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Science operation of the SOAR Adaptive Module (SAM)

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ABSTRACT

The adaptive module of the 4-m SOAR telescope (SAM) corrects ground-layer turbulence using a UV laser guide star. It has been commissioned in 2013 and in regular science operation since 2014A. SAM works with the CCD imager covering a $3'$ field or with the speckle camera. The instrument operates routinely and stably, delivering in the I band the image quality equal to the free-atmosphere seeing. Preparation of the observing runs and the operational sequence are covered briefly. Observing programs executed so far are presented, ranging from star clusters and binary stars to deep-space objects and gravitational lenses. Emission-line objects were observed with narrow-band filters and Fabry-Perot etalon. Future science use of SAM and its synergy with wide-field optical sky surveys are outlined. New instruments for SAM and its potential upgrades are considered.

Keywords: Laser Guide Star, Adaptive Optics

1. INTRODUCTION

I describe here science operation of the SOAR Adaptive Module (SAM), the first facility-class laser-assisted Ground-Layer Adaptive Optics (GLAO) astronomical laser system. There is currently a considerable interest in implementing GLAO at several observatories. First successful demonstrations of GLAO at MMT[1] and VLT do not count yet as science operation, although some interesting observations have been made with these systems. A true facility GLAO system for LBT, ARGOS,[3] is close to becoming operational. A similar effort is being made at the VLT.[6] These GLAO instruments are designed for operation in the infrared. Until now, SAM remains the only implementation of GLAO for visible-light astronomy.

SAM[8, 9, 11–13] has been fully commissioned by the end of 2013. Some scientific results have already been obtained by that time using commissioning data. Since 2013B, SAM was offered in a shared-risk mode, and its science verification (SV) program was executed in 2014.[*] Regular observing proposals for SAM are accepted since the 2014B semester.

After a brief recall of SAM in §2, the procedure for preparation and execution of observations is covered in §3. Then the science projects done with SAM are reviewed in §4. Finally, perspectives of future use of SAM and its potential upgrades are outlined in §5.

2. SAM IN A NUTSHELL

SAM is not a science instrument in its own right. It improves the seeing delivered by the telescope and feeds the corrected image to the "true" science instruments that actually produce useful data. So far, the optical CCD imager, SAMI, has been officially offered with SAM. The other "visitor" port of SAM, where a second instrument can be installed, has been occupied by the High-Resolution Camera (HRCAM),[10] used extensively for diffraction-limited observations (Table 1). In 2015, two observing runs were made with a Fabry-Perot etalon installed in the collimated space inside SAM.

The design of the SAM LGS system was presented in Ref. 12. The UV (355 nm) LGS is created by a pulsed frequency-tripled Nd:YAG laser (Q301-HD from JDSU). Its nominal 10 W power at 10 kHz pulse frequency has been verified in the laboratory, while the actual power at the telescope is about 7.5 W. The laser operated so far without any faults, as a turn-key device. Expanded parallel 8-mm laser beam is directed towards the 25-cm

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[*] Report on SAM SV at http://www.ctio.noao.edu/new/Telescopes/SOAR/Instruments/SAM/archive/svrep.pdf

Table 1. Science instruments working with SAM

Instrument	Pixel size (arcsec)	Field (arcsec)	Use
SAMI	0.045	184	CCD imager
HRCAM	0.0152	7.5	Speckle interferometry

Laser Launch Telescope (LLT) with one reflection from a flat mirror, remotely controlled in tip and tilt for beam alignment. The propagated beam has circular polarization and the $1/e^2$ diameter of 180 mm.

Back-scattered UV photons are collected by the SOAR telescope, pass through the SAM optics (two off-axis parabolic mirrors), and create the LGS image in its WFS. The Pockels-cell fast shutter inside the WFS transmits light only during the $1\,\mu$s range-gate pulses. The delay of the gate pulse determines the distance to the LGS $z = 7$ km. The WFS has a pixel scale of $0.375''$ with 8x8 pixels per sub-aperture and 10x10 sub-apertures across the pupil. This fine scale and the small $2.8''$ field size are not optimum for the LGS. We bin the WFS image 2x2 to increase operational robustness of the AO loop and its frequency (440 Hz, 2.5 ms per cycle). The AO loop works very reliably without divergence or other problems. A typical return flux on a clear night is about 1000 photons per sub-aperture per loop cycle. The LGS is sometimes enlarged by the local seeing, resulting in the loss of flux and in larger slope errors.

