Scientific Objectives and Design Study of an Adaptive Optics Visual Echelle Spectrograph and Imager Coronograph (AVES-IMCO) for the NAOS Visitor Focus at the VLT

Roberto Pallavicini[1], Filippo Zerbi[2], Jean-Luc Beuzit[5], Giovanni Bonanno[4], Piercarlo Bonifacio[3], Maurizio Comari[3], Paolo Conconi[2], Bernard Delabre[6], Mariagrazia Franchini[3], Paolo Di Marcantonio[3], Anne-Marie Lagrange[5], Ruben Mazzoleni[2], Paolo Molaro[3], Luca Pasquini[6], and Paolo Santin[3]

[1] Osservatorio Astronomico di Palermo, Italy
[2] Osservatorio Astronomico di Brera, Merate (LC), Italy
[3] Osservatorio Astronomico di Trieste, Italy
[4] Osservatorio Astrofisico di Catania, Italy
[5] Laboratoire d'Astrophysique, Observatoire de Grenoble, France
[6] European Southern Observatory, Garching, Germany

Abstract. We present the scientific case for an Adaptive Optics Visual Echelle Spectrograph and Imager Coronograph (AVES-IMCO) that we propose as a visitor instrument for the secondary port of NAOS at the VLT. We show that such an instrument would be ideal for intermediate resolution (R=16,000) spectroscopy of faint sky-limited objects down to a magnitude of V=24.0 and will complement very effectively the near-IR imaging capabilities of CONICA. We present examples of science programmes that could be carried out with such an instrument and which cannot be addressed with existing VLT instruments. We also report on the result of a two-year design study of the instrument, with specific reference to its use as parallel instrument of NAOS.

1 Instrument overview

The Nasmyth Adaptive Optics System (NAOS) under development for the VLT has a secondary F/15 focus which can feed a small parallel instrument, the main focus of NAOS being used by the near-IR camera CONICA. In response to an Announcement of Opportunity by ESO which is offering this secondary port for a Visitor Instrument, we propose to accomodate at this focus an Adaptive Optics Visual Echelle Spectrograph and Imager Coronograph (AVES-IMCO) conceived and designed by a Consortium of Italian and French Institutes, in collaboration with researchers at ESO. The Istitutes involved are the Astronomical Observatories of Palermo, Brera, Trieste and Catania in Italy, and the Laboratoire d'Astrohysique - Observatoire de Grenoble in France. The latter institute is acting on behalf of a consortium of French Institutes also responsible for NAOS.

The proposed instrument will provide spectroscopic and imaging capabilities which are either not covered by other VLT instruments or are significantly superior to them at least in three areas: i) medium-resolution spectroscopy of faint background-limited objects, ii) spectroscopy of single ojects in crowded fields, and iii) diffraction limited imaging and coronography of extended objects in the optical domain. The science cases presented hereafter fully justify the demand for an instrument with the capabilities of AVES-IMCO to complement the existing VLT istrumentation package.

The idea behind AVES-IMCO is to use the light concentrating power of Adaptive Optics (AO) in the 500–1000 nm range to narrow the spectrograph slit while retaining at the same time most of the light of the source. This drastically reduces the sky background and therefore enhances the instrument capabilities in the observation of faint sky-limited objects. Moreover, although the Strehl ratio will be lower in the optical than in the IR, NAOS will be able to provide nearly diffraction limited images in the V, R, and I bands, thus complementing the near-IR imaging capabilities of CONICA. All this, coupled with a very high intrinsic efficiency of the spectrograph (comparable to that of the ESI instrument at Keck), will provide outstanding spectroscopic and imaging capabilities, not matched by any other instrument forseen at present for the VLT. Fig. 1 shows a comparison of the expected efficiency of the AVES spectrograph (including telescope, AO transmission, spectrograph optics and detector) with the measured efficiencies of ESI at Keck [1] and UVES at the VLT (ESO Web pages) as well as with the expected efficiency of GIRAFFE at the VLT. In addition to its high *intrinsic* efficiency, AVES will profit of the advantage of the AO correction, which is crucial in the observation of faint sky-limited objects.

