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# ECHELLE SPECTROMETER OF MODERATE RESOLUTION FOR THE 6 M TELESCOPE: REDUCTION OF SPECTRA OF EXTRAGALACTIC OBJECTS

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**ABSTRACT.** *A software for processing of extragalactic object spectra, obtained with the moderate resolution echelle spectrometer "ZEBRA" of the 6 m telescope is presented. The main problems of data reduction associated with the system peculiarities, cross-correlation of spectral data, correction of nonlinearity in calculation, optimum integration of spectra are considered. The software can be used at a computer of PC AT class.*

## 1. INTRODUCTION

Solution of many problems of extragalactic astronomy is impossible without spectral devices of moderate and high resolution. The use of such instruments for investigation of faint fluxes became possible only with the appearance of modern detectors of low noise and high quantum efficiency. The employment of image tubes and TV counting systems in combination with classical spectrographs allows only partial solution of this problem: the observer has to choose between the width of a simultaneously registered spectral interval and the spectral resolution. With achievement of high spectral resolution, the problem of coordination of the slit width with the size of the detector's element grows more serious. One of the ways of solving the dilemma was the creation of echelle spectrometers allowing to comply with these requirements simultaneously (Klochkova, Panchuk, 1991).

The work at echelle spectrometers in SAO RAS was started in 1987. The first of such devices was a moderate-resolution echelle spectrometer "ZEBRA" (Gazhur et al., 1990). Being not quite suitable for the tasks of stellar astrophysics, for which it was first designed, the spectrometer remains unrivalled until now in investigation of the ultraviolet portion of radiation, excluding photographic versions of observations with the Main Stellar Spectrograph. The high transmission of the spectrometer in combination with a high-sensitive TV recording system, and practically complete overlapping of spectral orders make this system rather attractive for study of spectra of extragalactic objects with visual stellar magnitudes brighter than 18-19.

It is natural that efficient application of such mode of observations is impossible without a system of prompt reduction of results. We made the first attempt to create such a system by writting a number of programs for integration of spectra from the image taken with the spectrometer (Vlasyuk, 1987), which were to be fulfilled on the computer SM-4 and the TV system "KVANT". Personal computers made it possible to develop a system of express reduction of data, which realizes the facilities of the computer in accomplishment of the procedures that require a large number of operations, in convenient graphic representation of data, which takes some burden from a man working with a great amount of data. Such was the system DECH written by G. Galazutdinov (Klochkova, Galazutdinov, 1991) for reduction of stellar spectra taken with all echelle spectrometers of the 6 m telescope.

The reduction of spectra of extragalactic objects demands to solve the problems which are somewhat different from those posed by the reduction of stellar spectra. For this purpose the author has written a package of programs. This paper is to give a description of the algorithms used and to illustrate their application to concrete astrophysical data.

## 2. PROBLEMS OF REDUCTION ASSOCIATED WITH PECULIARITIES OF REGISTRATION SYSTEM

As the detector for the echelle spectrometer "ZEBRA" a TV system based on the 4-stage image intensifier EMI, television tube of supersilicon type and the apparature "KVANT" (Afanasiev et al., 1987) is used. Therefore, when reducing observational data the peculiarities of the recording system must be properly taken into account, and the distortions associated with them must be possibly corrected.

It is well known that all counting systems, which employ image intensifiers and television tubes, have an essential drawback: the instability of TV scanning and image tube focusing, depending on the time, temperature of the surrounding medium, and, most important, on the orientation of the system in the magnetic field of the Earth. The latter is the basic reason of the fact that, as the azimuth of the telescope changes, a raster displacement of the television detector takes place, and therefore the spectra themselves are displaced with respect to the coordinate system of the detector. The inhomogeneities on the surface of the detector are sure to be displaced as well. An experience shows that such a displacement may reach 4-5 channels in both coordinates. In solution of the problems which requires accurate knowledge of the wavelength scale this implies that the reference comparison spectrum should be registered for each spectral acquisition. This effect should be allowed for when it is necessary to correct the data for the inhomogeneity of sensitivity too.