3. OBSERVATIONS WITH SAM

Documentation on the SAM instrument and its software is available online.[†] In this Section, I describe its operation which may be of interest to other AO instruments. Three persons are required at night time: the telescope operator, the observer, and the SAM operator (the latter two can work remotely). In some cases, SAM and imager are operated by one scientist; training SOAR telescope operators for SAM is possible in the future.

The SAM operation became a routine. The complexity of the laser-assisted AO is neutralized to a large extent by the designs of the instrument and its software. Only one GUI is used to control the instrument, while some repetitive tasks are automated by scripts.

3.1 Preparation

Target lists are requested from observers two weeks prior to the observing run. The SAM support scientist at CTIO prepares the requests for laser propagation in a format required by the Laser Clearing House (LCH) and submits them at least two working days in advance of the night by uploading to the LCH web site. The authorized propagation windows are posted by the LCH on the same site, accompanied by e-mail alerts. Typically they become available on the day of observations or a day in advance. Exceptions when LCH forgot to process the request or an astronomer made a mistake are handled by phone calls to LCH. The LCH has provided timely responses to these unusual situations. Almost real-time interaction with the LCH also occurs when they issue additional blanket closures.

SAM is scheduled classically for specific nights, preferably grouped in runs. Between the runs, the instrument is powered off. Before each run, the SAM scientist switches the instrument on, starts its software, and makes daytime tests following the standard checklist procedure. This procedure has been successful in detecting hardware or software problems, leaving time for their fixes. For example, failures of the line transformer in the high-voltage DM driver, failed motor-control boards, or a stuck motor shaft. When possible, SAM is tested during engineering nights a few days before the science runs. The SOAR operations team, helped when necessary by engineers from CTIO, fixes the problems, sometimes during weekends. Fortunately, we have not yet lost any night time to SAM failures.

The filters in SAMI are installed by the SOAR operators during daytime, as in other instruments. SAMI can use 4x4 inch square filters in a wheel with 5 positions or 3x3 inch filters in another 7-slot wheel. The limited number of filters restricts sometimes the number of science programs that can be executed with SAMI on any given night. The HRCAM is normally used without laser and with a fixed set of filters in its own wheel.

[†] http://www.ctio.noao.edu/soar/content/soar-adaptive-optics-module-sam

3.2 Observing procedure with SAMI

The SAM overhead time, from the start of telescope slew on a new target to closing all four loops, can be as short as 5 min, with 7 min being typical. Most of this time is spent for acquisition of guide stars. The two SAM guide probes use stars within the square technical field of $5' \times 5'$, preferably avoiding the central $3' \times 3'$ science field. The guide probes are located in the telescope focal plane, up-stream from the DM (in the LGS mode the DM is not supposed to create variable tilts). Each guide probe is an array of 2x2 micro-lenses forming a quad-cell position sensor with a $3''$ square field.

The pointing errors of SOAR can reach $30''$. To determine exact pointing, a short-exposure image is taken with SAMI. A star with known coordinates is identified in this image to determine the field offset. Then the probe is positioned on the selected guide star and the high voltage of its APD detectors is switched on. Normally the star is detected immediately, allowing to close the two tilt loops (the fast 10-Hz loop using the SOAR M3 tip-tilt mirror and the slow mount loop). If the star is not detected (or if in doubt), the SAM operator launches the *Find* script which modulates the tilt rapidly with a radius of up to $5''$ and adjusts the probe position if the modulated signal from the guide star is detected. Otherwise, the operator selects an alternative star or revises the field offset. This procedure critically depends on good astrometry in the input star catalogs (we use USNO2 or 2MASS). Our experience shows that USNO2 is not always reliable (e.g. it lists some galaxies as stars). The SAM *observing tool* (OT) is an IDL software that helps formatting the target lists for LCH, but also allows pre-selection of guide stars and loading DSS2 images in the 5x5 arcmin field to assist in field identification. Guide stars pre-selected in the OT can be fed to the SAM software and used alongside with the catalogs.

