Potential Science for the OASIS Integral Field Spectrograph with Laser Guide Star Adaptive Optics

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Abstract

I review the science case for the Laser Guide Star system being built for the William Herschel Telescope (WHT) on La Palma. When used in combination with the NAOMI Adaptive Optics system and the OASIS visible-wavelength Integral Field Spectrograph, I demonstrate that there are substantial, exciting areas of astrophysical research in which the WHT can contribute.

Key words: instrumentation: adaptive optics, instrumentation: spectrographs

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1 Introduction

Many people have been involved in generating the science case for the addition of a Rayleigh Laser Guide Star (LGS) (Rutten et al. 2003; Clark et al. 2003; Rutten 2004) to the OASIS IFU spectrograph (Benn et al. 2003; McDermid et al. 2004a,b) combined with the NAOMI Adaptive Optics (AO) system (Myers et al. 2003; Jolley et al. 2004; Benn et al. 2004) on the William Herschel Telescope on La Palma. The co-authors listed on some versions of the LGS proposal are: Rene Rutten, Roland Bacon, Richard Bingham, Paul Clark, Roger Davies, Ron Humphreys, Tom Gregory, Johan Knapen, Gil Moretto, Tim Morris, Simon Morris, Richard Myers, Gordon Talbot, Richard Wilson, Tim de Zeeuw. As a member of this group, I (SLM) was invited to summarize this science case. I have chosen to only cover part of the science case, and also (as is traditional

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for conference reviewers the world over) to focus on science areas currently being pursued by myself or colleagues at Durham University. As a result, this is by no means an exhaustive list, but it is one that I am better qualified to write on, and it does contain some updates from the original proposal.

The topics discussed below will all be ones that can be attacked with the instrument combination in the title (i.e. in the optical, with relatively low Strehl), and using the WHT collecting area, although obviously many of them are also topics that larger aperture telescopes are also addressing. I have also tried to focus on cases where observations with the WHT are not only useful, but also where the OASIS+NAOMI+LGS combination there has some sort of an advantage or at least only a small number of competitors.

2 Science Changes produced by Installation of a Laser Guide Star

This subject was covered by several people attending the workshop, but in order to make this summary relatively self-contained, I will repeat some of it here.

Far and away the most significant change in the science potential for OASIS+NAOMI from the addition of the LGS is the gain in sky coverage. Some graphical demonstrations of the magnitude of this change were developed by Remko Stuik (Leiden), and shown in several of the presentations. Apart from deep in the galactic plane, the chance of finding a bright enough guide star for NAOMI without a LGS is never higher that 10%. In contrast, with an LGS, the probability of finding a suitable natural tip-tilt star (which is still needed) is above 80% for 2/3 of the sky, and above 60% for near 9/10 of the sky. As will be detailed below, this makes a qualitative difference to the types of science that can be done. Targets which are suited to 4m class high spatial resolution IFU spectroscopy are rare, and multiplying that rarity by the small sky coverage of an NGS AO system reduces the number of interesting science targets to near zero.

Some secondary effects are of mixed value. The LGS point spread function (PSF) can either be better or worse than the NGS PSF depending on the NGS brightness and location. For many science targets this means there will be an improvement in the delivered image quality, even if a usable NGS is in the field. For a few objects this will not not be the case. In all cases the PSF will be very far from the diffraction limit due to operation in the optical with a (relatively) modest number of correcting elements. As was emphasized during the meeting, and in some of the examples below, this sort of ’improved seeing’ can be extremely valuable. The predictable brightness and location of the LGS relative to the science target will make the science target PSF
more predictable and reduce the challenges of estimating the delivered image quality. Finally, the operational impact of keeping an LGS up and running may or may not impact on the efficiency of observing. Overheads could be increased by the need to lock on to the laser, but, conversely, its predictable and repeatable location and brightness could produce efficiency savings.

3 An Example of Galactic Science Enabled by a LGS

In the proposal, galactic science targets ranging from sub-stellar companions, through mass loss in stars, to exotic binary systems in crowded fields were considered. Here I will focus on one particularly intriguing science case - namely the search for intermediate mass black holes.

3.1 Intermediate Mass Black Holes in Globular Clusters

Although the evidence for stellar mass black holes \( (M \leq 10M_\odot) \) and for supermassive black holes \( (M \geq 10^6M_\odot) \) is now viewed by most astronomers as iron-clad, there is a ‘missing link’ mass range in between for which there is little observational support. One very promising hunting ground for black holes in this mass range is the core of a globular cluster. This is for two reasons. First, that many formation scenarios for such black hole masses place them at the bottom of potential wells in crowded stellar environments, and second, that the crowded stellar environment provides one with a surplus of test masses which can map out the potential well and be used to test for point gravitational sources.

Tragically, this same surplus of test particles makes crowding a real problem, and deblending the light from individual stars in order to have a clean velocity measurement requires high spatial resolution and a good knowledge of the PSF.