When observing relatively bright objects or faint objects, having bright emission features in the spectra, in the reduction of data one has to encounter another principal fault of counting systems as well: the restricted counting rate. In the accurate calibration of a counting system a correct account of this factor is also possible.

One of the noise sources in observations of faint objects, especially with the spectral resolution 1-2 Å, along with the statistical fluctuations of the signal itself, are the noises of the counting system caused first of all by random thermoemission of electrons from the surface of the photocathode. An effective means of reduction of this noise is the cooling of the photocathode, however, in data processing preference should be given to the algorithms which allow to attain the best signal/noise ratio when integrating the spectra.

## 3. SPECTRAL IMAGE REDUCTION

The experience of reduction of spectral data obtained with the echelle spectrometer "ZEBRA" shows that the detector sensitivity inhomogeneities, as a rule, do not exceed 2%. This allows to believe that there is no need to correct acquisitions for small-scale inhomogeneities of the detector. If for some reason such a necessity arises, we suggest to use for such reduction the algorithm proposed by Vlasyuk (1993a) and applied to reduction of spectral data with other counting systems used on the 6 m telescope.

The effect of displacement of spectra over the raster of the detector during observations leads, as has been noted, to the necessity of accumulating the comparison spectrum for each spectral exposure. Due to some design and other reasons, this requires excessive observing time. As an alternative we would suggest a mode of calibration of spectra in the wavelength scale, which diminishes the waste of observing time and provides an accuracy of line wavelength determination no less than 0.3-0.4 Å throughout the entire spectral range.

To realize this mode, one has to do acquisition of the comparison spectrum, allowing reduction to the wavelength scale with a required accuracy, either in the evening before the observations, or in the morning after them. During the observations it is suffice to accumulate the comparison spectrum for a comparatively short period of time (3-5 minutes). The relatively bright lines accumulated for this time permit to apply the above mentioned technique of cross-correlation calibration of the comparison spectrum image in each spectral integration obtained during a night. As a rule, analysis of the data obtained reveals a 3-4-element displacement of integration during the night both along and across the dispersion direction. Note that the true displacements of spectral details across the field of the detector is impossible to describe by a simplest-order distortion model. As has been pointed out (Vlasyuk, 1993a), these displacements are in good agreement with the square distortion model:

$$x' = a_0\cdot x^2 + a_1\cdot x\cdot y + a_2\cdot y^2 + a_3\cdot x + a_4\cdot y + a_5;$$

$$y' = b_0\cdot x^2 + b_1\cdot x\cdot y + b_2\cdot y^2 + b_3\cdot x + b_4\cdot y + b_5;$$

where $x$, $y$ and $x'$, $y'$ are the coordinates of the image element corresponding to one and the same spectral detail in the reference and the distorted coordinate systems (reference and short-exposure spectra, respectively), and $a_i$, $b_i$ are the coefficients of this model. The accuracy of such calibration is a determining factor of linearization of spectra to the wavelength scale. On the average the errors of such method do not exceed 0.2-0.3 of an element, which at a reciprocal linear dispersion of 0.6-1 Å/element corresponds to the linearization error 0.15-0.3 Å. Fig. 1 presents the result of a cross-correlation analysis for two spectral integrations of the comparison spectrum of 2 and 60 minutes.

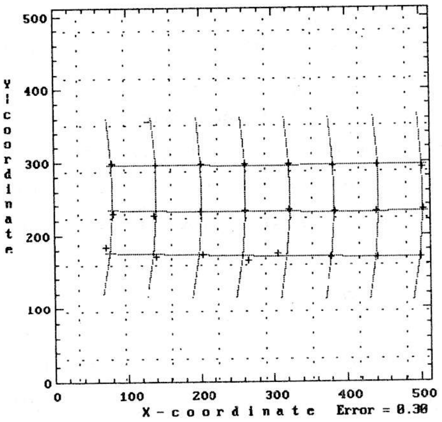

**Fig. 1.** *The result of cross-correlation analysis of two images of the comparison spectrum. Crosses show the measured positions, lines indicate position approximation.*

In the correction of the nonlinearities arising due to the restrictions in the counting rate, we suggest to correct all counts in the image proceeding from the nonlinearity model proposed by Jenkins (1987):

$$r = a\cdot(1 - \exp(-\rho/a)),$$

where $r$ is the registered counting rate of events, $\rho$ is the true counting rate, $\alpha$ is nonlinearity constant of the counting system. All these quantities are expressed in the number of events/(s·element). To measure the constant $\alpha$, one has either to measure the counting rate of events from the source, having the brightness varying by the known law (e.g. uniformly illuminating the slit and changing its width), or to investigate the variation of the counting rate ratio for two sources of different brightness, when it varies by an arbitrary law.

