Experimental Study of an Advanced Concept of Moderate-resolution Holographic Spectrographs

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Abstract

We present the results of an experimental study of an advanced moderate-resolution spectrograph based on a cascade of narrow-band holographic gratings. The main goal of the project is to achieve a moderately high spectral resolution with $R$ up to 5000 simultaneously in the 4300–6800 Å visible spectral range on a single standard CCD, together with an increased throughput. The experimental study consisted of (1) resolution and image quality tests performed using the solar spectrum, and (2) a total throughput test performed for a number of wavelengths using a calibrated lab monochromator. The measured spectral resolving power reaches values over $R > 4000$ while the experimental throughput is as high as 55%, which agrees well with the modeling results. Comparing the obtained characteristics of the spectrograph under consideration with the best existing spectrographs, we conclude that the used concept can be considered as a very competitive and cheap alternative to the existing spectrographs of the given class. We propose several astrophysical applications for the instrument and discuss the prospect of creating its full-scale version.

Key words: instrumentation: spectrographs – techniques: spectroscopic

Online material: color figures

1. Introduction

The optical design of any diffraction spectrograph uses one of two basic approaches (Palmer & Loewen 2014). The first approach relies on the use of a grating working in a single (usually the $+1\text{st}$) diffraction order, whereas the second one relies on echelle gratings working in multiple diffraction orders. In the first case, both the diffraction efficiency of the grating and the total instrument throughput can be very high. Also, this approach typically leads to relatively simple optical schemes with manufacturable optical components. However, an increase in the spectral resolving power requires increasing the grating frequency and narrowing the spectral working range. In echelle-spectrographs built according to the second approach, the diffraction orders are separated by a cross-dispersion grating or prism. Thus, the spectral image consists of many lines covering a wide range of wavelengths with high spectral resolving power. However, in addition to their technological complexity, such spectrographs are usually characterized by a lack of throughput.

For several research areas in modern astrophysics, it would be desirable to have an instrument occupying an intermediate position between the two above-mentioned groups in the resolution-throughput space. The authors had considered a possibility of building such a spectrograph on the basis of a cascade of volume-phase holographic (VPH) gratings (Muslimov et al. 2016a). As explained below, such a spectrograph combines the high efficiency of VPHs with an improved spectral resolution over an extended spectral range, which becomes possible due to the registration of multiple spectral images at the same detector simultaneously. This concept is new for astronomical instrumentation, so it should be thoroughly investigated before implementing a full-scale instrument mounted on a real telescope. For this reason, the optical scheme of a reduced and simplified laboratory prototype of the spectrograph was developed.

In this paper, we consider an experimental study of the prototype. We should emphasize here that there are a number of uncertain factors (mainly those related to the holographic materials and recording) influencing the actual performance of the instrument, which must be tested experimentally. The paper is organized as follows. Section 2 provides a short overview of the optical design of the spectrograph. Section 3 describes the manufacturing, alignment, and experimental study of the prototype. The latter includes throughput tests and measuring.
the actual spectral resolution. We also provide a brief comparison of the prototype performance with that of existing instruments of different classes. Section 4 summarizes the lessons learned from building the prototype. In Section 5, scientific cases which can be addressed by such an instrument are presented.

2. Concept of the Instrument and Optical Design

The concept of the instrument uses widely known properties of volume-phase holograms (VPHs). Such an optical element can provide high diffraction efficiency in a relatively narrow spectral region (Caulfield 1979). Outside of this region most of the incident flux is transmitted to the 0th order of diffraction. This feature can be used to couple several spectral and/or imaging channels in a single instrument as was shown, for instance, by Muslimov & Pavlycheva (2015). Particularly, if several VPH gratings are mounted one after the other in a cascade, each of them can create a spectral image in a dedicated narrow spectral range without affecting the beam propagation at other wavelengths. In this case the spectral image will represent a corresponding number of lines covering an extended spectral range with high dispersion and spectral resolving power. With a proper choice of groove frequency and incidence angle for each grating, it is possible to obtain a constant linear dispersion in each line and achieve tangential line centering. The lines in a spectral image can be separated by rotating the gratings in the sagittal plane. The first version of such an optical scheme was proposed by Muslimov et al. (2016a), although a similar concept can be traced back to Battey et al. (1995).

