Extragalactic science at very high spectral resolution

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Abstract. I briefly mention a few possible applications of very high spectral resolution spectroscopy with CRIRES to the study of nearby galaxies. This includes the fields of AGN, dynamically cold systems, super stellar and emission line clusters, and a more speculative program on the measurement of gravitational redshifts.

1 Introduction

One of the early attempts to use very high spectral resolution spectroscopy to study the central region of a nearby galaxy was motivated by the complex nature of the observed source: Pelat & Alloin (1980) used the spectral resolution delivered by an Echelle spectrograph at the Observatoire de Haute Provence as a compromise to compensate for the lack of spatial resolution. The intricate velocity structure of the [OIII] line in the central 200 pc of the active galaxy NGC 1068 was thus revealed, but even at a resolution of about 20,000, the lack of spatial resolution prevented any truly conclusive interpretation.

A new step was recently taken with the high spatial resolution provided by the Hubble Space Telescope (HST). Cecil et al. (2002) used STIS aboard HST to map the central region of NGC 1068 in the [OIII] and Hβ lines with 6 parallel slits, with the aim of resolving individual clouds and their kinematics. Even at a resolution of about 5000, the data clearly showed that there is no hope to nail down the velocity distribution in this region. As shown in Fig. 1, each spatial pixel includes numerous velocity components which themselves correspond to many unresolved clouds with various physical conditions. This illustrates the real potential of an instrument such as CRIRES, which will simultaneously deliver very high spectral resolution (up to \( R = 100,000 \)) and high spatial resolution.

In the following, I provide a short and non exhaustive list of scientific programs which could benefit from such a unique spectrograph. However I should first emphasize that, in general, CRIRES may not be the best adapted instrument to conduct detailed studies on nearby galaxies. Indeed, its maximum spectral resolving power of 100,000 requires bright sources. For most (nearby) extragalactic sources, the available flux is just not high enough. There are still a few niches for CRIRES which should be exploited, some of which I mention below.

2 Diagnostics

The Near Infrared domain available with CRIRES (1–5 µm) includes many lines to study the physics of both the gas components and the stellar populations. A
number of atomic and molecular emission lines can be observed, e.g. when the region under scrutiny is highly extincted, Br$\beta$ and Br$\alpha$ could really help, and the Pfund series could serve as a nice tool to get some handle on $A_V$. H$_2$ lines are often present, as well as higher excitation lines such as [FeII], [SiVI], ..., thus delivering excellent diagnostics of the physical status of the gas. The various line ratios would then inform us about the physical emission process: collisional excitation, ultraviolet fluorescence, X ray heating, fast shocks.

The stellar component is easily revealed by the numerous absorption lines which are present at these wavelengths: e.g., FeI, TiI, MgI lines, CO bandheads at 1.6 and 2.3 $\mu$m (Fig. 2; courtesy C. Boisson). These are powerful tools to derive the stellar kinematics and constrain the characteristics (age, metallicity) of the underlying stellar populations. However this will require to have reference template spectra at the same very high spectral resolution. This therefore implies a significant effort to observe with CRIRES a large sample of stars with a wide range of type and properties.

### 3 Dynamically cold systems and central stellar populations

The high spectral resolution provided by CRIRES could certainly help studying the kinematics and stellar populations of dynamically cold systems. Dwarfs and
spheroidals are thus excellent targets to constrain the radial profiles of dark matter, and we could think also of measuring the stellar kinematics of face-on disks to reveal their internal dynamical structure. However these sources are just too faint for CRIRES, even with an aperture such as a VLT unit.

As we go towards the lower end of the black hole mass ($M_{bh}$) versus velocity dispersion ($\sigma$) relation, the velocity resolution required to probe e.g. the centers of inactive galaxies increases. For late type spirals (Sc and later), $R = 30,000$ would probably be enough, with no need to reach the maximum resolution of CRIRES. The latter may be useful to reach the extreme end of that relation, i.e. to constrain the presence and mass of the very low mass black holes in globular clusters, although we would there be again starving for photons. Intermediate resolution of the order of 30,000 could also be used to help disentangling the blended metallic lines, hence to constrain the populations in the central regions of spirals. Spatial resolution is also a requirement here since significantly more than half of all spirals show the presence of relatively young stellar nuclei with $-14 < M_I < -9$ and a median effective radius of 3.5 pc (Böker et al. 2003, 2004).

Fig. 2. Absorption line identification in a small part of the NIR H band. (Courtesy of C. Boisson)
4 AGN studies

Although there will be only a handful of active nuclei for which sufficiently high signal to noise ratios can be reached with CRIRES, it will deliver unprecedented information on the physical status of the gaseous component in the central few hundreds parsecs of AGN. As illustrated in the introduction of this paper, the spectral resolution will directly address the gas velocity structures. Resolving these below the thermal width is a reachable goal using lines such as [FeII] or Brγ for lighthouses like NGC 1068 or Circinus. The very high velocity resolution achieved by CRIRES spectrography will also allow tracing the physical status of the gas independently for each velocity slice through e.g. the line ratios. The integrated stellar populations could then be analyzed in great details in the context of the AGN / nuclear star formation debate. Last but not least, we should be ready for surprises, as CRIRES data will definitely probe new grounds and hopefully reveal unexpected sights.

