A Mega Integral Field Spectrograph for the VLT

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Abstract. We describe MIFS, a second generation integral-field spectrograph for the VLT, operating in the visible wavelength range. It combines a 1′ × 1′ field of view with the improved spatial resolution provided by multi-conjugate adaptive optics and covers a large simultaneous spectral range (0.6–1.0 μm). A separate mode exploits the highest spatial resolution provided by adaptive optics. With this unique combination of capabilities, MIFS has a wide domain of application and a large discovery potential.

The MIFS low-spatial resolution mode (sampled at 0.′′2) combined with the initial MCAO capabilities planned for the VLT will provide ultra-deep fields with a limiting magnitude for spectroscopy of R ∼ 28. MIFS will improve the present day detection limit of Lyα emitters by a factor of 100, and will detect low-mass star-forming galaxies to z ∼ 7. The MIFS high-spatial resolution mode (3′′ × 3′′ field sampled at 0.′′01) is optimized for the next step in (MC)AO. It will probe, e.g., the relationship between supermassive central black holes and their host galaxy and the physics of winds from accretion disks in young stellar objects at unprecedented spatial resolution.

MIFS will extend Europe’s lead in integral-field spectroscopy. It capitalizes on new developments in adaptive optics, and is a key step towards instrumentation for OWL.

1 Introduction

The Hubble Deep Fields (HDFs)—the deepest broad band images obtained to date—have revealed the distribution in redshift and morphology of high redshift galaxies, and have generated an impressive number of follow-up studies at all wavelengths, so that nearly complete multi-wavelength imaging is available for distant galaxies. However, many important physical quantities (gas/star content, stellar population mix, kinematics) cannot be derived from broad-band imaging but require spectroscopic measurements. A significant investment of observing time on large ground-based telescopes, in particular Keck, has allowed completion of spectroscopic observations of the HDF north galaxies to R ∼ 24, most of which are at z < 1. To increase the redshift limit, one needs to achieve a better detection limit, higher spatial resolution, low sky background, and an ultra-stable and well-calibrated instrument. These requirements are one of the central drivers for NGST, to be launched in 2009.
We show here that ground-based astronomy can benefit from new technological developments such as multi-conjugate adaptive optics (MCAO), high-order deformable mirrors, second-generation image slicers, and panoramic integral-field spectrographs (IFSs) to challenge the capabilities of NGST well before 2009. We propose an instrument for the VLT, MIFS, which will not only provide the critical spectral information that is currently missing in our understanding of high-z galaxies, but will also allow major progress in many other areas of astronomy.

2 Design considerations

We first summarize recent technical developments which influence our design for MIFS, then discuss the scientific tradeoff we conducted to set its specifications, and conclude with a performance estimate.

2.1 Developments in adaptive optics

MCAO is being developed to overcome the problem of isoplanetic angle, which affects classical AO. First generation MCAO uses three or five reference stars to sense atmospheric turbulence in three dimensions, and two deformable mirrors conjugated with the main layers of turbulence. Compared to the classical (single layer) AO, MCAO dramatically improves the corrected field of view. The ESO AO group has shown that in median seeing conditions at Paranal, and with three natural guide stars of magnitude 13 or brighter, it will be possible to obtain a corrected field of view of $1' \times 1'$ with an improved and nearly constant PSF, and a Strehl ratio of a few % at 0.6 $\mu$m. This raises the exciting possibility to observe HDF-like deep fields from the ground at a resolution similar to that of HST.

The number of actuators in deformable mirrors is currently limited to a few hundred. This number will increase by almost an order of magnitude in the next generation of deformable mirrors which use micro-mirror arrays. This will considerably enhance the performance of AO, in particular at shorter wavelengths. In a further step, the multi-layer oriented MCAO technique which will use more guide stars and a larger field of view for the ground layer, should be able to reach a Strehl ratio of 20% at 0.5 $\mu$m. Example PSFs are shown in Figure 1.