The spectrograph prototype considered in this paper is based on the optical scheme described and modeled in the studies of Muslimov et al. (2016b, 2017a). For convenience, here we provide a recap of the scheme layout (see Figure 1) and its main parameters used previously for calculations and modeling. The spectrograph operates in the visible range 430–680 nm. The operating region is divided into three bands: 430–513, 513–597, and 597–680 nm. The dispersion unit consists of three VPH gratings operating in the corresponding sub-ranges. The spatial frequencies of the gratings are 1726, 1523, and 1205 mm$^{-1}$, respectively. Below we refer to them as Blue, Green, and Red gratings. Each of the gratings is imposed on a plane-parallel plate made of BK7 glass and protected by a cover glass (the substrate thickness is 2.6 mm and the cover glass thickness is 2.2 mm). The length of each spectral image line is 20 mm (so the reciprocal linear dispersion is 4.15 nm/mm). The limits on the line spacing in a spectral image are 1.5–4 mm. The gratings are consequently mounted in collimated beams (the Blue grating is the first, and the Red grating is the last), so two identical commercial Tessar-type lenses are used as a collimator and a camera. Each of the lenses has a focal length of 135 mm and an f-ratio of 2.8. The actual entrance f-ratio is assumed to be decreased to 4. It was shown previously that the scheme provides a spectral resolution of 0.125–0.203 nm, 0.125–0.330 nm, and 0.125–0.151 nm in the three subranges specified above, respectively. The spectral resolving power obtained by modeling reaches $R= 5124$. The spectral resolution is limited mainly by the camera aberrations and varies significantly across the image plane. More details about the spectral resolution computation can be found in Muslimov et al. (2016b).

3. The Prototype

When creating the spectrograph prototype with limited funds available, we focused on studying the most important features of the instrument—its high throughput, spectral resolving power, and ability to simultaneously register a wide spectral range with a single standard 2K × 2K CCD. The diameter of the collimated beam was chosen to be 40 mm in order to decrease the cost of the customized VPH-gratings. (At the same time, such a diameter still allows us to reach the required spectral resolution with a 30 µm entrance slit).

The grating plates did not have an anti-reflective coating. This mitigation allowed us to reduce the total cost of the spectrograph and the time required to build it. At the same time, reflection losses can be easily accounted for when analyzing the measured data. However, later we shall return to the reflection losses question when discussing the full-scale instrument.

The VPH gratings were manufactured in the State Institute of Applied Optics (Kazan, Russia). Each of the gratings was recorded by two parallel beams obtained from a single laser source on a layer of dichromated gelatin (DCG, see, e.g., Newell 1987) and then protected by a cover glass. The diffraction efficiency of such a grating depends on the thickness of the holographic layer, the modulation of the refractive index, and the slanting angle of the fringes. Recording a customized grating requires precise control over all of these parameters at the same time.

Figure 1. General view of the spectrograph prototype optical scheme. (A color version of this figure is available in the online journal.)
Two identical Tessar-type commercial lenses were used as the camera and collimator. We used the widely available Tair-11 lenses ($F = 135$ mm, $F/2.8$). This lens has a proper focal length and an entrance pupil large enough to cover the dispersed beam. The lens aberrations are sufficiently small and their exact values are known in advance. The collimator lens was diafragmed down to $F/4$.

All these optical parts were assembled and adjusted in a duraluminium box coupled with a $2K \times 2K$, $13.5\,\mu\text{m}$ pixel size CCD. Figure 2 shows the grating assembly as integrated into the instrument. A fiber assembly coupled in a $30\,\mu\text{m}$ slit and an aperture equal to the collimator aperture was used in all our experiments presented below.

### 3.1. Analysis of Throughput

An increased throughput is the key advantage of the proposed optical design. Consequently, its experimental measurement is the primary goal of our study. The throughput was measured in a mounting which includes a stabilized calibration light source operating in a wide range of wavelengths, a standard monochromator, and the spectrograph opto-mechanical unit and CCD. The throughput estimates were obtained by observing this light source at spectrograph opto-mechanical unit and CCD. The throughput values were obtained as fractions of the registered light energy after passing through the optics, in relative units of the incoming light energy. The obtained results are presented in Figure 3. The lowest solid curve in Figure 3 illustrates the measured throughput of the prototype.

