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The Coudé Echelle Spectrograph for the Xinglong 2.16 m Telescope

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Abstract A brief description of the NAO coudé echelle spectrograph mounted on the 2.16 m telescope at Xinglong station is given. This echelle spectrograph is located at the coudé focus with a prism cross disperser. The echelle image covers the spectral region from 330 to 1100 nm displayed in 80 spectral orders in one exposure through two light beams. With a slit height of 2 mm, spectral orders are separated by 15 to 23 pixels in blue region and by 7 to 19 pixels in red region. Alternatively, two additional resolution modes corresponding to different focal length cameras with resolving power $R = 16\,000$, $170\,000$ in the blue beam and $R = 13\,000$, $170\,000$ in the red beam could be provided by this spectrograph. The bias, dark, wavelength calibration, flat field and science exposure are described in details. The limiting magnitude for 1 hour exposure with an S/N ratio of 100 scales to $V = 9.5$ in the red path and to $V = 7.2$ in the blue path.

Key words: instrumentation: spectrographs — methods: observational – techniques: spectroscopic

1 INTRODUCTION

Advances in stellar astronomy depend on the available spectroscopic information, and hence on the performance of the spectrograph. In order to obtain high resolution spectra, a coudé focus is usually designed in most modern large telescopes which can provide information of stellar abundance and chemical evolution of galaxies. With dramatic development of the modern electronic detector, cross-dispersed echelle spectrographs can image the whole visible spectra with high resolution on a single CCD chip.

Echelle spectrographs provide a considerable multiplex advantage allowing the recording of a much larger portion of the spectrum than usually obtainable from normal grating spectrographs. This is particularly important whenever the emphasis is on spectral coverage. The most important difference with respect to a normal grating spectrograph is the comparatively high limiting spectral resolving power $R = m\,N$ due to observation in high spectral orders m of the echelle grating. Since in most applications the resolution is defined by an entrance slit,

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the advantage of an echelle against a low-order grating is made even greater. Typical gains in spectral resolution are a factor of five with the same entrance slit. Conversely, the entrance slit of an echelle spectrograph may be widened by a corresponding factor as compared to that of a low-order grating spectrograph to observe with the same resolution. Echelle spectrographs also have a considerably larger angular dispersion which allows the use of shorter cameras and hence a more compact design. Using an appropriate cross-disperser the format of CCD is particularly suitable to receive a large number of spectral orders, thus taking full multiplex advantage.

The echelle grating reflects the light of many orders in the same direction. To avoid mutual contamination of spectral features the orders are additionally dispersed by a prism or low-order grating in a perpendicular direction to that of the echelle dispersion. The resulting images of the entrance slit form a set of approximately parallel but slightly curved orders that can be exposed to a 2D detector such as CCD. The formats depend on whether a prism or a grating is used for the cross-dispersion.

In this paper we give a full description of the standard configuration of our spectrograph in Sect. 2, which includes the optical layout, and the electronic and mechanical systems. In Sect. 3 we give the spectral coverage and resolution of the spectrograph. In Sect. 4 we present the TV acquisition and guiding. In Sect. 5 we describe the various calibration exposures including bias, dark, wavelength calibration and flat-fields. The science exposure guide and limiting magnitude are presented in Sect. 6, and interference fringes are briefly discussed in the last Sect.

2 THE STANDARD CONFIGURATION

The Coudé Echelle Spectrograph of the National Astronomical Observatories (hereafter NAO) is used at the coudé focus of the 2.16 m telescope. The layout of the spectrograph optics is presented in Figure 1a–c. In the standard configuration the light is split by a dichroic filter at 15 degree angle face to incoming light with central wavelength 550 nm. This dichroic filter allows light longer than 550 nm to pass through the red collimator, and light shorter than 550 nm to be reflected to a small reflector, and then fed to the blue collimator. This is why it is also called a double beam echelle spectrograph. For the blue beam, the light is dispersed by a R2 echelle grating, size 256×128 mm and ruling density of 79 gr/mm, and is cross-dispersed by a mosaic of a 60 degree UBK7 prism. For the red beam, the light is dispersed by a R2 echelle grating with ruling density 31.6 gr/mm, and is cross-dispersed by a 60 degree ZF3 prism. These prisms separate the echelle orders and provide a convenient two dimensional format.

