SCIENCE

Under the Microscope: Galaxy Centres with OASIS

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Early-type galaxies are thought to be among the oldest known stellar systems, and as such have experienced the full diversity of evolutionary mechanisms at work in the universe. They are crucial laboratories for understanding how galaxies form and evolve from early epochs until the present day. A key aspect of unlocking their fossil evidence is by studying the dynamics of stars and gas, and characterising the stellar populations. To this end, the SAURON survey (de Zeeuw et al., 2000, Peletier et al., 2001, de Zeeuw et al., 2002) has undertaken a study of 72 representative nearby early-type galaxies and spiral bulges using the SAURON integral field spectrograph at the WHT (Bacon et al., 2001).

The SAURON survey has a spatial sampling of 0.94″×0.94″ per lenslet, therefore often undersampling the median seeing at La Palma (0.7″ FWHM). Towards the galaxy nucleus, however, there are often sharp, localised features in the kinematics, such as decoupled cores or central disks, as well as distinct stellar populations and ionised-gas distributions. Such features may only be partially resolved in the SAURON data, or perhaps not visible at all.

Additionally, at Hubble Space Telescope (HST) resolution, elliptical galaxies exhibit power-law central luminosity profiles. The slope of this power-law shows clear trends with certain global properties, such as the degree of rotational support, isophotal shape, and stellar populations. It is therefore crucial to fill the gap between the medium (few 100s of pc) to large-scale (few kpc) structures probed with SAURON and the inner (<200 pc) components probed by HST. We have thus begun a complementary study on a subset of the SAURON sample using the OASIS spectrograph, during its former life mounted on the Canada-France-Hawaii Telescope (CFHT), Hawaii. This follow-up survey is being continued with OASIS at the WHT, with the aim of completing all E/S0s of the SAURON survey by spring 2005. Here we give an overview of this follow-up survey, and future prospects for using OASIS in this field.

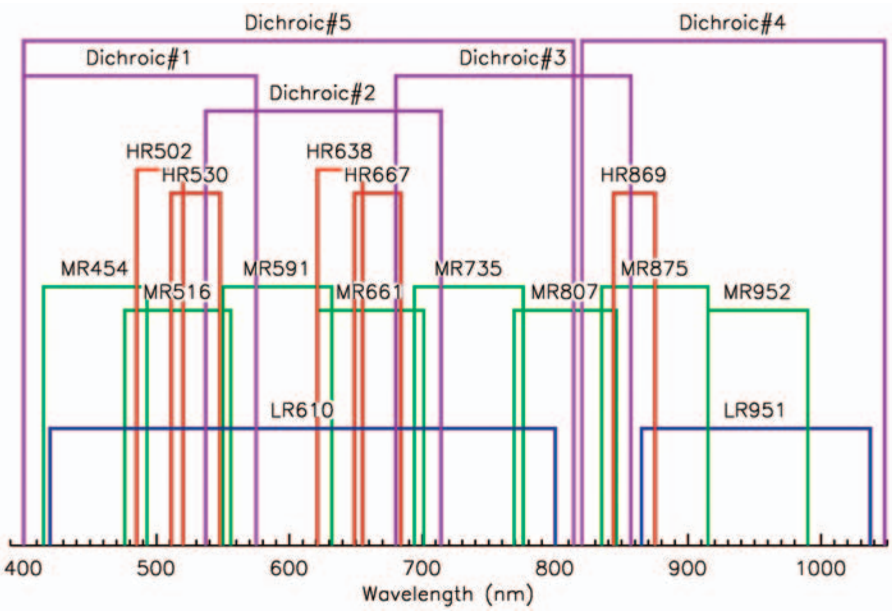

Figure 1. Spectral configurations of OASIS. Blue lines indicate the low-resolution (LR) modes (R~1000); green lines indicate medium-resolution (MR) modes (1000<R<2000); and red lines indicate high-resolution (HR) modes (R>2000). The dichroics are required to isolate the science light from the NAOMI AO system.

