TELESCOPES AND INSTRUMENTATION

The One Eye that Sees All: Integral Field Spectroscopy with SAURON on the WHT

P. T. de Zeeuw[1], J. R. Allington-Smith[2], R. Bacon[3], M. Bureau[1], C. M. Carollo[4], Y. Copin[3], R. L. Davies[2], E. Emsellem[3], H. Kuntschner[2], B. W. Miller[5], G. Monnet[6], R. F. Peletier[7], E. K. Verolme[1]

[1]: Leiden Observatory; [2]: Durham University; [3]: Observatoire de Lyon; [4]: Columbia University; [5]: Gemini International Project; [6]: University of Nottingham; [7]: European Southern Observatory

In 1999, a new and unique integral-field spectrograph, SAURON, made its debut at the WHT. SAURON has a large field of view and high throughput, and was developed as a private instrument in a collaborative effort between groups at Observatoire de Lyon, Leiden Observatory, and the University of Durham for the systematic study of the stellar and gaseous kinematics and the line-strength distributions of nearby early-type galaxies.

Galaxy dynamics and integral-field spectroscopy

Many elliptical galaxies and spiral bulges are triaxial and/or display multiple kinematic components. Triaxiality leads to velocity structures that are difficult to map with traditional long-slit spectroscopy. Furthermore, the central few arcseconds are often 'kinematically decoupled': the inner and outer regions appear to rotate around different axes. This makes two-dimensional (integral-field) spectroscopy of stars and gas essential for determining the internal structure of these systems, and for understanding their formation and evolution.

Substantial instrumental effort has gone into high-spatial resolution spectroscopy with slits (e.g., STIS on HST), or in small areas (e.g., the integral-field units (IFUs) TIGER and OASIS on the CFHT), to study galactic nuclei. By contrast, studies of the large-scale kinematics of galaxies still make do with long-slit spectroscopy along at most a few position angles. Therefore, the galaxy dynamics groups at the Observatoire de Lyon, Leiden Observatory, and the University of Durham joined forces to build SAURON (Spectroscopic Areal Unit for Research on Optical Nebulae), an IFU optimized for studies of the kinematics of gas and stars in galaxies, with high throughput, and most importantly, with a large field of view.

SAURON

The optical layout of SAURON is illustrated in Figure 1. A filter selects a fixed wavelength range, after which an enlarger images the sky on the heart of the instrument, the lenslet array (Figure 2). Each lenslet produces a micropupil. After the collimator, the light of each micropupil is dispersed by a grism, and a camera then images the resulting spectra onto a CCD. The CCD is rotated slightly to avoid overlap of adjacent spectra. This design is similar to that of the prototype IFU TIGER, which operated on the CFHT between 1987 and 1996 (Bacon et al., 1995), and of OASIS, a common-user IFU for use with natural guide star adaptive optics at the CFHT. Table 1 summarizes the basic specifications of SAURON.

The SAURON optics are optimized for the wavelength range 4500–7000 Å. Currently only one filter and one grism are available, for the range 4810–5400 Å. This allows simultaneous observation of the OIII and Hβ emission lines to probe the gas kinematics, and a number of absorption features (the Mg b band, various Fe lines and again Hβ) for measurements of the stellar kinematics (mean velocity, velocity dispersion, and the full line-of-sight velocity distribution), and the line

Spatial sampling	0.26″		0.94″
Field of view	9″ × 11″		33″ × 41″
Spectral resolution (FWHM)	2.8 Å		3.6 Å
Instrumental dispersion (σ)	70 km/s		90 km/s
Grism		514 lines/mm	
Spectral sampling	0.9 Å/pix		1.1 Å/pix
Wavelength coverage		4810–5400 Å	
Calibration lamps		Ne, Ar, W	
Detector		EEV12 2148 × 4200	
Pixel size		13.5 μm	
Efficiency (optics/total)		~35% / 14%	

Table 1. SAURON specifications.