In normal setting, we use a middle focal length camera which gives a resolution of 44 000 for the blue beam with a focal length of 640 mm and of 37 000 for the red beam with a focal length of 550 mm. It is off axis fold Schmidt type free of any central obstruction. As alternatives to the middle focal length camera, a long and a short focal length camera can be mounted on the coudé echelle spectrograph. For the red path, the long focal length camera ($F = 2\,500$ mm) gives a resolution of 170 000 and the short focal length camera ($F = 190$ mm) gives a resolution of 8 200. For the blue path, the long focal length camera ($F = 2\,500$ mm) gives a resolution of 170 000 and the short focal length camera ($F = 237$ mm), one of 12 000. However, the high resolution mode can be fully achieved only with a very narrow entrance slit corresponding to $0.2''$ on the sky. It is worth pointing out that the presently used CCD is not large enough to give a continuous spectral coverage (order overlap) for wavelengths longer than about 790 nm with the 31.6 gr/mm echelle and no continuous spectral coverage at all with the 79 gr/mm echelle.

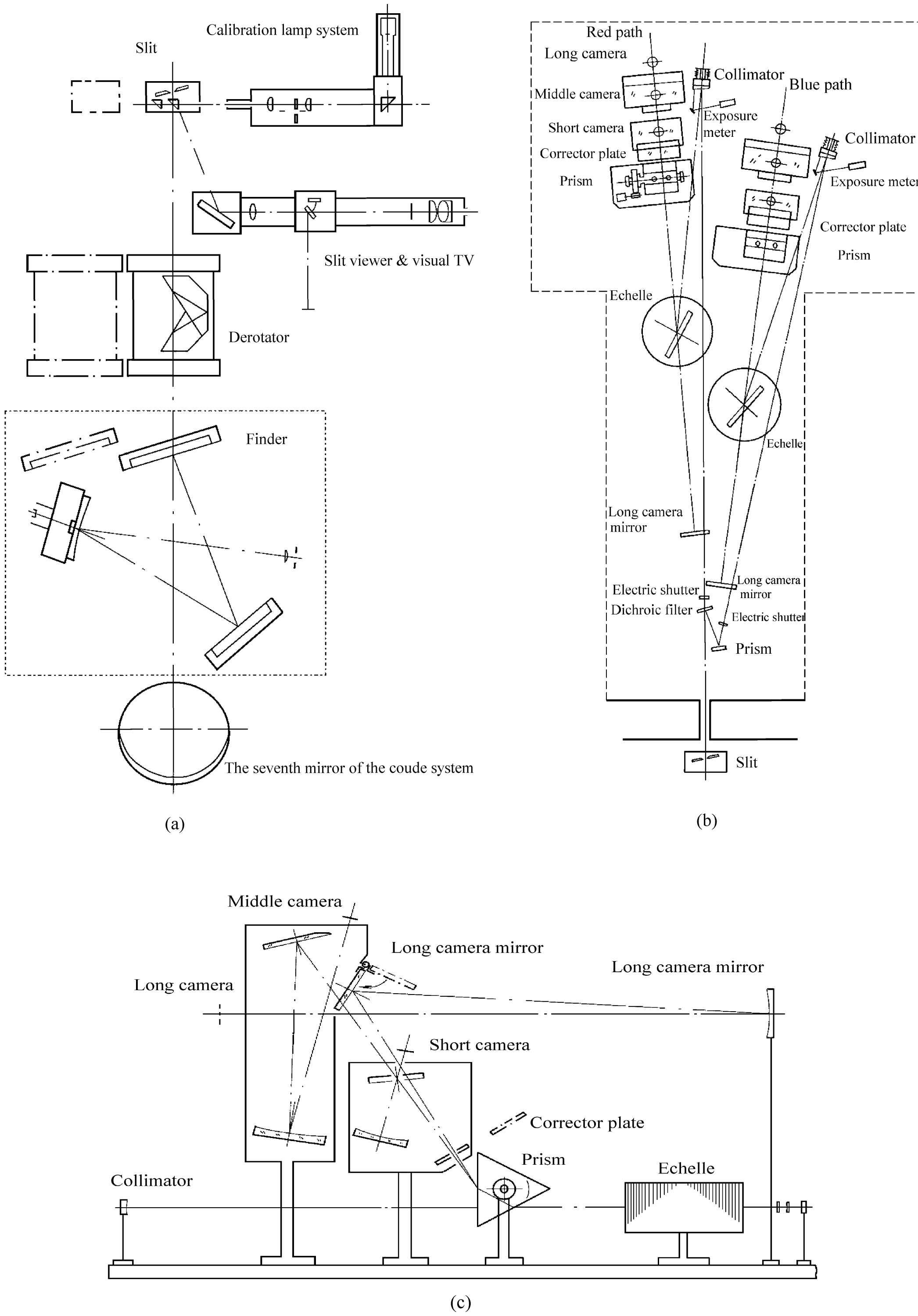

Fig. 1 Optical layout of the NAO coudé echelle spectrograph (a) top view of NAOCES optical layout before slit; (b) top view of NAOCES optical layout after slit; (c) side view of NAOCES optical layout after slit.

