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Fast CCD spectroscopy in the mode of charge shift

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Abstract.
A new method is described of spectral observations in the mode of charge shift in a CCD chip in the direction perpendicular to the dispersion. The vacant area of the detector is used for temporary storage of a sequence of spectra. This minimizes the time consumed for read-out and recording of images, which makes it possible to obtain a sequence of spectra with a higher time resolution. The mode is implemented with the BTA spectrograph SP-124. Photometric and positional stabilities of the technique have been investigated. Potential possibility of detecting a short-period signal and rapid nonstationary processes is shown. This mode of observation provides a maximum gain with exposure from fractions of a second to a few minutes.

Key words: astronomical instrumentation: telescopes – astronomical techniques: spectroscopy

1. Introduction

There are a number of tasks that require spectral data obtained with high time resolution (1–10s). This is a search for possible periodicities at times from ten to a few hundred seconds. These tasks emerge, in particular, when studying cataclysmic variables, single pulsating white dwarfs, binary degenerate objects, rapidly pulsating magnetic stars, X-ray binary systems containing a pulsar and others. Fast spectroscopy with moderate spectral resolution of pulsating white dwarfs has recently been conducted by Clemens et al. (1999). Using the low-resolution spectrograph of the telescope Keck II, they have found periodic radial velocity and flux variations in the spectrum of the white dwarf G 29-38 ($V=13\overset{m}{.}0$) with periods of 300–800 s, which are similar to those obtained from photometry. However, when analyzing high frequencies, the authors were limited by the CCD readout time. The minimum period acessible to them was about 50 s. To speed up the detector readout, binning was applied, which impaired the spectral resolution.

We have realized a method of observation with SP-124, which, on the one hand, makes more effective use of the CCD detector and, on the other hand, minimizes time losses for readout and image recording when doing spectroscopy with short exposures. This results in essential weakening of harmonics of covering factor on the periodogram.

The modified diffraction spectrograph SP-124 (Gusev et al., 1976; Afanasiev et al., 1991) installed at the BTA Nasmyth-1 focus is used to obtain moderate-resolution (2–10 Å) spectra. A CCD system produced by the firm Photometrics with the matrix TK 1024 (1024×1024 pixels) serves as the detector. Even with the slit as high as 40″, the extent of the spectrum across the dispersion is but a small part of the detector size in this coordinate, approximately 90 pixels. When doing spectroscopy of stellar objects, the detector is utilized even less effectively. With an average seeing of $\approx 2''$ the spectrum will take only about 5 pixels in height.

Readout of the image from the CCD and its recording represent a relatively slow process. Readout and storage of a detector area of 1024 × 90 pixels take about 12 s, including forced delays for image transfer to the BTA control room, and its archiving. This results in pauses between exposures, which, in high time-resolution ($< 10\,s$) spectroscopy, may be comparable with the time of acquisition. The occurrence of time windows at regular intervals complicates largely isolation of the periodic signal of the object, since the peaks on the periodogram of the process, which correspond to the covering factor of observations, are very intensive. This can be avoided by application of the observing technique we are describing.

2. Operation

The fast spectroscopy technique shifts the acquired spectrum to the clear area of the detector. In other words, the detector area free from the spectrum is used for temporary storage of a number of images. The displacement of the spectrum is accomplished by way of shifting the accumulated charge towards the readout register (Remington, 1994). The shift should be made across the dispersion by a value not less than the spectrum height. The latter is necessary to avoid overlapping of adjacent images. The shift value may change depending on the object brightness. For stellar tasks the shift may amount to 10–15 pixels. This will allow as many as 50 spectra to be "memorized" in the unexposed area of the detector. The undisplaced image is located in the middle of the CCD for the existing version of disposition of the detector in the spectrograph SP-124, and only the area extending to the readout register, i.e. half of the 1024 pixels, may be used for storage. Shift of each next spectrum displaces all previous ones closer to the readout register. The operation of shifting in contrast to readout is a process which is two orders of magnitude faster. A shift by one line takes approximately 0.2 ms, whereas readout of one line takes about 50 ms (for the readout frequency of 20 kHz). This implies that charge transfer to the storage area is virtually instantaneous. When the area is full, it is read out and stored. This requires 40 s (for the readout frequency of 20 kHz). Here is included the time the image is transmitted to the BTA control room and stored. In a normal mode a detector region of 1020×10 pixels is readout and stored during 7 s. For this reason, under the conditions of spectroscopy with shift we save up to 6 s in each exposure, depending on the number of spectra accumulated without readout. In high time-resolution (from 1 to 10 s) spectroscopy the saving of observational time turns out to be 35% to 75%.