5 Super stellar and emission line clusters

Another field where CRIRES could definitely contribute is the study of super stellar clusters in nearby galaxies. Such clusters are often observed in starburst galaxies and correspond in size and luminosities to globular clusters (Hunter et al. 2000). An image obtained with the WFPC2 camera aboard HST is provided in Fig. 3 as an illustration. The apparent size of these clusters requires high spatial resolution, and the mass range they probe imposes high spectral resolution.

Spectra at $R \sim 24,000$ of SSC B in NGC 1569 ($M_H = 12.3$ mag, Gilbert 2002) distinctly show the rich absorption line signatures present in the NIR domain, and only properly revealed with $R > 20,000$ (Fig. 4, courtesy of A. Gilbert, PhD Thesis, 2002). The masses of these clusters can be estimated via a measurement of the velocity dispersion (Gilbert 2002). The spectral information is also critical to constrain their age and metallicity: these are unique probes of the star formation processes in this mass range (and extreme conditions). Further illustrations can also be found in e.g. Mc Crady et al. (2003) for the case of a well-known starbursting galaxy, M 82, and in Gilbert et al. (2000) for a study of super stellar clusters in the Antennae galaxies. The latter study also emphasizes the richness of both absorption and emission lines in the NIR (Fig. 5), where both stellar and (atomic plus molecular) gas contributions are present.

The youngest members of these clusters are still embedded in HII region and heavily extincted, with $A_V$ up to 10 and more. As they may subsequently evolve into bona-fide globular clusters, it would be important to examine their nebular content as a probe of the early stages of massive star forming regions. Gilbert & Graham (2004) have recently examined such clusters in the Antennae galaxies and discovered supersonic Brγ lines in their high resolution echelle spectra. With widths of up to 105 km.s$^{-1}$, the observed emission lines correspond to the higher end of the flux vs line width correlation known for giant extragalactic HII regions. The so-called Emission Line Clusters (ELCs) thus exhibit massive
gas outflows, and would certainly deserves observational campaigns with high resolution spectrographs like CRIRES.

6 Gravitational redshifts?

On the speculative side, high spectral resolution spectroscopy may also provide a unique leverage on the direct determination of the mass of black holes in the centre of galaxies. The potential well has a direct influence on the frequency of the escaping photons. The Doppler effect is directly proportional to $\Delta \Phi / c$ where $\Delta \Phi$ represents the change in gravitational potential. We could therefore try to look for the relative Doppler shift induced by the strong potential gradient at the centre of galaxies. The expected mean effect is of the order of a few km.s$^{-1}$ for supermassive black holes in the centre of luminous early-type galaxies. We would then require spectroscopy with rather high spectral and spatial resolutions.
Although it seems illusory to disentangle this effect from non-gravitational motions in the gaseous component at scales of 10's of parsecs (Popovic et al. 1995), I would argue that such a study using stellar kinematics may be viable (see Stiavelli & Seti 1993). As the observed effect will be luminosity weighted, we need to focus on galactic centers with very cuspy luminosity densities (modest size ellipticals), but to maximize the potential gradient we would require objects with high velocity dispersion (massive ellipticals). There are of course many limitations that we can foresee: systematics must be mastered, unresolved structures can induce artefacts, and intrinsic redshifted populations would confuse the picture. Line Of Sight Velocity Distributions at such high resolutions have never been obtained, so this may be an opportunity for an exciting experiment. However, this experiment will probably require a number of tested cases before any strong conclusions can be made.

Fig. 4. Top 2 panels: H band spectra of a SSC B, a super stellar cluster in NGC 1569 at a resolution of $R \approx 2000$. Bottom 2 panels: zooming with echelle spectra at $R \approx 24,000$. From Gilbert (2002).
7 Conclusions

$R = 100, 1000$ spectroscopy is definitely too high for most of the targets we are used to when we study nearby extragalactic objects. However, there are still a few niches that a unique instrument like CRIRES can fill. The simultaneous delivery of high spatial and spectral resolutions will certainly be a productive tool to probe the central regions of active galactic nuclei. It may also serve its purpose to constrain the central stellar populations in late type spirals, or for the search of the lower end of central dark masses. Young massive clusters (SSCs and ELCs) are exciting targets to examine with CRIRES, thus entering the early stages of massive star forming regions. I then suggested that high spectral resolution spectroscopy could be a way to get a direct measurement of the potential well via gravitational redshifts detections. Finally, and although it seems clear from this short paper that extragalactic science will not be a privileged field for CRIRES, we should keep our minds open for surprises: CRIRES will certainly drive us towards unknown territories.

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