The detector we use is a TEK thinned back illuminated blue enhanced CCD, with 1024×1024 pixels of $24 \times 24\ \mu m^2$. The read-out noise is about $13e^-$ per pixel. The charge transfer efficiency is good. Fringing due to internal interference in the CCD is present, and is increasingly important towards the red part of the spectrum. The quantum efficiency of the CCD is given in Figure 2. Note that the sensitivity drops by a factor of four from the peak efficiency for wavelengths shorter than 400nm. The CCD saturation level amounts to 64000 ADUs.

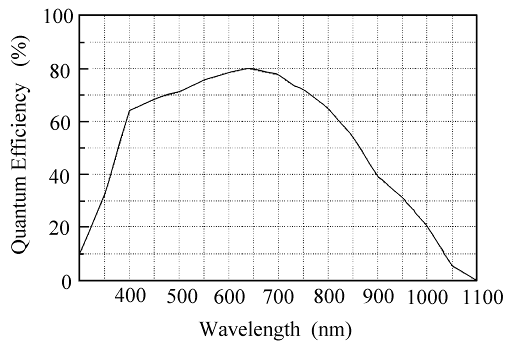

Fig. 2 Quantum efficiency of NAOCES TEK CCD as function of wavelength.

We summarize the specifications of the coudé echelle spectrograph in Table 1. More detailed descriptions of this instrument in technical aspects can be found in the paper of Jiang (1996).

3 SPECTRAL COVERAGE AND RESOLUTION

The wavelength coverage was designed to record the range from 330 to 1100 nm in one exposure through two light beams, e.g., from 330 to 580 nm for the blue beam and from 520 to 1100 nm for the red beam. But in normal setup, we use a TEK CCD of 1024×1024 pixels with $24 \times 24\ \mu m^2$ each in size which can only work from order 39 to 67, or from 580 to 335 nm, in the cross dispersion direction for the blue beam, and from order 60 to 95, or 945 to 585 nm, for the red beam.

The present detector is not large enough to cover the whole spectral range through either the blue path or the red path. In order to get the whole spectrum over the whole visible wavelength range, one has to take four CCD frames with different spectral coverages in the blue path, and two in the red path. The blue spectrum covers the range of 380–580 nm after merging the spectra of all orders from the four different frames. The red spectrum covers the range of 560–930 nm after merging from the two different frames. Normally, 19–30 orders can be extracted from one frame depending on the location of the orders on the CCD chip. The wavelength coverage is about 50 Å per order at λ380 nm and 125 Å per order at λ930 nm.

It is important to keep sufficient space between the echelle orders to permit an accurate determination of the inter order, scattered light and background, and to facilitate the data reduction. The spectral orders are separated by 15 to 23 pixels in the blue frame and by 7 to 19 pixels in the red frame.

4 TV ACQUISITION AND GUIDING

The front of the spectrograph slit is aluminised and tilted slightly with respect to the incoming beam to allow the use of an integrating TV acquisition and guiding system. Stars with $V \leq 12$ mag can be seen on the screen of the monitor in the control room. There is also a "field viewing" position (approximate field $5' \times 4'$) for object acquisition. But the finding mirror has to be operated by hand. Note that these are approximate magnitudes and critically depend on focusing, seeing, etc.

5 CALIBRATION EXPOSURES

Only well calibrated spectroscopy is useful for subsequent analysis, and the calibration includes both intensity and wavelength calibration, and it requires a considerable overhead of reference data. Calibration includes bias frames, dark current exposures, flat-field exposures of different types, and wavelength calibration using emission line spectra of laboratory sources or high-precision absorption features.

5.1 Bias and Dark Exposure

Several zero second dark exposures can be averaged and subtracted from the science images to remove the electronic bias (∼50–100 ADUs depends on the room temperature). Dark exposures of the same length as the object exposures should be used to subtract average dark current effects and to check for possible parasitic light in the spectrograph. The dark current of the CCD is $16\,e^{-}\mathrm{pixel}^{-1}\,\mathrm{h}^{-1}$. Furthermore, there is a small amount of diffused light exists between the orders of the spectrograph as inter-order background. Thus, bias, dark current and inter-order background light must all be removed from the science exposure in the data reduction.