The disadvantages of the technique consist in that the images in the storage area continue being bombarded by cosmic particles and are affected by dark current. The dark current of the CCD in the camera CH 260 of Photometrics firm is relatively low, about $15e^-$/pixels/hour. However, the accumulation of cosmic particle traces and dark current requires the total time of acquisition of spectra without readout of images to be limited.

3. Method accuracy

With the aim of testing the method and defining its accuracy characteristics we obtained spectra of different artificial sources of radiation.

1. A high-stability source of light made on the basis of a semiconductor photodiode. Direct current stabilization through the photodiode and comparatively short exposures made it possible to obtain a constant light flux in an isolated portion of the spectrum (with no allowance for the noise component). With the aid of this source we checked photometric stability and stability of the spectrum position across the dispersion.

2. The same photodiode, but the direct current it carried was modulated through a linearly varying saw-toothed voltage. Periodic variations of the direct current magnitude caused periodic variations of the photodiode radiation intensity. The voltage was modulated by a generator of low-frequency oscillations G6-15. The presence of the signal of the specified shape allowed the quality of separation of the signal to be analyzed in using the fast spectroscopy method with shift. A number of astrophysical objects, such as pulsating white dwarfs, cataclysmic variables and others have periodic variations of spectral and photometric characteristics at times of hundreds of seconds. The period (about 37 s) of intensity variations of the artificial source was chosen so as to conform to these periods in the order of magnitude.

3. To examine stability of the positions of individual spectral features, we used a line spectrum source — a lamp of SG3S type (its spectrum is shown on the right-hand panel of Fig.1).

In all three cases a circular diaphragm 1″ in diameter was mounted at the spectrograph entrance.

The position of the spectrum center across the dispersion, the position of the center of gravity along the dispersion, in the case of line spectrum source, and the location of the maximum of radiation, in the case the photodiode is used, must not change significantly during the experiment.

Let us name the collection of the spectra which were managed to obtain a frame. The frame was processed by the MIDAS facilities in the following order. First, cleaning of cosmic particle hits was performed. Then the constant and background components over the frame were removed. This was done by filtering of each image column on the basis of the algorithm of convolution of the spectra with a Gauss-like window. The algorithms were realized as the MIDAS procedure (Shergin et al., 1996). Further each spectrum was extracted. The time calibration was accomplished at the moment the first spectrum started to be exposed in the frame and at the moment the acquisition of the last terminated. The pause between two sequential exposures was computed proceeding from the time of the beginning and end of exposure of the frame and from the total number of spectra in it. The pause is determined in the main by the time for shifting the image to the storage area and by the necessary programme delay. For instance, with a shift of 15 pixels the pause is about 0.03 s. The time calibration of the spectrum in the frame was made in accordance with its pozition. The internal clock of the computer does not keep exact time well enough. We estimated its drift. A frequency meter was used for this purpose in the mode of period measuring. The frequency meter signals were fed through the input-output port of the CCD detector controller. The drift of the computer clock was from 0.05 to 0.1 s over 15 minutes. For

