On the Use of a Focal-reducer System for Slitless Fieldspectroscopy

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Summary. A slitless field-spectrograph for Cassegrain telescopes has been designed. It is based on the focal-reducer optical arrangement and grating prisms. With the “multiple diaphragm method” not only a gain in limiting magnitude of 3–4 mag has been achieved, but also other drawbacks of the classical objective prism camera such as low spectral resolution and the overlapping of spectra in crowded fields are avoided. Radial velocity measurements by the Pickering-Fehrenbach reversion method can be carried out with an accuracy of about ±13 km s⁻¹ per single plate, and a dispersion of 290 Å/mm.

Key words: slitless spectroscopy – focal-reducer techniques – grating prisms

1. Limitations of Slitless Spectroscopy

Slitless stellar spectroscopy has the main advantage of making use of the full field of the telescope. Therefore, in contrast to a single slit spectrograph the spectra of manifold stars are obtained with one exposure. The classical form of such slitless spectrographs is the objective prism (or grating) camera. With this type of instrument stellar fields up to several degrees in angular diameter can be photographed. Yet, it shows a number of disadvantages, which limit its range of application in astronomy.

Is R the diameter of the smallest achievable picture element at the focal plane of an ideal camera and D the reciprocal linear dispersion of the dispersing medium/camera arrangement, then the spectral resolution or purity which can be achieved is given by:

$$\Delta \lambda = D \cdot R.$$  (1)

In the case of slitless astrospectroscopy R is determined by three independent quantities: atmospheric seeing δ, diffraction at the entrance pupil A of the camera optics (2ρ = 2.44 · δ/λ), and the resolution r of the receiver. If further on fₑₑₑ is the effective focal length of the camera and/or telescope system and N its focal ratio (N = fₑₑₑ/A), then R is approximately given by

$$R \sim (r^2 + 5.95 \cdot \lambda^2 \cdot N^2 + \beta^2 \cdot f^2) \cdot \lambda/4.$$  (2)

Therefore, to achieve the best spectral purity, the camera focal length must be short, its focal ratio as small as possible, and furthermore the receiver’s resolution should be high.

In the case that $\beta \cdot fₑₑₑ > 2 \cdot (r^2 + 6 \cdot \lambda^2 \cdot N^2)^{1/2}$ the spectral purity is practically determined by seeing. On the other hand the application of short focus telescopes restricts the limiting magnitude. As is well known the limiting magnitude for direct stellar photographs is solely determined by the luminance of the night sky. Assuming the limiting magnitude is reached when the illumination by the star is about equal the illumination by the sky at the focal plane (Baum, 1957), the limiting magnitude for direct star photography is given by

$$m_{lim} \approx \text{const} - 5 \cdot \log R + 5 \cdot \log fₑₑₑ,$$  (3)

for the resolution limited case. This formula is of course valid for monochromatic light, too: For slitless stellar spectroscopy the limiting magnitude is also determined by the night sky illumination. However, although the night sky is dispersed too, the total sky brightness is contributing on account of the spectra of the sky elements, which overlap in the direction of the dispersion. Therefore the limiting magnitude in comparison to the direct exposure is reduced by a factor $q$:

$$q \approx \frac{\delta \lambda \cdot W}{\pi/4 \cdot R^2 \cdot D}$$

which is the ratio of the area of the stellar spectrum to the smallest picture element:

$$m_{lim} = m_{lim}^\delta - 2.5 \log q.$$  (4)

Here $\delta \lambda$, W are the spectral sensitivity range of the receiver and the widening of the spectra, respectively. Introducing (4) into (3) we arrive finally at the following formula in the case of slitless spectroscopy:

$$m_{lim} = \text{const} + 5 \log fₑₑₑ - 2.5 \log \frac{4 \cdot \delta \lambda \cdot W}{\pi \cdot D}.$$  (5)

It shows that the limiting magnitude is resolution independent.

A further disadvantage of slitless field spectrographs is the overlapping of stellar spectra in denser star fields. In addition in such rich fields like globular clusters or the Magellanic Clouds the sub-threshold stellar spectra act as an increased sky background and therefore further reduce the limiting magnitude.

Finally, it should be mentioned, that in slitless spectroscopy no comparison spectrum can be placed beside the stellar spectra.

The slitless field-spectrograph for Cassegrain telescopes to be described here was designed to reduce or avoid those disadvantages discussed above.

