Long-Slit Spectroscopy at La Silla: an Annotated Menu

W.W. ZEILINGER, ESO

1. Introduction

Spectroscopy of extended objects finds application both in Galactic (e.g. gas kinematics in planetary nebulae) and extragalactic fields. For many years measuring the kinematics in galaxies was restricted to the analysis of emission lines which can be traced relatively easily out to great distances from the nucleus. By contrast, absorption lines in galaxies are much more difficult to measure, because they are broadened by the velocity dispersion of the stellar component and since the intensity of the continuum decreases quite rapidly away from the centre. Only with improved detectors and improved data analysis techniques was it possible to access also this piece of information on the kinematics of extended objects. Also in the case of analysing spectra of faint point sources, long-slit spectroscopy allows an efficient sky subtraction.

The last years have seen a quite rapid evolution on the sector of the instrumentation. Until the mid-eighties most of the data were still obtained with image tube spectrographs (e.g. a Boller & Chivens spectrograph equipped with an EMI image tube as it was available at ESO) on photographic plates. The plates needed then to be digitized in order to be processed further. The subsequent step was the replacement of photographic plates with linear detectors. The first generation of linear detectors at La Silla was the Image Dissector Scanner (IDS) in combination with the Boller & Chivens spectrograph at the 3.6-m telescope. This detector allowed a very limited spatial resolution. There were two channels of which one usually was used for measuring the background. Only with CCDs was it then possible to obtain a similar field as with photographic plates. The spectral and spatial resolution, however, depended mainly on the pixel size, which for the first CCDs was quite large (30 μm^2) and somewhat constrained the observing programmes. There, the situation improved considerably with the arrival of the high-resolution CCDs. The latest upgrade now introduced multi-purpose instruments like EFOSC and EMMI. This generation of instruments not only allows a convenient change of wavelength ranges, dispersions and slit widths in the course of a night but give the observer also flexibility in selecting direct imaging or spectroscopic mode.

In the following chapters a brief guide to the instruments at La Silla with long-slit spectroscopy capability is presented. Since there is a variety of instrumentation available, this article is intended as a help for the potential user in selecting the most adapted instrument for his purpose. For the basic description of each instrument one may refer to the respective operating manuals of the instruments.

2. The Instrumentation Available at ESO

In Table 1 an overview is given over the specific instrumentation presently available at La Silla. For comparison also the Boller & Chivens spectrographs at the 3.6-m and 2.2-m are included although they are not offered any more. The setup of the instruments depends of course very much on the specific observing programme. In the following discussion more emphasis will be given to aspects of kinematic observations (i.e. obtaining radial velocities and velocity dispersions) because they require high spectral and spatial resolution on the one hand, and on the other hand a relatively large wavelength range needs to be covered in order to analyse as many lines as possible. The major applications of long-slit spectroscopy, particularly in extragalactic astronomy, are centred upon a few "traditional" wavelength regions of interest:

- for *emission lines*: the region around Hα (λ6563 Å) including the [N II] lines (λ6548 Å, λ6583 Å) for analysing the gas kinematics;
- for *absorption lines*: λλ3700 – 4400 Å (including the Ca II K and H lines and the G band) and λλ4900 – 5900 Å (including Fe I λ4921 Å, Mg I λ5175 Å, E band and the Na blend λ5893 Å) for deriving the kinematics of the stellar component. Limited information about the gas kinematics may also be obtained in these wavelength regions by measuring the [O II] doublet (λλ3727-29 Å) and the [O III] line (λ5007 Å) respectively.

At the same time the observer wants to obtain as much spectral resolution as possible in these wavelength regions. In the case of kinematic observations, for example, a sampling better then 1 Å pixel^{-1} is desirable. Because of the higher red sensitivity of CCDs most part of the observational work is now done in the region >4900 Å. The physical size of the detector, then, determines the wavelength interval covered. Nowadays CCDs usually have 1024 pixels (or more) in the direction of the dispersion, so that each of the relevant wavelength regions can be observed with one grating setting only. For each instrument the optimal grating (or grism) has been selected in order to cover a wavelength region of about 1000 Å centred at $\lambda \approx 5200$ Å (except for the EMMI Blue Channel configuration which refers to λλ3700 – 4400 Å). The resulting sampling and spectral resolutions are compiled in Table 1. The entrance slit widths ω and spectral resolution σ_{inst} listed in Table 1 for each instrument are calculated for the maximum spectral resolution satisfying the Nyquist sampling theorem.

