*Bull. Spec. Astrophys. Obs.*, 1998, 44, 127–131

# On the problem of high spectral resolution observations of faint objects

**V.E. Panchuk, I.D. Najdenov, V.G. Klochkova, A.B. Ivanchik, S.V. Yermakov, V.A. Murzin**

Special Astrophysical Observatory of the Russian AS, Nizhnij Arkhyz 357147, Russia

*Received December 8, 1997; accepted December 21, 1997.*

**Abstract.** Advantages are briefly discussed of gaining in spectral resolution, which is accompanied by losses in signal level, as compared with the attempts to improve the accuracy of measurement of line parameters by means of rising the S/N ratio alone with increasing the exposure time. To partially solve the problem of observations of faint objects at the BTA a new design echelle spectrometer is proposed.

**Key words:** high resolution spectroscopy

## 1. Introduction

In comparison with spectroscopy of extended extragalactic objects, the task of observing stars with a high spectral resolution is traditionally given lower priority. The reason is fundamental: in spectroscopy of extended objects the limiting magnitude is proportional to the squared telescope mirror diameter, whereas in high spectral resolution spectroscopy of stars (i.e. when the angular diameter of the turbulent disk of a star is larger than the spectrograph slit width) the limiting magnitude is proportional to the telescope mirror diameter. A "natural" response of some researchers of stars and starlike objects is preferential use of low and moderate spectral resolution techniques, where one succeeds in minimizing losses at the spectrograph input. However, over the last decade new problems of spectroscopy of cool stars, interstellar and intergalactic medium, mapping of stars' surfaces, search for low–mass companion stars have been posed and being solved. All these problems are limiting for large telescopes, that is why the development of high–resolution spectroscopy facilities at large telescopes is of great concern. Suffice it document to mention that the first device put into operation at the 10 m Keck telescope is the high–resolution echelle spectrograph HIRES (Fogt et al., 1994). In order to show how the achievements in technology of manufacturing solid–state light detectors and the development of cross–dispersion spectral systems alter psychology of a spectroscopist, we now present some considerations on the relationship of principal characteristics determined in the process of observations.

## 2. Optimization of spectroscopic observations

Let us first find out which way — rise in spectral resolution with some loss in the S/N ratio or increase in the S/N ratio with a fixed spectral resolution — is better for the purpose of reduction of equivalent width determination errors.

We will use the following designations and relations:

$\lambda$ - wavelength in Å,
$\Delta S$ — instrumental function width of the spectrograph in Å,
$R = \lambda/\Delta S$ — spectral resolution of the device,
N — number of counts for 1 Å per 1 s at the continuous spectrum level,
t — exposure time in seconds,
Nt — number of counts per 1 Å at the continuous spectrum level,
$\Delta A$ — pixel size in Å,
$Nt\Delta A$ — number of counts per pixel,
$\Delta\lambda$ — line half-width at half intensity,
r — line depth resolved by the spectrograph,
$Ntr\Delta\lambda$ — line equivalent width,
e — sum of read–out noise and dark count per 1 pixel,
$(Nt\Delta A + e^2)^{1/2}$ — statistical error of measurement of the number of counts per each pixel.

Consider three versions of the relation between the characteristics of the device of the light detector and the spectral line parameters.

Case A: ($\Delta A > 2\Delta\lambda$ and $\Delta A > \Delta S$). Let the width of the pixel $\Delta A$ exceed the line width $2\Delta\lambda$ and the instrumental function width $\Delta S$. The relative line intensity is then measured as the ratio of the number of counts in the pixel falling at the given line to the number of counts in the adjacent pixel falling at the continuous spectrum. Since the equivalent width equals $\mathrm{Nt}r\Delta\lambda$, the relative measurement error of equivalent width measurement in the case of unresolved line is proportional to $(r\Delta\lambda)^{-1}\left[\Delta A(\mathrm{Nt})^{-1}+e^2(\mathrm{Nt})^{-2}\right]^{1/2}$. If the number of counts per 1 Å is such that $\Delta A \gg e^2/\mathrm{Nt}$, then the equivalent width measurement error is proportional to $(r\Delta\lambda)^{-1}\left[\Delta A(\mathrm{Nt})^{-1}\right]^{1/2}$. Thus if the spectral resolution is managed to be increased (i.e. to decrease $\Delta A$) without loss in the number of counts falling at 1 Å, the equivalent width measurement error is then proportional to $R^{-1/2}$. This holds for case "B": ($\Delta A > 2\Delta\lambda$ and $\Delta S > \Delta A$), which is a condition satisfied most frequently at large diameter telescopes.