The OASIS Spectrograph

The OASIS integral-field spectrograph, mounted behind the NAOMI Adaptive Optics (AO) system (Benn et al., 2002, 2003) in the GRACE Nasmyth enclosure of the WHT (Talbot et al., 2003), was offered to the ING community in semester 2004B, and was awarded time during 15 nights for a variety of science projects. OASIS is based on the TIGER lens-array concept (Bacon et al., 1995) and is designed for high-spatial resolution observations, specifically with the assistance of AO. There is a selection of gratings and filters available, giving low and medium spectral resolution modes within the 0.43µm to 1µm wavelength range. Via the use of different enlargers, there is also a range of spatial samplings which can be adapted to suit the available PSF. Figure 1 and Table 1 summarise the

Mode	Enlarger (mm)	Sampling (")	FOV (")
Spectral	8.5	0.09	2.7×3.7
	12.5	0.14	4.0×5.5
	22	0.26	7.7×10.3
	33	0.42	12.0×16.7
Imaging	62	0.02	37.6

Table 1. OASIS spatial configurations.

available instrument modes. With the addition of AO capabilities provided by NAOMI, OASIS is one of the most versatile optical integral-field spectrographs currently in operation.

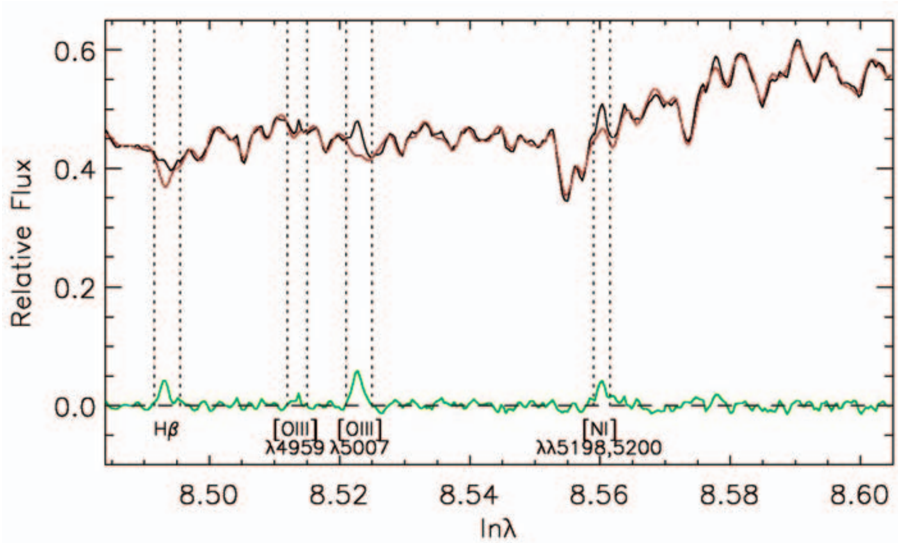

Figure 2. Optimal template fit to the central spectrum of NGC 2768. The lower spectrum shows the residual emission lines after the template-fit, which are fitted using single Gaussians to obtain the gas properties. Vertical lines show regions around the emission that are excluded from the fit.

Observations

For this project, OASIS was configured to give similar spectral coverage and resolution as SAURON by using the MR516 configuration. The data were reduced using the publicly available `XOasis` software (Rousset, 1992) developed at CRAL (Lyon). Galaxy observations were composed of two or more exposures, which were merged by first aligning the galaxy nucleus of the separate reconstructed images. Co-spatial spectra were then combined, taking into account the error spectra that are propagated through the reduction. In order to provide reliable, unbiased measurements, the data cubes are binned in the spatial dimension to a minimum signal-to-noise ratio of 60 per pixel using the Voronoi 2D-binning developed by Cappellari & Copin (2003).

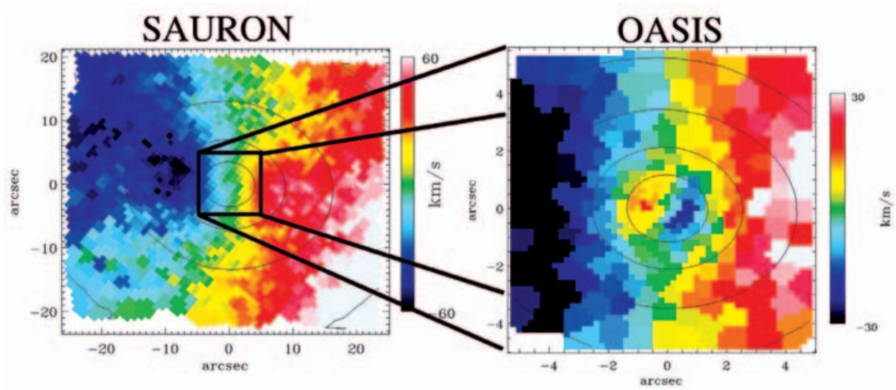

Figure 3. Spatially binned SAURON (left map) velocity field of NGC 4382 (Emsellem et al., 2004) showing the outline of the OASIS field (right map).

