SLITLESS SPECTROSCOPY OF STARS WITH GRATING-PRISM AND FOCAL REDUCER TECHNIQUES

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ABSTRACT

A slitless field spectrograph for Cassegrain telescopes has been designed. It is based on the focal reducer optical arrangement and grating prisms. Together with the "multiple diaphragm method" not only a gain in limiting magnitude of 3 to 4 magnitudes has been achieved, but also other drawbacks of the classical objective prism camera are avoided.

1. INTRODUCTION

The objective prism (or grating) camera is the most efficient stellar spectrograph, because it makes use of the full telescope field, and no light losses occur at a slit and those in the optics are small in comparison to slit spectrographs.

After the pioneering investigations by Fraunhofer, Angelo Secchi was the first to apply the objective prism method extensively to astro-spectroscopy. He used a prism of considerable dimensions (6 inch diameter, 12° refracting angle). Since that time, and with the introduction of photography, the objective prism camera yielded a wealth of astro-spectrographic information which could never have been achieved by slit spectrographs.

2. LIMITATIONS OF THE OBJECTIVE PRISM ARRANGEMENT

In spite of these advantages the objective prism camera shows certain drawbacks and limitations which should be discussed briefly:

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i) No comparison spectrum can be placed beside the stellar spectra. Therefore only relative radial velocities can be obtained via the Pickering reversion method. This has been perfected by the introduction of the direct vision prism by Fehrenbach (1947).

ii) The limiting magnitude is determined by the sky background brightness which contributes as if it is undispersed, and by the angular dispersion of the prism.

iii) The spectral purity or resolution, $\delta\lambda$, is given solely by the seeing angle β and the angular dispersion $d\varepsilon/d\lambda$:

$$\delta\lambda = \frac{\beta}{(d\varepsilon/d\lambda)} = D \cdot f \cdot \beta \ .$$

Here D is the reciprocal linear dispersion (r.l.d.) and f is the effective focal length of the camera (see e.g. Geyer, 1966, 1972). We made the assumption that the resolution of the photographic emulsion is matched to this spectral resolution. Therefore even under best seeing conditions ($\beta \leq 1''$) long focus objective prism cameras ($f_o > 300$ cm) yield poor spectral purity ($\delta\lambda > 5$ Å if $D \geq 200$ Å mm^{-1}). This is just the limit for MK classification.

Besides the technical limitations, the largest dimensions for objective prisms in use are about 100 cm in diameter for cameras which do not exceed the quoted focal length limit.

iv) The overlapping of spectra in crowded stellar fields reduces the effectiveness of the objective prism camera considerably. The number of blended spectra is directly proportional to the angular extension of the spectra and thus to the angular dispersion, but does not depend on the focal length of the camera.

3. FIELD SPECTROSCOPY WITH FOCAL REDUCERS AND GRATING PRISMS

Today several wide field Ritchey-Chretien telescopes are in use, thus the situation for slitless field spectroscopy has been changed. It demands the design of spectroscopic equipment making use of the full usable field of the telescope.

We are of the opinion that the best solution is the focal reducer arrangement. As a pilot instrument we have designed such a field spectrograph on this basis for the 106-cm-f/14.5 Cassegrain telescope of the Hoher List Observatory. The guiding principles for the design were the outlined drawbacks of the classical objective prism camera which we tried to reduce or to avoid.

As is generally known, a focal reducer is an optical system for a long focus and low aperture ratio telescope. It shortens the focal length considerably and transforms the aperture ratio of the telescope to f/2 or f/1 typically. B. Schmidt was the first to construct a focal reducer system for the 60-cm refractor of Hamburg Observatory (Hellerich 1938). In an afocal arrangement focal reducers were first used by Meinel (1956) and Courtes (1960). Actually in this layout focal reducers differ from slit spectrographs only by the introduction of a field lens in the vicinity of the telescope's focal plane. It projects the entrance pupil of the telescope onto the entrance pupil of the camera optics, thus making the whole telescope field available.

