## Conclusion

I hope to have convinced the reader that the VLT will allow very significant advances in our knowledge of the Magellanic Clouds, and perhaps more importantly of stellar evolution in general: I would like to stress once again how unique the Clouds are for studying the various stages of the evolution of massive stars and the late stages of evolution of stars of all masses. The most useful of all the foreseen focal-plane instruments for that purpose appears to be FUEGOS, and I very much hope that its construction will not be unduly delayed by budgetary restrictions.

# Nuclei of Non-Active Galaxies with the VLT

*M. STIAVELLI, Scuola Normale Superiore, Pisa, Italy*

### 1. The Physical Properties of Galactic Cores and Nuclei

Since the very beginning of extragalactic studies it was realized that galaxies have very compact central parts. However, only in the last decades it has been fully appreciated that atmospheric seeing was the major limiting factor for the angular resolution that could be achieved from the ground and that, in turn, the observed core properties were often just artifacts of the limited resolution available (Hoyle 1965; Schweizer 1979, 1981). Of the two galaxies known in the late 1970s with truly resolved cores, one, M31, had a nuclear, very dense, spike roughly in the centre of its broader core, while the other, the radio galaxy M87, presented a central spike in the light profile, which was interpreted as due to an unresolved non-stellar point source. Despite this, the notion of *isothermal cores* was introduced, i.e. of cores with a light profile that flattens to a plateau at small radii. This was partly inspired by theoretical arguments, in practice it reflected precisely the kind of profile that seeing effects were producing. On the other hand, spectacular phenomena like the M87 optical jet opened up the issue of the nature of the nuclear energy sources in galaxies and of the possible existence of nuclear supermassive black holes. It is very intuitive that a supermassive black hole would affect the stellar orbits in the core, producing spikes in velocity dispersion and nuclear rotation curves with steep gradients. Theoretical arguments showed that a black hole would influence also the core light profile, by capturing stars in a very concentrated cusp detectable in the light profile. Indeed, both indicators were used by Young and collaborators (1978, 1979) to claim the existence of a central black hole in M87. Unfortunately, even models without a central black hole can be constructed able to give adequate fit to the data (Binney and Mamon 1982).

Developments in the following years were in a way frustrating. On the one hand the red herring of isothermal cores was brought up and followed by several investigators, who found less and less truly isothermal cores as the resolution increased. Even in the late 80s it was possible to find statements concerning a broad subdivision of galaxies into those with isothermal cores and those without. On the other hand, dynamicists were able to produce (often contrived) models able to fit the observed kinematic and photometric profiles of galaxies without the need of a supermassive black hole. Unfortunately, the intrinsic freedom allowed by stellar dynamics equilibrium configurations and the availability of powerful and flexible modelling techniques, makes it difficult to obtain an irrefutable proof of the existence of a black hole in any given galaxy (see, e.g., Kormendy 1993). Although the central black hole hypothesis is probably the simplest to explain objects like M87, it is important to obtain such a proof by improving resolution and accuracy of observations.

Galaxy cores are also important as benchmarks for theories of galaxy formation. Great progress has been made in this field, often guided by our interpre-

