Science drivers for SAMplus

Abstract
We briefly describe a series of science drivers for an effort to upgrade SAM (SOAR Adaptive Module) – an adaptive optics system based on GLAO. The idea is to upgrade the deformable mirror (DM), wave front sensor (WFS) and real time computer (RTC) from its 60 to 241 actuators; this will extend the AO performance to the V and B bands, allowing a significant improvement in the spectroscopic performance when operated with instruments like SIFS, BTFI and SAMOS.

1. Introduction

Adaptive Optics (AO) assisted spectroscopy has opened a new window for astrophysics in the NIR. Spectrographs like SINFONI/VLT and NIFS/Gemini have been essential in this effort. Extending the possibility of doing AO assisted spectroscopy in the optical, especially by extending AO to the R, V and B bands will open new opportunities for various areas of Astronomy. Important diagnostic lines such as Hα/[NII] as well as Hβ/[OIII] will be impacted by such a possibility. Bellow we outline some science cases that support the effort to upgrade SAM (SOAR Adaptive Module using Ground Layer Adaptive Optics - GLAO) in order to extend the exquisite spatial resolution down to the blue. The current version of SAM (Tokovinin et al 2016) has a deformable mirror (DM) with 60 actuators; in this proposal we discuss an upgrade of SAM to 241 actuators with a corresponding wave front sensor (WFS) and real time computer (RTC).

The estimated cost is US$ 500 000,00.

Table 1: PSF parameters
Uncorrected with real SOAR optics, current SAM and upgraded SAM (SAMplus). Observations at zenith, wavelength 0.50μ

Parameter @0.50μ	FWHM (arcsec)			Energy in 0".3 diam.		
Seeing	Good	Typical	Bad	Good	Typical	Bad
SOAR, uncompensated	0.624	0.768	0.949	0.124	0.086	0.060
Current SAM	0.375	0.525	0.700	0.216	0.140	0.091
SAMplus	0.256	0.392	0.578	0.310	0.191	0.115

At 0.50μ, under median seeing (0.77"), the current SAM improves the PSF to 0.53". The upgraded SAM will improve this to 0.39" (see Table 1). But under good seeing (0.62") the PSF can be improved to 0.25" at 0.50μm and to 0.19" at 1.0 μm. The gain in Strehl ratio is shown in Fig 1 for median and good seeing.

Science with AO in the optical has a very broad perspective both in spectroscopic as in imaging mode (see Close 2016 for a recent comprehensive review). Some adaptive secondary mirrors have reached optical wavelengths, obtaining moderate Strehl ratios on small FoV. MagAO at the Magellan telescope (Close et al. 2010), ZIMPOL/SPERE at VLT (Roelfsema et al 2010) are examples. SAM works with GGLAO; this means that the degree of correction is more modest than other systems designed to reach nearly diffraction limit, but the FoV is much larger: 3x3 arcmin^2. Other GLAO based systems are in operations such as ARGOS at the LBT with corrections of 4x4 arcmin^2 (Mazzoni, et al 2016) or will be implemented in the future, like the GLAO module GALACSI that will allow the MUSE spectrograph at VLT to correct over a FOV of 1x1 $arcmin^2$ (La Penna et al 2016).