The schematic assembly of our focal reducer system (manufactured by Jena Optik) is shown in Fig. 1. The field lens achromate has a diameter of 160 mm, and is well placed outside the telescope focus, so that the focal plane is fully accessible. This is essential for my method of sky background reduction. The collimator and the field lens have been designed to reduce the coma of the Cassegrain telescope so that a field of 40 minutes of arc can be used. The longitudinal chromatic rest aberration is small, and yields chromatically blurred images with less than 0.01 mm diameter within a wavelength range of 150 nm with the f/2-f = 100 mm Schmidt camera (Fig. 2). With this instrument the focal length is reduced to 200 cm. The limit for direct photography in the blue is about 19^m with 10 minutes exposure time, and which conforms with the theoretical expectation for plate-resolution limited images.

This type of focal reducer was modified to a slitless field spectrograph by inserting dispersing media in the parallel path of rays in front of the Schmidt camera. Since we like to apply the reversion method for radial velocity measurements we choose grating prisms for the dispersing elements. This not very well known type of grating is made of blazed transmission gratings cemented onto the hypotenuse of a glass prism. Making the groove angle of the grating nearly equal to the refracting angle of the prism, direct vision for a certain first order wavelength is achieved, whereas zero- and higher orders are deflected beyond the camera's field angle. A simplified theory of the grating prism was given by Geyer and Schmidt (1976), the full theory, including the distortion of out axis rays, was given by Nelles (1978). With this type of grating, which can be placed directly in front of the camera, the necessary angular dispersion is obtained. The reciprocal linear dispersions of our three grating prisms in use are 450, 290, and 150 Å mm^{-1} with direct vision wavelength of 485, 370, and 300 nm. This is achieved with a f/2-f = 100 mm Schmidt camera.

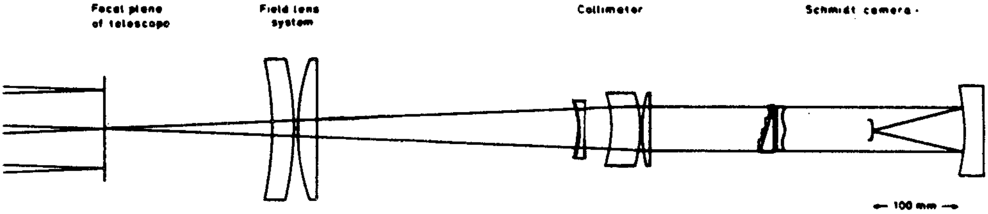

Fig. 1. Optical arrangement of the focal reducer of the Hoher List Observatory.

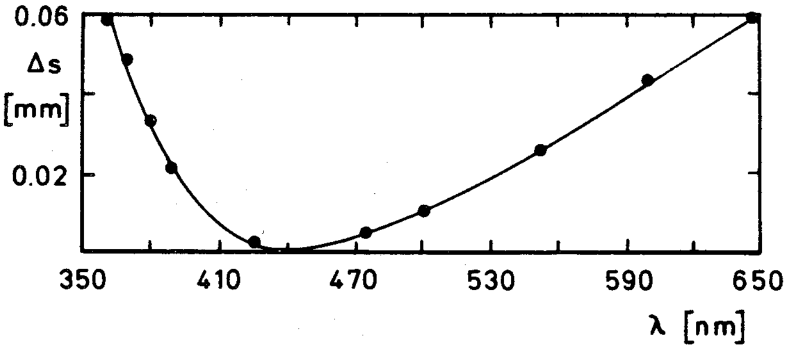

Fig. 2. Longitudinal chromatic aberration of the focal reducer system for the 106 cm - f/14.5 Cassegrain telescope of the Hoher List Observatory.