2.2 Advanced slicers

Three different concepts of IFS are in use: lenslet IFSs such as TIGER, OASIS or SAURON (2,3,5), lenslet-fiber IFSs such as VIMOS (17) or GMOS (8), and slicer IFSs such as 3D (21) and SINFONI (19). Each concept has its pros and cons, but not all of them can be expanded to a very large number of spatial elements and not all have a high packing efficiency. The advanced slicer technique pioneered by the Durham group (3) is the most promising in terms of packing efficiency (nearly 100%) and overall size. It is also one of the concepts selected as an alternative for a MEM design for ESA’s NIR spectrograph on NGST (18). Two prototypes are being tested. Application of this concept to visible wavelengths is being investigated at Lyon in collaboration with LAS and ESO.
Table 1. Main requirements

|                        | Baseline       | Goal            |
|------------------------|----------------|-----------------|
| Field of View & Sampling | $60'' \times 60''$ @ $0.2''$ | $120'' \times 120''$ @ $0.2''$ |
|                        | $3'' \times 3''$ @ $0.01''$ | $6'' \times 6''$ @ $0.01''$ |
| Wavelength range       | 0.6–1.0 $\mu$m | 0.35–1.0 $\mu$m |
| Resolving power        | 1500–3000     | 1500–5000       |
| Total throughput       | 0.15           | 0.20            |

2.3 Tradeoffs

The main requirements for MIFS are summarized in Table 1: a wide field of view, high spatial resolution and large simultaneous spectral range. To meet these requirements, a very large number of detector elements is needed, since in any IFS, the total number of pixels is the number of spatial elements times the number of spectral elements times the packing efficiency of the IFS. The baseline already has 90,000 spatial elements. The number of spectral elements is driven by the requirement of maximum simultaneous spectral coverage (limited to an octave for a grating spectrograph) and the necessary spectral resolution. The latter is set by the science goals (§3) but is also constrained by the need to avoid the bright sky-emission lines in the red part of the spectrum. To cover 0.6–1.0 $\mu$m at a resolving power of 1500, one needs 1600 pixels of 2.5 ˚A. This translates to a total of 144 Megapixels for an instrument with 100% packing efficiency.

Selection of the spectral range is a matter of science goals, competitiveness, and technological limitations. Because of redshift, the study of distant galaxies naturally benefits from the infrared. However, an 8–10 m class ground-based telescope is not competitive with NGST at $\lambda > 2.2$ $\mu$m\(^1\). The 1–2.2 $\mu$m window might be a compromise: galaxies can be studied to $z \leq 5$ using diagnostic lines such as [OII], and MCAO will perform better in this wavelength range than at shorter wavelengths. However, the price per infrared detector pixel is excessive, and their performance in readout noise and dark current, despite their continuous improvement, is not as good as achieved by CCD detectors. Furthermore, such a spectrograph would have to be cooled at $\lambda > 1.6$ $\mu$m, which is difficult to achieve for an instrument as large as the one envisioned here.

The 0.6–1 $\mu$m wavelength range provides the best solution. MCAO will give a significant improvement in spatial resolution, and the technology to build and operate a large instrument is available. Galaxies with $z \leq 7$ are accessible via the Ly$\alpha$ emission lines, while medium to low-$z$ galaxies can be studied in detail using the [OII] or H$\alpha$ emission lines. At $\lambda < 0.6$ $\mu$m, MCAO will have difficulties to produce increased spatial resolution, and the high-$z$ galaxies cannot be observed. However, the MIFS concept, even at the spatial resolution set by natural seeing, is still very competitive and an extension of the 0.6–1.0 $\mu$m baseline to shorter wavelengths should be a design goal (Table 1).

\(^1\) This is true at low to medium spectral resolution. NGST can study only relatively bright mid-IR sources at resolving powers $R > 10000$.  

Fig. 1. Left: An example of a possible MIFS 3D deep field location (red box is $1' \times 1'$). Right: LR (upper box) and HR (lower box) simulated MIFS PSF for median seeing (left), 1% (center) and 20% (right) Strehl ratio.