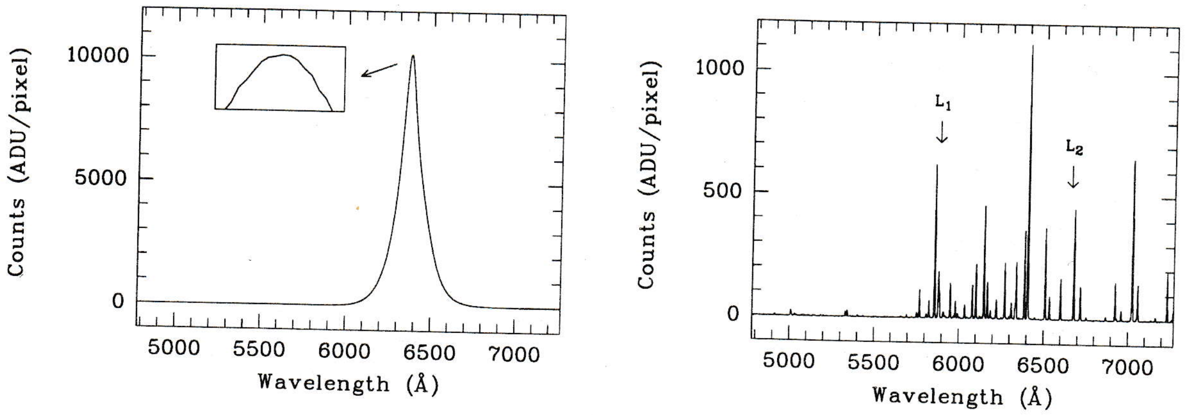

Figure 1: *The spectra of the photodiode (left) and of the lamp SG3S (right) obtained with the spectrograph SP-124 with a dispersion of 2.43Å/pixel. In the box on the left panel is shown a magnified image of the photodiode spectrum near the maximum of radiation. The profile is close to Gaussian. The maximum of radiation falls at the wavelength 6368 Å. On the right panel of the figure are displayed two lines:* $L_1 - NeI(\lambda 5852.49)$ *and* $L_2 - HeI(\lambda 6678.15)$ *(see text).*

this reason, timing of the computer clocks with the machines storing exact time signals was performed through the computer network. The timing is accomplished every 5 minutes. The accuracy of time calibration was 0.05 s during the whole experiment.

The possibility of studying periodic processes by means of the fast spectroscopy technique can be illustrated by the example of analysis of the light curve of the photodiode whose emission was modulated. To obtain the light curve, the flux in a band of 20 pixels (50 Å) centered on the maximum of emission of the photodiode, 6368 Å, was summed up. All in all 16 frames were obtained each containing 30 spectra. The exposure time was 1 s, and the total time of acquisition of spectra was about 1000 s. Concurrently with the recording of spectra we determined the mean period and its error, P=37.631±0.007 s, with the aid of the frequency meter. The maximum deviation from the mean turned out to be 18 ms. This is less than the accuracy of time calibration. The greatest peak corresponds to a period of 37.67 s, which is close enough to the modulation period. In Fig.2 is presented also the phase curve obtained by convolution of the light curve with a 37.63 s period. The root-mean-square deviation of the points in phase from the smooth run of the curve is approximately 0.001, which corresponds to an uncertainty of 0.04 s. This is in good agreement with the accuracy of time calibration.

The light curve of the permanently emitting photodiode (Fig.3a) reflects stability of photometric characteristics. As can be seen from the figure, the standard deviation is about 0.001. This corresponds to an error $\approx 0\overset{m}{.}001$ in the stellar magnitude estimate. Proceeding from the total flux value, one can evaluate the Poisson noise component as $\approx 4 \cdot 10^{-4}$. For such large fluxes a considerable contribution will be made by the CCD sensitivity inhomogeneity, which is 0.5%. After averaging over the region of flux integration the sensitivity inhomogeneity contribution may be estimated to be $\approx 5 \cdot 10^{-4}$. Using all the estimates made to derive the significance of the peaks on the periodogram, it can be inferred that significant harmonics are completely absent. When the Poisson noise predominates as in the case of photometrying the average intensity line in the spectrum of the lamp SG3S (Fig.1, right panel), the standard deviation of the light curve points differs from the Poissonian statistics by less than 10%. To reveal variations of the location and shape of the line profile, the flux ratio in the blue and red wings V/R of the line is often used. It should be noted that during the experiment with the permanently emitting photodiode the ratio V/R of its emission band fluctuated within ±0.002 (σ=0.001, see Fig.3b). Any significant periodicity in the variation of V/R is absent.

Special attention should be given to positional characteristics. In Fig.3 are presented the data on the behaviour of the maximum location of the photodiode emission (case c) and the center of gravity of two lines, NeI (λ 4852.49) and HeI (λ 6678.15) in the spectrum of the SG3S lamp (e and f; see also Fig.1, right panel). The lines in the spectrum of the lamp were selected so that one of them was closer to the center, while the other — closer to the edge and their intensities would be comparable. The time of one exposure was 5 s. In all three cases the locations of the spectral feature being analyzed remained unchanged to a high accuracy. The standard deviation did not exceed 0.02 pixel. We did not reveal periodic variations. The location of the center of gravity underwent insignificant variations with a period ≈600 s (Fig.3d). However, the amplitude of these variations was ex-