As can be seen from the plot, the measured throughput is not that high compared to theoretical expectations (Muslimov et al. 2016a). This can be explained within the framework of our engineering simplifications. However, in the future, the use of high-quality collimating/projection optics and effective anti-reflection coatings will allow us to raise it above 50% (the solid thick curve in Figure 3). Furthermore, this limitation is still not final due to the fact that the efficiencies of the used gratings can be enhanced. The measured efficiencies of the gratings appeared to be lower than the values predicted by computations. There are a few possible explanations. First, as we mentioned before, the efficiency depends on the parameters of the holographic layer. In our case these parameters could be made to have small errors during holographic recording or, more likely, they could be changed during the DCG post-processing or degraded with time. Second, the angles of incidence in the two planes define, on one hand, the resolution and mutual positions of the image lines and, on the other hand, the grating efficiency curves. Therefore, during the instrument alignment the condition of maximum efficiency could be broken to keep the resolution. We also should note here that gratings are never tested under conical diffraction conditions at the manufacturing stage. However, the found mismatch in the holographic layer parameters and/or replay angles is not a fundamental limitation of this design. In Section 4 we consider possible ways to avoid it in the future.

We should note that the presented results include only the transmittance of the spectrograph optics, with no account for the light loss due to atmospheric extinction, telescope reflectance, or light cutoff at the fiber input/output. The actual mounting conditions of the future full-scale instrument are not defined yet, nor are its specifications and detailed optical design. This makes an assessment of the on-sky performance of the instrument almost impossible and complicates comparison with the existing instruments. However, for a better understanding of the proposed spectrograph advantages, we compare the corrected experimental throughput with that of a number of existing instruments. We took the throughput data sets for Keck-HIRES (Vogt et al. 1994) and X-shooter at VLT (Vernet et al. 2011) and corrected them for losses in the telescope optics (Bass 1995). Similarly, we used the data for BTA-Scorpio corrected for the CCD quantum efficiency (Afanasiev & Moiseev 2005). Finally, we corrected the data for Subaru FOCAS (Ebizuka et al. 2011) for telescope losses and atmospheric extinction (Buton et al. 2013). The comparison of the throughput curves is shown in Figure 4. HIRES demonstrates a performance typical for echelle spectrographs. Its typical spectral resolving power is 67000, while the throughput is relatively low. X-shooter is a unique spectrograph constructed by a consortium of Institutes from a number of countries. It covers the entire wavelength range from...
UV to IR and shows probably the best performance for this class of instruments. For the spectral range under consideration it provides a spectral resolving power of 3300–9100 in the UVB and 5400–17400 in the VIS, where the exact value depends on the slit width. The typical value for Scorpio with VHPG550 is $R = 500$. FOCAS provides $R = 2500$ with the VPH650 grism and $R = 3000$ with VPH520. From this plot one can see the niche between the existing types of spectral instruments, which corresponds to our prototype. When compared to a classical high-resolution echelle spectrograph, our solution provides a substantially higher throughput, but the spectral resolving power is lower (see the next subsection for the prototype spectral resolving power). Compared to a typical low-resolution spectrograph, it has a slightly lower throughput due to a larger number of optical components and a complicated alignment process. These two factors will be present even if we exclude the imperfections of the gratings. However, it has a higher resolving power. In comparison with the recent highly efficient echelle-based design used in X-shooter, the prototype shows similar maximum throughput and less perturbations of the curve, therefore the effective throughput is considerably higher. In the context of spectral resolution, the performance approaches that of an echelle spectrograph, although the exact ratio strongly depends on assumptions about sampling. We would like to emphasize that this performance was achieved with relatively simple optical components and can be significantly improved in the future. Finally, the throughput curves for our spectrograph are close to those of the FOCAS instrument, while the spectral resolving powers are comparable. Nevertheless, in contrast with FOCAS, the prototype allows us to register all the spectra simultaneously at the same detector. To achieve this capability, we must reconcile with the irregularity of the throughput. We have to use a narrow-band grating to minimize the gratings crosstalk. As a result, the throughput drops around the sub-range boundaries. Relying on these comparative studies we propose several application strategies for our concept, which are described in Section 4.