## 4. INTEGRATION OF SPECTRA: OPTIMAL ALGORITHM

Solution of the problem of optimal extraction and integration of spectra from the bidimensional matrix of data was greatly stimulated by Horne (1986) and Robertson (1986). These papers were conditioned by attempts to attain the best signal/noise ratio in the CCD spectra, i.e. to realize hereby the high quantum efficiency of these devices and to minimize the effect of the CCD readout noise. These papers suggest the optimum weighting of counts and choice of weights in accordance with the principle of minimum estimate dispersion. An essential restriction of the suggested algorithms was the assumption of small curvature of spectra. Application of this principle to spectra with a noticeable curvature (the value of curvature over the whole length of a spectrum exceeds the width of the spectrum itself) was suggested by Marsh (1989), and Mukai (1990). For optimal integration of spectra with an arbitrary curvature we suggested the following modification of the principle of optimal integration. From the spectrum under investigation for each spectral order a functional dependence is determined of the coordinate of the spectrum center on that corresponding to the direction of dispersion. For the spectra obtained with the echelle spectrometer "ZEBRA" it is suffice to approximate this dependence by a 2nd-degree polynomial. The mean error of such approximation is within 0.1-0.15 of an element.

The problem of determining the instrumental profile as a function of wavelength can be solved by construction of the profile quantified with the decreased step across the dispersion direction, the quantification being made under the assumption that the spectrum center coincides in height with the value approximated by the polynomial. Thus, for each spectral order we have a set of quantified profiles CNT($\lambda_i$) for the set $\lambda_i$. As a rule this set contains from 10 to 20 such profiles. The increase in the step of quantification causes incomplete filling of the resulting profile CNT ($\lambda_i$) especially in spectrum fragments with a small curvature of spectra. A smooth profile is constructed from CNT($\lambda_i$) by the Forsaite method of polynomial approximation, in which the nonzero weights have the profile points with the nonzero values. Fig. 2 shows the example of such approximation for one of the contours. The profiles thus obtained have no analytical expression, however, profiles of arbitrary shape can be approximated in this manner. The approximation of these profiles at each point by the least-squares method provides the polynomial wavelength dependence of the *i*-th point, *Profile* ($i,\lambda$), which is further applied to optimal integration.

As it is known from (Horne, 1986), the optimal estimate of the spectra $f_{\mathrm{opt}}(\lambda)$ is given by

$$f_{\mathrm{opt}}(\lambda) = \frac{\sum \dfrac{\mathrm{Spec}(x,\lambda)\cdot\mathrm{Prof}(x,\lambda)}{\sigma^2(x,\lambda)}}{\sum \dfrac{\mathrm{Prof}(x,\lambda)\cdot\mathrm{Prof}(x,\lambda)}{\sigma^2(x,\lambda)}},$$

where Spec $(x,\lambda)$ are the counts of the spectrum on the two-dimensional counting system, Prof $(x,\lambda)$ is the profile across the dispersion, $\sigma^2(x,\lambda)$ is the variance of spectrum counts.

In the calculation of $f_{\mathrm{opt}}$ $(\lambda)$ summation is made over all points of the profile, for Prof $(x,\lambda)$ we take the values from the defined, as described above, function Profile $(i,\lambda)$. To compute $\sigma^2(x,\lambda)$ we use the expression

$$\sigma^2(x,\lambda) = \sigma_0^2(x,\lambda) + f_{\mathrm{appr}}(\lambda)\cdot\mathrm{Prof}(x,\lambda),$$

where $\sigma$ $(x,\lambda)$ is the variance of noises of the system, which are independent of the signal (as a rule, this is a constant, if there is no additional information on the character of the noises); $f_{\mathrm{appr}}$ $(\lambda)$ is the estimate of the spectrum point value obtained, for example, by means of ordinary summation of signal in a fixed window.