In principle the diffraction limited core of the MCAO PSF should be critically sampled, i.e., $0''01$ at 0.8 $\mu$m. However, MCAO will deliver at best a Strehl ratio of 10-20%, and such fine sampling is impractical given the size and faintness of the targets. We therefore selected a low-resolution spatial sampling of $0''2$. This is compatible with the measured size of very faint distant galaxies (typical half-light radius $0''1$). With a field of view of $1' \times 1'$ sampled at $0''2$, the total number of detector pixels is already very large. For individual bright targets we selected a $3'' \times 3''$ field, sampled at $0''01$, to make optimal use of the MCAO PSF.

2.4 Modular concept

The baseline instrument requires a $21k \times 21k$ detector. This cannot match one monolithic spectrograph, so we will split the instrument into a number of modules. This also reduces the cost. The number and size of the modules will be selected during phase A: various choices are possible, from 17 modules with a $2k \times 4k$ detector each to a smaller number of modules with a larger detector. Optical quality, volume, weight and cost will all be part of this tradeoff.

MIFS will be set up at the VLT Nasmyth focus. The MCAO module will feed the $1' \times 1'$ field of view into the preoptics. This enlarges and splits the field of view into a number of separated beams. Two enlargers define the two MIFS modes: low resolution with $0''2$ sampling, and high resolution with $0''01$ sampling. Each sub-field of view is then fed into an IFS module, which consists of an advanced slicer, a classical grating spectrograph and a CCD detector.

2.5 Performance

We have computed the MIFS performance for extended high-$z$ objects with $0''1$ half-light radius and an exponential surface brightness distribution. The objects were convolved with the MCAO PSF provided by ESO. We took a conservative approach, and assumed a Strehl ratio of only 1.5%. Even with this very modest
Table 2. Estimated MIFS limiting magnitude for extended objects (0''1)

| Res. | R band | I band |
|------|--------|--------|
|      | R mag F (erg s^-1 cm^-2) | I mag F (erg s^-1 cm^-2) |
| 1600 | 26.7   | 3.10^-19 |
| 160  | 28.2   | 25.2   |

Strehl ratio, a gain of 3.8 in encircled energy within a 0''2 pixel is obtained. We assumed a total throughput of 0.15 and a detector readout noise and dark current of respectively 3e^- and 2e^-s^-1. Integration time was set to 80 hours split in 80 exposures of 1 hour. The typical sky brightness at Paranal was used. The resulting limiting magnitude and flux given in Table 2 are for a summation radius of 0''3 and for a S/N of 5 per resolved spectral element (2 pixels). Table 2 also reports the limiting magnitudes after summing over 10 pixels in the spectral direction which gives an effective spectral resolution of 160.

Detailed analysis of the noise shows that MIFS is sky-photon-noise limited. It is thus possible to coadd spatial and/or spectral pixels a posteriori without loss of performance. However, to reach this performance in practice, and sum exposures up to 80 hours of integration time, requires a very stable instrument and full control of all possible systematic effects. This would be very hard to do with a multi-slit spectrograph but can be achieved more easily with an IFS because of its complete spatial sampling of the field of view. For example, it is possible to optimally coadd all exposures taking into account the unavoidable differences in spatial resolution of the individual exposures.

3 Scientific objectives

Integral-field spectroscopy is the observing mode optimised for study of resolved objects of every type. Thus, MIFS will be the instrument of choice for studies ranging from Solar System objects, including planetary weather, asteroid surfaces, and cometary activity, star forming regions, including objects with proto-stellar and proto-planetary disks, late stages of stellar evolution, especially extreme AGB mass loss (η Carina) and planetary nebulae, supernova remnants, galactic nuclei, starbursts, AGN and merging galaxies, etc. We restrict discussion to the study of the formation and evolution of high-z galaxies, the key driver for the MIFS low-resolution mode, and to the unprecedented opportunities for studies of galactic nuclei and young stellar objects provided by the high-resolution mode.