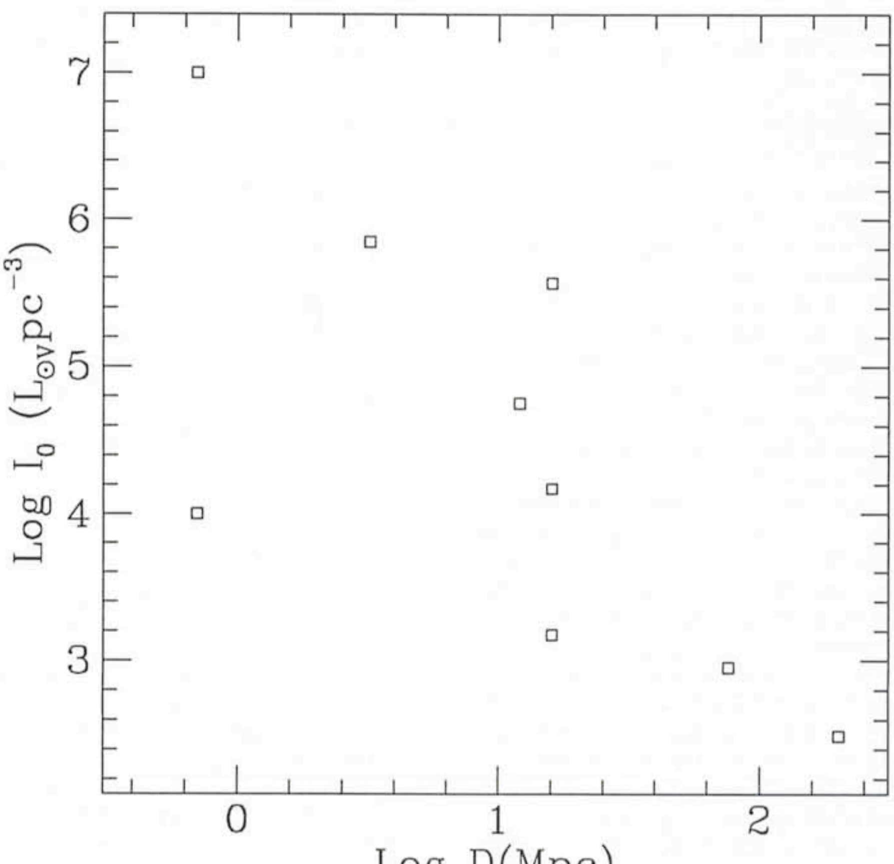


Figure 1: *The apparent central light density of galaxies appears to anticorrelate with galactic distance. This is a resolution effect also present in Hubble Space Telescope data (Crane et al. 1993).*

tation of what the core properties were and how they originated. For instance, the discovery of counter-rotating and decoupled cores was seen as a proof that merging and accretion is occurring, with the remnants of tidally destroyed companions settling into the cores of larger galaxies with their residual angular momentum. Better data and new indicators have shown that this is probably not the case, since (at least some of) these decoupled nuclei turn out to be much more metal rich than the main galactic body (Bender and Surma 1992, Davies et al. 1993), in opposition to the dissipationless merging prediction. Should all decoupled cores have the same property, what was seen as a successful prediction of late-time merging would turn into a fatal blow to this idea. Most likely, further strong constraints on the formation of galaxies will come from deeper studies of their cores.

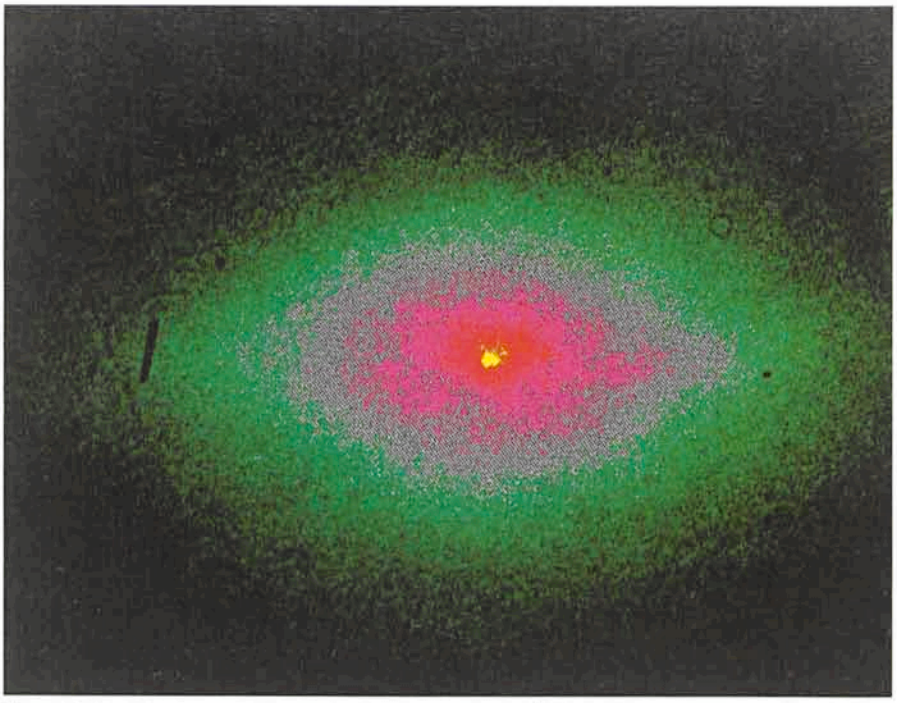

Figure 2: *Hubble Space Telescope FOC image at 3420 Å of the core of the Sombrero Galaxy (NGC 4594). Visible are the point-like nucleus as well as the dust lanes and patches (from Crane et al. 1993).*

## 2. Progress with the Current Generation of Telescopes

Cores are the brightest parts of galaxies. In addition, the desire of having a spatial resolution as high as possible forces us to consider relatively nearby objects. Why then should one use a large telescope? Shouldn't telescopes of the 3.6-m class or even smaller be adequate? This question has two opposite aspects.