Performance calculations show that in its *spectroscopic mode* AVES-IMCO will secure in two hours a S/N=10 for objects as weak as V=22.5, i.e. nearly two

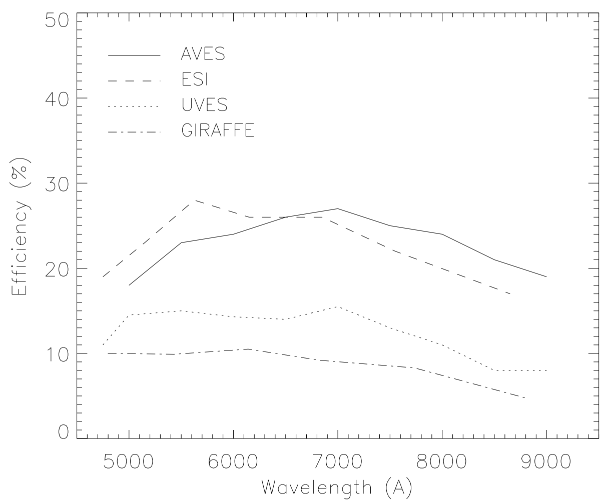

Fig. 1. Comparison of the total efficiency of the AVES spectrograph with those of ESI at Keck and of UVES and GIRAFFE at the VLT

magnitudes fainter than conventional spectrographs with comparable resolving power like GIRAFFE at the VLT, and almost three magnitudes fainter than higher resolution spectrographs like UVES (which is probably the most efficient high-resolution spectrograph in operation on 8m class telescopes). This will open up to our investigation the *late-type main-sequence stars* in the galactic bulge, in many globular clusters, in distant parts of the halo and in Local Group galaxies like the Sagittarius dwarf galaxy and the Magellanic Clouds, thus allowing us to investigate the chemical evolution of the Galaxy and of Local Group galaxies by using not only evolved stars (which in most cases is not sufficient to meet the science goals), but also turn-off and main-sequence stars. At S/N of a few (e.g. for radial velocity determinations) AVES-IMCO will reach in two hours objects as faint as V=24. Finally, AVES-IMCO will provide full spectral coverage over the range 500-1000 nm in a single exposure, thus providing a further advantage with respect to similar-resolution multi-object spectrographs like GIRAFFE which provide only one spectral order at a time.

In its *imaging/coronograph* mode AVES-IMCO will deliver nearly diffraction limited images with better angular resolution (20 mas at 800 nm) than attainable in the near IR, even though NAOS is not optimized for visual observations. AVES-IMCO in imaging/coronograph mode will be unique at the VLT and will be a necessary complement to the near IR observations obtained by CONICA in many areas, like, e.g., in the study of young stellar objects, protoplanetary disks and circumstellar regions. A variety of broad and narrow band filters, as well as coronograph masks, will be used for imaging observations with AVES-IMCO.

Finally, AVES-IMCO will be the first instrument at the VLT to explore the potential of Adaptive Optics for spectroscopy and imaging at visible wavelengths thus paving the road to future generations of optical instruments at very large telescopes.

2 Scientific objectives

An intermediate resolution optical spectrograph capable of observing objects as faint as V=22.5 at S/N>10 for abundance determinations, and as faint as V=24 for radial velocities, opens to spectroscopic investigations a large number of astrophysical problems, ranging from distant galaxies to solar-system objects, which can only partially be addressed with the instruments available at present at the VLT and everywhere in the world. Moreover, the implementation of imaging and coronograph functions in the same instrument further enlarges the range of science topics that can be tackled effectively, and often uniquely, with the proposed instrument. The scientific objectives have been discussed extensively by the AVES-IMCO Science Team in their proposal to ESO. Here we focus only on two scientific objectives that we consider of primary importance for the spectroscopic and imaging capabilities of AVES-IMCO and for which there is a strong scientific interest within our Consortium. We stress however that other scientific objectives, both galactic and extragalactic, are no less important and they can make AVES-IMCO a quite attractive instrument for the scientific community at large. At present, there is no other facility at the VLT with the capabilities foreseen for AVES-IMCO. The ESI spectrograph at Keck has an intrinsic efficiency comparable to that foreseen for AVES (cf. Fig. 1), but it is not optimized for AO and hence should be surpassed by AVES in all observations in which the sky background becomes the dominant source of noise.

