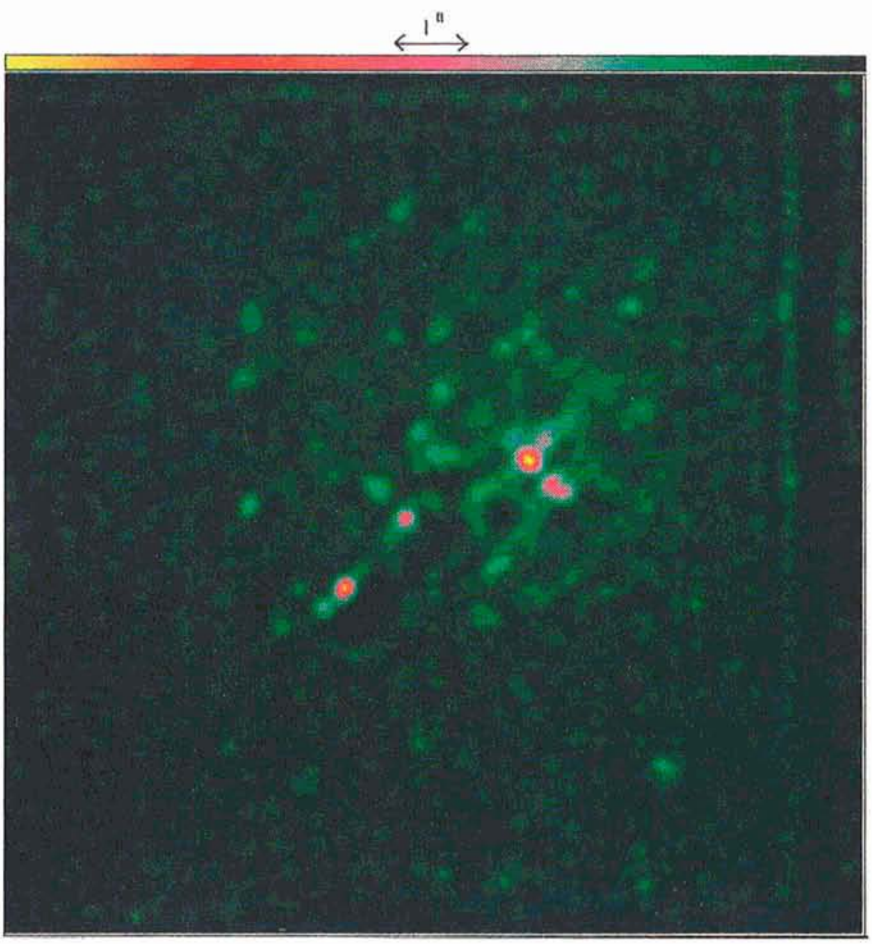


Figure 5: *The R136 region in the Large Magellanic Cloud 30 Doradus nebula, imaged at 2.2 μm by adaptive optics/Sharp II. The resolution is 0.2″ FWHM, north is up and east left. The scale is indicated. Fainter stars in the cluster may be either OB stars or perhaps red supergiants.*