Results

From the 2D-binned data cubes, it is possible to derive the following properties:

Stellar Kinematics: These are derived by directly fitting the spectra in pixel-space (Cappellari & Emsellem, 2004), which avoids contamination by nebular emission lines, which can often be strong in the central regions of early-type galaxies (Figure 2). Template mismatch was minimised by building an 'optimal template' from a library of stellar population models from Vazdekis (1999).

Gas Kinematics: By subtracting the optimal template, one obtains a residual spectrum in which the emission-line features are revealed. We then determine the distribution and kinematics of the ionised-gas, by fitting the emission-line profiles of these continuum-free spectra with simple Gaussians.

Line Strengths: The OASIS spectral range contains a number of key absorption features which can be used as diagnostic tools to determine the age and metallicity of the stellar populations within a galaxy. To remove the contaminating emission lines, the Gaussian fits are subtracted from the original data before measuring the absorption line strengths. Finally, the absorption line strengths are calibrated onto the well-established LICK/IDS system (e.g. Trager et al., 1998).

Figure 3 shows an example of how the OASIS data can be used to reveal central features of galaxies in the SAURON survey. The left panel of this figure presents the SAURON velocity field of NGC 4382. There is a low-level 'kink' in the zero-velocity (green) contour near the galaxy centre. The OASIS data (right panel) clearly reveal this as a counter-rotating decoupled component.

Figure 4 presents the OASIS stellar (left panel) and gas (right panel) velocity fields for NGC 2768. The stellar component rotates around the apparent short-axis of the galaxy. The gas, however, rotates around the apparent long-axis, perpendicular to the stars. This illustrates how we can separate the stellar and gas properties, using the optimal template fit. There is some evidence of non-axisymmetry in the stellar velocity field, which may indicate the presence of a bar.

Figure 5 presents a map of Hβ absorption strength (after emission subtraction) for the galaxy NGC 3489 (left panel) showing a strong peak in the central 1″, indicating a young stellar population. The right panel of Figure 5 quantifies this, plotting Hβ absorption strength against the abundance-insensitive metallicity indicator [MgFe50]' (Kuntschner et al.) from the OASIS data. The young population in the core of this galaxy indicates that it is in a post-starburst phase, with a luminosity-weighted age of around 1.5 Gyr. Equivalent SAURON data are also shown, illustrating that both data sets are consistent.

Future Prospects: NAOMI

The integral-field capabilities of OASIS are ideal for exploiting the corrected PSF delivered by the NAOMI AO system, and commissioning results indicate that NAOMI is performing well at optical wavelengths (Figure 6). There are several objects in our sample which have a suitable guide star nearby, for which we have been allocated observing time to push the limits of spatial resolution, and measure stellar motions close to the putative central supermassive black hole residing at the galaxy centres. There are few targets in the sky with such conveniently placed bright stars, and so this project provides a glimpse of what will be possible on many targets when the GLAS laser guide-star system becomes available in 2006. More information on GLAS can be found on the web page: http://www.ing.iac.es/About-ING/Strategy/glas_web_announcement.htm.