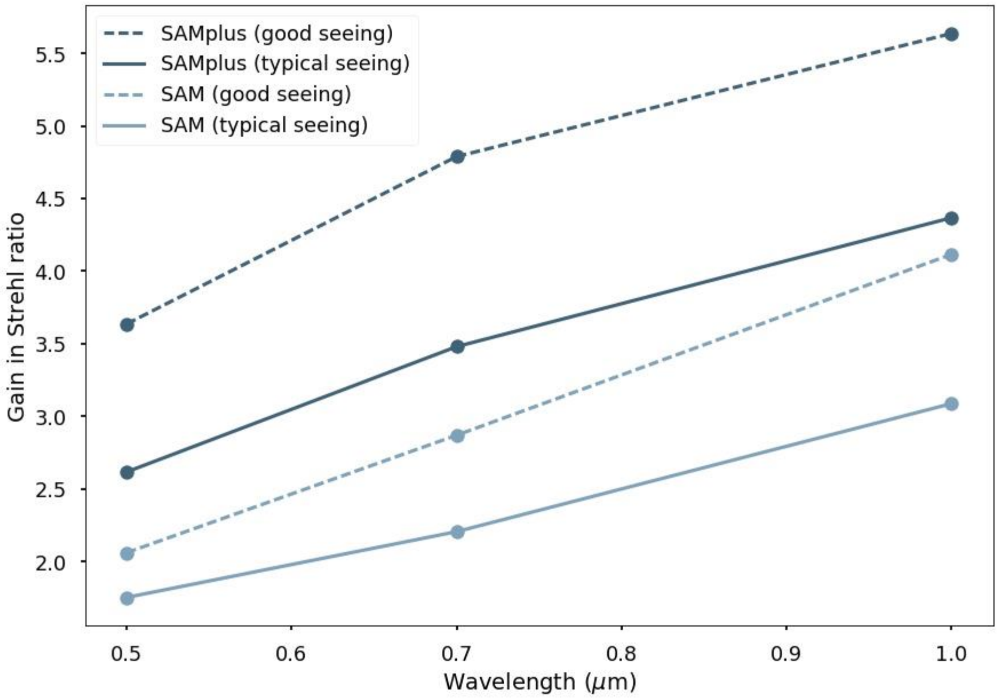

Figure 1: The gain in Strehl ratio for SAM and SAMplus under typical and good seeing conditions.

The alternatives to GLAO in the optical are seeing-limited FP, like the BTFI, seeing-limited IFUs like GMOS (Gemini telescopes), VIMOS (VLT) and SIFS (SOAR – now in Science Verification phase). HST is currently an alternative with very high spatial resolution but limited instrumentation and access.

2. Science with Integral Field Unit (IFU) spectroscopy + SAMplus

The SOAR Integral Field Spectrograph (SIFS - de Oliveira et al 2010) is a fiber-fed spectrograph with 1200 fibers. Although quite late in being commissioned, it is now in the phase of science verification and the preliminary data look good. It is expected to have soon a report for the SAC and Board assessment. SIFS was built to be operated with SAM.

2.1 LSST follow-up observations

In the era of LSST, follow-up observations will be critical, especially for the millions of transients and variable objects it will discover. The SOAR telescope is situated strategically for such efforts. Being at the same latitude and longitude as LSST allows quick response and must be prepared for this.

Characterizing galaxies in which supernovae exploded will be of great importance. Nebular emission associated to any kind of transient may be crucial in many cases and IFU observations with good spatial resolution may be of great help. Characterizing crowded fields (stellar clusters or multiple stars) is also of strong interest.

2.2 Nuclei of galaxies

Active galactic nuclei are objects in which a supermassive black hole accretes gas from the environment. Observations with high spatial resolution are critical in characterizing ionization cones, NLR and winds in general. They are also important in characterizing the geometry, physics and the feeding/feedback processes, which are relevant to the co-evolution between galaxies and black holes. The study of compact stellar components such as inner bulges, bars and star-forming structures and their connection to the AGN phenomenon will greatly benefit from improvement in spatial resolution as has already been demonstrated in the NIR (Davies et al 2007; Storchi-Bergmann et al 2010).

3D observations with good spatial resolution (~0.2" is required; this will be possible in the red, under good seeing) will allow supermassive black hole masses to be measured (Kormendy & Ho 2013). In using the Jeans method, this may be critical for measuring a growing number of cases. Combining data with additional lower resolution and larger FOV may also allow the Schwarzschild method to be used.