3.1 High-redshift galaxies

In the next five years, much progress will be made in our understanding of the global properties of galaxies up to z~1–2, through systematic studies with multi-object spectrographs with high multiplex capabilities such as VIMOS. Resolved spectroscopy is required to measure the mass distribution and stellar population mix in the galaxies. Such measurements will remain very difficult to make since these galaxies are both very faint and very small. Even the new generation of
multi-slit spectrographs cannot afford to have 0′′.′′2 slit width and thus will not, or just barely, resolve the interesting galaxies. For the z=3–4 range, and presumably also for the z =0.8–1 range, MIFS will allow us to take the next step, i.e., spectrally resolve the brighter galaxies. This is the same step that has revealed so much about nearby galaxies in the past 30 years, and allows addressing many fundamental properties directly: (i) how are stellar populations distributed in z=0.8–1 galaxies (do we find young ‘kinematically distinct cores’?) (ii) detection of stellar absorption lines in z=3–4 galaxies, and their kinematics.

MIFS with its IFS capability will be able to perform such a study in its low-spatial resolution mode, and reach galaxies down to R=26.7 (28.2 at lower spectral resolution). With this limiting magnitude, MIFS will be able to study 76% of the z < 1 galaxies, 67% of the 1 < z < 3 galaxies and 41% of the z > 3 galaxies in the HDF (based on the photometric redshifts in the HDF-North). We estimate that 80% of the detected objects with 1 < z < 3 will have at least a few resolved spectral elements. The number of resolved elements is likely to be larger in the case of detected emission lines. Figure 2 shows a simulated MIFS deep field. It was computed from a 1′ × 1′ window of the HDF-North, convolved with the appropriate MCAO PSF (§2.5) and binned with a 0′′.′′2 pixel.

3.2 Search for Lyα emitters

The MIFS spectral window allows a blind search for Lyα galaxies in the range 4 < z < 7. With a detection limit of 3–5×10^{-19} erg s⁻¹ cm⁻², MIFS will explore a completely new parameter regime, and will reveal the emission-line objects that are too faint to be detected with broad-band imaging; an object with E(Lyα) of 3×10^{-19} erg s⁻¹ cm⁻² and an equivalent width of 100 Å would have R ∼ 29.7.

The expected number of objects that MIFS will detect in a field of 1′ × 1′ is difficult to estimate, as it requires extrapolation of the current narrow-band imaging detections at 2×10^{-17} erg s⁻¹ cm⁻² by two orders of magnitude. At the present detection level, Lyα galaxies are relatively rare: 1–3 objects per arcmin² only, but narrow-band imaging surveys typically probe only a range of 0.05 in z, while MIFS covers the range 4 < z < 7 in a single exposure.

In order to obtain a more reliable estimate, we used a hybrid model of hierarchical galaxy formation ([11]), which follows the history of dark matter in the standard Λ cold dark matter scenario using large N-body simulations. The history of baryons is computed with semi-analytic recipes which include cooling, star formation, merging, chemical evolution and dust absorption. We take the specific dust absorption on Lyα into account empirically, by rescaling the model predictions to fit the observed numbers of Lyα emitters at z ∼ 3.4 ([9]). This leads to dust absorption by a factor of eight, with a nearly negligible resonant scattering. The simulations have a mass resolution of 10^{10} M_☉. The predictions of the model reproduce the observed properties of R < 26 galaxies in the HDF, and are limited to E(Lyα) > 10^{-18} erg s⁻¹ cm⁻². At this level, the model already predicts about 150 Lyα emitters per arcmin² in the range 4 < z < 7 (and an additional 675 for 2 < z < 4). 90% of the 152 high-redshift objects are too faint to be detected in broad-band imaging. While one should be cautious not to overestimate the
accuracy of the model predictions, there are two reasons to be optimistic: (i) the detection limit of MIFS will be a factor three better than used in the simulations, and (ii) some high-redshift Ly\(\alpha\) galaxies were already discovered serendipitously in long-slit HDF follow-up observations: Dawson et al. ([10]), discovered 11 galaxies at \(3 < z < 6\) of which only one does not have detectable Ly\(\alpha\) emission. Five of these Ly\(\alpha\) emitters have no detectable continuum (I\(_{AB}\) > 25). This is very encouraging since a blind search with a long slit is particularly inefficient.