Case "C" ($\Delta A < 2\Delta\lambda$ and $\Delta S > \Delta A$). The pixel width $\Delta A$ is smaller than the line width $2\Delta\lambda$ and less than or equal to the instrumental function width $\Delta S$. For simplicity, take the line profile to be of triangular shape. Then in comparison with case "A" the relative equivalent width measurement error will increase by the multiplicand $(2\Delta\lambda/\Delta A)^{1/2}$, i.e. it is now proportional to $(\Delta\lambda/2)^{-1/2}r^{-1}\left[(\mathrm{Nt})^{-1}+e^2/\Delta A(\mathrm{Nt})^2\right]^{1/2}$. For low read-out levels, i.e. at $e^2 < \mathrm{Nt}\Delta A$, the equivalent width determination error does not already depend on $\Delta A$, while at a low signal level, $e^2 > \mathrm{Nt}\Delta A$, the error increases with decreasing $\Delta A$. Thus for the low S/N ratio spectra it makes no special sense to realize case "C".

So, in order to improve the equivalent width measurement accuracy it is more advantageous to increase the spectral resolution until the signal level is equal to read-out noise instead of increasing the exposure time at a specified spectral resolution. It goes without saying that the limit at which further increase in spectral resolution becomes unprofitable — for different groups of astrophysical objects with comparable $\Delta\lambda$ and for different characteristics of the detector (read-out noise and linear pixel-size) — is at different R values. Hence it follows that a large telescope needs to be equipped with several spectral devices differing in $R = \lambda/2\Delta A$. We illustrate this statement in Fig.1.

Here on a logarithmic scale the spectral resolution estimated for the condition $\Delta S = 2\Delta A$ is laid off as abscissa, the number of counts per 1 Å is plotted as ordinate. The inclined lines show the conditions $\Delta A = e^2/\mathrm{Nt}$ satisfied for two types of the first home-made CCDs used in our observations — one of 580 × 530 pixels with a read-out noise of $26e^-$ and the other of 1160 × 1040 with a $6.5e^-$ read-out noise. The vertical arrows indicate the R values corresponding to different devices placed at the Nasmyth 2 focus (Z – the moderate resolution echelle spectrograph (Klochkova and Panchuk, 1991), M – the Main Stellar Spectrograph, the Schmidt camera of 1:2.5 with a CCD (Panchuk, 1995), L — high resolution echelle

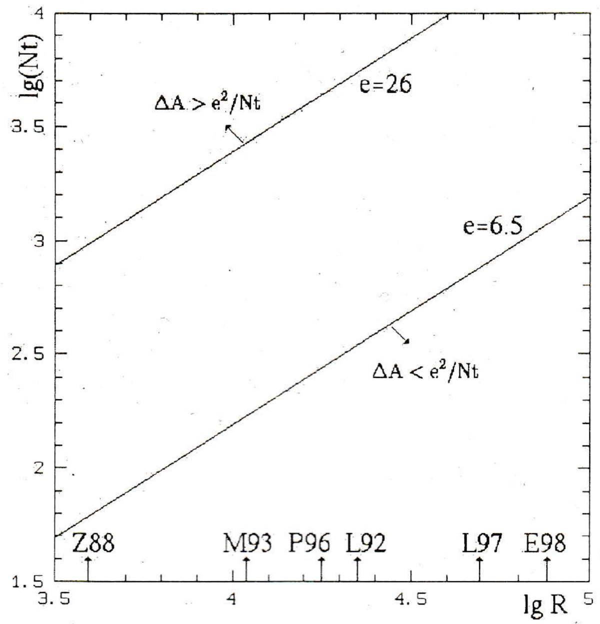


Figure 1: *To the choice of optimum spectral resolution (for designations see the text)*

spectrograph (two modifications — Panchuk et al., 1993; Klochkova, 1995). For convenience of comparing different systems we assumed everywhere a two-pixel resolution at the wavelength of 5500 Å, this is actually the upper estimate of R. The values of R do not pretend to be accurate here, since Fig. 1 is intended to illustrate the idea but not accurate estimates. The parameters of an echelle spectrograph with a large collimated beam diameter (E) manufactured in 1997 and the parameters of the prime focus echelle spectrograph (P) are also noted. The numbers in these notations indicate the year of introduction of this type of observations. The upper left corner of Fig. 1 corresponds to the region where the equivalent width determination error for the CCD of 530 × 580 is no longer dependent on $\Delta A$, i.e. it makes sense to increase the spectral resolution in this region. For the 1040 × 1160 CCD the similar region takes up a greater part of the figure, and only in the lower right corner at given levels of the signal Nt accumulated in the band 1 Å wide it makes no sense to increase spectral resolution. So, in the optimization of spectrum line measurement the parameters of the CCDs and those of the spectrographs possess equal rights, and as the read-out noise of the CCDs approaches a physical limit, the problem of reasonable (remaining in the frames of case "B") decreasing of $\Delta A$ (i.e. increasing R) will be of paramount importance.