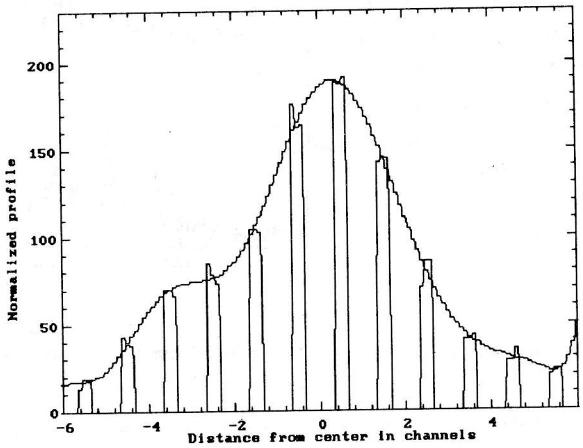

**Fig. 2.** *Approximation of the cross profile of one of spectral orders.*

Fig.3 presents for comparison an interval of a night-sky spectrum obtained by ordinary integration and by the method of optimal integration. We believe that the suggested method of integration of signal is flexible and accurate enough, which is especially important at the existing displacements of spectral integrations over the raster of the counting system. We shall add hereto that the suggested mode provides an essential gain in the spectrum quality when working with CCD system, where the effect of the detector noises is greater.

## 5. REDUCTION OF EXTRACTED SPECTRA

The spectra obtained by optimal integration undergo the following procedures of reduction:

- reduction to a uniform wavelength scale;
- definition of sensitivity of a spectral order from a standard star spectrum, and reduction of a spectrum to a unified system of relative fluxes;
- determination of parameters of spectral details.

Let us consider the details of these procedures as applied to spectra of extragalactic objects.

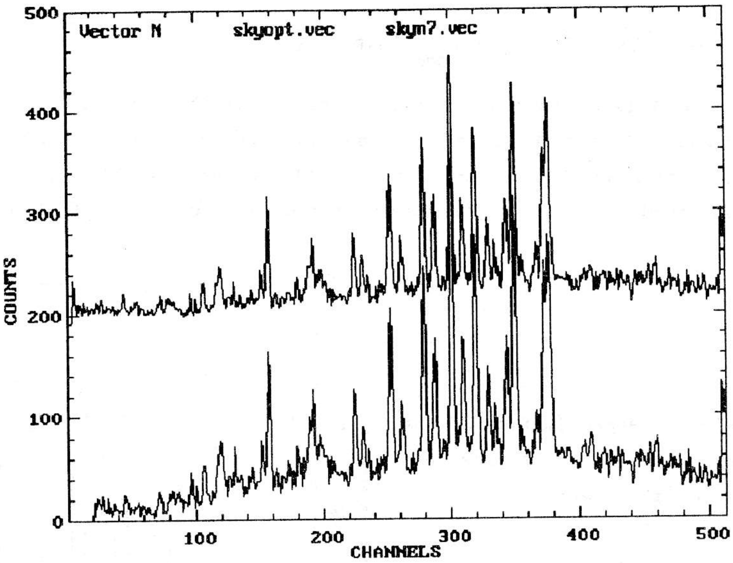

**Fig. 3.** *One of the spectrum orders of the night sky obtained by optimal integration (lower spectrum) and by usual summation. The spectral range - from 7100 Å (right) to 7600 Å.*

### 5.1. Reduction of spectra to a uniform wavelength scale (linearization)

As a reference comparison spectrum, we use the spectrum of an argon-filled lamp. We prefer it to the one of a helium-neon-argon-filled lamp since the latter has a poorer set of spectral lines, what is important in the construction of the dispersion curves for each order. By the way, note that both lamps do not have sufficient set of lines in the range shorter than 3800 Å.