4. LIMITING MAGNITUDE GAIN

For slitless spectrographs and objective prism cameras the limiting magnitude is determined by the sky brightness and dispersion:

$$m^{\circ}_{\mathrm{lim}} = \mathrm{const.} + 5 \cdot \log f - 2.5 \cdot \log \frac{V \cdot |\lambda 1 - \lambda 2|}{D \cdot R^2} \qquad (1)$$

where f is the effective focal length of the telescope-focal reducer arrangement, $|\lambda_1 - \lambda_2|$ the sensitivity range of the film, D the reciprocal linear dispersion, and R the resolution of the film emulsion. This formula is valid for $f \leq 400$ cm (resolution limited case).

It is the great advantage of a focal reducer slitless spectrograph that sky background suppression is partly possible, which shifts the limiting magnitude towards fainter one by 3 to 4 magnitudes. This is attained by the "multiple diaphragm method": At first a direct photograph of the stellar field to be studied is taken in the telescope focal plane. Then according to this photograph small holes are drilled into a metal sheet at the position of the objects to be studied. Finally this multiple diaphragm is placed back into the Cassegrain focus, and now the photograph is taken via the field spectrograph. The sky brightness is reduced by this method by the ratio of hole image diameter to the length of the spectrum. The gain factor p is therefore:

$$p = \frac{q \cdot |\lambda 1 - \lambda 2|}{d \cdot D} \qquad (2)$$

Here are $q = \frac{f_{\mathrm{tel}}}{f_{\mathrm{effect}}}$ the factor of focal length shortening, and d the hole diameter. Thus the gain in limiting magnitude is $\Delta m_{\mathrm{lim}} = 2.5 \log p$, and therefore the limiting magnitude with diaphragm becomes

$$m^{\mathrm{diaph}}_{\mathrm{lim}} = m^{\circ}_{\mathrm{lim}} + \Delta m_{\mathrm{lim}} = \mathrm{const.} + 5 \cdot \log f - 2.5 \cdot \log \frac{V \cdot d}{q \cdot R^2} \qquad (3)$$

We arrive to the important result that the limiting magnitude is now independent of the dispersion used. In Fig. 3 are shown the limiting magnitudes for the 450 Å mm^{-1} and 290 Å mm^{-1} grating prisms as a function of exposure time and widening.

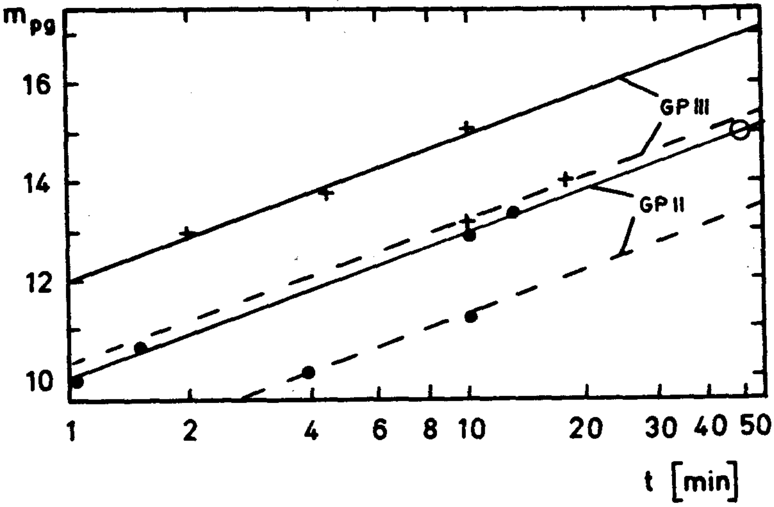

Fig.3. Magnitude versus exposure time relation for the multiple diaphragm method. The hole diameters are 2 mm. The dispersions are 290 Å/mm for GP II and 450 Å/mm for GP III. Heavy line is the relation for unwidened-, dashed line for 0.2 mm widened spectra.