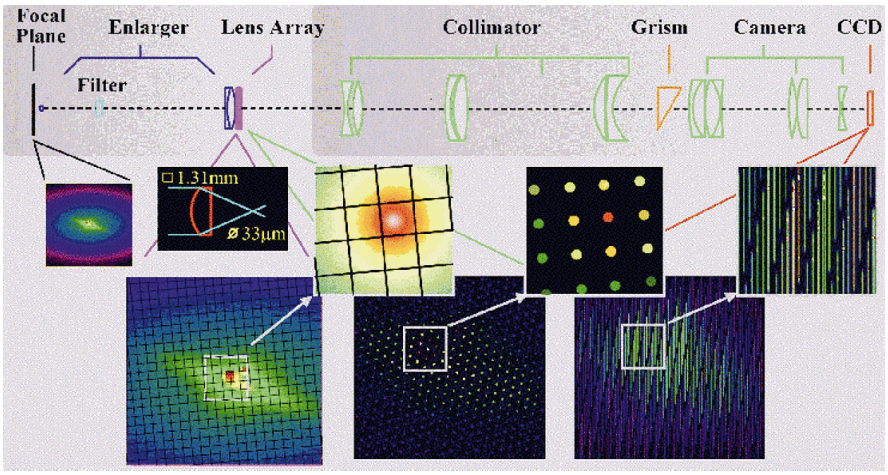
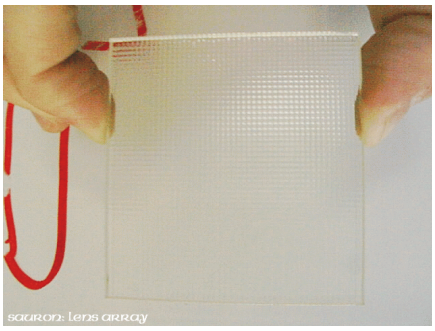
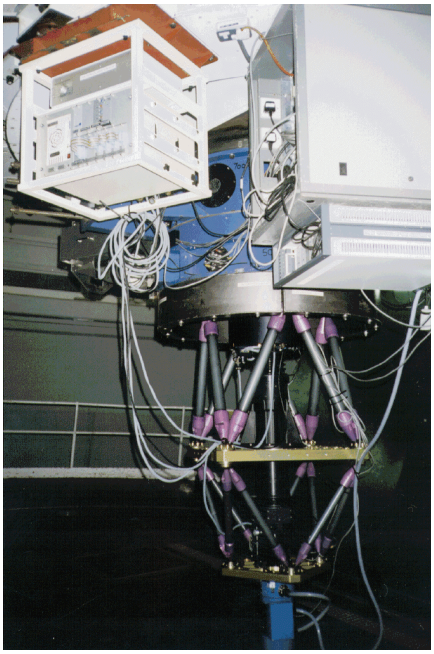


Figure 1 (top). Optical layout of SAURON.

Figure 2 (bottom). The SAURON lenslet array is made of fused silica, and consists of over 1600 square lenslets, each 1.35 mm on the side.

Figure 3 (right). SAURON mounted on the Cassegrain port of the WHT.





strengths (age, metallicity, and abundance ratios).

A new feature of SAURON compared to existing IFUs is the ability to do simultaneous sky subtraction. This is achieved by means of an extra enlarger which observes a patch of sky 1.7 arcmin away from the main field, using about 100 lenslets.

Each of the lenslets normally images 0.94 × 0.94 arcsec on the sky. This undersamples the typical seeing at La Palma, but provides essentially all one can extract from the integrated light of a galaxy over a remarkably large field of view, 33×41 arcsec, observed with a filling factor of 100% (1500 lenslets). SAURON therefore does justice to its name, as its mythical predecessor was also known as 'The one eye that sees all'.

SAURON contains a mechanism for switching to another enlarger, resulting in a 9×11 arcsec field of view, sampled at 0.26 × 0.26 arcsec. This mode can be used in excellent seeing to study galactic nuclei with the highest spatial resolution achievable at La Palma without adaptive optics.