Valiant attempts to conclusively demonstrate the presence of an intermediate black hole were made by van der Marel et al. (2002); Gerssen et al. (2002, 2003) and Gerssen (2004). As an example, using the Hubble Space Telescope (HST) STIS spectrograph, radial velocities for 64 stars in the core of the globular cluster M15 were measured and combined with velocities measured from the ground for 1800 other stars. Unfortunately, although it was possible to show that a model with a 1700 \( M_\odot \) black hole gave a better fit to the data than one without one, the ‘no black hole’ model was still statistically consistent with the data.
An AO fed IFU able to observe the cores of several nearby globular clusters may well be able to improve the statistics to the point at which the black hole solution is shown to be inescapable. However, detailed modelling is still needed to show that (a) the OASIS spectral resolution is sufficient, and (b) that the PSF improvements from NAOMI+LGS in the optical are sufficient for this approach to generate new science.

4 Examples of Nearby-Galaxy Science Enabled by a LGS

The workshop poster carried a dramatic image illustrating the additional science to be gained by increasing the spatial resolution of velocity measurements in the cores of nearby galaxies [http://www.ast.cam.ac.uk/ING/conferences/aoworkshop/aoworkshop.php]. This image was literally the ‘poster-child’ for the workshop and was very persuasive. I do not propose to go into this science case in any detail, but do include a few references here for completeness.

4.1 Detailed Dynamics of Nearby Spheroid Dominated Galaxies

The SAURON IFU spectrograph had an extremely well defined and focussed science goal. As I will outline later, this has not stopped it from being used for a number of other science projects, but it has certainly amply achieved its builders’ goals as described in Bacon et al. (2001); de Zeeuw et al. (2002) and Emsellem et al. (2004). The core goal of understanding the formation process for elliptical galaxies and the bulges of spiral galaxies has been advanced by the quantification of the percentages of counter-rotating cores, rotationally supported disks and the measurement of spatially resolved stellar ages and abundances in these systems.

As illustrated in the conference poster and also in McDermid et al. (2004a) and Copin et al. (2004), higher spatial resolution observations of galactic cores often brings to light substructure that was invisible at coarser resolution. As with most of the cases in this review, the greatly increased sky coverage of a LGS system is needed to enable observations of a reasonable sample.

4.2 Nearby Active Galactic Nuclei

I do not propose to comment at any length on the use of OASIS+NAOMI with a LGS to study Active Galactic Nuclei (AGN) either, as this was also covered by several other speakers at the workshop. However, I could not resist a
nostalgic revisit to a paper from twenty years ago (Morris et al. (1985)) which I claim already showed both the power of 3D spectroscopy for unravelling the complex dynamics of gas in the inner regions of AGN, and also the difficulty in using those measured dynamics to make general conclusions.

I would also claim that Ferruit et al. (2004), who present some recent OASIS data, faced the same problem. Indeed, a pessimist might conclude that a large fraction of the observed gas dynamics in AGN cores is chaotic, and, like the weather on the Earth, driven by the (AGN equivalent of) flaps of butterfly wings in China.

In order not to leave this topic on a wholly negative note, it is true that a similar conclusion might have been drawn about the stellar dynamics discussed in section 4.1. As shown by the papers referred to there, large enough samples of high quality 3D data may allow more general and useful conclusions to be drawn.

Some of the first AO assisted IFU observations were of ‘the usual suspects’ AGN - NGC 4151 and NGC 1068. These targets can be used as their own guide stars and are hence well studied. I believe that until a sample of size comparable to the SAURON galaxy survey has been observed, at a similar level of detail, ‘general and useful conclusions’ will remain elusive. There is also a well known link between AGN activity and star formation (and corresponding star formation driven winds). These two phenomena are so closely inter-related that it would seem foolish to me to study one without studying the other. It has always been one of the great strengths (and weaknesses) of 3D spectroscopy that, with a single observation, one generally gets more information than can easily be dealt with on all of the phenomena in the region observed. For this reason, this approach may be the only one able to discover some underlying physical principles hidden amongst the complex phenomenology of the inner regions of AGN.

5 Examples of Distant-Galaxy Science Enabled by a LGS

At first sight, one might suspect that using a 4m class telescope with fine spatial sampling to observe extremely distant (and hence faint) objects spectroscopically would be doomed to failure. In general, this suspicion is in fact true, and most of the results presented below are from 8m class telescopes. Two factors act to open up a significant expanse of ‘discovery space’ for OASIS+NAOMI with a LGS. The first is that, in emission lines many extragalactic objects have regions of high surface brightness, and second, that many of these regions are in fact small, or knotty, so that any improvement in image quality over natural seeing can, to a certain extent, compensate for a smaller
telescope collecting area.

5.1 Extreme Star Formation

Observations in the sub-mm region of the spectrum have shown that there is a significant population of dusty galaxies forming stars at extra-ordinary rates ($\approx 1000 \, M_\odot \, yr^{-1}$). Key questions for these objects are: Are these massive galaxies with extreme star-formation rates, or simply an extremely active phase in more mundane systems? What drives the immense luminosity? What are the dynamical masses? What are the metallicities of the various components?

Swinbank et al. (2005) demonstrate that a combination of optical and Near-IR (NIR) IFU observations can begin to unravel the answers to these questions. HST imaging has already also demonstrated that the spatial scales of interest are significantly less than an arcsecond.