## 3. The prime focus echelle spectrograph and the MSS

For high spectral resolution observations the devices permanently located at the N2 focus of the BTA are used (Klochkova, 1995, Panchuk, 1995). However for a number of tasks to be performed, it is needed to rule out the influence of the second and third mirrors, i.e. to realize the high spectral resolution (R ~ 20000) directly at the prime focus. Refer to the first group of such tasks, for instance, the observations of absorption spectra of quasars with V > 15 – 16, when the S/N ratio at an hour exposure is rarely higher than S/N=5. The observations of brighter objects at short (comparable with the signal read–out time) exposures, for instance, the observations of supershort–period ($P \sim 1^h$) cepheids of SX Phenix type at different pulsation phases or the observations of fast rotators with a spectrophotometrically inhomogeneous surface, refer to the second group. To the third group belong the spectropolarimetric observations for which a contribution of instrumental polarization on the third (flat) mirror of the BTA is important. In all these cases the gain due to the elimination of losses of light at the second and third mirrors and instrumental polarization at the third mirror is of principle importance. As compared to the Nasmyth–2 focus echelle spectrometers, the placement of the echelle spectrometer at the prime focus ensures a 1.4–fold minimum gain in light by removing the second and third mirrors from the optical path (the reflection coefficient of a fresh aluminium coating is taken equal to 0.85).

Examine the principal parameters of the PF echelle spectrometer, which is equivalent in spectral resolution to the CCD–equipped MSS (Panchuk, 1995). The spectral resolution is proportional to the product of the tangent of the diffraction grating blaze angle $tg\Theta_b$ and the collimated beam diameter $d_{coll}$. The diffraction grating employed in quasar observations with the MSS has $tg\Theta_b = 0.47$ with a collimated beam of $d_{coll} = 258$ mm. Hence we obtain that the use of the classical echelle with $\Theta_b = 63.5°$ reduces by nearly a factor of 5 the diameter of the collimated beam of the echelle spectrograph of the same resolution. Such a spectrograph will have the overall dimensions allowing it to be operated in the prime focus cage. Therefore, if the throughout of this echelle spectrometer at the prime focus compares favourably with that of the MSS at the N2, the manufacture of such an apparatus is worthwhile.

## 4. The spectrograph design and the observing procedure

The choice of the spectrograph design (Fig.2) is determined by the quantity R, the overall dimensions of the PF cage and the restrictions on the rigidity of the structure of the device.

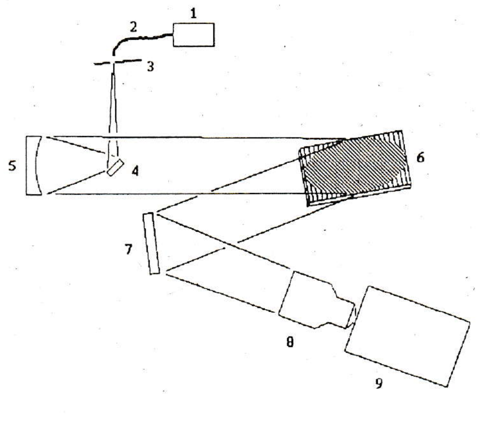


Figure 2: *A simplified scheme of the prime focus echelle spectrograph.*
*Designations: 1 – calibration spectrum sources, 2 – fiber optics, 3 – dekker, 4 – refracting mirror, 5 – collimator, 6 – echelle, 7 – grating of cross dispersion*

