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DEVELOPMENT OF A MULTIFUNCTIONAL INSTRUMENT FOR THE 1.4m MILANKOVIĆ TELESCOPE

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Abstract. In this work, we present an idea for the construction of a multifunctional device for the 1.4m Milanković telescope at the Astronomical Station Vidojevica. The device would be optimized to operate in three modes - low resolution spectroscopy, image polarization and photometry. This work is a collaborative project of astronomers in Astronomical observatory of Belgrade (AOB) and the Special Astronomical Observatory of the Russian Academy of Sciences (SAO RAS), which has a long history in designing and building similar instruments. We will present the main idea of the project and the possible technical solution of the device that is optimal for the Milanković telescope.

1. INTRODUCTION

The Astronomical Observatory in Belgrade (AOB) has a long tradition of the astronomical observations: e.g., photometry and polarimetry on a 65cm refractor (e.g. Vince et al., 1997) or solar spectroscopy (e.g. Vince et al., 1997). However, regular night-time observations (including polarimetric) were interrupted as early as 1980 due to light pollution above the observatory and even solar observations were stopped since 2004.

To continue the astronomical observations in Serbia, the Astronomical Station Vidojevica (ASV) station was established. The construction of the ASV began in 2003 on the summit of mountain Vidojevica in the south of Serbia. Today it has the complete infrastructure to run the station, three optical telescopes for observations and numerous auxiliary instruments (e.g. Vince, 2021).

The Milanković telescope is the largest telescope on the ASV. It is a f/8 Nasmith telescope with a primary mirror diameter of 1.4m and 33% obscuration from the secondary mirror. The design features two Nasmith ports that are equipped with a precise derotator. Currently, one port is equipped with the ikonL CCD camera[1]

[1]https://andor.oxinst.com/products/ikon-xl-and-ikon-large-ccd-series/ikon-l-936

from Andor company and various broadband and mid-band filters for photometry and imaging. The second port is equipped with an iXon897 EMCCD camera[2], also from Andor company, for observation with the Lucky imaging technique.

The 1.4m Milanković telescope was installed in 2016 and, due to inertia, photometric and astrometric measurements were immediately performed according to the observational projects of the time. The second Nasmith port was free, so the Cherny-Turner spectrograph, initially acquired for the 60cm telescope at ASV (Vince and Lalović, 2005), was installed on this telescope (Vince et al., 2018). However, there were numerous technical problems that prevented the spectrograph from being put into regular use. The examination of the polarimetric capabilities was also done. We have tested a Savart plate received from SAO RAS, which can be rotated manually in two fixed positions. After some successful tests, we decided to start this project, which we are still working on today.

The use of small ground-based telescopes has an important role in observational astronomy, especially in follow-up projects of large international projects such as LSST, JWST, Gaia and so on. In addition to photometric observations, spectroscopic and polarimetric observations can also be effectively performed on small telescopes. Many telescopes are equipped with spectrographs (e.g. DFOSC[3] on 1.54m telscope), polarimeter (e.g. RoboPol[4] polarimeter on 1.3m telescope) or both (e.g. MAGIC on 1m telescope, which we will mention in this paper).

Our ambition is to equip the 1.4m Milanković telescope with a multi-functional instrument that will unite three functionalities - spectroscopy, polarimetry and photometry. We are working on the realization of this idea in cooperation with SAO RAS team. In this paper, we will present the conceptual design and general characteristics of the future instrument. The first section is intended for introduction. The second section details the conceptual design of the multi-mode device. We also provide preliminar calculations for the optical elements of the future instrument and calculate photon statistics with the aim of determining the efficiency of the instrument for different observational functionalities. The last section is the conclusion.

2. CONCEPTUAL DESIGN OF THE MULTI-FUNCTIONAL INSTRUMENT

Our ambition is to create an instrument that combines the following three observational functions: **Spectroscopy** - slit spectrograph with spectral resolution power R=1000-3000, **Polarimetry** - imaging polarimeter with polarization degree error $<0.1\%$ for a ≤ 15 magnitude star-like object in the V band, and **Photometry** - CCD photometry in various broadband and mid-band filters with a field of view without aberrations $\geq 10'$.

Figure 1. shows the conceptual scheme (left panel) and three-dimensional presentation (right panel) of the future multi-functional instrument (credit: L. Pančić). The design of the instrument is very similar to the MAGIC focal reducer designed by the SAO team, which is installed on the 1m Zeiss-1000 telescope at the SAO observatory (Afanasiev et al., 2023)

[2]https://andor.oxinst.com/products/ixon-emccd-cameras

[3]https://www.eso.org/public/teles-instr/lasilla/danish154/dfosc/

[4]https://robopol.physics.uoc.gr/

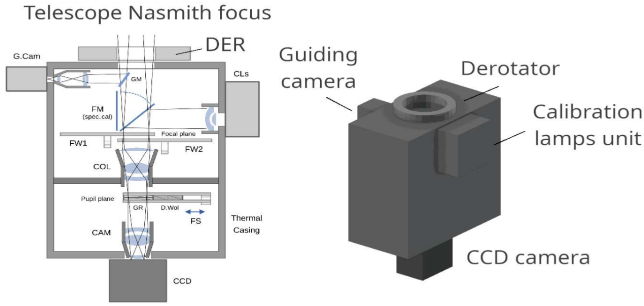

Figure 1: Schematic presentation of the future multi-functional instrument (left) and its 3D visualization (right). Credit: L. Pančić

Following the optical path of light from the telescope to the CCD camera, the multifunctional instrument consists of the following elements:

1). The spectrograph will be mounted directly on the existing derotator (DER). The load capacity of the derotator on our telescope is about 150 kg, while the planned weight of the device is less than 35 kg.