We conclude that MIFS will be able to observe the population of \(z > 4\) galaxies. Most of the objects will be new, and cannot be observed with present instrumentation. This population of new galaxies should be different from the population of Lyman break galaxies: they are low-mass galaxies experiencing strong star formation, and are the progenitors of present day normal galaxies.

### 3.3 Galactic nuclei

HST has revealed that the nuclei of many nearby normal galaxies harbour a supermassive black hole, as well as cusped density profiles, stellar and/or gaseous disks. The black hole causes a strong gradient in the mean velocities of stars and gas, and a central increase of the velocity dispersions, which can be modeled to measure the black hole mass (e.g., [15, 20]). The nuclear properties turn out to correlate with the global structure of the galaxies (e.g., [13, 14, 15]), so that studying the nuclei provides important constraints on galaxy evolution.
In the center of M31, the distribution of light and the stellar kinematics as seen by OASIS and STIS is complex ([4]), and similar asymmetries no doubt occur in the nuclei of other galaxies. At intermediate and larger scales, the ongoing SAURON survey of the two-dimensional kinematics and stellar populations of nearby galaxies already shows that departures from axisymmetry are likely to be the rule rather than the exception ([12]). Unfortunately, high resolution measurements of the two-dimensional stellar kinematics is very demanding for HST given its limited aperture. In order to make progress, one needs an IFS with much higher spatial resolution than is available today. SINFONI, which will be on the VLT in 2004, will deliver 0′′.06 spatial resolution at 2 µm over a 2′′ × 2′′ field. The next step would be achieved by MIFS in its high resolution mode (0′′.01) given that MCAO achieves a Strehl ratio of 20% or higher (so that the diffraction peak can be differentiated from the outer halo). The field of view of 3′′ × 3′′ is well-matched to the size of the nuclear stellar and gaseous disks, and the decoupled kinematic cores seen in many nearby objects.

3.4 Young stellar objects

Many young solar mass stars are surrounded by Keplerian disks with masses and sizes similar to our primitive Solar System ([6]). The evolution of physical conditions in these disks eventually governs planet formation in our Galaxy. A crucial unknown is the launch point of the collimated winds observed in these systems (somewhere in the disk, or the stellar magnetosphere?), and the resulting impact on the internal structure and evolution of the disk. Spectro-imaging in atomic forbidden lines near 0.6µm with TIGER, OASIS and STIS revealed the two-dimensional wind kinematics and excitation conditions down to 0′′.1 (15 AU) of the star ([1,16]). A resolution of ≃ 0.01″ is needed to resolve the regions within 1 AU where wind acceleration and collimation take place, and to constrain the wind origin. Since atomic winds emit very little in the near-infrared, neither SINFONI nor NGST are likely to bring significant advance. The high-resolution mode of MIFS will allow this decisive step, in a field of view ideally matched to the bright inner wind regions. A resolving power of 5000 would be crucial for resolving velocity gradients in the wind acceleration region. In its low-resolution mode, MIFS will probe in unprecedented detail the two-dimensional kinematics and excitation conditions of large shock fronts and Herbig–Haro objects at larger distance from the star, providing key constraints on the wind magnetic field.

4 Phased development and risks

Given its key importance for the construction of extremely large telescopes, MCAO is a strategic area of research and development. ESO is currently building a demonstrator that should be on sky in 2003. This is essential to acquire expertise in MCAO but the demonstrator will not have science capabilities.