Experience shows that typical integration times with e.g. the SUSI camera at the 3.5-m NTT or the standy-by camera at the 2.5-m NOT are, respectively, 2 and 5 minutes. Therefore, the use of these cameras often leads to low-efficiency observations, since the integration time is shorter or comparable to the read-out time. From this point of view, and considering that so far the angular resolution which could be obtained was dictated by atmospheric seeing rather than telescope diffraction limit, a large telescope does not seem to be necessary. In fact, at the CFHT it is a well established procedure to diaphragm the main mirror reducing its size to 1.8 m to improve optical quality and angular resolution.

From what we have seen, one could therefore argue that a small telescope in space would be better than a large telescope on the ground. This is not true. Indeed, it is now becoming apparent that many galaxy cores remain unresolved even at the HST resolution. Crane et al. (1993) have observed a sample of 10 objects with the FOC camera. They find an anticorrelation between the central density and the distance of the galaxy (see Figure 1), well described by a power law with power 1.8. Since a power of 2 would indicate that the core properties are just the result of a finite resolution effect, we have to conclude that even at their resolution of about 0.05 arcsec FWHM the derived core properties are strongly affected by resolution. It is unlikely that this will be changed significantly by COSTAR, since the gain in resolution will only be moderate. In addition, some cores, and perhaps the most interesting ones, like those of NGG 4261 (Ford et al. 1993), of Sombrero (NGC 4594, Crane et al. 1993, see also Figure 2), and of NGC 3557 (Zeilinger et al. 1993), contain dust. This is a reason to shift the preferred observational wavelengths to the Near Infrared. Note that after COSTAR only the UV (and dust!) sensitive FOC will sample the Hubble Space Telescope PSF properly.

Not only direct images but also long slit spectra are desired. Indeed, spectra allow one to derive stellar kinematical information, stellar line-strengths, and ionized gas kinematics and metal content. These data are essential in understanding dynamics and formation of cores.

The need of both high spatial and wavelength resolution forces one to use very narrow slits and high dispersions, at the price of reducing the signal to noise. As an example, a one-hour spectrum of the core of NGC 1399 with EMMI Red Arm at the NTT, with 0.5 Å resolution, only yields a signal to noise of about 30 in the core, adequate to derive kinematical information but not enough to carry out more sophisticated analyses involving the study of line profiles. The latter will probably be fundamental in proving the existence of a black hole in a given galaxy since they probe directly the stellar distribution function. Another example is the rotating gas disk in the nucleus of NGC 3557 identified by Zeilinger et al. (1993). The disk was detected in a spectrum taken at the ESO 3.6-m telescope with a resolution of 1 Å per pixel, by resolving the [N II] ($\lambda$ 6583.4 Å) into two wings both appearing in the core of the galaxy. East and west of the nucleus only the approaching and receding wings, respectively, are observed, thus producing a typical-looking rotation curve. This spectrum already gives strong hints for the existence of a central black hole in this galaxy (Zeilinger et. al. 1993). A further attempt to derive more accurate line shapes by using the echelle spectrograph CASPEC at the 3.6-metre telescope failed because even with 4 hours of integration not enough photons were collected. For very high resolution work, a 3.6-metre-class telescope is simply too small to observe galaxy cores with typical B surface brightness of 17 magnitudes/arcsec$^2$ or more.

## 3. Developments with the VLT

A number of factors concur to make the VLT (see Figure 3) a superb telescope for a variety of applications: the site, the size of the unit telescope, the instrumental developments. Here we will consider separately the contribution that CONICA, FORS, ISAAC, and UVES will make to the study of galaxy cores.