5. RESULTS

By this diaphragm method the problem of spectra blending by overlapping is also solved. All stars which may cause the blending of the objects to be studied can be masked easily. Therefore field spectroscopy in crowded fields like globular clusters is possible. With this equipment we obtained widened spectrograms of magnitude 16 at 290 Å mm^{-1} within 120 minutes exposure time. These are of good quality, and their spectral purity is given by the resolution of the photographic emulsion and is nearly seeing-independent. Therefore MK classification of faint stars becomes feasible. With the reversion method we also obtained relative radial velocities with an accuracy of about ±12 km s^{-1}.

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DISCUSSION

McCarthy: What is the size of your telescope? Do you have any examples of spectra to show us?

Geyer: We designed this field spectrograph for a f/14.5 Cassegrain reflector of 106 cm (42") aperture. This telescope is identical to the ESO 40" reflector.

The spectra are of good quality from Hα to the Balmer limit for a 450 Å mm^{-1} and the 290 Å mm^{-1} grism. The 156 Å mm^{-1} grism is blazed at about 3000 Å mm^{-1}, therefore good spectra are obtained at about 3500 Å to 4400 Å. As examples I am showing a few spectra at a dispersion of 290 Å mm^{-1} for different spectral types.

Fehrenbach: We have used the method you are proposing with my reversing prism. The main advantage of your method is the use of masks. With our objective prism with a diameter of 60 cm (giving 200 A mm^{-1}) the limiting magnitude is 12.5 to 13 and the precision is about 4 km sec^{-1} for an average of three plates.

Geyer: The accuracy for radial velocity measurements with our grism method is about 8-10 km sec^{-1} for a reciprocal linear dispersion of 290 Å mm^{-1} and three films. With our masking method we reach of course fainter magnitudes than you.

Spinrad: Of course you have to know the objects of interest for spectra (in the holes) in advance!

Geyer: This is only partly true. With my masking method in only two to three exposures we can cover the whole telescope field. In practice we drill holes at each star position on the direct plate in the telescope focal plane and cover those holes for stars which should overlap.

Blanco: In the direct mode what is the scale you obtain in seconds of arc per mm?

Geyer: The scale of our 106 cm, f/14.5 Cassegrain reflector is about 14 sec of arc per millimeter. We normally expose our direct plates in the telescope focus for 20 min on unfiltered 103a-D or 103a-O plates, which yields about 18.5 apparent magnitude.

OPEN DISCUSSION

Geyer: In addition to my contribution on grating prisms and slitless spectroscopy with a focal reducer system, I would like to show briefly how the speed of a spectrograph for classification can be improved. We have to consider how to reduce the light losses at the slit, and above all in the spectrograph optics. In the latter case we have to think about the reduction of reflecting surfaces and how to avoid oblique rays.

Since the telescopic seeing disc is circular, the rectangular slit cuts off more light than a circular one would do. By the Bowen and/or Richardson image slicer technique the slit losses are considerably reduced, of course. Yet the widening of the spectra must then be done by moving the plate. A very simple type of spectrograph along these lines was proposed more than 50 years ago by B. Meyermann. It can be used together with the grating prism ("grism"). In front of the telescope focus is placed a simple negative lens as a collimator. At the telescope focus is placed an iris diaphragm which defines the circular slit for an object at infinity. Then follows the grating prism and a simple positive lens as the camera lens. If both lenses are made of identical glass and have identical focal ratio the whole system is free of chromatic aberration. Of course such a system can also be modified as a field spectrograph but then the advantage of sky suppression gets lost. The spectral purity is of course given by the focal length of the telescope, and therefore this spectrograph should be mainly used as a prime focus spectrograph. Radial velocity measurements can again be obtained by the Pickering reversion method (see also Geyer and Schmidt, 1976, Mitt. Astron. Gesellschaft, No. 40).