5.2 Wavelength Calibration

Most of the former laboratory sources have been removed in favour of Th-Ar or Th-Ne lamps since thorium is shown to have a very dense emission line spectrum that covers the whole visible spectral region. It is carried by inert gases which, themselves, show some strong emission lines.

The NAO coudé echelle spectrograph is equipped with a Th-Ar and a Fe calibration lamp. One of the first things you have to do before your first observing night is to check the wavelength coverage you intend to take. A high signal-to-noise ratio Th-Ar or Fe spectrum is necessary for a good wavelength calibration. In normal setup, Th-Ar lamp is the default setting. The exposure time can be given for the calibration lamp at a certain slit width. The exposure time of 10–15 seconds for the blue path and of 5–8 seconds for the red path are recommended with a slit width of 0.5 mm. If the CCD is saturated with strong Th lines, a remnant charge may be present at the position of these lines. Wait a few minutes and then do a short dark. This will normally remove the remnants.

5.3 Flat-fields

Flat-field exposures are important for data extraction, and are used to remove the CCD pixel response. Order flat-field exposures produce a spectrograph slit image in much the same way as those of astronomical objects. Consequently, the order flat-field can be used to detect the order positions on the CCD if there is no change of the cross-disperser settings between the object and flat-field exposure.

Flat-field exposures for spectrographic slit images can be of different kinds. Normally, such exposures follow the same light path as the astronomical source producing the same type of spectral orders on a 2D detector such as CCD. If the slit height used for such a flat-field is the same as that of the object exposure, a pixel-by-pixel flat-field correction will result in high noise for near-background pixels. Therefore the order spectra are often extracted and the corresponding 1D spectra are used for flat-field calibration. This approach is only approximate, and often the flat-field slit height is increased with respect to that of the object exposure. Such a procedure results in lower noise but a different geometry of the light sources.

Flat-fields can be obtained with internal or external lamps of the coudé echelle spectrograph. There is no agreement on the way to obtain the best flat-fields, experience has shown that flat-fields using a white screen inside the dome illuminated by several halogen lamps have good uniformity. The exposure time depends on the light intensity and slit width. The best exposure times are those which give approximately the same number of counts as obtained in the science exposures. If this is not known beforehand, it may be advisable to take several sequences of flat fields with different exposure levels. Furthermore, a series of flat fields should normally be taken to reduce the noise by averaging.

An exposure time of 30 minutes gives a flat-field level of 500 ADUs at 450 nm with a background level of 125 ADUs at inter-orders. A level of 2000 AUDs are obtained after 400 seconds at 600 nm. In special cases, such as when removing the interference fringes, a stellar flat field may be preferable. The star used for that purpose (fast rotating, type O – B) should be guided at the same position of the slit as the program objects, in order to illuminate the same pixels on the CCD. Due to the high stability of the coudé echelle spectrograph mount, it is normally sufficient to do wavelength calibration and flat fields at the beginning and end of the observations for the same wavelength range used. Switching between science and calibration exposures is done by moving a small mirror in front of the entrance slit.

6 SCIENCE EXPOSURE GUIDE AND LIMITING MAGNITUDE

Here, we provide some rough guidelines from which it should be possible to estimate approximate exposure times for science objects by taking into consideration the different grating efficiencies, CCD detector quantum efficiencies etc. The expected S/N ratio obtained by a CCD with a finite read-out-noise and dark current, is

$$S/N = \frac{3600 n_0 t \times 10^{-0.4(m-m_0)}}{(3600 n_0 t \times 10^{-0.4(m-m_0)} + (w b^{-1} N_r)^2 + w^2 t D)^{0.5}} ,$$

where

$$\begin{aligned}
n_0 &= \text{efficiency in } \mathrm{e^{-} s^{-1}\, pixel^{-1}} \text{ for a star of magnitude, } \mathrm{m_0} \\
w &= \text{width of the spectrum in pixels, perpendicular to dispersion} \\
N_r &= \text{read-out-noise in } \mathrm{e^{-} pixel^{-1}} \\
D &= \text{dark current in } \mathrm{e^{-} pixel^{-1}\, h^{-1}} \\
t &= \text{exposure time in hours} \\
b &= \text{binning factor perpendicular to the dispersion direction} \\
m &= \text{stellar magnitude} .
\end{aligned}$$