The total throughput of SAURON, including atmosphere, WHT and detector, is 14%.

The mechanical design of SAURON is similar to that of OASIS; it is light and strong, and minimizes flexure. Figure 3 shows the instrument mounted on the Cassegrain port of the WHT. SAURON weighs less than 300 kg, as compared to about 1500 kg for ISIS, which normally occupies this port. In order not to have to rebalance the WHT when SAURON is mounted, four counterweights totalling 580 kg are bolted on with the instrument: these are visible as a steel ring surrounding the top of SAURON. The dewar, made available by the ING, can be seen at the very bottom of the photograph.

The plan to develop SAURON was hatched in the summer of 1995, and the first work started in late spring 1996. The instrument was completed in January 1999. This fast schedule was possible because SAURON is a special-purpose instrument with few modes, and because much use could be made of the expertise developed at Observatoire de Lyon through the building of TIGER and OASIS. While SAURON was constructed as a private instrument, plans are being developed to make it accessible to a wider community.

Commissioning the Eye

SAURON was commissioned on the WHT in early February of 1999, during time shared with the ESA STJ team (see *ING Newsletter*, **1**, 13). In the preceding days, the instrument was checked, together with the software to run it, and the interface to the WHT environment. We paid particular attention to the optical alignment of SAURON and the detector, to be sure that the spectra were aligned accurately with the columns of the CCD.

The instrument performed very well from the moment of first light, on February 1. We modified an internal baffle slightly, to avoid some residual light leak between the main field and the sky part. A small tilt of the filter removed an unwanted ghost image. The slow read-out of the CCD led to some inefficiencies, but this is being fixed by the ING.

Figure 4 presents some calibration data taken during commissioning. Panel a) shows a small part of an exposure with the grism taken out, which produces an image of the micropupils. Panels b) and c) show spectra obtained with the internal

tungsten and neon lamps, respectively. The former shows the nicely aligned continuum spectra, while the latter shows the emission lines used for wavelength calibration.

Data Analysis

Each SAURON exposure produces a CCD frame containing about 1600 individual spectra. These are extracted by means of an optimal algorithm based on a full optical model of the instrument. The resulting data cube is reduced in the standard manner, archived, and analysed by means of a set of programs modelled on the XOASIS package.

We have developed a special pipeline, fittingly called Palantir, to analyse the SAURON data cubes in a very systematic manner. The first module of Palantir removes the instrumental signature, the cosmic rays, and also does the wavelength and flux calibration and the sky subtraction. The second module allows merging of individual exposures and mosaicing of different pointings for the same object. Measurement of the kinematic quantities and the line strengths is then done with dedicated algorithms. The reduced data is archived at Leiden Observatory, and will be made public in due course.

First Results

Figure 5 shows results from the first SAURON observing run (February 14–20, 1999). Reconstructed total intensity, stellar Mg b line strength, mean velocity and velocity dispersion, and emission-line gas intensity and velocity maps are presented for the E6 galaxy NGC 3377. The stars show a striking rotating disk pattern with a spin axis misaligned ~10° from the photometric minor axis. The Mg b isophotes seem to follow the continuum light. A comparison with the Hβ isophotes will reveal whether this galaxy contains a younger stellar disk. The gas also reveals non-axisymmetric structures and motions. These results are based on a total of only four 30 min exposures (no spatial binning was applied). The large angular extent of the maps should be noted.