Guiding with two probes, on opposite sides of the science field, is preferable for PSF uniformity, but guiding with one probe works well too. *All* science targets had guide stars down to the $R = 18$ limit, i.e. the SAM has a complete sky coverage. Such a star gives ∼60 counts per 10-ms cycle of the tip-tilt loop.

When the guide loop is closed, the SAM operator opens the laser shutter and acquires the LGS. For centering, the un-gated LGS image is captured by the acquisition camera fed by a flip mirror in the WFS. The LLT electronics is powered on (it is off most of the time to avoid heat generation), and the LGS is centered, compensating for differential flexure between LLT and SOAR axes (typically less than $10''$). Then the flip mirror is retracted, the LGS tilt loop is closed, and the high-order loop is closed as well (the LLT electronics is powered off automatically at this time). The LGS acquisition is straightforward and takes less than a minute. If the telescope slew was small, the laser photons reach WFS without re-centering the LLT, in which case the two LGS loops are closed in a few seconds. Experience shows that SAM often remains operational with a light cirrus clouds because the LGS is located below the clouds.

Most LCH interrupts are quite short (∼10 seconds). The laser is shuttered automatically by the SAM software, which can also handle blanket closures. The LGS loops are opened automatically just before the interrupt, while the science exposure is normally paused during this time. The SAM operator closes the laser loops manually after the interrupt. The interrupts are displayed in the SAM OT on the plots of target elevation vs. time.

The first target of the night is usually used to check the relative focus between SAM WFS and SAMI. The focus might change because of temperature or because of SAMI filters of non-standard thickness, although it was found to be quite stable. To test the focus, two short exposures are taken with closed AO loop and WFS defocused by ±4mm from the nominal. The image size should be enlarged by the same amount if the nominal focus is correct. Otherwise, the new focus is found by linear interpolation between bracketing exposures. Once focused, another test exposure is taken to measure the delivered image quality (DIQ).

SAM can operate in open loop, without laser. In such case, the DM is flattened passively. Its flexure depends on the instrument rotator angle and is accounted for by the lookup table. The LGS, if available, still helps to focus the telescope in open loop by measuring the focus term and nulling it by adjusting the telescope focus. Open-loop operation happens when the image quality is not critical or for targets that are not in the LCH list (e.g. photometric standards).

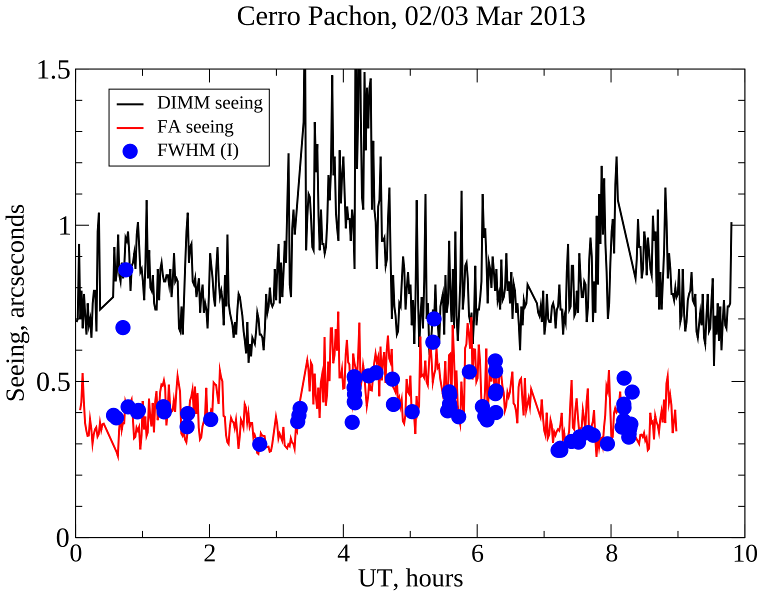

Figure 1. DIQ of SAM (circles) compared to the free-atmosphere seeing (red line) and the total seeing (black line).