The expected growth of S/N ratio as a function of V magnitude and exposure time can be calculated based on the formula above. For middle focus set-up, Figure 3 gives the expected S/N ratio at a wavelength of 450 nm as a function of exposure time for stars with different magnitudes using the blue path. Similarly, Figure 4 shows the same at a wavelength of 600nm using the red path. These curves serve only to give an approximate guide to what may be expected. In addition, a few observational data points with slit height of 2 mm are plotted in Fig. 3 and Fig. 4. In practice, one can sum the pixel values of object light perpendicular to the dispersion direction (around 10–14 pixels depends slit height and seeing condition) at any interested wavelength on the order. The approximate S/N ratio is equivalent to

$$\Big(\sum_i 7.15(\text{signal} - \text{background})\Big)^{0.5},$$

where the unit of signal and background is ADU.

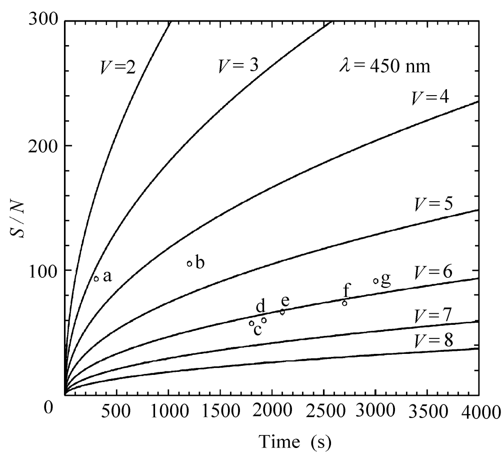

Fig. 3 Expected S/N at 450 nm as a function of exposure time for stars of different magnitudes. Circles represent the observational data. The name and visual magnitude of the labelled stars are: a— HD155763, $m_v = 3.17$; b— HD144206, $m_v = 4.71$; c— HD71148, $m_v = 6.32$; d— HD127334, $m_v = 6.38$; e— HD110897, $m_v = 6.00$; f— HD71148, $m_v = 6.32$; g— HD99747, $m_v = 5.80$.

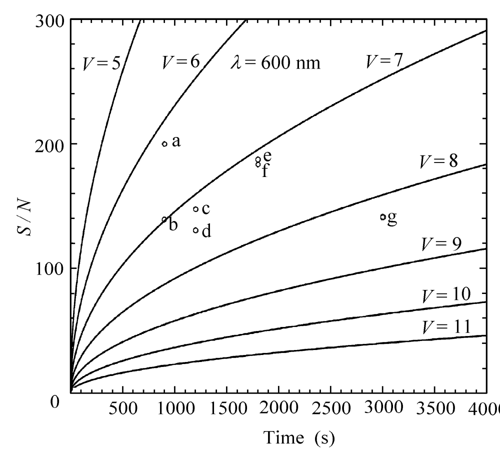

Fig. 4 Expected S/N at 600 nm as a function of exposure time for stars with different magnitudes. Circles represents the observational data. The labelled stars are: a— HD7351, $m_v = 6.33$; b— HD223617, $m_v = 6.96$; c— HD178717, $m_v = 7.18$; d— HD170970, $m_v = 7.42$; e— HD178717, $m_v = 7.18$; f— HD200063, $m_v = 7.28$; g— HD22694, $m_v = 8.24$.

The accuracy of the spectral data may be estimated by comparing them with some completely independent measurements from different spectrographs. The comparison between the high resolution spectrum of Sirius taken from the NAO coudé echelle spectrograph by Zhao et al. (2000) and the Kurucz & Furenlid (1979) atlas used by Sadakane & Ueta (1989), which covers the wavelength region between 353 and 441 nm at a dispersion of 0.11 nm mm^{-1}, shows a very good agreement between the two sources of data, with a marginal tendency for the equivalent widths of Sadakane & Ueta to be somewhat ($\sim 3\%$) smaller. A detailed description of the comparison can be found in Zhao et al. (2000).

7 INTERFERENCE FRINGES

Fringes are produced by interference effects between the silicon substrate within the CCD. The fringe pattern depends on the CCD type, the quality of the chip, and the wavelength range illuminated. Fringes also appear in flat field exposure. They are most prominent towards the red and are almost negligible in the blue. The effectiveness of fringe removal depends upon the reduction method used, such as flat field or fast rotating stars. The fringes in the red can, in general, be corrected with an accuracy of better than 3% when appropriate methods are used.

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