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2. The Optical and Mechanical Lay-out of the Focal Reducer Field-spectrograph

Nowadays several wide field Ritchey-Chrétien telescopes with field diameters up to 1.5 are in use. Therefore, it is desirable to design a spectroscopic equipment which makes use of the full field of such telescopes. The best optical arrangement for such an equipment is the focal-reducer. Its basic principle is to reduce the focal length of the telescope considerably. At the same time the focal ratio is also transformed to values of f/2 or f/1 typically. Schmidt seems to be the first who designed a focal reducer for the 60 cm−f/15 refactor of Hamburg Observatory in 1933 (quoted by Hellerich, 1938). In an afocal arrangement focal reducers were for the first time used by Meinel (1956) and Courtes (1951, 1960). Actually in this lay-out 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. Such an instrument manufactured by Jenoptik is in operation recently at the 106 cm−f/14.5 Cassegrain telescope of the Hoher List Observatory of Bonn University (Fig. 1). The schematic assembly is shown in Fig. 2: The field lens achromate has a diameter of 16 cm and is well placed outside the telescope focus by 25.5 cm. This is essential for our method of sky background reduction in the case of slitless spectroscopy (see below). The collimator three

lens achromate with an affective focal length of 72.2 cm and the field lens have been designed to reduce the coma of the Cassegrain telescope, so that a field of about 40' can be used. The distance between the last lens of the collimator and the entrance pupil of the camera is about 20 cm. Since here the beam of 5 cm diameter is parallel, all types of optical filters, Fabry-Perot interferometers and dispersing media for slitless spectroscopy can be inserted in front of the camera, which is a classical Schmidt system of focal ratio 2 with f = 10 cm. Presently we use this camera with films of 2.5 × 2.5 cm size, which are cut from normal 35 mm roll film.

The factor m by which the focal length of the telescope is reduced is given by

\[ m = \frac{f_{\text{coll.}}}{f_{\text{cam.}}} \approx 7.2. \]

This yields an effective focal length for the whole system \( f_{\text{eff}} = f_{\text{coll}}/m \approx 200 \text{ cm}. \) \( f_{\text{coll}} \) and \( f_{\text{cam}} \) are the focal length of the collimator, of the camera and of the telescope, respectively. Of course the scale factor is determined by \( f_{\text{eff}}. \) In our case the usable field diameter is 27'.

The longitudinal chromatic rest aberration of the field lens and collimator system is shown in Fig. 3. It is quite small, so that the chromatically blurred images are less than 0.01 mm in diameter within a wavelength range of 200 nm, and do not exceed 0.015 mm within a spectral range from 350 nm to 650 nm.

We modified this type of focal reducer to a slitless field-spectrograph by inserting dispersing media in front of the camera aperture. Since the camera is of short focal length only dispersing media with high angular dispersion are suited. Further on they should be of direct vision type for the application of the Pickering-Fehrenbach-reversion method of measuring relative radial velocities (Pickering, 1887; Fehrenbach, 1947). On the other hand a deflection of the path of rays towards the camera is then avoided. Also losses by vignetting are reduced to a minimum because the dispersing medium can be placed close to the entrance pupil of the camera. Such dispersing elements are the so-called grating prisms (“grisms”), if they are used in an inverted position (Carpenter, 1963; Geyer and Schmidt, 1976). This type of dispersing medium is made of blazed transmission gratings cemented onto the hypotenuse of a glass prism. Making the groove angle \( \vartheta \) nearly equal to the refracting angle \( \varphi \) of the prism, direct vision for a certain first order wavelength \( \lambda_0 \) is achieved, whereas zero- and higher orders are deflected beyond the camera’s field. Therefore nearly the entire angular dispersion is produced by the transmission grating and not by the prism. A simplified theory of the grating prism was given by Geyer and Schmidt (l.c.), the full theory including the distortion of the out axis rays, was given by Nelles (1978). The three grating prisms, which are presently at our disposal are listed in Table 1.

Table 1. Optical and geometrical data of grisms for the focal reducer of Hoher List Observatory

<table>
<thead>
<tr>
<th></th>
<th>GP I</th>
<th>GP II</th>
<th>GP III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruled width</td>
<td>65 × 65</td>
<td>65 × 65</td>
<td>65 × 65</td>
</tr>
<tr>
<td>( D/\lambda, f = 100 \text{ mm} )</td>
<td>146</td>
<td>292</td>
<td>456</td>
</tr>
<tr>
<td>( \lambda_0 ) (Å)</td>
<td>3050</td>
<td>3814</td>
<td>4850</td>
</tr>
<tr>
<td>( \vartheta )</td>
<td>17°95</td>
<td>12°33</td>
<td>10°55</td>
</tr>
<tr>
<td>( \varphi )</td>
<td>10°55</td>
<td>10°55</td>
<td>10°55</td>
</tr>
<tr>
<td>Grooves/mm</td>
<td>600</td>
<td>300</td>
<td>200</td>
</tr>
</tbody>
</table>