Active or inactive binary black holes at the sub-arcsec scale must exist (Merritt & Miloseveljevic 2005). Double AGN have been observed at larger distances (~arc-min) in merging systems. However after the galaxies merge, it may take a Gyr for the black holes to settle at the centre of the newly formed galaxy, before they merge forming a larger black hole. Such objects have been elusive and the reason for it is that for detecting them, a combination of high sensitivity and spatial resolution is required. GLAO-assisted spectroscopy may be instrumental in reaching and characterizing such systems.

2.3 Young stars and star-forming regions

Young stars are known to have circum-stellar nebular emission (Beck et al 2010). T Tauri stars display extended emission with both accretion discs and jets. Herbig-Haro objects are typical jets launched from young stars accreting gas. GLAO-assisted spatial resolution will allow a better understanding of the environment closest to the star, both in terms of accretion and ejection. Massive stars also have frequently circum-stellar nebulae. Eta Carinae is, perhaps, the best-known case.

Star forming regions in nearby galaxies can reveal star formation under distinct metallicities and environments. They may actually be better observed than in the Milky Way where such objects are systematically and heavily obscured by dust.

2.4 Compact nebulae

Compact nebulae such as SNR, PN, Novae shells and H II regions, both of Galactic and extragalactic origin benefit from having 3D spectroscopy with improved spatial resolution down to the V band. Physical and chemical conditions can be studied in the optical with unprecedented spatial resolution. Especial interest exists in the kinematic studies of shocked regions.

2.5 Gravitational arcs and multiple lensed quasar systems

IFU observations of gravitational arcs and lensed quasars (Bolton & Burles 2007) may help in characterizing such objects; observations with high spatial resolution may, sometimes, be critical. The frequency of giant luminous arcs strongly depends on the high mass end of the galaxy cluster distribution. This is important to probe cosmological models

2.6 Globular clusters and multiple stars

Globular clusters as well as multiple stars are critical for measuring the basic parameters of what we know about stars: their masses, metallicities, radii and ages. Improving spectroscopy with higher spatial resolution will provide more and more accurate information in crowded fields (see Tokovinin et al 2006 for examples).

3 Science with Fabry-Perot (FP)+SAMplus

Fabry-Perot (FP) spectroscopy takes the unique advantage provided by the GLAO over a large FOV (~3x3 arcmin^2). The niche for a FP device used with SAM is extended emission-line objects and/or systems with large filling factors such as centres of normal and interacting galaxies or AGNs, young stars, Herbig-Haro objects and resolved planetary nebulae, projects for which excellent spatial resolution is needed. The Brazilian Tunable Filter Imager (BTFI - Mendes de Oliveira et al 2013) was built to be operated with SAM. An independent operation of SAM with a FP etalon was also commissioned. An upgrade of the BTFI is foreseen and the possibility for observing in the blue (especially the [O III] lines) is of great interest.

3.1 Inner rotation of nearby spiral galaxies

Kinematic studies of emission-line properties with high spatial resolution spectroscopy will provide a new look to the central regions of galaxies, especially for spirals. High-resolution velocity maps of galaxies are important in the study, for example, of the cusp-core problem. The well-known cusp-core problem requires velocity maps taken in the inner kiloparsecs of nearby symmetric, undisturbed and bulge-less galaxies, for determining the contribution of the gas motions to the overall kinematics of the galaxy (Torres-Flores et al 2014). GLAO corrected velocity fields of undisturbed nearby galaxies will provide a prime sample for study of the cusp-core problem.