2.1 Chemical evolution of the Galaxy and of Local Group galaxies

It has long been recognized that element synthesis is an on-going process and that the chemical composition of cosmic matter may change from place to place and with time. The challenge to observe and understand the chemical composition of stars in different environments is topical in modern astrophysics. The spectra of stars contain a wealth of lines from atoms and molecules which are apt to provide accurate abundances for many elements through state-of-the-art modeling of stellar atmospheres. Elemental abundances, and in particular abundance ratios, provide fundamental insights into galaxy evolution and important constraints for any theoretical interpretation.

Because low-mass stars are extremely long lived, in fact their Main Sequence lifetimes are of the order of the age of the Universe, their chemical composition may be considered as the fossil record of the composition of the interstellar medium at the time the star was formed. Observations of main-sequence stars of different ages allow tracing the chemical evolution of the stellar system (galaxy or galaxy component) to which they belong. It is important to stress that for this purpose it is crucial to observe main-sequence and turn-off stars, which are much fainter than the giants of the same colour, both because it is possible to estimate their ages and because their chemical composition should not be altered by mixing episodes as is generally the case for giants.

Among the elements observable in stars, lithium plays a special role: it is one of the few elements produced in the Big Bang and knowledge of its "primordial" abundance allows the determination of the baryon to photon ratio at the time of nucleosynthesis, and therefore the baryonic density of the Universe. Furthermore lithium is a sensitive probe of stellar structure and mixing episodes, by virtue of its fragility. Only main-sequence stars of spectral type F and early G retain their pristine lithium abundance while lithium is generally depleted (diluted) in giants, due to their extensive convective zones, with the exception of the very rare Li-rich giants in which Li is produced; therefore any investigation aimed at the determination of the "primordial" lithium abundance should concentrate on observations of the main-sequence stars and turn-off stars.

From the above considerations it is clear that accurate measurements of chemical abundances of *late-type main sequence* stars in different environments such as: i) the galactic disk, ii) the galactic bulge, iii) the galactic halo, iv) external galaxies, represent a key to our understanding of the chemical evolution of the Galaxy and of Local Group galaxies. It is also clear that observations of *clusters*, both open and globular, are crucial in this respect, since they provide natural homogeneous samples of stars with a well-defined age and chemical composition. Accurate abundance determinations of main-sequence stars in the astrophysical environments indicated above will provide crucial information on problems such as the origin of the bulge and of the halo, che chemical gradients in the halo, the star formation history, chemical evolution and distance of the Magellanic Clouds, the nucleosynthetic history of Local Group galaxies, and the lithium abundance in distant open and globular clusters, in the Magellanic Clouds and in dwarfs galaxies like Sagittarious.

While main sequence stars in the galactic disk and in nearby open clusters can be observed with existing and future VLT instruments (UVES and GIRAFFE), most *main sequence* stars in globular clusters, in distant open clusters, in the galactic bulge, in the halo and in external galaxies are out of reach for medium/high resolution spectroscopic observations. All these stars shall become accessible with AVES-IMCO, which, in addition, is ideally suited for spectroscopic observations in crowded regions where the AO correction allows reducing the contamination by nearby objects. For instance, the Sagittarius dwarf galaxy is contaminated by a rich population of foreground disk and bulge stars which in fact provide useful relatively bright (V<16) stars sufficiently close (<10 arcsec) to the target stars for a good AO correction. Close inspection of the Sagittarius fields show that the surface density of these objects is indeed sufficient to access turn-off stars in the Sagittarius galaxy. AVES-IMCO has the capability of obtaining medium resolution spectra for these faint stars, which will allow a detailed abundance analysis.

2.2 Imaging of young stellar objects and circumstellar regions

The past years have demonstrated the tremendous progress in the knowledge of astrophysical objects when observing at sub-arcsecond resolution. NAOS on the VLT will provide diffraction limited images down to the optical domain, although the Strehl ratio decreases at shorter wavelengths, as expected. Direct imaging and spectroscopy in the 500 to 1000 nm domain with AVES-IMCO will certainly improve the scientific output expected from NAOS and the near-IR camera CONICA. Observations at optical and near-IR wavelengths are complementary in deriving color information and spectral energy distributions as well as for setting constraints on the physical and optical properties of emitting or scattering sources, and on relative astrometry of visible counterparts. Moreover it is possible to observe prominent emission lines of astrophysical interest in the optical, such as Hα, OI, SII and others.