### 3.1 CONICA

CONICA is the Coudé Near-Infrared Camera (Lenzen and von der Lühe 1992). It is the prime instrument for exploiting the high resolution potentially available at the single VLT unit. In fact, the diffraction limit of a single VLT mirror is for a given wavelength almost 4 times as small as for the Hubble Space Telescope. With adaptive optics it is expected that the diffraction limit will be reached in the Near Infrared for $\lambda > 2.2$ micron and that partial correction will be attempted at 1.25 micron. The PSF for the case of partial correction is characterized by a diffraction limited core with most of the power in the PSF wings, i.e., a situation similar to that of the pre-COSTAR HST, so that one will be able to exploit all techniques developed for HST data. The CONICA Camera will be able to sample with 0.012 arcsec pixels the PSF at 1.25 micron, yielding a resolution of 0.032 arcsec FWHM, and with 0.024 arcsec pixels the PSF at 2.2 micron, yielding a (fully corrected) resolution of 0.057 arcsec FWHM. Thus effectively exceeding, with well sampled images, the spatial resolution provided by HST at optical wavelengths. The gain of a factor 2 in resolution over HST is certainly welcome, but very important is also the ability to take such high resolution images in the Near Infrared, where the effects of obscuration by dust are much less important.

The major problem of adaptive optics at the VLT, at least until the technique of artificial reference stars will be introduced, is that only a small fraction of galaxies will be suitable for such a study, since adaptive optics requires the presence of a reference star (brighter than about 15) within the isoplanatic patch, i.e. at, say, less than 10 arcsec from the target. Luckily, many galaxies turn out to have central point sources (Lauer et al. 1991, Crane et al. 1993). For a number of objects including, e.g. M87, the central (non-thermal) point source is bright enough to serve as a reference star. When this is possible, this is an optimal observing mode since reference star and target coincide in position. CONICA offers other possibilities for galaxies without a suitable reference star near the core. These techniques include speckle imaging and various forms of coaddition. A basic requirement is that an object in the field of view is bright enough to get enough photons in a very short integration time to, e.g., allow for the measurement of the frame reference coordinates and carry out a "shift and add" operation. A typical elliptical galaxy core with surface brightness $\mu_J = 13.8$ and $\mu_K = 12.7$ will be detected as 20 photons/sec/pixel (0.012 arcsec/pixel) in the J band and as 110 photons/sec/pixel (0.024 arcsec/pixel) in the K band. These fluxes are too small to use sampling rates larger than 10 Hz. However, many galaxies turn out to be brighter by about a factor 10 at milliarcsec scales compared to the arcsec scales; in addition, many contain point sources brighter than 20 in V. The latter are usually too faint to serve as reference stars for adaptive optics but can be used to align the images. Globular clusters may also be suitable for similar purposes, provided some are present in the restricted FOV of 3 arcsec in J and 6 arcsec in K.