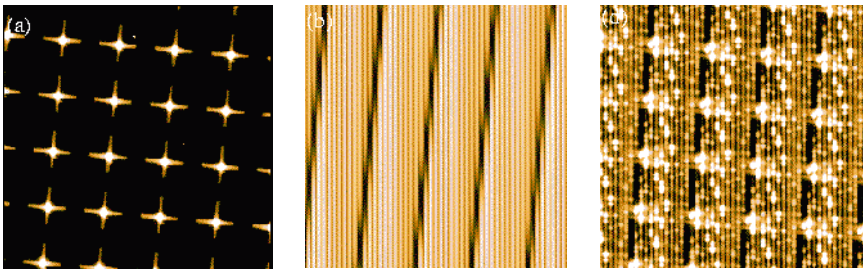


Figure 4. Examples of various SAURON calibration measurements, taken during commissioning. Each panel shows only a small part of the entire CCD frame so that details can be seen. a) Micropupil image taken with the grism out. Each dot is the diffraction pattern from one square lenslet. b) Continuum image using the tungsten lamp. c) Neon arc.

During our run in October 1999, we observed the E3 galaxy M32 to test the high-resolution mode. Figure 6 shows the integrated intensity and the mean velocity field of the central region of M32, derived from a single 45 min exposure with good seeing. The velocity field is very regular, is consistent with axisymmetry, and has a peak amplitude of about 50 km/s. Individual velocity measurements are accurate to a few km/s. The velocity dispersion in M32 is significantly smaller than the SAURON instrumental dispersion, except in the inner few arcseconds (e.g., van der Marel et al., 1998), and we do not show this here.

Figures 5 and 6 also illustrate a key advantage of integral-field spectroscopy over traditional aperture and long-slit spectroscopy: by integrating the flux in each spectrum, the surface brightness distribution of the galaxy is recovered. As this is derived from the same spectra that are used to obtain the kinematics and line strengths, there is never any doubt about the relative location of these measurements and the galaxy morphology.

The SAURON project: structure of E/S0/Sa Galaxies

We built SAURON to measure the intrinsic shapes and internal velocity and metallicity distributions of early-type galaxies, and to gain insight into the relation between the stellar and gaseous kinematics and the stellar populations in spheroids. Our strategy is to study a representative sample of nearby ellipticals, lenticulars, and early-type spiral bulges. The SAURON data are combined with high spatial resolution spectra of the nuclei, and interpreted through state-of-the-art dynamical and stellar population modelling.

Our sample was constructed as follows. We first compiled a complete list of accessible E/S0 galaxies and Sa bulges for which SAURON can measure the stellar kinematics: $-6^\circ \leq \delta \leq 64^\circ$ (zenith distance), $cz < 3000$ km s^{-1} (spectral coverage), $\sigma > 90$ km s^{-1} (spectral resolution). The objects span a factor 50 in luminosity ($M_B < -18$) and cover the full range of environment, nuclear cusp slope, rotational support, and apparent flattening. The galaxies were then divided into six categories (E/S0/Sa; field/cluster) and a representative sample of 72 objects was selected to populate the ellipticity versus absolute magnitude planes homogeneously (Figure 7). Based on our two observing runs in 1999, we hope to complete the observations of the entire sample by early 2002.

The detailed measurements will be compared with fully general galaxy models constructed by means of Schwarzschild's numerical orbit superposition technique (e.g., Cretton et al., 1999). The dynamical modelling uses all appropriate imaging and spectral data that are available, including HST and OASIS