For identification of lines of the comparison spectrum we used the atlas of argon emission lines compiled by V.G. Klochkova from a photographic spectrum with a higher spectral resolution. On the basis of this spectrum we were able to select 12 - 15 lines in each order, which were weakly blended, to construct a dispersion curve with sufficient confidence. When plotting the dispersion curve, the user should identify the lines from the atlas and indicate their position in the comparison spectrum. The accuracy of the dispersion curve is determined by that of position of spectral lines as center of gravity and is about 0.15-0.2 Å.

### 5.2. Determination of sensitivity in orders

At obtaining spectra of extragalactic objects it is needed, as a rule, to reduce various spectral orders to a unified system of relative energetic orders, i.e. to solve the so-called problem of "lacing of orders". We use for this the acquisition of spectra of a spectrophotometric standard whose fluxes are tabulated rather frequently. For this purpose one can use, for example, the data from (Massey et al., 1988). The linearized spectra of the standard star undergo integration in the same spectral intervals as the table spectra do. Having divided point by point the normalized table data by the flux values derived from the spectra and then interpolated these data, one can obtain the curve of relative sensitivity for each order. Using the curve, the spectra of the objects under study can be reduced to the unified system of units. The quality criterion of the accomplished procedure is, first of all, the coincidence of different spectral orders in the regions of their overlapping, and also the continuum in the corrected spectra of the objects whose energy distribution is known.

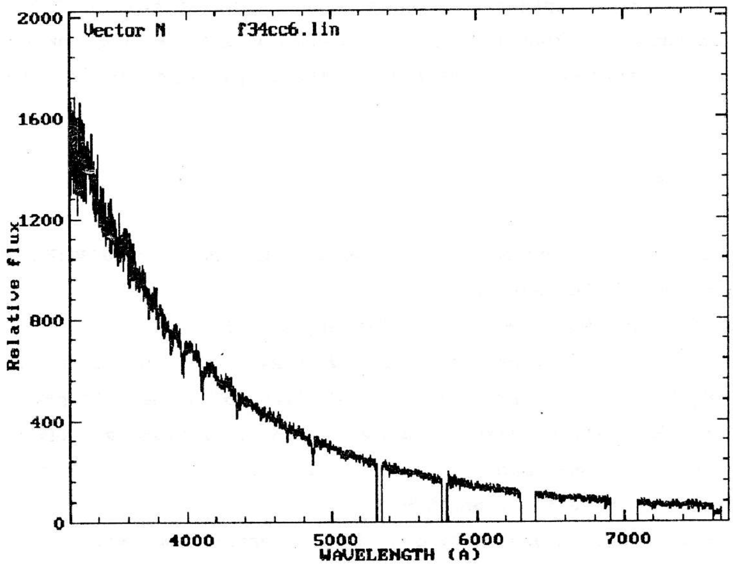

**Fig. 4.** *The composite spectrum of a standard star Feige 34 reduced to relative intensities.*

### 5.3. Determination of parameters of spectral details

After lacing of spectral orders the spectrum is reduced to a kind common for all spectral data obtained with: the multiobject fiber spectrograph (MFS), multipupil fiber spectrograph (MPFS), and TV scanner of the 6-m telescope. This allows to apply the data processing we have described in other papers (Vlasyuk, 1993a, Vlasyuk, 1993b).

Fig. 4 presented the spectrum of a photometric standard, Feige 34, reduced to relative energetic units. It demonstrates a high informativity of the obtained data: about 2000 of independent counts constitute the spectrum. We only add that a number of problems are awaiting solution. Among them there is the solution of the problem of Gauss-analysis of spectral line profiles.

## 6. CONCLUSION

Let us note in conclusion that further progress in the use of the echelle spectrometer consists in installation of a CCD system instead of a TV counting system. The devices of this kind available at SAO are of higher quantum efficiency, positional stability, and uniformity of sensitivity. This will allow to increase both the space-penetrating power and at the same time the quality of spectral data.

The procedures described here are realized on a personal computer of IBM PC AT/386 class using the algorithmic languages Fortran and C. The total time required for the reduction of one spectral integration is less than one hour.

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