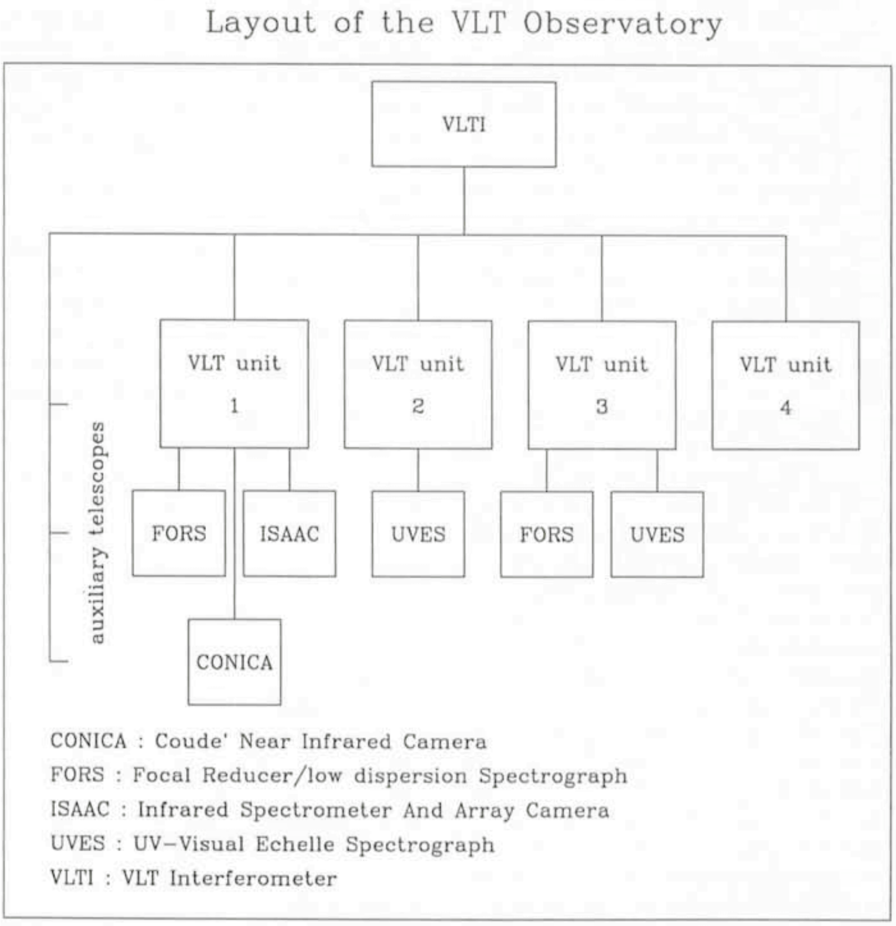


Figure 3: *Schematic drawing of the VLT with the instruments considered in the text.*

At lower resolution, the capability of extending the observing wavelength to 5 micron is also very important, especially since no high-resolution data are available for galaxies at these wavelengths. In the L and M bands respectively, a diffraction-limited resolution 0.093 and 0.12 arcsec FWHM will be obtained for a significant fraction of the sky, thanks to the less demanding requirements of adaptive optics at these wavelengths. In addition to the high resolution achieved, these wavelengths will allow unique opportunities for those objects with cores obscured by dust lanes, like, e.g., NGC 5128.

### 3.2 FORS

FORS is a focal reducer with parallel beams (Appenzeller and Rupprecht 1992). For imaging application the setup of choice will be the High Resolution mode with 0.1 arcsec/pixel. Such a pixel size should allow a suitable sample of the typical seeing conditions at the VLT Observatory. The large collecting area of the VLT unit however would imply very short exposure times and therefore inefficient observations. Apart from the resolution benefits in using very short exposures, we therefore expect that the use of FORS in the study of cores will primarily be spectroscopic. With a grism and narrow slits, it will be possible to obtain spectra with a resolution of about 100 Å/mm of the core regions of galaxies. In good seeing, with a 0.4 arcsec slit, spectra with 2.5 Å per pixel and S/N 200 in the centre will be obtained in one hour for typical galaxy cores. Such a resolution is adequate for deriving accurate kinematical properties (errors smaller than 20 km/s in radial velocity and velocity dispersion), line profiles, and absorption line strengths. Therefore, with a moderate amount of telescope time, it will be possible to make a complete two-dimensional mapping with high spatial resolution of the cores of nearby galaxies. Such a mapping will allow us to construct an accurate dynamical model for the core and also to infer its stellar population properties and possibly its star formation history.

### *3.3 ISAAC*

The Infrared Spectrometer and Array Camera (Moorwood 1992) is another Near-IR instrument for the VLT. The instrument has a relatively large field (up to 2 arcmin) and medium spectral resolution capabilities. In imaging applications, particularly interesting would be the inclusion of the tip-tilt option of the secondary mirror. Such control should allow diffraction limited imaging in the L and M bands, where the images would however be undersampled by the 0.125 arcsec pixels. Despite the problems of undersampling (possibly cured by a reduction in pixel size with the use of detectors of a new generation) imaging at these wavelengths, and also in J and K, with ISAAC can be an important complement to CONICA given the larger field and the higher sensitivity resulting from being at the Nasmyth focus rather than at the coudé. The use of a shift-and-add technique should in any case guarantee very good spatial resolution at the longer wavelengths. The expected count rates from a typical galaxy core are 4000 and 5600 counts/pixel/second, respectively in the J and K bands. They should allow integration times shorter than 0.1 second.

Especially interesting is the possibility of obtaining long-slit spectra at a resolution of 5000 (for a 1 arcsec wide slit). Indeed, Near-IR spectroscopy of galaxies is a relatively new field which will benefit considerably from the availability of ISAAC at the VLT. The observation of CO lines is perhaps the only way to derive central velocity dispersions for heavily obscured cores like NGC 5128. In addition, important applications will be possible also in stellar population studies.