2.1 *The Boller & Chivens Spectrographs*

Originally the Boller & Chivens spectrographs were available at the 3.6-m, 2.2-m and 1.52-m telescopes. But presently only the one at the 1.52-m telescope is offered. This type of spectrograph turned out to be a very stable instrument optimized for long-slit spectroscopy of extended sources. In particular, the optimized collimator/camera focal length ratio allows small instrumental dispersions to be considered with relatively large slit widths. A wide range of gratings is available which allow to cover more or less the full optical wavelength band in various dispersions. A detailed list of the gratings together with their relative efficiency curves may be found in ESO Operating Manual No. 2. The dispersions typically used are of the order 58 Å mm^{-1} yielding a resolution of about 0.9 Å pixel^{-1}.

The change in the instrument orientation with respect to gravity as the telescope tracks the object in the sky is the principal cause for instrumental flexure, with the amount depending mainly on the zenith distance and the slit orientation. For the Boller & Chivens spectrographs the maximum shift measured in consecutive comparison line spectra was <0.5 pixel in an interval of 3 hours.

2.2 *EFOSC1 and EFOSC2*

The *ESO Faint Object Spectrograph and Camera* is available at the 3.6-m (EFOSC1) and its twin is available at the 2.2-m telescope (EFOSC2). This type of instruments uses grisms for spectroscopy which have a fixed wavelength range. Grisms have in general a higher efficiency than gratings. At EFOSC1 the highest dispersion available is about 120 Å mm^{-1} covering the wavelength region between 3600 Å to 8600 Å (grisms B150, O150 and R150) in intervals of about 2000 Å, yielding a maximum resolution of about $\sigma = 1.7$ Å pixel^{-1}. Only EFOSC2 contains a set of grisms (#7, #8, #9 and #10) which is really useful for kinematic work ($\sigma = 1.3$ Å pixel^{-1}). But, as is evident from Table 1, in order to exploit the full resolution of EFOSC, a very narrow entrance slit is required (about 0.7 arcsec). At the level of a comparable instrumental setup EFOSC (and also EMMI) may be considered about three times more efficient than the Boller & Chivens spectrographs. No significant instrumental flexure has been measured.

Table 1: *Instrument configurations for long-slit spectroscopy*

telescope (1)	instrument (2)	scale slit length (3)	detector dimensions (4)	grating dispersion (5)	sampling [Å pixel^{-1}] (6)	ω (7)	σ_{inst} (8)
3.6-m	B & C[a]	36.67 174	RCA #8 640 × 1024 (15 μm) pixel	#26 59.5	0.89	1.6	44
	CASPEC[b]	24.07 114	TEK #26 512 × 512 (27 μm) pixel	6.5[c]	0.18	2.1	7
	EFOSC	22.47 180	RCA #8[d] 640 × 1024 (15 μm) pixel	O150[e] 130	2.0	0.7	85
NTT	EMMI Blue	15.05 360	TEK #28 1024 × 1024 (24 μm) pixel	#12[f] 38	0.91	0.8	58
	EMMI Red	23.15 360	Th #18[g] 1024 × 1024 (19 μm) pixel	#6 28	0.53	0.9	25
2.2-m	B & C[a]	59.33 294	RCA #11 640 × 1024 (15 μm) pixel	#26 59.5	0.89	2.6	44
	EFOSC2	17.47 300	Th #17 1024 × 1024 (19 μm) pixel	#8[h] 68	1.3	0.7	52
1.52-m	B & C	45.33 252	FA #27 2048 × 2048 (15 μm) pixel	#26 67.2	1.00	2.0	49

[a] … no longer offered
[b] … long-slit mode with short camera (f/1.6) and 31.6 groves mm^{-1} echelle grating
[c] … dispersion at Hα region
[d] … expected to be replaced by a Tek 512 × 512 (27 μm) pixel CCD (#26) during Period 49
[e] … EFOSC O150 grism with fixed wavelength range λλ5000–7000 Å
[f] … wavelength region λλ3700–4400 Å
[g] … expected to be replaced by a coated FA 2048 × 2048 (15 μm) pixel CCD (#24) during Period 49
[h] … EFOSC2 #8 grism with fixed wavelength range λλ4640–5950 Å

Notes to the columns:
(3) line 1: scale on the detector [arcsec mm^{-1}]
line 2: maximum slit length [arcsec] which can be used in the unvignetted field
(4) with the exception of EMMI the direction of dispersion is always aligned with the columns of the CCD
(5) line 1: grating allowing a central wavelength around 5200 Å
line 2: dispersion [Å mm^{-1}]
(7) minimum entrance slit width [arcsec] which satisfies the Nyquist theorem
(8) instrumental profile [km s^{-1}] using the slit width given in col. (7) calculated at $\lambda = 5200$ Å

Regarding the operation of EFOSC, one has to remember that there is no slit viewer. The positioning of the object on the slit has to be done via direct imaging and calculating the offsets with IHAP batches. Depending on the accuracy of the positioning, this may be a time-consuming task, especially if the instrument is rotated.