3.3 SAM performance

At long wavelengths and under moderate seeing, the compensation order of SAM is sufficiently high to "remove" the ground-layer turbulence. The FWHM of SAM images has been remarkably close to the integrated free-atmosphere (FA) seeing measured by the site monitor (Fig. 1). A shorter wavelengths (e.g. in the V or Sloan g' filters) the correction is partial, and the PSF of SAM is a little wider (but still better than the natural seeing). Our experience indicates that good FA seeing is encountered in about half of scheduled nights. In the remaining nights, the seeing is dominated by the free atmosphere, and SAM gives little or no improvement in closed loop. Its DIQ still matches the FA seeing, but it is not as good as might be expected by its users.

3.4 Speckle observations

In the speckle mode, HRCAM reaches the diffraction-limited resolution (30 mas at 540 nm) even without laser.[‡] Data accumulation (image cubes of 200x200x400 with 10-ms exposure) takes only a few seconds, and the use of telescope time is dominated by the overheads: slewing, centering, change of filters, etc. On average, HRCAM observes about 150 targets per night, or about 4 minutes per star. Reaching this productivity is possible through optimization of the observing sequence (minimize large slews, update pointing offset on every target). An observing tool that selects stars from the program, sends their coordinates directly to the telescope control system, and keeps track of the progress has been used. After pointing each target, SAM flattens the DM passively and sets the atmospheric dispersion corrector. The laser can be used to sharpen images of faint targets, increasing the number of photons per speckle and the magnitude limit of speckle interferometry. In such case, there is no need to acquire guide stars, and the use of laser does not entail additional overheads for observations in the same part of the sky (without centering the LLT).

4. SCIENCE PROGRAMS DONE WITH SAM

After 2.5 years of SAM operation, a review of its use is in order. The science programs are grouped according to the type of objects. During 2014, SAM received only a small number of proposals, but its use has steadily increased in 2015, making it the second most popular instrument at SOAR.

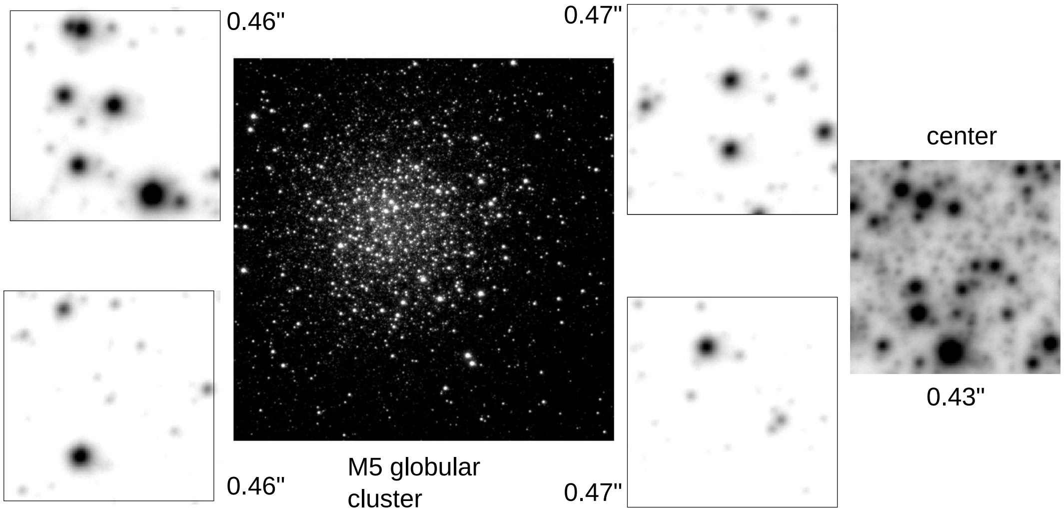

Figure 2. The M5 globular cluster was observed with SAM on March 2, 2013. Fragments of the full frame show the uniformity, with numbers indicating the FWHM resolution in each fragment.

4.1 Star clusters

By concentrating the light of stars in a smaller number of pixels, SAM reduces photometric errors in dense stellar fields dominated by confusion.[5] The gain in sensitivity in such case is proportional to the square of the image size. Figure 2 illustrates the image quality and its uniformity by observations of the globular cluster M5 taken in the SAM SV program.