3.2. Analysis of Spectral Resolution and Ghost Levels

Next, we obtained spectra of scattered solar light fed through the fiber assembly to the described spectrograph prototype. One such image is shown in Figure 5. A vertical section of this image taken at the frame center (Figure 6) illustrates the relative intensities of the spectral bands accumulated with each of the gratings. The difference between the bands is explained by the grating manufacturing and alignment issues mentioned above. Moreover, the grating efficiencies are convolved with the CCD quantum efficiency and the light source intensity.

The cascaded design of the dispersion unit can suffer from secondary spectral images, which appear because of the presence of non-working diffraction orders and overlapping efficiency curves of individual gratings. Hereafter we refer to these undesired images as “ghosts,” as adopted in spectroscopy, even though their nature is different from that of the ordinary spectral ghosts.
In order to extract the observed solar spectra, we reduced the CCD frames in a standard manner including the following steps: cosmic-ray hit removal, electronic bias subtraction, scattered light subtraction, spectrum extraction, etc. The wavelength calibration procedure was carried out using a list of known solar spectral lines. The DECH software\(^7\) was used to process all the steps. As an output result we obtained a series of solar spectra that we used to study the possible influence of ghosts from secondary reflections and to measure the spectral resolution. An example of the output solar spectra is shown in Figure 7. Comparing the standard high-resolution solar spectrum with the observed one, as well as analyzing closely located spectral doublets, we estimate that the measured spectral resolving power is generally lower than the modeling results and theoretical predictions. The best spectral resolving power of \(R = 4000-4100\) was obtained for the Blue band at 500–510 nm. The corresponding theoretical value is 1905, whereas for the entire Blue band it varies between 1898 and 3776. The highest value in the Green band is \(R = 2600\) at 544–555 nm. The theoretical value for this narrow region is 3944, and for the Green band it is 1916–4460. The Red band exhibits \(R = 3500\) at 572–582 nm. The corresponding theoretical value is 3994 and for the whole band it is 3953–5124. The actual image plane for each of the bands is tilted and shifted relative to the other bands, so the alignment of the detector implies searching for the best-fit plane. Thus, the difference between the observed and computed values for the Green and Blue gratings is due to the redistribution of aberrations between the green and blue image lines. So the result for these two gratings can be considered acceptable. As for the observed results for the Red grating, we assume that the recording wavefronts could have some imperfections like a small defocusing and/or tilt, which affect the image quality and the line centering. The suggestions on the dispersion unit

\(^7\) http://www.gazinur.com

Figure 4. Comparison of the corrected throughput of the prototype with those of existing astronomical spectrographs of different classes. (A color version of this figure is available in the online journal.)
modifications listed in Section 4 could help to eliminate such effects. In order to provide a visual demonstration and a quantitative estimate for the misalignments causing the observed resolution changes, we performed the following modeling. We optimized the values of angular positions of all the gratings, the dispersion unit positions, the focusing of the lenses, and the Red grating residual optical power to fit the measured instrument function widths. We found that the observed spectral resolution may be affected by the following alignment errors: the collimator focusing error is 0.59 mm, the collimated beam decentering is 10.4 mm; the dispersing unit angular position errors (X/Y) are 2°72/1°01; the Blue grating angular position errors are 0°08/−1°00, the errors for the Green grating are −1°00/−1°01 and for the Red grating they are equal to 0°67/0°99; the Red grating residual focus is 32.3 m, the camera focusing error is −0.69 mm; the CCD can be decentered by 0.98 mm and turned by −1°03 around the X axis. Note that these values are not the actual measured quantities, but they can provide an estimate of the scale of the alignment problem. Presumably, these deviations are due to the search for a compromise between the mutually contradicting conditions of the maximum resolution and maximum efficiency, as was explained above.

Visual inspection of the morphology of the scattered light of the working spectral orders has revealed traces of spectral ghosts at typical levels of considerably less than 0.5% (the zoomed area in Figure 6 demonstrates the strongest ghost). These ghosts are due to secondary reflections and non-zero residual spectral orders other than the used first order (see explanation above). Meanwhile, such a level is almost perfect. This is probably the most important result in our study which allows us to conclude that the use of a cascade of holographic gratings in astronomical spectrographs enables one to obtain very high quality spectral data with signal-to-noise (S/N) ratios of up to S/N = 1000. We also note that this result should be considered as a lower limit due to the simplifications made in our prototype. We are certain that a high-quality solution would allow us to obtain several-fold better results.