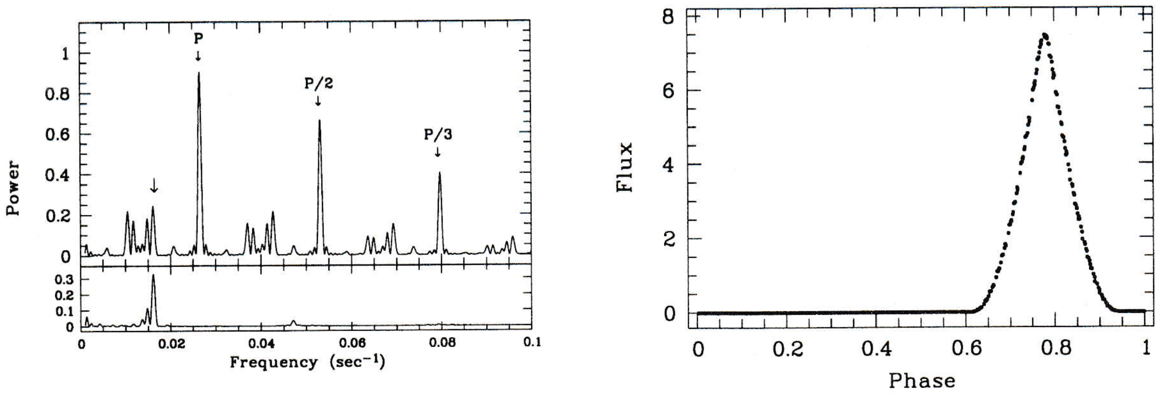

Figure 2: *The upper part of the left panel displays the power spectrum of the photodiode light variation with modulated intensity (see text). The location of the harmonic P is indicated, which corresponds to the period of modulation 37.63 s. Besides, multiple frequencies P/2 (half period), P/3 are indicated. The arrow marks the location of the harmonic corresponding to the most poweful peak (period 62 s) on the power spectrum of covering (lower part of the left panel). This corresponds to the period of repetition of the beginning of exposure of the next frame. On the right panel is presented the modulation period phase curve.*

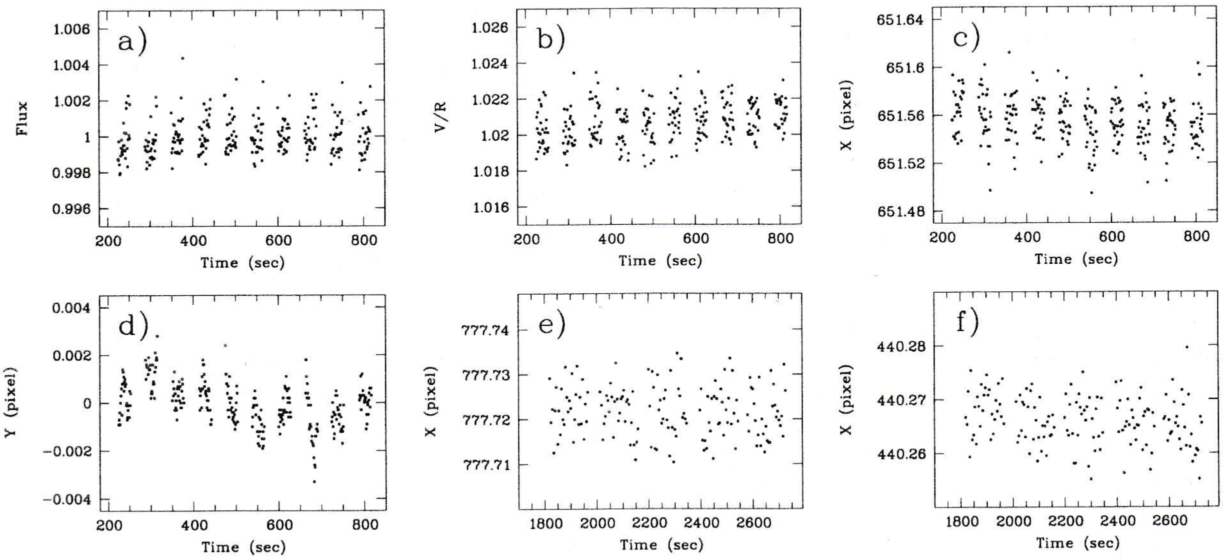

Figure 3: *Time variation in photometric and positional characteristics: a) flux variation in the portion of the spectrum $\approx 50\,\AA$ of the permanently emitting photodiode (normalized to the mean flux value), b) ratio of the fluxes in the "blue" and "red" wings of its emission band, c) position of the maximum of intensity of this band, d) position of the spectrum center of gravity across the dispersion, e) and f) position of the center of gravity of the lines L_1 and L_2 (Fig.1, right panel).*

tremely small, $\approx$0.001 pixel. Such variations may be caused by the thermal instabilities of the CCD, as well as by the instability of the light source position on the entrance slit. A change of the position of about 0.001 pixel on the detector corresponds to a change of the position of $\approx$4 micron on the entrance slit. The CCD we use has the temperature instability to an accuracy of 0.1 K. The temperature was kept as accurate during the whole experiment. According to the investigations of Buffington et al. (1990), this may result in linear deformations with an amplitude of 0.03 micron. Thus in our case linear deformations within amplitude of $\approx$ 0.001 pixel may be expected. This is why the variations shown in Fig.3d may in principle be completely explained by temperature instabilities.