3.2 AGN studies

Maps of gas kinematics of the central parts of AGNs have revealed the presence of gas inflows towards the nuclei of AGNs in IFU data-cubes. Although these maps have proved very useful for such studies, the small field-of-view of typical IFUs only allow observations of the central parts of the objects. From such data sets it is not possible, for example, to identify if the gas that feeds the black hole is transported along the bar in the disk, if a bar is present or not nor what is the mechanism for the formation of the Circumnuclear Star Forming Regions. These are crucial questions in the study of AGN-starburst phenomenon. In this sense, the large field-of-view of Fabry-Perot spectroscopy allows not only the study of the central parts of the AGNs but also typically of the whole galaxy. Such studies have been done, for example for the classical prototypes of Seyfert galaxies NGC 1068 (Cecil et al 1990) and NGC 4151 (Asif et al 2005). In addition, it is well known that extended structures as the ones associated to outflows in AGN cover a wide range of dimensions, requiring a larger field-of-view (see, for instance, Keel et al 2015). If one combines IFU data, over a small FoV with Fabry-Perot data-cubes covering larger field, both GLAO corrected, the kinematics of structures such as nuclear bars and spiral arms, highlighted by stellar formation, can be compared to those present in their nuclei. This would allow us to investigate if and how the ionized gas and stellar kinematics are connected on these scales. This is particularly relevant to probe the gas feeding into the supermassive black hole and the nuclear outflow in nearby galaxies. The same maps can be used to derive electron densities (using the ratios of the two [SII] lines).

3.3 Structure of dwarf galaxies and star-forming regions

Study of the kinematics of dwarf galaxies (Moiseev et al 2015) with stellar masses of ~10^8 and gas masses of 10^8 to $5x10^9$ Msun which are compact and star forming are hampered by the small sizes of these objects, a problem that can be solved by GLAO corrected FP maps. Structure and kinematics of these galaxies can be studied, in particular to allow the determination if they are prolate or oblate systems (by identifying if they have changes in their rotation axes, as a function of radii). In addition, the kinematics of star-forming complexes in external nearby dwarf and giant galaxies can be studied with unprecedented resolution. What under normal seeing is thought to be one component, with GLAO spectroscopy it becomes multiple resolved spatial components. This is specifically important in the study of tidal dwarf galaxies, newly born galaxies, formed out of merging/interacting systems (see below).

3.4 Merging/interacting galaxy systems

Such system may have potentially extended tidal features as well as interesting small-scale details. In the tidal features often newly born clusters and the so-called tidal dwarf galaxies are found. The typical strong Hα emission line present in these objects indicates their young ages. Their structure and kinematics can only be properly studied with GLAO-corrected maps. The 3x3 $arcmin^2$ GLAO-corrected field is very suitable for the study of tidal features in merging/interacting systems in the nearby universe, and a number of young objects in formation can be studied in one shot. In addition, small-scale details in interacting galaxies can be studied in a unique fashion with FP, given the possibility of identifying non-circular motions in different areas of the system. This is crucial for understanding the overall kinematics of the systems (Camps-Fariña et al 2017).

3.5 Herbig-Haro (HH) objects

There is great interest in the study of optically visible knots found near young stars, known as HH objects. These mark locations where a highly collimated jet of partly ionized plasma ejected by a young star collides with the ambient material at speeds of several hundred km/s, creating regions of shock-excited gas that emit line spectra (Raymond et al 1994). Balmer lines like Hα form primarily in a thin shell excited by collisions at the shock front while forbidden lines like [NII] and [SII] originate in the cooling zone behind the shock front. Therefore, studies of the properties of the line emission across the spatial extent of these jets, outflows and shocked regions, are essential to understand the excitation conditions of the gas and its kinematics, and ultimately to determine the physical mechanisms involved in mass loss in pre-main sequence stars. The space motions of HH objects are typically a few hundred km/s and, combined with their typical distances of several hundred pc, this implies that it is possible to determine their proper motions. In principle when combined with radial velocity measurements it is possible to determine accurate space motions and 3D flow orientations (Movsessian et al 2009). However, nearby, bright HH objects are typically large, sometimes exceeding an arc minute in extent, and they have highly complex morphologies. So while proper motions can be measured for all structures in HH objects, radial velocity information has always been a challenge. FP area spectrophotometry enables to spatially resolve the velocity field and determine emission-line fluxes and line ratios at every point in the volume delineated by the HH object. FP observations with a GLAO-corrected field allow building maps of the shock kinematics, the electron density, and excitation distribution. HH objects are highly complex both morphologically and kinematically, and for meaningful comparisons with shock models spatial resolution is essential, to resolve the shock structures and to identify changes in the shocks on timescales of a few years.