We have chosen $D_{coll} = 50$ mm, which at the PF relative aperture of 1:4 yields $F_{coll} = 200$ mm. The collimator is assembled according to Newton scheme, the dimensions of the flat refracting mirror are such that it falls within the central shaded part of the collimated beam. The diameter of the shaded part is determined by the relation between the main mirror diameter and the PF cage diameter. As the camera's objective a fast 4–lens aplanat is used having a focal distance $F_{cam} = 140$ mm and a relative aperture of 1:1.8, the resolution at the centre is no less than 80 gr/mm, that over the field at a distance of 3 mm from the edge along the frame (24 × 36 mm$^2$) diagonal is 35 gr/mm. These parameters allow a two–pixel resolution over the whole area of the CCD used (17 × 19 mm$^2$) to be realized. The light transmission is 0.9, the drop in illumination over the frame (24 × 36 mm$^2$) is no more than 20 %. An echelle grating of 75 gr/mm, $\Theta_b = 63.5°$, is used, the size of the shaded area is 120 × 60 mm$^2$, the concentration in the working order is 70 % in fractions of the reflected light. As a cross–dispersion element a grating of 300 gr/mm, working in the first order, is used, the size of the shaded area is 90 × 90 mm$^2$, the concentration in the working order is 90 % in fractions of the reflected light. The instrument is equipped with additional cross–dispersion gratings 600 and 1200 gr/mm. The orientation of the echelle grating conforms to case "C" according Schroeder and Hillard (1980), i.e. $\alpha = \beta$, and $\gamma = 6°$. Such a configuration permits the centres of all optical elements to be arranged in one plane. The slit part is a turrel mounting with several deckers of fixed sizes. The sizes of the working

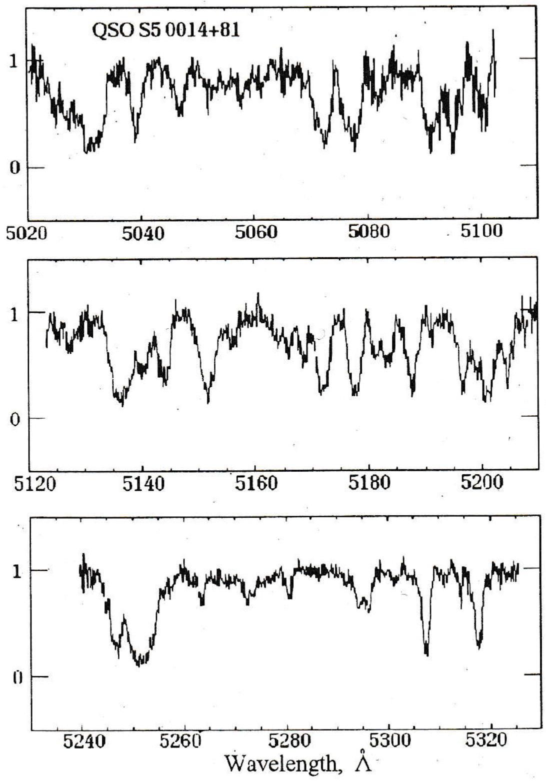


Figure 3: *Fragments of the three orders of echelle spectrum for the quasar S5 0014+81*

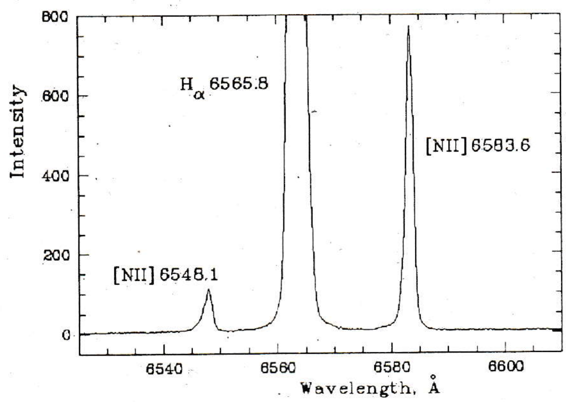


Figure 4: *Fragment of the echelle spectrum of proto-planetary nebula RAFGL 618 in* $H_\alpha$

rectangular entrance diaphragms are 4 × 0.5 arcsec and 4 × 1 arcsec. The inclination of monochromatic slit images due to the non–zero $\gamma$ angle value is made up for by changing the orientation of the decker. In the preslit part are mounted the optics of the TV guide and the optics of the calibration channel, the latter being thick fiber–optics passing radiation to the spectrograph entrance. All the optical and mechanical units are mounted on a single frame, on the opposite side of which (i.e. outside the optical part volume) the electronic units of the calibration and control systems are fixed (design and execution of V.I. Fateev). The proposed design of the spectrograph made it possible to minimize deviations of the centre of gravity of the structure, reduce its weight and use such an orientation of the CCD cryostat that enables observations at the prime focus of over 15 hours without replenishing liquid nitrogen.