The first science paper produced by SAM presented the color-magnitude diagram of the globular cluster NGC 6496.[2] The image quality in these early commissioning data of May 2012 was excellent, reaching $0.25''$ in the I band. However, it was not uniform over the field, showing an asymmetry likely related to the wind direction (the SAM loop worked then with a low frequency of 233 Hz). Despite this, accurate photometry was possible by fitting field-dependent PSF with DAOPHOT.

J. Santos (Brazil) is conducting a large survey of globular clusters in the Magellanic Clouds using SAM. This program was granted 8 nights in the 2015B semester. It exploits the potential of SAM in crowded fields.

R. Salinas has observed several globular clusters with SAM with the aim of detecting new variable stars in their central crowded regions. He used the technique of difference imaging (paper in preparation). SAM data were marginally useful in his another paper.[7]

4.2 Binary stars

SAM can help in resolving close binary stars, especially the faint ones beyond the reach of speckle interferometry. C. Briceño has discovered a couple of new binaries among young T Tauri stars using SAM in commissioning mode. Continuation of this binarity survey is planned in 2016. The author surveyed faint low-mass companions to nearby stars and discovered one new $0.2''$ binary.[16] However, for binary stars the "detection power" of SAM in terms of resolution and dynamic range is inferior to the classical AO in the infrared or speckle.

Combination of speckle interferometry with laser-enhanced seeing is a promising technique. It was used in May 2015 for the survey of Kepler-2 field (PI J. Schmitt). SAM worked with the laser, but without guiding. Cubes of short-exposure images were acquired with HRCAM and re-centered in post-processing. The other data products are the power spectra and the "lucky" images re-centered on the brightest pixel. While the re-centered images are equivalent to long exposures with SAMI, the alternative techniques deliver higher resolution when the flux allows it. In the sub-optimal seeing conditions of the May run, the median FWHM resolution of long-exposure images was $0.43''$, but the binarity of targets as faint as $I = 15^m$ could be probed down to $0.15''$ separation. The paper is in preparation.

[‡] See http://www.ctio.noao.edu/ atokovin/speckle/

Yet another application of SAM to binary stars is the project led by N. Law. His team studies wide low-mass binaries. The purpose of observations with SAM is to measure accurate positions and to determine whether these pairs are physically bound or not. The data are not yet processed, so the astrometric accuracy of SAMI is still to be characterized. Images of some globular clusters taken at several epochs with SAMI during commissioning can be helpful in this endeavor.

4.3 Emission-line objects

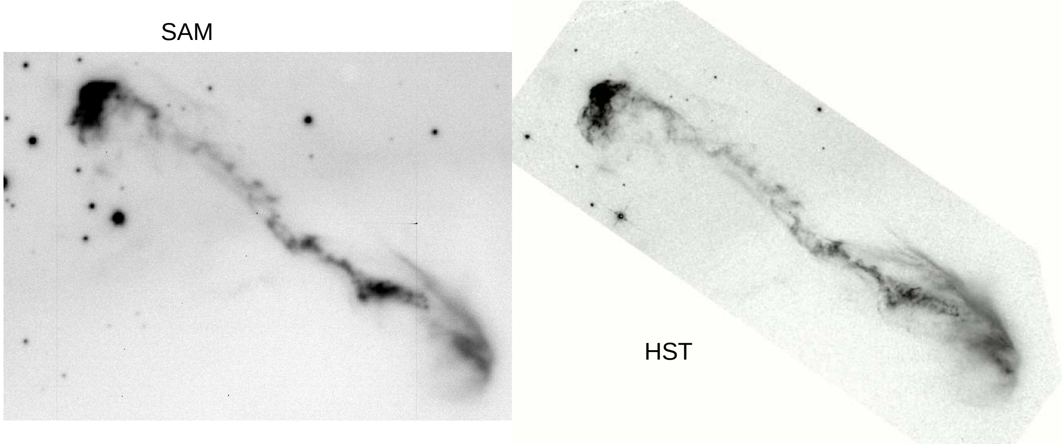

Figure 3. Images of HH 47 with SAM and HST in the S[II] filter. The SAM image taken under $0.9''$ seeing has a resolution of $0.45''$. Credit: C. Briceño.