3.6 Giant HII regions (GHR) in our Galaxy and in the SMC and LMC

GHR are ideal laboratories to study the effect of strong stellar winds and stellar evolution on the kinematics of the warm ionized gas. These regions are known for containing massive stars. The strong stellar winds associated with these stars can modify the kinematics of the interstellar medium and produce expanding bubbles, shells and shocks. In addition, the final evolutionary stage of these massive stars (e.g. supernova) can inject an important amount of energy in the interstellar medium what produces large bubbles, which are usually linked with X-ray emission. In this context, GHR are ideal laboratories to study the effect of strong stellar winds and stellar evolution on the kinematics of the warm ionized gas. The possibility of having FP spectroscopy with GLAO-corrected 3x3 arcmin^2 field and sub-parsec resolution is unique and most important in such studies, particularly in the identification of small-scale bubbles caused by young massive stars (Ambrocio-Cruz et al 2016).

4 Direct imaging

4.1 Crowded stellar fields

Imaging with GLAO can help in studying crowded fields such as multiple stars and stellar variability in globular cluster. Salinas et al (2016) presented observations of four Galactic globular clusters, M 2 (NGC 7089), M 10 (NGC 6254), M 80 (NGC 6093), and NGC 1261, taken with the ground-layer adaptive optics module at the SOAR Telescope, SAM. They showed that the higher image quality provided by SAM allows for the calibration of the light curves of the great majority of the variables near the cores of these clusters as well as the detection of new variables, even in clusters where image-subtraction searches were already conducted.

4.2 LSST follow-up observations with exquisite spatial resolution.

Broad and narrow band imaging will be of fundamental importance in the era when the LSST will discover millions of variable objects and quick follow-up observations will be necessary for full characterization of such objects and their environments. Better spatial resolution will provide more information in an era when the HST will no longer be available for imaging in the optical.

4.3 Colour-magnitude diagrams of globular clusters

High quality BVRI photometry, obtained with SAM, in the field of the globular cluster NGC 6496 (Fraga et al 2013) has shown the potential of GLAO for studying magnitude-colour diagrams of such systems. By extending the AO to the blue, more accurate photometry can be performed for a larger number of objects.

4.4 The structure of galaxies

The studies of structure of galaxies have nay aspects that benefit from improved spatial resolution. This has been demonstrated in many magnificent ways by the HST (e.g. Faber et al 1997). In the post-HST era GLAO systems will be the best approach to observations in the optical with high spatial resolution that demand FoV of a few arcmin. This has already been demonstrated with SAM in the study of the bulge of NGC 3962 (Salinas et al 2015).

5 Multi-slit spectroscopy (SAMOS)

A multi-slit spectrograph (SAMOS – SOAR Multi-object Spectrograph; Robberto et al. 2016) has already been proposed and funded. Such a spectrograph will obviously benefit from improvements of spatial resolution extending to the blue. Specific science cases have already been elaborated. In their text, 5 topics were addressed (and will not be replicated here):
A – Exoplanets in the galactic bulge
B – Formation and evolution of the galactic bulge
C – Star formation in the Magellanic Clouds
D – Galactic outflows
E – Clusters of galaxies

6 Synergies

Combinations of distinct instruments may provide additional synergies. For example, galactic outflows can be observed by direct imaging (narrow and broad band), as well as with spectroscopic observations using Fabry-Perot, Multi-object and IFU techniques. Clusters of galaxies can be better studied by combining direct imaging and MOS. Studies of star-forming regions can be performed with direct narrow band imaging, FP and IFU for the nebular component and broad band imaging and MOS for the stellar component.

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