4. Potentialities of the method

To illustrate potentialities of the fast spectroscopy technique with a CCD, we present 29 spectra

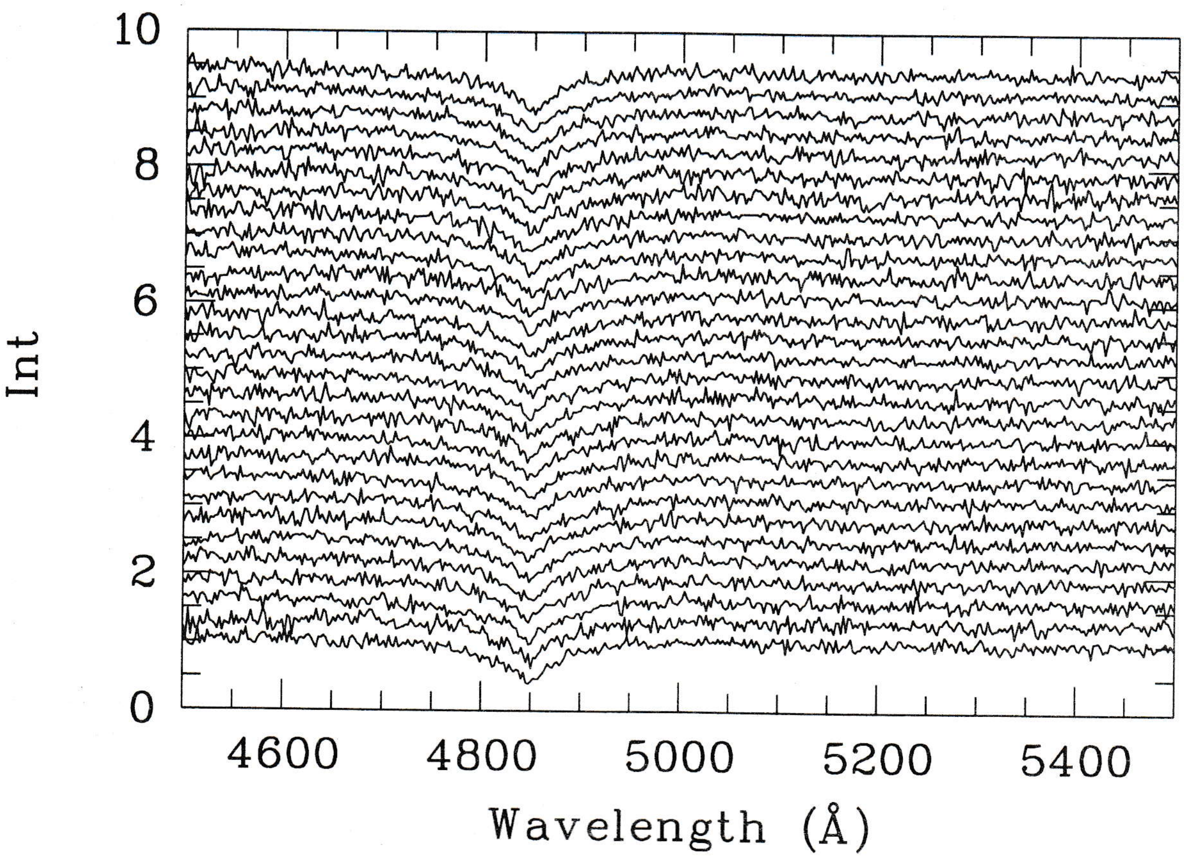

Figure 4: *The sequence of normalized spectra of the white dwarf WD 1647+591 near the line H_β. The exposure time of a separate spectrum is 10 s. The pauses between the adjacent spectra are less than 0.05 s.*

(1 frame) of the pulsating white dwarf WD 1647+591 (V=$12^{m}_{.}2$) with a time resolution of 10 s (Fig.4). The end of exposure of one of them and the beginning of the next one were separated by 0.05 s. The entrance aperture was a circular diaphragm of 1″.