2.3 EMMI

The *ESO Multi Mode Instrument* at the NTT has a similar concept as EFOSC. In addition to grisms also gratings are available where the observer may change remotely the central wavelength in the course of the night. A dichroid allows simultaneous observations in the Blue and Red Channel. As for EFOSC, also EMMI needs a rather narrow slit in order to exploit the full spectral resolution.

The difference between EMMI and EFOSC becomes important mainly in terms of spectral resolution: with an integration time of 1 hour spectral information down to a surface brightness level of about $\mu_B \approx 21$ mag arcsec^{-2} was reached, with both the 3.6-m and the NTT, but in the case of EFOSC the instrumental dispersion was $\sigma_{inst} \approx 150$ km s^{-1} while with EMMI $\sigma_{inst} \approx 20$ km s^{-1} was obtained. For a similar surface brightness level, two hours of integration time at the 1.52-m telescope were needed ($\sigma_{inst} \approx 45$ km s^{-1}) using an RCA CCD as detector. This demonstrates that the Boller & Chivens at the 1.52-m telescope is for many applications a serious alternative to other instruments, particularly to EFOSC2 at the 2.2-m. The strong points of EFOSC and EMMI are their high spatial resolution and their efficiency in reaching faint surface brightness levels.

Since at the NTT the instrument adapter follows the field rotation, the amount of instrumental flexure present in the spectra depends on the length of the exposure time and of the position of the object on the sky. After a 2.5-hour integration a shift of about 0.4 pixels was measured. This amount of shift can, however, be easily corrected by taking arc spectra before and after the object spectrum.

2.4 CASPEC

An interesting alternative for high-resolution long-slit spectroscopy to the above cited instruments is the *ESO Cassegrain Echelle Spectrograph* at the 3.6-m telescope. A description of the latest upgrade is given by Pasquini and Gilliotte (1991). By replacing the cross disperser with a flat mirror in combination with an interference filter an about 50 Å wide region can be isolated allowing a spatial coverage of about 2.4 arcmin. In the present configuration several interference filters are available for the Hα, [O III] (λ5007 Å) and [O II] (λλ3727-29 Å) regions at various redshifts.

In principle one can use CASPEC also in its standard configuration if the interorder spacing (ranging from 5 to 19 arcsec as a function of wavelength) is sufficient for the required spatial extension. However, regarding throughput, the cross disperser is certainly less efficient than the flat mirror in the long-slit mode.

One may consider CASPEC about a factor 2.5 less efficient than the Boller & Chivens with an optimal 600 groves mm^{-1} grating in a comparable wavelength region and with comparable detectors.

3. Detectors

The detector is one of the decisive factors in determining not only the spectral and spatial resolution and coverage but also the total efficiency of the instrument. A certain limitation of the overall performance were the RCA CCDs with their rather high read-out noise (typically between 40 and 60 e$^-$) and often bad cosmetics. This forced the user to maximize the integration time which on the other hand produced an excessive number of cosmic-ray hits on the CCD. The removal of cosmic rays without modifying the underlying spectrum is not always an easy task, especially in the area of the object image. The safest approach consists in splitting the total exposure time in several shorter exposures. Then, one can rather easily remove cosmic-ray events by comparing intensities on a pixel-to-pixel basis. Here the change to the low read-out noise CCDs (like e.g. the Ford/Aerospace, Thomson and Tektronix CCDs which are available now at La Silla) improves the situation.

But one has to pay attention that in particular the FA and Th CCDs have a much lower relative quantum efficiency than the RCA and Tek CCDs. An RCA CCD has typically a peak RQE of about 75% while the FA and Th CCD have only about 45% relative quantum efficiency. The difference becomes dramatic especially in the wavelength region λλ4000 – 5000 Å where it goes up to ΔRQE ≈ 50%. Therefore, in order to use a given instrument/detector combination at its maximum efficiency, one should compute beforehand whether the observations are going to be sky or noise limited.

The fact that the CCDs become progressively larger has on the one hand the obvious advantages in terms of larger wavelength coverage and gain in spectral resolution, which may improve also the efficiency of spending observing time. But on the other hand one has to realize that in the present configuration of the data-acquisition systems at La Silla a certain limit of data-processing capability has been reached or even exceeded. The HP-based computers are e.g. not capable to handle the full 2048 × 2048 pixel array data of the FA CCD. It has also to be taken in consideration that the read-out of a 1700 × 1700 pixel window, which is the maximum possible, takes about 3 minutes. Therefore the observer is well advised to select a read-out window as small as possible for his purpose in order not to lose too much time in read-out and handling of the images.