The next step will be to build a fully operational MCAO system using three wave-front sensors on natural guide stars and two low-order deformable mirrors.
This should easily achieve the Strehl ratio of 1.5% at 0.8 $\mu$m assumed in §2.3. When combined with MIFS in its low-resolution mode, this will provide the deep fields needed for the programs described in §§3.1 & 3.2. We have found many areas of blank sky that fulfill the requirements of having guide stars brighter than $R = 13$ with the correct geometrical configuration, and at high galactic latitude. An example located near the HDF south is shown in Figure 1.

The MIFS high-resolution mode demands higher performance from (MC)AO, and the science goals described in §§3.3 & 3.4 will only be achieved with a second generation AO system, so will presumably come a few years later.

In case MCAO is late achieving the first phase goals, MIFS can be used in natural seeing. Even in this configuration it would be a unique instrument in terms of field of view, spatial sampling and spectral coverage and resolution. With $0\farcs7$ median seeing, there is no hope to resolve the tiny high-redshift galaxies, but MIFS will be able to obtain significant results in integrated spectroscopy. Its performance will be less than those given for phase 1, but, e.g., the search for Ly$\alpha$ emitters would still be unchallenged by other instruments.

In terms of the design of the IFS itself, most of the required technology is in hand. The feasibility of advanced slicers was demonstrated by the ongoing prototype studies. Instrument stability will be eased given the small number of moving parts. The cost can be kept within reasonable limits by working with optical industry to design an IFS module that would minimize the cost of the optics.

5 Conclusions

MIFS is a true second generation IFS. The first generation is being used to study in great detail individual objects that were previously discovered with imaging surveys. With its large field of view and simultaneous spectral coverage, MIFS combines the discovery potential of an imaging device with the measuring capabilities of a spectrograph, while taking advantage of the increased spatial resolution provided by MCAO. This makes it a unique tool for discovering objects that cannot be found in imaging surveys. The phased development described in §4 minimizes risk, and guarantees that the main scientific goals will be achieved.

Providing new contraints on the formation and evolution of galaxies at high redshift is the primary scientific objective we have used to set the specifications of the low-resolution mode of MIFS. The spectroscopic deep fields obtained with MIFS will constitute a tremendous treasure of information which will become a lasting reference, similar to the Hubble Deep Fields of today. MIFS deep fields will cover the visible spectral window and will perfectly complement the NGST (IR) and ALMA (mm) spectral windows. Multi-wavelength coverage of the same fields by these three facilities will provide nearly all the measurements we will need in order to answer the critical question of the formation of galaxies.

Using the best spatial resolution that can be achieved at one VLT unit to look at the environment of, e.g., supermassive black holes and young stellar objects is the main driver for the high-resolution mode of MIFS. But these two subjects are only a tiny fraction of the science that could be carried out with
such instrumental capabilities. Any object that has spectral features in the visible range and needs high spatial resolution is a potential target.

The first generation VLT instruments provide nearly complete coverage of observational parameter space (spatial/spectral resolution and wavelength range). MIFS expands this to high spatial resolution spectroscopy at visible wavelengths. It has a large potential for discoveries, builds upon the leading role that Europe has in integral-field spectroscopy, maximizes the return from the new developments in adaptive optics, and will keep the VLT competitive for the next decade.

In the longer term, ESO plans to construct OWL. MCAO is on the critical path. Achieving regular scientific use of MCAO with a VLT instrument would be a key step towards realising OWL. OWL MCAO is not only challenging by itself, but also for the required instrumentation. Much of the science case for OWL requires high spatial resolution spectroscopy. As 1 arcsec$^2$ requires 630,000 spatial elements to properly sample the OWL PSF, the constraints on the spectrographs will be enormous. While still short of achieving the requirements for OWL, MIFS with its 90,000 spatial elements is a major step beyond the capabilities of the present IFS; MIFS has 30 times the number of spatial and spectral elements of VIMOS, and 180 times those of SINFONI.

Acknowledgments. We thank Norbert Hubin, Rodophe Conan and the ESO AO division for providing very valuable MCAO performance simulations. This work was supported by the Programme National Galaxies from INSU/CNRS.

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