This technique turns out to be most efficient at exposure times of a few fractions of a second to a few minutes. The technique obtains spectra of short-period and rapid nonstationary processes. Fig.5 shows stellar magnitudes accessible to observations. The relations are computed on the basis of the detectability threshold of the spectrograph SP-124 with the slit completely open (Neizvestny et al., 1998) with allowance made for the CCD readout noise and sky background. According to Neizvestny (1982), the sky background at SAO in the V band on a moonless night is $21^{m}_{.}4/\square''$, and the mean seeing, according to Afanasiev (1995), is 2″. At short times the length of exposure is limited by the uncertainty of time calibration (left vertical dashed line of Fig.5). With long acquisitions the total time of CCD exposure without readout is restricted by degradation of the image by cosmic particle traces and by the value of dark current. The inclined dashed line represents a situation where the Poissonian noise is comparable with the CCD readout noise. Below this line is the region of fluxes at which the signal is higher than the CCD readout noise. The pair of solid lines refer to two signal/noise ratio values 10 and 100 in a single exposure.

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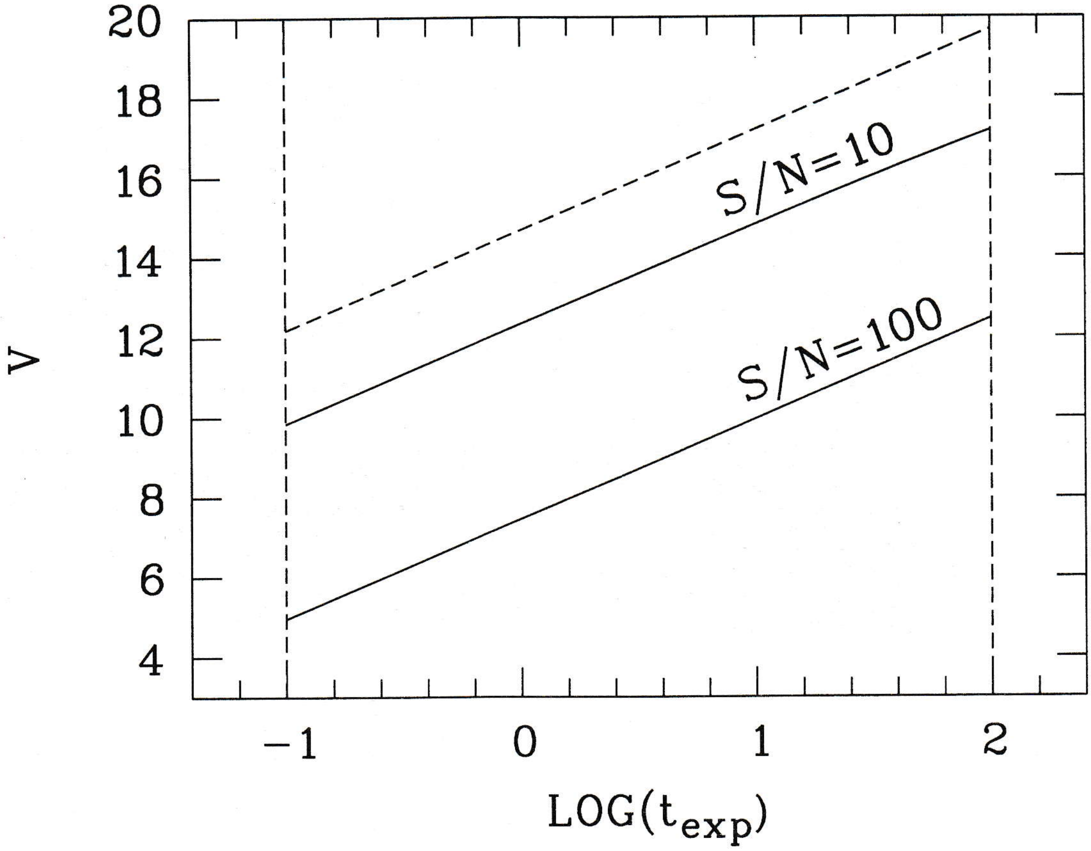

Figure 5: *The relation between the stellar magnitude in the V filter, for which the specified S/N ratio can be obtained. Time is measured in seconds. The calculation is accomplished for the completely opened slit and the mean seeing of 2″. The vertical dashed lines mark the exposure time boundaries within which a maximum gain is achieved in using the fast spectroscopy technique as compared to the ordinary mode of observation. The inclined line represents a situation the Poissonian noise is comparable with the CCD readout noises.*

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