To summarize the analysis of the experimental data presented above, we can conclude that the results obtained with the prototype should be considered as a successful verification of the concept. The results are fully consistent with all the key features of a spectrograph based on cascade of VPH gratings. Further design enhancements and potential scientific applications are discussed below.

4. Lessons Learned and Notes About a Full-Scale Instrument

The experience obtained during the development, construction, alignment, and operation of the spectrograph prototype allows us to make several conclusions concerning the implementation of this or similar designs in the future:

1. It may be reasonable to arrange the gratings in a red-to-blue order cascade. This may help decrease the channel crosstalk (Muslimov et al. 2017b), although some geometrical conflicts might arise.
2. Simultaneous focusing of several spectra onto the same detector can cause significant difficulties. At least some of them can be eliminated by proper tolerance designation and wavefront control during the hologram recording.
3. Reflection on multiple surfaces leads to a notable decrease in total throughput. Therefore, a more complex (and costly) anti-reflection coating should be used. Alternatively, the design could be changed in order to decrease the number of refracting surfaces.

We should note here that some of the difficulties with the prototype are attributable to the used holographic material, i.e., dichromated gelatin (DCG). DCG processing consists of several steps, which complicates the precise control of the grating efficiency curve. Moreover, DCG has a high sensitivity to environmental conditions, so each grating should be protected by a cover glass (even in this case there is a high risk of grating degradation). Most of these issues can be resolved in a design using modern photopolymer holographic materials proposed by Zanutta et al. (2017a, 2017b). More information on photopolymer properties can be found in Bruder et al. (2010) and other publications by these authors. Among them we should emphasize the experimentally proven possibility of calibrating the refractive index modulation. This property allows one to produce customized VPHs with a high
efficiency in the dedicated region. In addition, this advanced concept can be applied not only when building a new instrument, but also when upgrading an existing one.

Summarizing all the conceptual advantages and shortcomings of the cascade-VPH spectrograph and its features which we encountered during our work on the prototype and this paper, we can propose the following strategies for building a full-scale spectrograph:

1. **Building a simplified version of a multichannel VPH-spectrograph.** With the presented concept it is possible to create a high-performance instrument analogous to the leading VPH-based designs like Ebizuka et al. (2011) and Tamura et al. (2016). The cascaded design allows one to reach a high throughput and a moderately high spectral resolution over the entire working range at the same time. The spectrograph uses only one camera and a single detector and has no customized dichroic splitters. A spectrograph similar to the described prototype would be much cheaper and simpler, so it could be of special interest for a large number of observatories owning mid-class telescopes. However, our solution has some obvious limitations like the throughput irregularity shown above or the possibility to implement some special observational modes like the integral field measurements.

2. **Competing with low- to medium-resolution echelle spectrographs.** As was demonstrated above, the proposed design is notably different from echelle spectrographs. An interested reader can easily estimate the difference in performance between our prototype and a potential equivalent echelle spectrograph. Even the best commercially available echelle grating (Nelson et al. 2010) has limited efficiency, which does not exceed 58%. Using a typical transmission of a cross-disperser prism (Hearnshaw 2009) and assuming that the spectrograph has a simple collimating mirror and a camera identical to the one used in our experiments, one can find that for an equivalent echelle-based scheme the maximum throughput is 38.5% at best. Meanwhile, with a blaze angle of 63° (Nelson et al. 2010) and a focal ratio of 4 such a spectrograph could reach R7600 with the 6 m telescope. Moreover, the use of more complex optics or a further mitigation of the spectral resolution would not help one to achieve a significant increase in the echelle spectrograph throughput. On the contrary, modeling has shown that using an advanced camera and AR coatings would allow one to build a VPH-based instrument with a throughput approaching the maximum of 60% (Muslimov et al. 2017a). In addition, different target specifications would require a customized (and therefore, much more expensive) echelle. A customized VPH can be produced using exactly the same equipment and materials as a standard one, so the cost difference will be relatively small. Thus, we can conclude that although echelle spectrographs are beyond competition in high-resolution application, for the given niche a cascaded VPH has significant advantages. Below we discuss a number of scientific applications where an increased throughput is a critical requirement, whereas the spectral resolving power of \( R = 5000 \) is sufficient.