SAM+SOAR deliver a lower spatial resolution than the Hubble Spase Telescope (HST), but collect a larger number of photons owing to the 4.1-m aperture of SOAR compared to the 2.4-m HST. Observations in narrow spectral bands are often photon-starved. In this case, SAM can work better than the HST. It is also more flexible and accessible.

Several programs on emission-line objects are planned using SAMI with narrow-band filters. Figure 3 shows the image of the Herbig-Haro (HH) jet HH 47 in the S[II] narrow-band filter taken with SAM on February 14, 2015,[§] and the earlier HST image. The purpose of this program (PI C. Briceño) is to measure the projected jet velocity by comparing new and archival images. Indeed, the displacement is already obvious in the Figure. It can be noted that various features are displaced by different amounts. Continued observations of jets with SAM will use a combination of custom narrow-band filters to probe physical conditions in the jets. The line ratio S[II] 6717/6731, gives the electron density, while N[II] 6583/N[I] 5198+5200 provides the ionization fraction, in addition to $H\alpha/H\beta$ ratio that traces where the pre-shock gas is neutral, and O[III] that traces areas of high temperature and shock velocity.

The team of A. Ardila observed with SAM nearby galaxies NGC 1232 and NGC 1482 in the $H\alpha$ band to study star-formation regions with high spatial resolution. The results are still being processed, while nice images resulting from this effort were generated with a resolution twice better than in the PR image of NGC 1232 from the VLT.

On March 17, 2015, successful observations of several targets were made using the Fabry-Perot (F-P) etalon inside SAM. This option was considered in the SAM design, and its collimated space was dimensioned with this mode in mind. The F-P is installed on the translation stage inside SAM and can be moved in or out of the beam. The existing F-P etalon with a resolution of about 15 000 just fits in the available space, with 1-mm gaps on both sides. Selection of one F-P order is done by the interference filter in the SAMI wheel. Multiple filters are needed to accommodate different redshifts of the observed galaxies. This project is led by C. Mendez de Oliveira and P. Amram. Figure 4 shows a quick-look result after processing the data cube on the night of observation.

[§] See also at http://www.ctio.noao.edu/soar/content/herbig-haro-object-hh4647

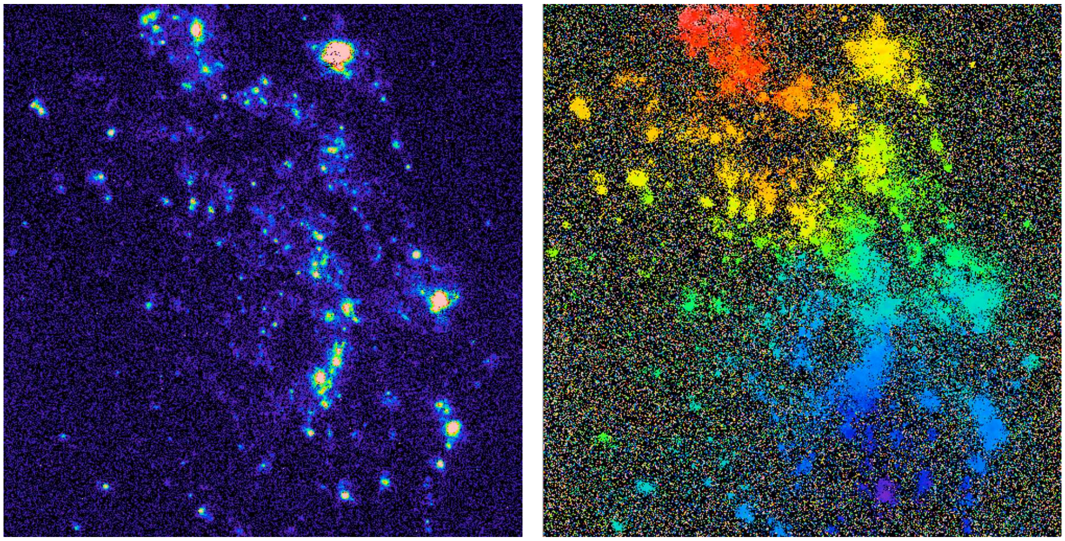

Figure 4. Preliminary results of observing the galaxy NGC 3621 with SAM and F-P in March 2015. The left image shows the flux in the Hα line, the right-hand image is the velocity field. Credit: P. Amram.