More locally, Swinbank et al. (2003) show that optical IFU observations of galaxies with spectroscopic evidence for a recent cessation of rapid star formation may help us to determine the cause of this truncation. Although probably a heterogeneous group, galaxies with strong Balmer absorption features in their spectra (from A stars), but weak emission lines indicating an absence of O and B stars, likely include objects caught in transition between star forming ‘spirals’ and passive ‘ellipticals’. High spatial resolution absorption line spectroscopy will no doubt be extremely time consuming on a 4m class telescope, but is definitely not impossible, and the spatial resolution of an LGS system should deliver many of the benefits outlined in section 4.1 for the SAURON project.

5.2 Gravitational Lensed High Redshift Galaxies

One of the images used in the original science case for a LGS for the WHT was that of the gravitationally multiply-lensed galaxy behind the cluster Cl 0024+1654 [http://hubblesite.org/newscenter/newsdesk/archive/releases/1996/10/]. The gravitational lens increases the total flux collected from a distant galaxy and spreads the unlensed image out over one or more magnified images. Unfortunately, such fortuitous alignments of galaxies with locations of strong lensing are rare, and, again, asking for the additional requirement of a bright natural guide star reduces the sample which can be studied with high spatial resolution to near zero. The cluster Cl 0024+1654 is a case in point, with the nearest available star 65 arcsec away and 16.5 magnitude in R (making it a suitable tip-tilt reference for LGS AO, but of no use for NGS AO).
Swinbank et al. (2003) demonstrated the power of this approach on a z≈1 galaxy, where they show that by using an IFU, and correcting for the distortions in the image by the lensing process, one can derive accurate rotation curves, and hence mass-estimates at high redshifts. These measurements also allow the construction of Tully-Fisher diagrams at times when the Universe was half its present age. These in turn can be used to test models for galaxy formation.

5.3 Lyman \(\alpha\) Emitters

Objects with redshifts between 3 and 7 have rest frame Lyman \(\alpha\) at observed wavelengths convenient for ground based AO assisted IFU observations.

The SAURON IFU spectrograph on the WHT has been used on some lower redshift (z≈3) strong Lyman \(\alpha\) emitters, deriving some exciting conclusions about feedback from star formation at high redshift (Bower et al., 2004; Wilman et al., 2005). Although extremely long exposure times may be needed, LGS AO assisted IFU observations of these, and other similar objects, could greatly improve our understanding of the gas dynamics and the radiative transfer of Lyman \(\alpha\) photons in galaxies. As an example, in the Lyman Break Galaxy (LBG) C15 discussed in Bower et al. (2004), a clear velocity shear can be seen across the line emitting region (even with seeing limited spatial resolution). At the moment, the interpretation of that shear remains ambiguous. Are we seeing an outflow tilted to our line of sight, or are we seeing coherent rotation, holding out the promise of a total mass estimate for this object?

In several knots of the large Lyman \(\alpha\) emitter studied by Wilman et al. (2005), there is strong absorption which they interpret as evidence for an outflowing wind covering the whole source. Higher spectral and spatial resolution observations, although no doubt extremely expensive in observing time, might be able to confirm this interpretation.

6 Conclusions

I hope this review has demonstrated that despite its now ‘small’ collecting area, and the traditionally photon starved nature of IFU observations, there is still a substantial range of interesting astrophysical questions that can be addressed using the LGS with NAOMI and OASIS on the WHT. The combined gains from focussing on high surface brightness emission line objects and increasing that surface brightness by image sharpening with AO will keep the WHT scientifically competitive on targets with no natural guide star.
Fig. 1. Single Gaussian fits to SAURON observations of the Steidel ‘blob 1’. The region plotted is 41×33 arcseconds in angular size. Panel (a) shows the intensity of the fitted line (red–white: 0–2 × 10^{-17} ergs per cm^{2} per sq. arcsec); Panel (b), the central wavelength of the line (blue–red: 4970–4990 Å); Panel (c), the width of the line (red–white: σ = 0–15 Å). The plots allow us to quantify the velocity structure seen in the halo. The circles show the regions of interest (see Bower et al., 2004), with the top left circle identifying the LBG C15 referred to in section 5.3.

I would like to end with a comment on serendipity. This might seem unlikely to be relevant for a small field of view, high spatial resolution instrument like OASIS, but I would claim that, to a first approximation, the chances of serendipitous discoveries are related to the number of independent spatial and spectral samples, and the uniqueness of the planned targets of the instrument. Some historical examples that demonstrate this, despite having relatively small sky coverage were published by McCarthy et al., (1988); Dev et al., (1998). A recent IFU example of serendipity (admittedly from a ‘wide field’ IFU) was published by Jarvis et al., (2005). OASIS can sample a substantial volume of space, if one views its wavelength axis as a redshift range, and will be one of the very few instruments able to deliver AO image quality over most of the sky. In amongst all the careful discussions of signal-to-noise and detection limits, it is good to also remember how exciting astronomical discovery is, and how often astronomers have been surprised by what they have found.

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