3. **Replacing the existing spectrographs with transmission dispersers.** There are a large number of obsolete low- to
medium-resolution spectrographs using VPH gratings and grisms. They can be re-built with a new cascaded or multiplexed VPH disperser. In the majority of cases some parts of the existing instrument, especially the camera and collimator optics and the detector assembly, can be re-used. This strategy is of special interest for instruments which already use interchangeable VPH dispersers like the one reported by Clemens et al. (2004) or the one mentioned by Afanasiev & Moiseev (2005). In this case one can actually obtain a new instrument with a substantial gain in performance. For instance, thanks to the simultaneous registration of spectra, one can obtain a substantial gain in the observation time. On the other hand, the expenses in terms of design and manufacturing would be minimal. We must note that a more advanced version of this strategy was already proposed and explored in Zanutta et al. (2017a, 2017b). In this case, even the geometry and all the mechanical parts of the instrument can be kept.

5. Science with the Spectrograph

The presented spectrograph has a number of advantages in comparison with the existing low-resolution spectrographs (with a resolving power of less than or about R1000 for the whole visible range, and a total throughput higher than 50%) and high-resolution echelle spectrographs (with the resolving power higher than R10,000, and a total throughput of less than or about 10%). Our cascade-VPH scheme has advantages over both of the above-mentioned types of spectrographs, as it can achieve a resolving power of at least R5000 and a total throughput of up to 50%. This solution provides a comparatively high resolving power while keeping the broad spectral region typical of echelle-spectroscopy with a much higher throughput. Naturally, the resolving power of the prototype is lower than that of echelle-spectrographs.

This spectrograph is an intermediate solution between low-resolution spectrographs with a single grism/VPH and echelle spectrographs. In the first case one can observe very faint targets with a resolving power of R1000–R2000 (150–300 km s\(^{-1}\)). In the second case, we can not detect fainter targets by using echelle-based spectrographs. An echelle spectrograph covering the entire optical range can detect stars only down to the 15th magnitude, or down to the 18th magnitude if we use 8–10 m class telescopes. Therefore, a cascade-VPH spectrograph is more effective in the studies of faint and low-contrast objects.

The main advantage of the cascade-VPH prototype is the possibility of studying low-contrast and faint objects, since it has: (i) a higher resolving power of about 60 km s\(^{-1}\), (ii) a total throughput of up to 50%, and (iii) a wide spectral range.

**Requirement on the spectral resolution.** In such a case we may accurately distinguish between H II regions and planetary nebulae and stellar winds in massive stars. Massive stars on the Main Sequence and beyond, at the final stages of their evolution, are observed in galaxies in the Local Universe at distances of up to 50 Mpc; as a rule they are observed against a strong background (H II regions). They are LBV stars (Luminous Blue Variables), B[e]-supergiants, WR-stars (Humphreys & Davidson 1994; Fabrika et al. 2005; Sholukhova et al. 2011; Neugent et al.
2012; Sholukhova et al. 2015); their magnitudes are fainter than 18. LBV stars in their cool stage may have emission line widths (FWHM) of about 150–200 km s$^{-1}$. They produce the surrounding nebulae as a result of mass loss due to strong winds. Distinguishing between the nebulae and the winds is very important. The same is valid when searching for objects in nearby galaxies (Fabrika & Sholukhova 1995), as this is an important clue for understanding these targets. X-ray sources in galaxies also produce jets and nebulae; the large nebula S26 in the nearby NGC 7793 galaxy (Pakull et al. 2010), which looks like a copy of the famous Galactic source SS 433 (Fabrika 1997), the only known super-Eddington accretion disk in the Galaxy, is one example. The black hole binaries (accretion disks) in our Galaxy have dispersion velocities (Soria et al. 1999; Rahoui et al. 2017) ranging from 400 to 1000 km s$^{-1}$; in the case of surrounding nebulae, a cascade-VPH spectrograph can reveal the difference between the broad emission lines and the H II regions. We note that in addition to the spectral resolution, other properties (throughput and spectral range) are also very important.