Blanco: Geyer has described the prism-grating combination he uses with a focal reducer. In various other talks at this meeting a grism or grating-prism combination used in the converging beams of large reflectors have been mentioned. In response to several questions addressed to me personally, I would like to remark on the differences between these two types of grating-prism combinations. In Geyer's device the prism is used to prevent deviation of the diffracted spectrum from the optical axis so that by reversing the prism and grating according to Pickering's method the measurement of radial velocities is possible. In this application, the dispersing device is used in a collimated beam.

In the case of the grism used in the converging beams of large reflectors, as we have done at Cerro Tololo and at Kitt Peak, the dispersion is achieved by a blazed transmission grating and the prism is only used to correct the first order optical aberrations that affect the spectrum because the grating is used in a converging beam. No attempt is made in this case to correct the deviation of the beam. Details of this device were published by Bowen and Vaughn in Publ. A. S. P. 85, 174.

Fehrenbach: Since 1952 at the Haute Provence Observatory we have used a prism with direct vision in the converging beam.

Kinman: The instrument Geyer has described seems very similar to one used by Dr. George Herbig in his Hα survey with the Crossley reflector at Lick some years ago.

Mendoza: At Tonantzintla Observatory, under Dr. C. Firmani we have an OMA system which is approximately 100 times faster than using a photographic plate. Both use a Meinel spectrograph. The resolution of the OMA system is between 1 and 2 Å. The spectrograms are widened 0.6 mm at 128 Å mm^{-1}. More details can be found in Rev. Mex. Astron. Astro., 1977.

M. Bruck: I have been asked to make some comments on COSMOS. COSMOS scans photographic plates at intervals of 16 microns, recording in each case the transmission on a scale of 120 between clear plate and zero transmission. The output may be recorded in map form. Alternatively, the sizes of star or galaxy images may be obtained and it is possible to discriminate between stars and galaxies. In the case of objective prism spectra in which this colloquium is interested, the mapping mode is used, the output being converted to relative light intensities by means of a step filter calibration recorded on the UK Schmidt plates. At present the scanning spot size is 16 microns, but since the unwidened spectra are very narrow (about 50 microns) a smaller spot of 8 microns is about to be incorporated. Details of the Cosmos machine can be found in Pratt, 1977, Vistas in Astronomy, Volume 21.

Welin: In addition to the way pointed out by Gratton there is another approach to getting to fainter limiting magnitudes with objective prism spectra. At Uppsala I have a filter isolating the region 3900 – 4500 Å. This reduces sky brightness (on IIaD plates) by a factor of about 5 (and simultaneously decreases overlapping), and thus permits the exposure time to be lengthened considerably. Most of the common classification features are contained in this wavelength interval.

Fehrenbach: The use of a filter (4000 – 4400 Å) has allowed Martin and Azzopardi to gain almost two magnitudes in their study of the LMC.

Gratton: The use of unwidened spectra improves the limiting magnitude of objective prism plates at the cost of a larger increase in plate noise. The situation is improved by combining the results from 4 or 5 plates. We have had success with this technique by using a cross correlation method. The gain, relative to a normal widened plate, by using 4 plates is of the order of 2 magnitudes, without a decrease in definition.

What we do is to use a small number (40 or 60) readily identifiable lines to find a good relationship between an abscissa x on the spectrum and wavelength. A list of about 6400 lines, identified by wavelength, is then introduced into the computer and the line strengths are automatically derived by best fitting. In some cases, however, the original wavelengths had to be modified and some lines had to be added to obtain a good fit.

Lynga: Your point about widening is an interesting one. We should try to understand why we widen spectra. In the case of classification I guess that the eye somehow uses the noise spectrum at right angles to the dispersion, while, if you record a spectrum one-dimensionally, you may consider the spectrum as a number of parallel exposures. The accuracy improves as the square root of this number while the exposure time increases with the number. One should thus use a small widening when planning to record the spectra.

Andersen: If one uses a microdensitometer capable of measuring high densities, it seems preferable to use narrow, heavily exposed spectra with less overlapping rather than wide, less dense spectra as used in visual classifications. The photometric noise should be the same, and one is working in addition at higher contrast.