To overcome the SAMI readout noise, the binning of 4x4 (pixels of $0.18''$) is used. The F-P mode was used again successfully by the same team on December 3-4, 2015. However, it is not yet offered for general use.

Some SV programs intended to use SAM for detecting faint nebulae around stars. In this area, SAM has no advantage over other ground-based imagers; it concentrates the light in the core of the PSF but does not reduce its wings.

4.4 Extragalactic programs

SAM is well suited for deep high-resolution imaging of faint and distant deep-space objects. Here its complete sky coverage and a moderately wide $3'$ field play an essential role. Observations of nearby galaxies in narrow bands were covered above. D. Murphy used SAM in 2013 for two nights to get a very deep high-resolution image of a peculiar galaxy in a cluster, apparently affected by recent interaction (he calls it "Cosmic Skidmark").[4] Images of "green bean" galaxies dominated by the green glow of ionized gas were taken with SAM for by M. Schirmer.

Spectacular images of thin gravitational arcs produced by lensing distant galaxies were obtained with SAM during its commissioning. No proposals for continuing this effort have been accepted so far. However, the program by V. Motta was executed in December 2015. She and her team took high-resolution images of lensed-quasar candidates revealed in a wide-field survey. This is an excellent example of future science use of SAM, where it will complement wide-angle surveys by studying interesting objects with higher spatial and/or spectral resolution.

Yet another promising application of SAM will be to study globular clusters (GCs) in other galaxies. Even a small gain in resolution over seeing might be critical here to distinguish GCs from stars. Some results in this area are reported in Ref. 7.

5. OUTLOOK AND UPGRADES

The niche of SAM, high angular resolution at visible wavelengths, is occupied by the HST. Although SAM is not competitive with HST in angular resolution, it offers the best resolution of faint targets available from the ground and has some advantages, namely accessibility, larger aperture, and flexibility. The last two factors are best illustrated by the use of SAM with F-P.

In the era of large wide-angle surveys, such as Pann-Stars, PTF, and, eventually, LSST, SAM will play a key role in follow-up observations with high spatial resolution. The obvious programs are gravitational lenses (including lensed quasars) and supernovae, especially when they become faint and difficult to separate from their host galaxies. Morphology of distant galaxies is another potential application for SAM.

It was planned originally that the visitor port of SAM will be used by the fiber-fed integral-field spectrograph, SIFS. This instrument is still not commissioned, but its use with SAM remains possible. If SIFS is not available, SAM can be connected by a fiber bundle to the Goodman spectrograph for spectro-imaging in a small field a few arcseconds across. These instruments can observe galactic nuclei or star-forming regions in other galaxies.

An alternative approach to spectroscopy with SAM is proposed by the team led by M. Robberto. They develop a multi-slit spectrograph, SAMOS. Its slits will be defined by the digitally controlled micro-mirror array, hence will be fully configurable. SAMOS will be a very compact instrument mounted in place of SAMI and using the same CCD.

The diffraction-limited observations with HRCam, spawned by the development of SAM, will continue to be an important part of the SOAR science. They will play a critical role in the ground-based support of space exo-planet missions like TESS and PLATO, to screen their objects of interest for close companions. N. Law leads the development of a new robotic AO system for SOAR to address this need. It will use natural guide stars for full or partial turbulence compensation, in combination with a better (compared to HRCam) EM CCD as a science detector, as well as an IR camera.

Increasing use of SAM will justify its future upgrades. The critical AO elements of SAM, DM and WFS detector, were state-of-the art technology in the 1990-s, but are obsolete now. The new EM CCD camera with range-gating capability, OCAM^{2}S, will increase the sensitivity of the SAM WFS, no longer needing the Pockels-cell shutter and insensitive to polarization. The same number of laser photons can be used then more efficiently to increase the compensation order. The DM can be replaced by a magnetically-actuated mirror from ALPAO. Increased compensation order will enhance the SAM performance at shorter wavelengths, where it currently offers only a partial correction.

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