For the bright stars in our Galaxy, the main advantage is a good spectral resolution and the highest throughput. Magnetic fields of up to 100 Gauss can be measured for the brighter stars (Monin et al. 2002) with a higher S/N ratio. If we look at the spectra of standard DA white dwarfs, we cannot resolve the narrow absorption lines that appear at the centers of the hydrogen lines (H$\beta$, H$\alpha$); however, using the whole range with a cascade-VPH spectograph, we can implement such a resolution. The same is true for magnetic white dwarfs if we use polarimetry. It is also necessary to cover the entire visible range, where hydrogen or helium lines may shift by hundreds of angstroms and may have various unexpected broadenings. Especially interesting is the fast line-profile variability in the spectra of OB stars (Kholtygin et al. 2003); these stars are bright, and in a few minutes of exposure the S/N ratio can increase to about 1000. Therefore one needs to have both a good transmission and a good spectral resolution for these stars.

**Requirement on the throughput.** Recently, objects of a new type—ultraluminous X-ray sources (ULXs)—have been discovered in nearby galaxies. For these sources, it is important to have sufficient throughput, as well as good resolution and optical range. These are super-Eddington accretion disks or intermediate mass black holes (IMBHs). Optical spectroscopy of these 21–24th magnitude targets is very important (Cseh et al. 2013; Fabrika et al. 2015), as there are only a few such spectra, since these objects are very faint. Again, they are observed against strong H II region backgrounds with different ionizations and different velocities. Distinguishing between the H II regions (O III); $\lambda \lambda 4959, 5007$, N II; $\lambda \lambda 6548, 6583$, S II; $\lambda \lambda 6716, 6730$) and hydrogen, He I, and He II emission lines is possible for ULXs. The centers of young stellar clusters in star-forming galaxies host very massive stars (VMS) with masses higher than 200 solar masses (Crowther et al. 2010; Solovyeva et al. 2017), which can evolve into IMBHs in a short time. We must have good resolution in the entire spectral range, because in the blue and yellow regions, we observe high-ionization nebular lines ([O III]), and in the red region, we observe the low-ionization lines ([OI], [N II], [S II]), which may differ in their structure and velocities. In these same young stellar clusters, it is difficult to find high- and low-ionization nebulae with different dispersion velocities. This may be of critical importance, because one can detect both narrow and broad lines, emissions and absorptions. This is a new field in modern astrophysics.

Finally, a cascade-VPH spectrograph can be effectively used in the studies of exoplanets. In particular, it will be a very effective instrument in the hunt for scattered light from hot-Jupiter exoplanets (Grauzhanina et al. 2015) and for spectral studies of transit events caused by giant planets (Langford et al. 2011; Grauzhanina et al. 2017). These studies are presently among the hottest topics in modern astrophysics.

**Requirement on the spectral range.** Nearby galaxies like M 33, M 31, M 81 host many novae-like objects. Besides massive stars and X-ray sources one observes novae and recurrent novae (Darnley et al. 2016), which can appear as bright 16–17th magnitude targets and then become fainter over a week or longer. Observations of novae show that their emission lines become narrower with time, dropping from several thousand km s$^{-1}$ to 100 km s$^{-1}$ (depending on the ionization state) as their brightness decreases.

When we consider our Galaxy with its brighter targets of up to the 18th magnitude, the main reasons are the spectral resolution of up to R5000 and the wide spectral range $\sim$450–680 nm. The presented spectrograph can also be effectively used in spectrophotometric studies of photometrically variable magnetic white dwarfs (Brinkworth et al. 2013; Valeev et al. 2015, 2017), as well as in their moderate-resolution spectropolarimetric studies (Valyavin et al. 2006; Landstreet et al. 2012) by equipping the spectrograph with polarimetric optics (Naidenov et al. 2002). For magnetic white dwarfs, a search for kilogauss magnetic fields in white dwarfs and hot subdwarf stars can be performed. Using spectropolarimetry with such a resolution allows one to observe targets like T Tauri stars (Smirnov et al. 2004) where both the emission and absorption lines can be measured.

The spectrograph can be easily updated to use different spectral ranges with the same spectral resolution and throughput. The main spectral features must be shifted to have maximum (or nearly maximum) throughput. They are H$\gamma$, H$\beta$, H$\alpha$, the main He I lines (H$\lambda 471, 4922, 5015, 5876, 6785$), the Bowen blend C III/N III ($\sim$A4640), the He II line A4685, and the main nebular lines O III; $\lambda \lambda 4959, 5007$, N III; $\lambda \lambda 6548, 6583$, S III; $\lambda \lambda 6716, 6730$. It is also possible to install an additional VPH into the cascade to create a broader spectral range.
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