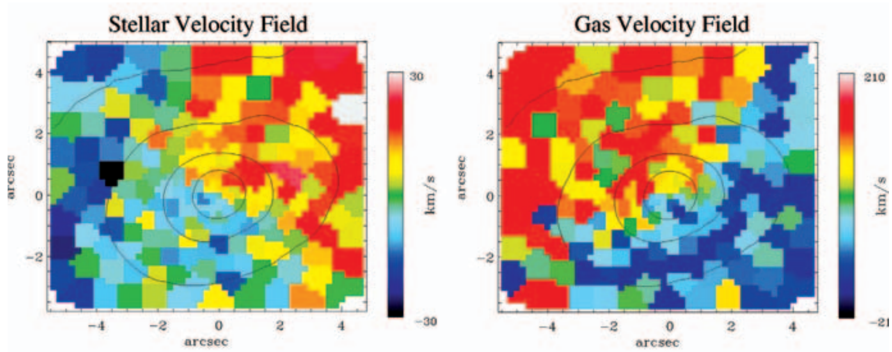

Figure 4. OASIS stellar (left) and ionized-gas (right) velocity fields for NGC 2768 showing the decoupled rotation of the stars and gas. Isophotes from the reconstructed image are overplotted, showing the total flux within each OASIS spectrum. Distortion of these isophotes indicates dust features.

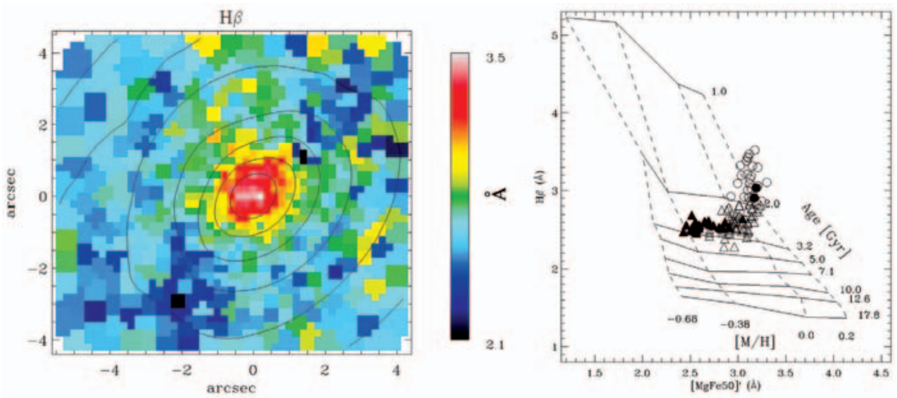

Figure 5. Left panel: OASIS map of Hβ absorption strength in NGC 3489. Right panel: Hβ absorption strength versus an abundance-insensitive metallicity index, overplotted with a grid of stellar population models from Vazdekis (1999). Open symbols: OASIS measurements; filled symbols: SAURON measurements, binned in 1" circular annuli. Circles indicate measurements inside a 1" radius of the centre; triangular symbols indicate measurements outside this radius.

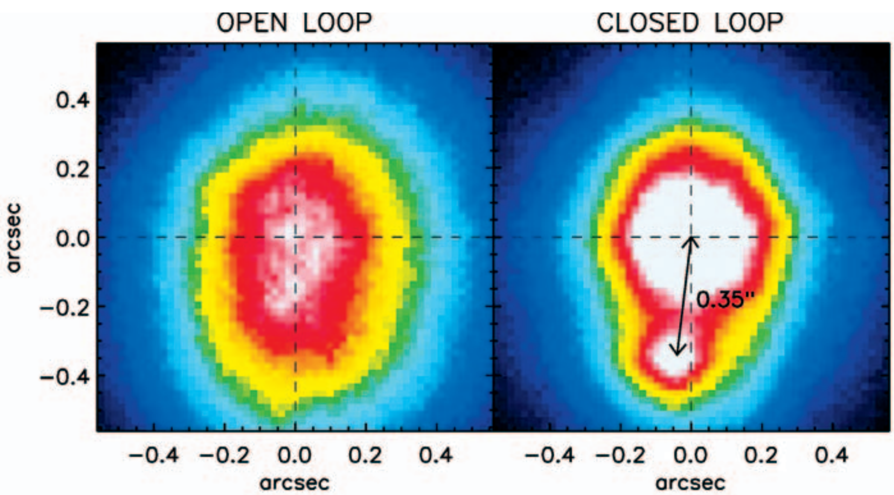

Figure 6. OASIS R-band images of a close binary (V_{mag}~ 9+10) in 0.5" natural seeing ("open loop") and with NAOMI correcting the PSF ("closed loop") to 0.2" FWHM.