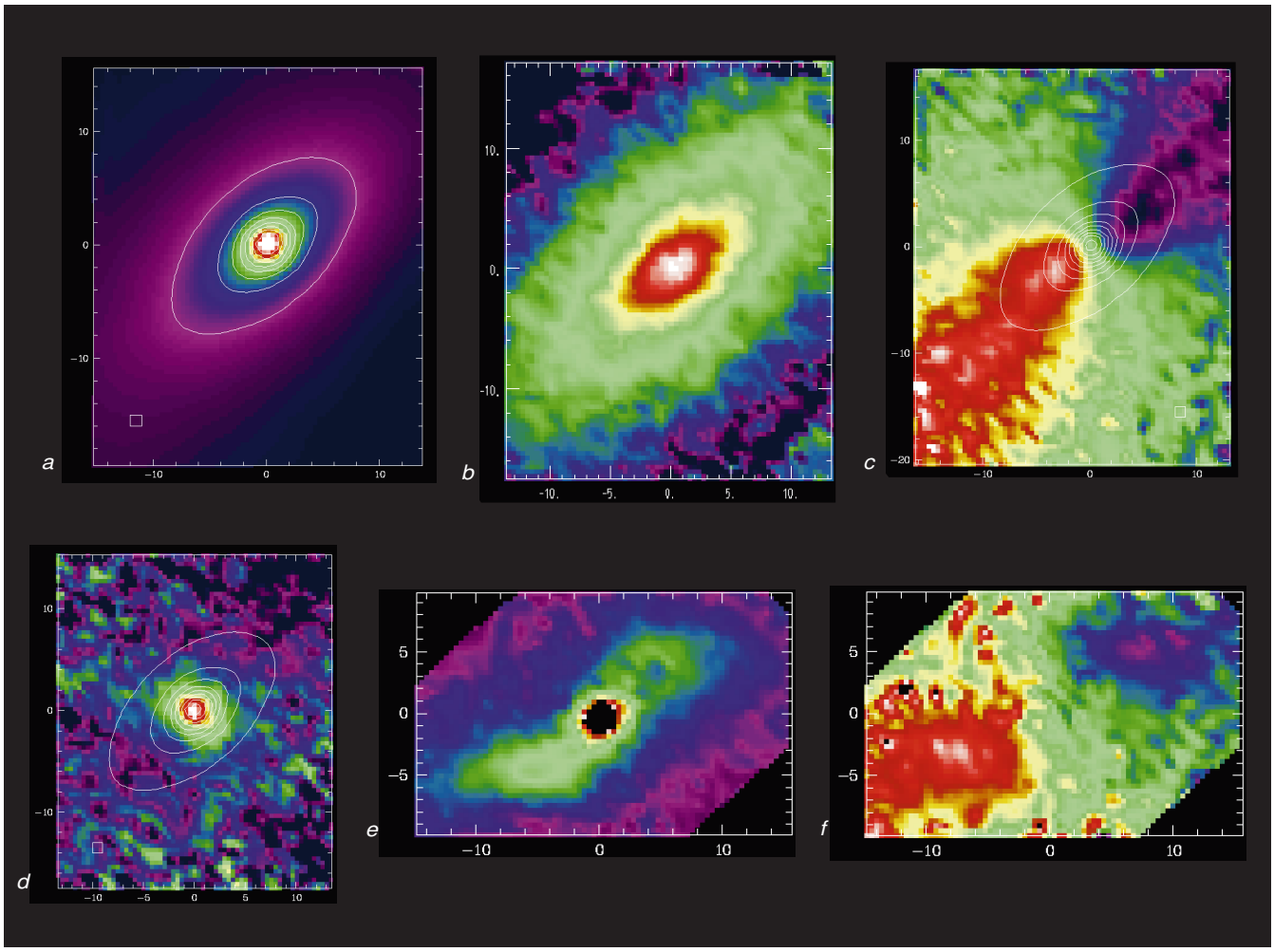


Figure 5. SAURON measurements of the E6 galaxy NGC 3377. Each pixel is 0.94″×0.94″ and the FOV shown is 30″×39″. a) Reconstructed total intensity. b) Stellar Mg b index. c) Stellar mean velocity. d) Stellar velocity dispersion. e) Gas total intensity ([OIII] λ5007). f) Gas mean velocity.