### *3.4 UVES*

The prime instrument for the study with high wavelength resolution of both line profiles from stellar absorption lines and ionized gas emission lines will be represented by the UV-Visual Echelle Spectrograph (Dekker and D'Odorico 1992). This instrument will profit from the size of the VLT and allow for observations which have not been possible so far.

In good seeing, with a 0.4 arcsec slit exploiting the 0.19 arcsec/pixel of the blue arm, one will be able to obtain high spatial and spectral resolution. Stellar kinematics in the blue arm will be carried out preferably on the CaII H + K band and on the G band. The slit length will have to be limited at 8 arcsec to avoid order overlapping. The overall efficiency should be around 8 per cent. For a galaxy of typical surface brightness $\mu_B$ = 17.6, a signal-to-noise of 20 will be reached with two hours of integration. Such a signal to noise would be adequate to derive kinematical information. It appears that several galaxy cores may have low velocity dispersions in the range of the few tens km/s (see, e.g., M33), such cores would require the use of UVES to be detected outside the local group.

The red arm would allow for a higher sensitivity. With a 0.7 arcsec slit and 0.31 arcsec/pixel one could obtain high resolution spectra of the MgI blend and of the Ca + Fe E band, which are the standard regions used for stellar kinematical measurements. A signal to noise exceeding 30 should be obtained with two hours of integration.

Longer integrations will probably be of interest to improve the accuracy of the measurement but also to allow for a more reliable determination of the line profiles, which will give a direct observational constraint on the stellar distribution function in the parent galaxy. Such a measurement will have an impact both on the problem of galaxy formation and on that of the presence of central black holes, since the various models make very clear and specific predictions on the distribution function properties.

One possible additional application for such an instrument is in the direct measurement of the gravitational potential in galaxy cores. Such a measurement is made possible by gravitational redshift, which for a big galaxy is expected to be of the order of 10 km/s. The effect has already been detected in accurate radial velocity profiles (Stiavelli and Setti 1993) but it would require a very high resolution and signal to noise to actually measure the potential variation in the core, i.e. reach a velocity resolution below 1 km/s.

In addition to stellar kinematics, gas emission lines will also be measured and used to derive information on the physical properties of gas in the dust and gas disks often seen in the centres of ellipticals. This is especially important since these dust rings appear to be involved in the fuelling of nuclear activity in normal galaxies and could also be the progenitors of the kinematically decoupled stellar disks observed in some galaxies.

## 4. Further Desirable Instruments

The VLT interferometer (Beckers and Merkle 1991) would represent another step further in terms of angular resolution, since it should allow a resolution of about 0.004 arcsec, corresponding to about a factor 10 improvement over HST. It is very hard at this stage to predict the kind of impact that such an instrument would allow. It is perhaps significant to note that it would allow for galaxies in the Virgo Cluster a resolution in physical distance scales comparable to what can be obtained now with the Hubble Space Telescope on M32. If M32 remains unresolved with HST, it is extremely important to understand if it is an extreme, not too significant, object or, rather, a typical core for low mass galaxies. Do NGC 7457 (Lauer et al. 1991) and NGC 4621 (Crane et al. 1993), both unresolved with HST, have similarly compact nuclei? The major limitation for such a study will again be the availability of a suitable reference star. It should be noted that the quasi point-like source in M87, for instance, is partially resolved by HST and therefore cannot be used for this application.

As we have seen, the instruments already foreseen for the VLT guarantee enormous improvements with respect to what can be done now from the ground or from space. Is there any other improvement possible? The need of being able to take high spatial and frequency resolution spectra could be satisfied with a Fabry-Perot spectrograph. Such an instrument could allow for the measurement of the velocity dispersion and rotation velocity fields of galaxy cores. This kind of instruments has been so far limited by technical reasons and by their relatively low sensitivity, requiring the use of a very large telescope.

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# From Planets to the Big Bang with High-Resolution Spectroscopy at the VLT

*R. FERLET, Institut d'Astrophysique de Paris, France*

## Introduction

Some years ago, M. Harwit showed that most cosmic discoveries were connected with the occurrence of a significant technical step or the opening of a new window on the Universe. Without question, high-resolution spectroscopy associated with very large collecting area will be such a major tool to attack vital astrophysical problems. Beside serendipitous discoveries, there are several areas of research to be investigated with a high-resolution VLT spectrographic capability. The VLT should not miss the opportunity to venture into an almost virgin universe and make discoveries.