A great amount of information will be gained with AVES-IMCO from high angular resolution observations of young stellar objects (YSO), especially about their close circumstellar environment: accretion disks, base of the collimated jets, and presence of companions. Note that in this case the AO correction will be done on the target itself, as for CONICA. These observations will provide new information on the way stellar systems form and evolve and will allow addressing fundamental questions such as star formation and early stellar evolution, origin of planetary systems, physics of accretion disks and collimated jets, and dust disks around main-sequence stars.

AO observations on 4m class telescopes have already enabled the detection of the outer parts of a few circumstellar disks. The turbulent structures of jets have also been resolved. On the VLT, AO will enable to observe these extended structures at higher resolution and higher contrast. The challenge will be trying to observe the innermost parts of these disks in order to understand the accretion processes and also to observe the very base of the collimated jets to identify their driving mechanism(s) and intrinsic dynamics. Even though the emitting disks will be certainly studied better in the IR domain, our knowledge of the jets is expected to benefit from observations in the optical (SII, OI, NII) where the improved resolution allows detailed studies of their fine structure and of their dynamics, in particular at the base of the jet.

Of great importance is also the issue of multiplicity which seems much more common among YSOs than among main sequence stars. In the past years it was indeed observed that a large fraction of stars ($\geq$50%, and maybe up to 100%) in Taurus, Ophiuchus and Orion clouds form multiple systems. Similar results were found in older clusters such as the Pleiades. Important questions are whether stars tend to form in multiple systems and separate afterwards, which means that there is a link between multiplicity and PMS evolution, or whether multiplicity rates depend on initial conditions and change from cloud to cloud. An obvious way to answer these questions is to study the multiplicity in more remote star forming regions (e.g. Perseus) which so far have not been surveyed. In principle 20 mas resolution observations allow tackling these issues. Also, the gain in angular resolution will enable to detect new, tighter multiple systems with larger contrast, even in those complexes that have already been surveyed. Optical observations by AVES-IMCO and IR observations by CONICA will be complementary, when the objects are bright enough in the optical, to establish the star spectral energy distributions.

Debris disks around main-sequence and old pre-main sequence stars are tracers of km–sized bodies (planetesimals, comets) and hence of relatively evolved stages of planetary system formation. Unlike the disks around T Tauri stars, they are mainly optically thin and can be seen through scattered light. They are therefore best seen in the optical domain. Diffraction limited images of a few disks were obtained with coronographs on ADONIS and the HST. A great deal can be done with AVES-IMCO in its imaging and coronography mode: the optical domain allows detecting fainter disks, closer to the star, and their detailed structures (e.g. gaps due to planets), while the IR domain helps constrain their grain population.

3 Design study

In response to the above described scientific case, we have designed a compact high performance echelle spectrograph and imager coronograph. A detailed description of the characteristics and performances of the instrument is given in [2] as well as in the documentation prepared for the instrument Preliminary Design Review. Here we only summarise the main points.

AVES is a compact cross-dispersed echelle spectrograph designed to operate at magnification one with a slit of 0.3 arcsec and AO correction, providing a spectral resolution R$\sim$16,000. The same optical component acts as collimator and camera. A front optics adapts the F/15 output beam of NAOS to the F/3.2 required by the AVES spectrograph and combines also an imaging optics which acts both as a coronographic imager and for target acquisition in the spectrographic mode. A 3-D view of the full instrument is shown in Fig. **??**. The spectrograph is accomodated on the exterior of NAOS, while most of the fore-optics is attached to a plate inside NAOS.