The CCD system incorporates the cryostat camera and the controller unit, connected by a cable 3 m long. The controller is housed in a commercial 19–inch casing and is connected to the computer (two coaxial cables 200 m in length). The system ensures control by the CCD in the frame mode. The read–out of a frame fragment and the binning over the two coordinates are possible. The read–out time of a frame of 1050 × 1170 pixels is 101 s with a reduction rate of 12 kpixels/s. The signal reduction channel is characterized by the following parameters:
16–digit analog–to–digital conversion;
charge–code conversion coefficient — 2.3e$^-$/ADU;
read–out noise — 6.5e$^-$;
bias level — 1600 ADU;
stability of the bias level — 0.5 ADU;
integral nonlinearity of the channel — no higher than 0.05 %;
differential nonlinearity — no more than 0.5 ADU.

The image is aligned on the CCD frame as follows: 1160 work pixels are oriented along the spectral order, 1040 pixels are oriented in cross–dispersion direction. The pixel size is 16 × 16 microns. The CCD angular scale is 11.45″/mm or 0.37″/pix. With 2.5″ seeings the spectral order is 14 pixels in height, i.e. one can work with a 4–pixel binning across the main dispersion, reducing twice the caused impact by read–out noise. The spectral resolution estimated from spectra is R=20000.

Observations are performed according to usual way (calibration by continuous and line spectra, registration of the spectrum of a fast–rotating star, dark–frames) that can be modified if it is needed for a particular programme. With a properly organized sequence of observations, about 90–95 % of night time is used for signal registration. The registration of observational data is performed in the environment Nice (Knyazev and Shergin, 1994). The reduction of images is made in the MIDAS system.

## 5. Results

In Fig. 3 are shown fragments of the echelle spectra of the quasar S5 0014+81 ($m_V$ = 16.5) obtained with the PF echelle spectrograph within the frames of the programme of study of absorption spectra of bright quasars (authors of the programme are D.A. Varshalovich and A.V. Ivanchik). The total length of the echelle spectrum recorded simultaneously is about 4000 Å. To compare with the level achieved previously one can use Fig. 4 from the paper by Varshalovich et al. (1996), where a spectrum of the same object (100 Å long), recorded in the BTA MSS observations carried out under the same seeing conditions in 1994, is given. It should be noted that apart from the gain in the number of simultaneously transmitted spectrum elements under the conditions of retaining the spectral resolution, the PF echelle spectrometer increased the limiting magnitude in high spectral resolution observations of faint objects.

In Fig. 4 is presented an echelle spectrum fragment of the protoplanetary nebula RAFGL 618 (IRAS 04395+3601, $m_V = 17$), which was recorded in carrying out the programme of spectroscopy of "post-asymptotic giant branch" objects (author of the programme is V.G. Klochkova).

**Acknowledgements.** Credit for widening the scope of potentialities of the 6 m telescope in the area of high resolution spectroscopy of faint objects is due to D.A. Varshalovich. The work on the manufacture of the spectrograph is supported by the International Science Foundation (Project ISF NUO 300 and J86100) and the Federal Programme "Astronomy". The creation of the light detectors for echelle spectroscopy at the 6 m telescope is funded by SAO. The authors are grateful to Yu.N. Parijskij, D.A. Varshalovich, Yu.Yu. Balega, J.A. Stepanian for taking interest in and giving much attention to the work.

## References

Klochkova V.G., Panchuk V.E., 1991, Preprint SAO RAS, No. **70**

Klochkova V.G., 1995, High resolution echelle spectrometer (LYNX) of the 6 m telescope, user's manual, SAO report, No. **243**

Knyazev A.Yu., Shergin V.S., 1994, Operation system Linux and data reduction system MIDAS in Linux, SAO report, No. **226**

Panchuk V.E., 1995, The Main Stellar Spectrograph, Schmidt camera 1:2.5 with CCD, user's manual, SAO report, No. **245**

Panchuk V.E., Klochkova V.G., Galazutdinov G.A., Ryadchenko V.P., Chentsov E.L., 1993, Pis'ma Astron. Zh., **19**, 1061

Schroeder D.J., Hillard R.L., 1980, Applied Optics, **19**, No. 16, 2833

Varshalovich D.A., Panchuk V.E., Ivanchik A.V., 1996, Pis'ma Astron. Zh., **22**, 8

Vogt S., Allen S., Bigelow B., Bresee L., Brown B., Cantrall T., Conrad A., Couture M., Delaney C., Epps H., Hilyard D., Horn E., Jern N., Kanto D., Keane M., Kibrick R., Lewis J., Osborne C., Pardeilhan G., Pfister T., Ricketts T., Robinson L., Stover R., Tucker D., Ward J., Wei M., 1994, Proc. SPIE, **2198**, 362