4. Concluding Remarks

In the previous sections, emphasis was given on instrumentational aspects for obtaining science data. But there are several additional points which, already at the moment of the observation, influence the quality of the results obtainable from the data reduction.

4.1 Sky subtraction

The subtraction of the night sky from spectra of extended sources is very crucial, in particular for absorption-line measurements. Ideally one would record the sky "on-line" together with the object spectrum on the same exposure, provided that the slit length is sufficient to have a region where the contribution of the object light is negligible. Due to the relatively small field at the 3.6-m telescope (about 3 arcmin), problems with the sky subtraction may arise very easily, especially if the angular extent of the object exceeds 60 arcsec and deep spectra want to be obtained. A rather reliable solution to this problem proved to be bracketing the object exposure by two exposures of a blank sky region having a comparable exposure time.

4.2 Comparison spectra

Good arc spectra are also an important factor in obtaining high-quality data. In the case of the Boller & Chivens spectrographs traditionally He/Ar lamps are used, which provide an arc spectrum with satisfactory S/N ratio even with short exposures (typically ≤120 seconds). At EFOSC and EMMI the situation is somewhat different: in particular in the case of EFOSC1 where the light of the calibration lamps is projected at a large distance from the lamps, the resulting arc spectrum is quite faint. At EFOSC2 and EMMI the results are better, but compared to the Boller & Chivens generally longer integration times are needed (up to 500 seconds) in order to arrive at an adequate intensity level. There is also the problem that in the wavelength region λλ5000 – 6000 Å there are only few Ar lines which, furthermore, are also faint, whereas the He lines easily saturate even with a 1-second exposure. In the case of EMMI the Th lamp proved to be more useful in this wavelength region. In addition the arc spectra are often contaminated by internal reflections ("ghosts"). But in general an accurate solution for the wavelength calibration up to about 0.1 pixel could always be achieved. In the context of the accuracy of the wavelength calibration also the instrumental flexure is an important factor as discussed before.

4.3 Selecting the "right" instrument

Apart from the purely instrumental questions, another important criterion for selecting a certain telescope/instrument combination is the operating efficiency of a given system. Depending on the configuration there may be a considerable time overhead in preparing and processing the exposures. There are no major differences in the operation of the different telescopes. All the four telescopes in question have a sufficiently accurate pointing that the object will be found in the central region of the field. Apart from the 1.52-m telescope, there are also similar procedures to determine and control the telescope focus. In many applications of long-slit spectroscopy it is necessary to rotate the instrument. A remote control of the rotator is available only at the 3.6-m telescope and the NTT. At the 2.2-m and 1.52-m telescopes the rotation of the instrument requires a manual action at the telescope which can be carried out in most cases only if the telescope has been put to the zenith. The 1.52-m telescope has no autoguider unit which may be a certain disadvantage for long exposure times although the tracking is generally very good.

The Boller & Chivens, CASPEC and EMMI have a slit viewer allowing a direct positioning of the object on the slit. In the case of EFOSC the positioning has to be done via offsets calculated from direct images.

Regarding the instrument control and data-acquisition system, the operation of EMMI is certainly the most time-consuming one. One needs on the average about 5 minutes to handle an exposure which compares to about 2 minutes with other instruments.

For most "standard" observations the Boller & Chivens spectrograph at the 1.52-m telescope may turn out to be all in all the more efficient instrument, since, altogether, there is much less time overhead due to positioning the object on the slit, instrument rotation, obtaining the arc spectra, read-out time of the CCD, etc. This becomes particularly important when the science exposure times are short (typically <1 hour). In addition, the newly available FA CCD at the 1.52-m telescope allows to cover a wavelength range of up to 2048 Å with a sampling of 1 Å pixel^{-1}. For high-resolution work at faint surface brightness levels, on the contrary, EMMI is clearly the most adapted instrument.

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References

ESO CCD Manual, 3rd edition (La Silla, May 1991).

ESO Operating Manual, No. **2:** The Boller & Chivens spectrographs (1989). No. **4:** EFOSC (1989). No. **9:** CASPEC (1989). No. **14:** EMMI (draft 1991).

Melnick, J., EFOSC2: Notes for observers (La Silla, April 1991). EMMI: Notes for observers (La Silla, Sept. 1991).

Pasquini, L. and Gilliotte, A., *The Messenger*, **65,** 50 (1991).