The switching between the two modes of operation (imaging and spectroscopy) is obtained by means of two mechanisms, one internal and one external to NAOS. Both modes of operation share the same atmospheric dispersion compensator (ADC) and pre-slit optics. After the ADC there is an intermediate F/20 focus where the coronographic masks and the slits for spectroscopy are accomodated. After the F/20 focus a toggling mechanism inserts either the direct imaging or the spectroscopic lenses. The direct imaging lens consists in 2 doublets and a folding mirror, which provides an image of sky on the AVES CCD. These doublets change the F/20 into F/45 providing a plate scale of 9 mas per pixel. A filter wheel accomodates several narrow and broad filters for imaging. The spectroscopy fore-optics consists instead in a pupil relay lens and an imaging triplet. The entrance slit (F/15) is re-imaged on the focal plane of the spectrograph with the adequate F/ratio (F/3.2).

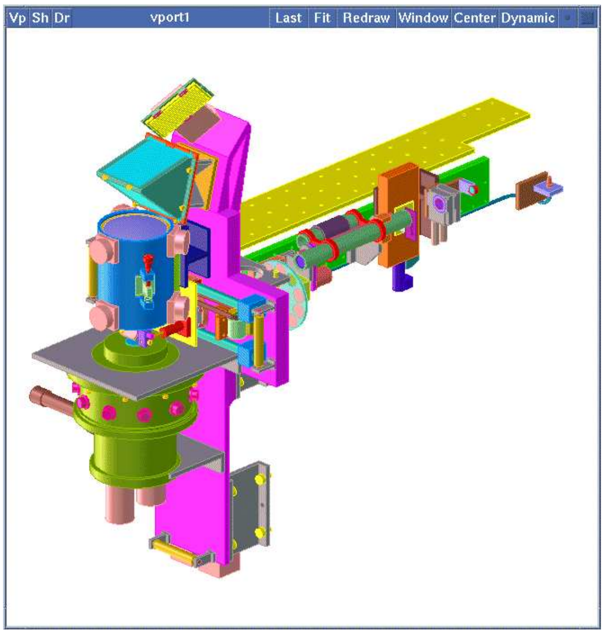

Fig. 2. Overall view of the AVES-IMCO instrument

Dispersion and cross-dispersion are obtained via an echelle grating 79 l/mm blazed at 63 deg (R2) and a Schott SF4 prism with 52 deg apex angle. The spectrograph will be operated between order 22 and order 44 providing a full coverage of the 504 – 1045 nm wavelength range.

Some features need to be emphasized. Since high efficiency is a primary requirement, the wavelength coverage is limited to above 500 nm to ensure that optimal coatings are used and the AO correction is adequate. The selected echelle grating (R2 79 l/mm silver-coated) is probably one of the most efficient echelle grating ever produced. Another key feature is that the full spectral range is covered in one exposure without gaps. The whole spectrograph is less than 60 cm in length (w/o cryostat) to be easily accomodated on the external side of the NAOS structure by means of a carbon-fiber baseplate which acts as an optical bench.

The spectroscopic and imaging functions of the instrument share the same 2k$\times$2k red-sensitive (QE>60% at 900 nm) 15μm pixel CCD detector. A continuous flow cryostat and a standard ESO FIERA controller, redesigned to meet the stringent weight constraints for the NAOS parallel instrument, will be used. Instrument control electronics and instrument control software have been designed to be fully VLT compliant. The instrument has its own calibration system and will have its own data archival system.

4 Current status of the project

Our Consortium has completed a 2-year (1999-2000) design study of the AVES-IMCO instrument with funds from CNAA in Italy and CNRS in France. A Preliminary Design Review was successfully held in September 2000 and suggested modifications to the proposed design were implemented. A letter of intent was sent to ESO in October 2000, followed in April 2001 by a formal proposal for a VLT Visitor Instrument for the secondary focus of NAOS. A revised proposal will be submitted after this meeting for evaluation by ESO STC and OPC. The project is partially funded in Italy and France with the expectation that additional funds to completion will be made available as soon as the project is approved by ESO. The construction, installation and operation of the instrument will be entirely supported at national level with funds and manpower provided by our Consortium and drawn from national sources. Only limited support (subject to future negotiations) will be requested from ESO, mainly in the area of interfaces and standards. The construction phase will last 2 years after a Final Design Review expected to be carried out by ESO after acceptance of the proposal.

References

1. A.I. Sheinis, J.S. Miller, M. Bolte, B.M. Sutin: Proceedings SPIE **4008**, 522 (2000)
2. R. Pallavicini, et al.: Proceedings SPIE **4008**, 167 (2000)