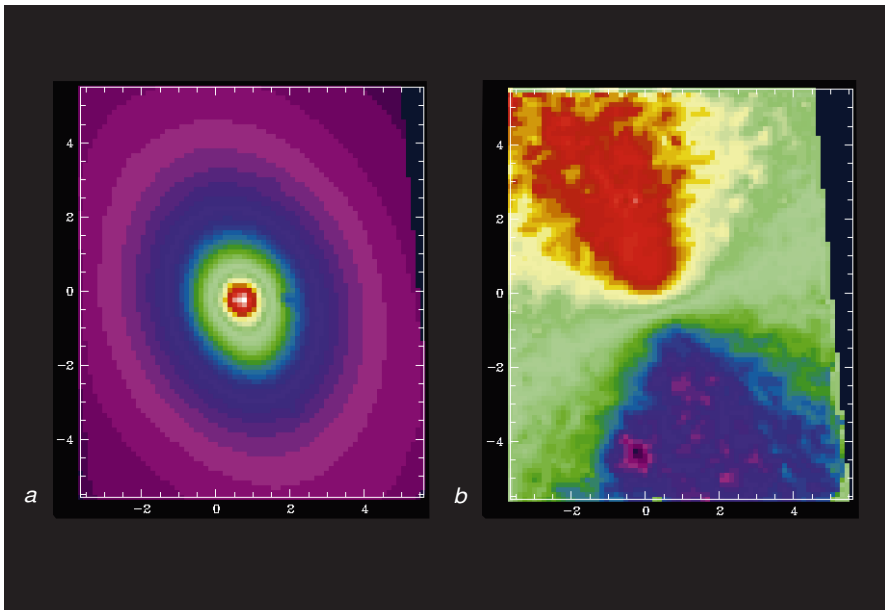


Figure 6. SAURON measurements of M32. a) Reconstructed total intensity. b) Stellar mean velocity. The FOV is 9″×11″, and the spatial sampling is 0.26″×0.26″.

spectra to constrain the mass of a central black hole. When combined with the constraints on the stellar populations derived from the line-strength distributions (Kuntschner & Davies, 1998), this will shed new light on the fundamental connections between the large and small scale dynamics, the formation (and existence) of supermassive black holes and galactic nuclei, and the history of metal enrichment in early-type galaxies.

It is a pleasure to thank René Rutten, the ING staff, in particular Tom Gregory, and Didier Boudon and Rene Godon for enthusiastic and competent support on La Palma. The SAURON project is made possible through financial contributions from NWO, the Institut National des Sciences de l'Univers, the Université Claude Bernard Lyon I, the universities of Durham and Leiden, and PPARC.

References:

Bacon, R., et al., 1995, *A&AS*, **113**, 347

Cretton, N., de Zeeuw, P. T., van der Marel, R. P., Rix, H-W., 1999, *ApJS*, **124**, 383

Kuntschner, H., Davies, R. L., 1998, *MNRAS*, **295**, 29

van der Marel, R. P., Cretton, N., de Zeeuw, P. T., Rix, H-W., 1998, *ApJ*, **493**, 613 ¤

Tim de Zeeuw (tim@strw.leidenuniv.nl)

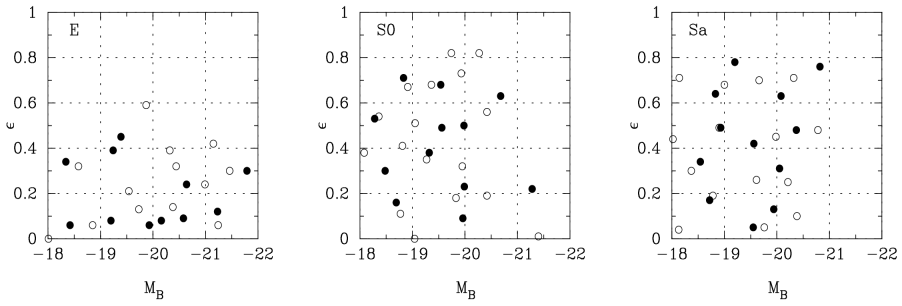


Figure 7. Distribution of E, S0, and Sa galaxies in the SAURON sample in the plane of ellipticity ε versus absolute blue magnitude M_B. Open circles: field galaxies. Solid circles: cluster galaxies.