Here, we are talking about resolving power R of at least $1-1.5 \times 10^5$, simply because many important pending problems cannot be tackled with lower resolution. Many of these are reviewed in the proceedings of the ESO Workshop on "High Resolution Spectroscopy with the VLT" held in Garching in 1992. We will briefly give here only a few exciting examples of potential achievements in various fields through high-resolution absorption spectroscopy at the VLT.

## Technical Advances

Measurements of equivalent widths of interstellar lines (IS) are indeed quite independent of the resolution. However, it is well known that they can yield very large errors on column densities when multiple components are present on the line of sight and when lines are saturated (on the flat part of the curve of growth). The former situation appears very general, even for the short lines of sight of the solar neighbourhood. The latter one is less common, at least for part of the IS lines in the visible spectrum. But both cases will become severe limitations when probing the diffuse IS medium beyond what is currently reachable in the galactic plane with the available telescopes.

Sufficient resolution is required to resolve the velocity structure of the lines of sight. This is the only way to gain information on individual clouds, on average separated by a few km/s, that is now badly needed instead of integrated properties. Amongst physical parameters, temperature is directly accessible only through the intrinsic width of the lines. For purely thermal broadening, the width increases with decreasing mass of the studied ions, and the lightest element having an observable resonance line in the visible is lithium (the lighter elements hydrogen, deuterium and helium show up in the currently unaccessible far UV, except Ly$\alpha$ observable with the Hubble Space Telescope but which is always heavily saturated and blended). Nevertheless, even through the Li I doublet, IS gas at 1000 K gives a full width at half maximum of 2.57 km/s, requiring already R $> 1.2-10^5$. Higher resolution is mandatory in order to derive true b-values from cooler IS gas, even though careful profile fitting analysis of several lines may help to artificially increase the resolution by a factor of perhaps 2 or so depending on the signal-to-noise ratio. Moreover, using lines of different ions in the same velocity components will allow to also determine any turbulent velocity, another important and poorly known parameter for the dynamics of the interstellar medium.

## Astrophysical Considerations: Interstellar Medium

The $Li^7$ equivalent width for IS diffuse clouds such as those in front of $\zeta$Oph or $\varrho$ Oph in which typical temperature is very likely below 100 K, is of the order of the mÅ, claiming thus for S/N ratios well above 100. Because both stars are bright enough, these two lines of sight are well studied with the ESO CES at La Silla, which has provided $R=10^5$ for more than ten years. The CES is usually fed by a 1.4-m telescope. The jump to an 8-m-class one will so much increase the number of potential targets that many stars more deeply embedded in cloud cores will become accessible, allowing thus to link the properties of the diffuse clouds currently studied in absorption to those of the denser and colder regions detected in the IR or mm radio range.

A more specific programme would be the measurements of the IS abundances of light elements, in particular beryllium and lithium which are only observable in the visible range around 3130 Å and 6707 Å respectively. The knowledge of their present-day abundances, and even more uniquely of the ratios Be/Li and $Li^7/Li^6$, is a key-milestone to severely constrain cosmological scenarios and galactic chemical evolution models. This kind of observations needs extremely high S/N ratios. For instance, IS $Li^6$ has been recently detected for the first time towards $\varrho$ Oph (Lemoine et al., 1993), thanks to a S/N ratio $\geq$ 2700 per pixel, implying a limiting detectable equivalent width of 0.043 mÅ (3 $\sigma$). The resulting $Li^7/Li^6$ ratio $\sim$ 12.5 is in strikingly good agreement with the meteoritic value which is thought to be representative of the early solar system, and cannot as yet be explained by the most recent and elaborated evolutionary models. This has been achieved after 13 hours of integration time with the CES linked to the ESO 3.6-m telescope via fiber optics, on a $m_v \sim 5.0$ star. The same measurement is going to be published for $\zeta$ Oph ($m_v=2.7$) with a S/N ratio above $\sim$ 7000! (see Figures 1 and 2). However, this is restricted to the 4–5 stars on the whole sky which are bright enough but still shining through a dense cloud to enhance the expected column density. It should be done in many individual clouds in order to statistically establish the significance of the first results and to directly test the cosmic ray production of Li; the gain from one VLT unit should even allow to see possible variations in the