Summary

The central regions of nearby early-type galaxies contain a wealth of structure and detail that we are only just beginning to uncover. Galaxy properties show connections on vastly different scales, and by understanding these relationships, we gain insight into galaxy formation mechanisms. The OASIS follow-up of the SAURON survey will provide a unique data set for a large sample of objects, complementing the panoramic view delivered by SAURON, and giving a comprehensive picture of galaxy structure.

Acknowledgments: It is a pleasure to thank the staff of the ING and CRAL for all their hard efforts in ensuring an efficient transfer and installation of OASIS at the WHT. Thanks also to the CFHT staff for their support of OASIS during its time there. ¤

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The Largest Known Planetary Nebula on the Sky

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The enormous Sloan Digital Sky Survey (SDSS) spectroscopic catalogue has many applications but the discovery of Planetary Nebulae (PN) had not been recognised as among the potential scientific returns. However, the INT recently played a key role in the identification of a record breaking PN discovered serendipitously from the SDSS.

The vast majority of PN in our own galaxy have been identified via wide-field narrow-band Hα surveys of the type currently ongoing using the INT (`http://astro.ic.ac.uk/Research/Halpha/North/`) or through wide-field low-resolution slitless spectroscopic surveys, with both techniques attempting to isolate objects showing very high equivalent width emission lines that are characteristic of PN. The potential of the relatively high-resolution, pointed spectra that make-up the SDSS spectroscopic database involved a serendipitous observation during the course of a search for high-redshift gravitational lenses. The idea behind the gravitational lens search is to target luminous (massive) galaxies at intermediate redshifts, $0.2<z<0.6$, which constitute the optimal line-of-sight for detecting gravitationally lensed background sources (Hewett et al., 2000). The population of high-redshift star-forming galaxies, many of which possess strong Lyα emission, provide a high surface density of readily detectable background sources. The first such object was discovered by Warren et al. (1996) and the application of the SDSS survey for lenses at lower redshifts has been demonstrated by Bolton et al. (2004).

Examining the results of an automated search of the SDSS DR1 spectroscopic database for emission lines from putative high-redshift sources, one particular galaxy showed an unambiguous emission line detection with a somewhat weaker feature to the blue. The emission line pair was immediately identifiable as emission from [OIII] 4959, 5007. Not an entirely unexpected occurrence but the unusual feature of the detection was that the wavelength of the detection placed the emission at essentially zero radial velocity. Querying the output of the emission line search for similar detections produced more spectra showing a similar signature. All of the objects possessing [OIII] emission occurred in an approximately circular region with a diameter of ~1.5°, with not a single detection anywhere else on the sky. Investigation of SDSS spectra of stars, quasars and even sky fibres revealed further detections, all concentrated in the same region of sky.

A series of checks fairly rapidly eliminated the majority of instrumental artifacts or transient phenomena as the cause of the emission. Discrete enquires of the SDSS team produced the news that [OIII] emission had occasionally been detected but this was due to auroral activity. However, the detection of the [OIII] emission in two SDSS spectroscopic fields observed on different nights and confirmation

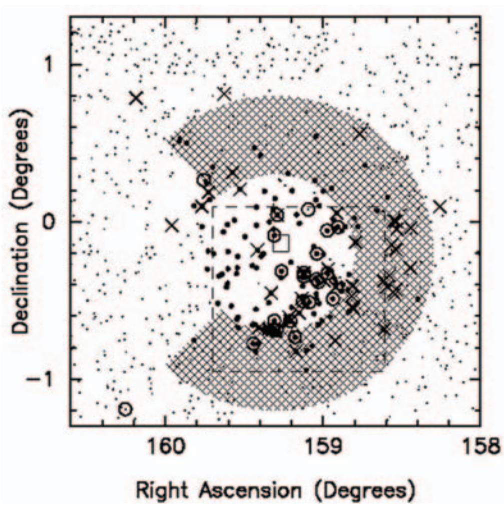

Figure 1. Spatial distribution of spectra with detectable [OIII] 4959, 5007 (dots), Hα (circles), and [NII] 6583 (crosses). The hatched area indicates a region where composite spectra also show unambiguous evidence of [OIII] 4959, 5007 emission. Positions of objects with SDSS spectra for which no individual detections were obtained are also indicated. The dashed outline shows the area included in the narrow-band images of Figure 2. The location of the white dwarf PG 1034+001 is marked by a box.