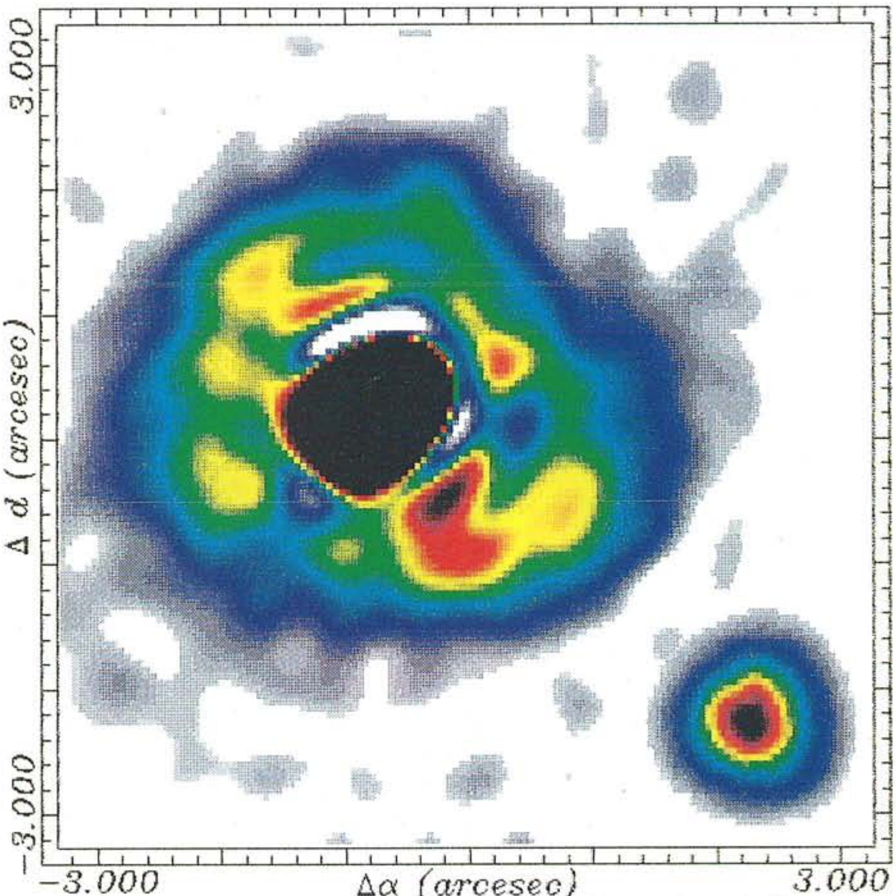


Figure 6: *The Seyfert I galaxy NGC 7469, imaged at 2.2 μm with adaptive optics/Sharp II. The image is 6.4×6.4″ and the estimated resolution is 0.6″ before detailed deconvolution and cleaning treatment. The nucleus is saturated and isophotes were removed. North is up and east left, exposure time 20 seconds. The PSF is at the lower right.* *See also page 20 of this issue.*

Hence systematic studies of stellar populations become possible in the near infrared. One application is to determine the low mass, faint star distribution in star forming regions at an early stage, as proposed among others by S. Strom and C. Dougados. The comparision with Hubble Space Telescope images taken in the visible at a similar angular resolution will be extremely instructive in determining with accuracy the colours of individual objects.

We illustrate here (Fig. 5) the first result of a programme aimed at constraining the Initial Mass Function by observing with AO the rich active region R136 in the 30 Doradus nebula in the Large Magellanic Cloud [11]. It contains more than thirty massive Wolf-Rayet, O and B stars and is known to be a location of recent massive star formation.

Star Forming Galaxy: NGC 7469

The SAb galaxy NGC 7469 is a Seyfert I galaxy presenting an active nucleus surrounded by a starburst region. The star formation triggering process is not known and several hypotheses have been formulated: tidal effects from a companion, bar, etc. AO observations carried out in July 1993 demonstrated the existence of a structured ring (Fig. 6) which was mapped in J, H and K bands despite bad observing conditions. The preliminary data analysis [12] indicates that the main emission comes from red supergiants (M0-M5) and that fairly high starburst activity ($L_* = 10^{11}\ L_\odot$) is consistent with the luminosity measured by others. This observation provides a good example of AO capabilities on relatively faint objects, as the magnitude of the nucleus, used for referencing, is 12.

The galaxy NGC 1068 is also currently being studied and results should soon become available.

High-z Galaxies

This programme searches for primeval galaxies. As they are not sufficiently bright to provide adequate referencing, a completely different strategy is used:

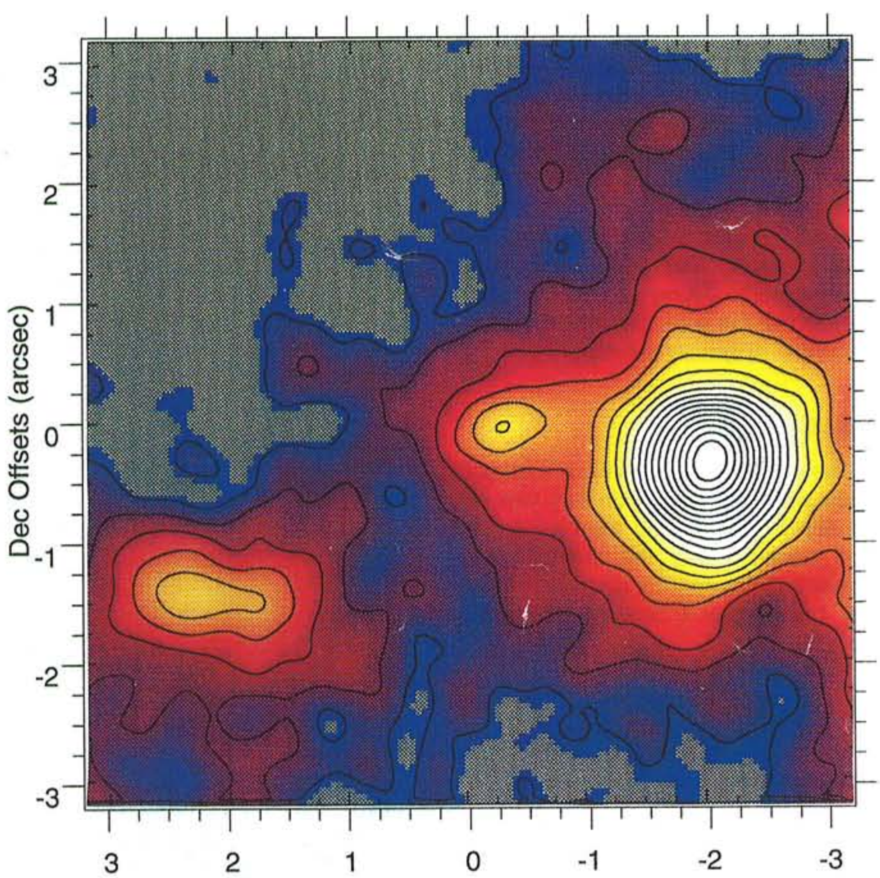


Figure 7: *Image of a rich field of galaxies at z = 0.42 at 2.2 μm, given by adaptive optics/ Sharp II. Resolution is 0.4″. The two known galaxies in the cluster J1836.3CR are clearly spatially resolved and a third source (centre of image) unknown till now is detected. Contours are 5, 10, 15…100 % of $m_K = 15.2$ arcsec^{-2}. The reference star ($m_V = 13$) is 25″ away and isoplanicity limits the resolution. The 5σ limit for 1 hour integration is $m_K = 21.1$.*

stars adequate for referencing are selected in fields which are expected, from a variety of criteria, to be rich in remote galaxies. These fields are systematically mapped as far from the star as possible, given the size of the isoplanatic field (usually 20–30″, depending on the seeing, the amount of expected correction and the wavelength of operation).

In the beginning phase of this programme two galaxies were observed in K in the cluster J1836.3CR at a redshift z = 0.42 [13]. The spatial resolution is 0.4″ and the galaxies are clearly resolved (Fig. 7). Their integrated magnitudes are K=15 and K=18. The V-K colours indicate the brighter source to be an elliptical and the fainter a spiral galaxy, as confirmed by the examination of the clearly visible shape of the images. This programme will be pursued in a systematic way in order to determine the colours and morphological types of remote galaxies.

The ESO Adaptive Optics system was initially conceived as a technological prototype. Its performance now makes it a valuable tool whose uses will continue to grow and fully exploit the excellent seeing of the 3.6-metre after the recent improvement of the dome thermal control. It is hoped that this continuous operation and scientific productivity shall ease the design and operation of the AO system(s) on the VLT for a broad community of astronomers, especially as regards the ground follow-up of the Hubble Space Telescope and of the ISO satellite mission to be carried out between 1995 and 1997.

Many other aspects of adaptive optics need to be covered in the future, if possible before the VLT system(s) are put into operation: infrared wavefront sensing (possibly reaching magnitudes m_K=8–10), improved wavefront sensing at visible wavelengths using ultra low noise, fast readout CCDs (reaching m_V=17–18 for low-order AO correction), understanding the detailed properties of turbulence and its associated optimized correction [14]. And this is without speaking of laser artificial stars, which could easily be tested and put into operation, after proper study of stray light effects, on the powerful ComeOn Plus/Adonis system.

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