First Sodium Laser Beacon at La Palma

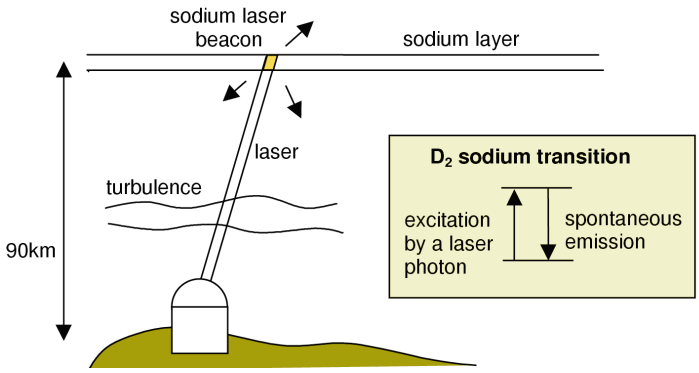
L. Michaille, J. C. Quartel, J. C. Dainty, N. J. Wooder (Imperial College London), R. W. Wilson (ATC), T. Gregory (ING)

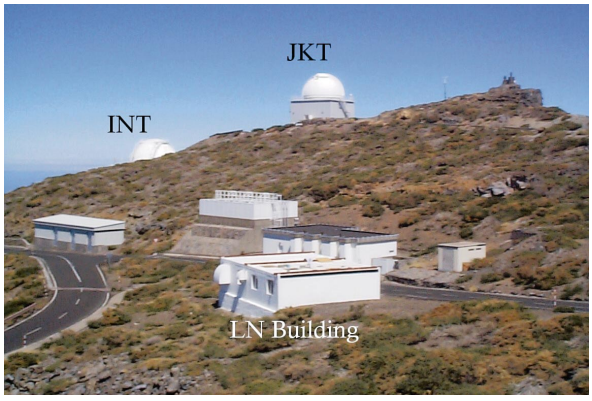
In the ING Newsletter No. 1, an ongoing project to implement an adaptive optics system on the WHT was described. Called NAOMI (Nasmyth Adaptive Optics for Multiple Instrumentation), this system will be capable of eliminating, to a large degree, the image degrading effects of atmospheric turbulence.

As with any adaptive optics system, NAOMI will rely on measuring light from a relatively bright reference object, or "guide star", close to the desired target in order to make the necessary correction. At visible wavelengths, however, it is often not possible to find a sufficiently bright star in the neighbourhood of the astronomical region of interest. One would like to be able to simply dial-up a guide star exactly where it is needed, and this is possible with the use of a "sodium laser beacon".

At an altitude of 90 km, well above the troublesome turbulence (which rarely reaches beyond 25 km altitude), is a 15 km thick layer of sodium atoms which, just as in a sodium lamp, can be excited to spontaneously emit light. To achieve this from the ground we can use a laser tuned to an absorption wavelength (589.0 nm) of the sodium atoms. The excited region of atoms creates a bright spot in the sky, the sodium laser beacon, which can be used as the guide star for an adaptive optics system (Figure 1).

A Laser Guide Star (LGS) system is being planned for the WHT to compliment the NAOMI system. In preparation, the Applied Optics group at Imperial College London has been investigating some practical aspects of creating and using sodium beacons for adaptive optics. Amongst these is a study of the sodium layer dynamics at La Palma using observations of an experimental sodium laser beacon. We have built a laser system which launches a 25 cm diameter, diffraction limited beam from the liquid nitrogen building located roughly midway between the JKT and the WHT (Figure 2). Part of the laser beam is directed through a small sodium oven and by measuring the absorption we can lock the (tuneable) laser output to precisely the correct wavelength





Figures 1 and 2. Left: A laser, tuned exactly to the D2 transition of sodium, can be used to excite the sodium layer at 90 km altitude. The beacon thus created can be used as the guide star for an adaptive optics system. Right: The Liquid Nitrogen (LN) building which houses the laser. The beam is launched through a hole in the roof.