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3. Limiting Magnitude Gain by Sky Background Reduction

As was shown, this focal reducer field-spectrograph corresponds to a slitless spectrograph with a focal length of about 200 cm. For direct exposures (103a-O film) we reach at the 106 cm Cassegrain reflector a limiting magnitude \( m_{\text{lim}} = 19^m \) within 10 min exposure time, which is in accordance with the theoretical expectations. For spectra this limiting magnitude is reduced according Eq. (5) with \( W = 0.1 \text{ mm} \), \( D = 292 \text{ Å/mm} \) and \( \delta \lambda \sim 1000 \text{ Å} \) (O-plate) to about \( m_{\text{lim}} \sim 12^m \), which was actually observed. It is the great advantage of a focal reducer slitless spectrograph that sky background suppression is partly possible, which improves the limiting magnitude by 3–4 mag. This is attained by our "multiple diaphragm method": At first a direct exposure of the stellar field to be studied is taken in the telescope focal plane. Then according to this photograph small holes of diameter \( d \) are drilled in a metal sheet at the positions of the objects to be studied spectroscopically. Finally this multiple diaphragm is placed back into the cassegrain telescope focus. Now a second photograph is taken by the field spectrograph. The sky brightness for spectroscopy is reduced by this method by the ratio of hole image diameter to the length of the spectrum. In the case of rectangular holes of the size \( W \times d \) the gain factor is

\[
p = \frac{\delta \lambda \cdot m}{D \cdot d},
\]

which corresponds to a magnitude gain of

\[
\Delta m_{\text{lim}} = 2.5 \cdot \log p.
\]

Thus the limiting magnitude given by (5) is increased to

\[
m_{\text{lim}}(d, W) = \text{const.} + 5 \cdot \log f + 2.5 \cdot \log \frac{\pi \cdot m}{4 \cdot d \cdot W}.
\]

For circular holes the gain factor is slightly increased, and yields a magnitude gain of about 0.5°1–0.5°2 in reality. If widening of the spectra is done by moving the telescope, the hole diameter determines the maximum achievable widening:

\[
W \leq d/m.
\]

The limiting magnitude by sky background reduction according to Eq. (7) is independent of the linear dispersion and of the spectral sensitivity range of the receiver.

On the other hand if widening is done by moving the receiver, \( W \) can be allowed to be

\[
W > d/m
\]

and therefore \( d \) can be made even smaller than in (7), where it is restricted by (8). In this latter case the limiting magnitude is only

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The original mechanical layout of the focal reducer system has been complemented in the institute's workshop in the following way. First of all an offset \( x-y \) optical guiding arrangement ("goose neck") was installed in front of the field lens achromate, slightly behind the telescopes focus. Moreover a special double shutter plate-holder for \( 9 \times 12 \text{ cm} \) plates was designed, which allows to take direct photographs at the telescope's focal plane. The offset guider, which can be moved over the whole telescope field with an accuracy of 0.05 mm thus allows to centre the obtained plate onto the star field. Finally a special turning table for the grisms was designed, which allows to place them close to the entrance pupil of the Schmidt camera. Thus the grisms can be rotated in any angular position with an accuracy of 0.5° for obtaining reversed spectra according to the Pickering-Fehrenbach method for radial velocity determinations.
It is given by

$$g = \frac{4 \cdot W \cdot \delta \cdot m^2}{\pi \cdot d^2 \cdot D}.$$  \hspace{1cm} (10)

By this diaphragm method the problem of spectra blending by overlapping is also solved. All stars which may cause the blending of objects to be studied, can be masked easily. Therefore field spectroscopy in crowded fields like globular clusters is possible.

4. Results and Concluding Remarks

Figure 4 shows the exposure time versus limiting magnitude relation for GP II and GP III. Presently, the widening has to be done by moving the telescope. To give an impression of the quality of the spectra, Fig. 5a shows a considerably widened single spectrum of P Cyg and Fig. 5b that of the central part of IC 4665 obtained by means of the reversion method. The spectral purity on 103a-O films is about 7 Å for GP II and about 3 Å for GP I, respectively. Therefore MK classification is well possible in the latter case.

Our first results in the determination of relative radial velocities by the reversion method show, that an accuracy of \(\pm 13\) km s\(^{-1}\) on a single exposure can be achieved with GP II. Measuring absolute radial velocities demands the presence of about 10 stars with known radial velocities in the field, which can be realised only very seldom. This disadvantage can be overcome by the double image principle proposed by Nelles (l.c.). Such an instrument would make it possible to study the cinematics of a large number of fainter stars e.g. in the Magellanic Clouds. At present we are improving the outlined possibilities by the application of an image intensifier in connection with an f/3 camera.

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