2). Telescope guiding is an important element for spectroscopy because it prevents drifting of the star image on the spectrograph's slit due to tracking errors. Currently, there is no guiding system on the telescope, and the telescope tracking error is around 5 arcsec per hour. Our proposal is to develop a commonly used guiding system consisting of off-axis mirror (GM) and direct it to the guiding CCD camera (G. Cam). Such a system typically decreases the tracking errors down to less than 1" per hour which is enough for the observations with 1-2" slit.

3). The calibration unit is a simple system with lamps (continuum lamp or combination of LEDs for flat-field calibration and emission line lamp for wavelength calibration in the Ulbricht integrating sphere), lens to provide a light beam with the focal ratio of the telescope, and flat mirror to direct the light beam from lamps to the spectrograph slit. The ADAM spectrograph, one of the instruments developed at the SAO RAS, is a good example of how the calibration unit can be solved (Afanasiev et al., 2016).

4). FW1 and FW2 indicate two filter-wheels that will hold slits with different slit-widths for spectroscopy, mask for polarimetry (to avoid blending of the ordinary and extraordinary rays), and different broadband and mid-band filters for spectroscopy/polarimetry/photometry. Slits and mask must be placed in the focus of the telescope.

5). Collimator lens is marked with COL on the optical scheme. Spectral resolution power is proportional to the focal length of the collimator, however, from an instrument design perspective, the focal length and its diameter, are determined from two conditions for photon conservation (see the example bellow).

6). In the parallel light beam between the collimator and the camera lens systems, there is a dispersive element for spectroscopy (GR) and a polarization analyzer for polarimetry (D.Wol). These two optical elements are placed on a filter slider that can be shifted with a stepper motor. Depending on which mode of the instrument we want to use (spectroscopy, polarimetry, or photometry), the appropriate optical

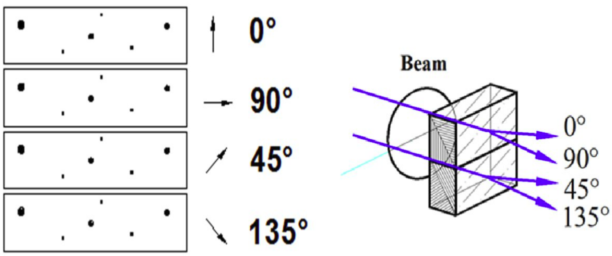

Figure 2: An example of the arrangement of a double Wollaston prism and the corresponding CCD image output (see the text). Credit: E. S. Shablovinskaya

element is placed in the optical path of the device (in the case of photometry, it is an empty field).

For the dispersion element in the MAGIC focal reducer, they use a VPH grisms, that is, a combination of VPH grating and prism. VPH grism are usually used to improve the spectral dispersion (compared to just using a grating) , to create a straight pass dispersive element (in-line spectrograph), and for higher transmission. Because of the design presented in the Figure 1., the use of a VPH grism is foreseen for our instrument too.

For the polarization analyzer in the MAGIC instrument, they use double Wollaston prism. The Wollaston prism consists of two wedges glued together in such a way to separate light into two linearly polarized output beams with orthogonal polarization. Double Wollaston prism consists of two Wollaston prisms oriented in a such a way to get four linearly polarized output beams with different polarization angles: 0, 90, 45, and 135 (Figure 2). The advantage of using a double Wollaston prism is that the three Stokes parameters, Q, U and I can be determined from a single CCD image.

7). The camera lens is the next optical element (CAM). The focal length of the camera lens is calculated from the reciprocal linear dispersion and the condition that the spectral resolution element must be sampled with at least two pixels of the CCD camera. Its diameter is calculated from the anamorphic factor (see the example bellow).

Case study for the spectrograph. Here, we describe the design of the grism spectrograph with goal to resolve spectral lines with a precision of 100 km/s[5]. Thus, the spectral resolution power of the device should be $R = c/v \geq 3000$, where c is the speed of light. The corresponding spectral resolution at $\lambda = 6563\mathring{A}$ is $d\lambda = \lambda/R \leq 2.2\mathring{A}$.

For in-line diffraction $\alpha = -\beta = A = \theta$, where α and β are the angle of incident and diffracted light relative to the grating normal, A is the apex of the prism and θ is the blaze angle of the grating. The grating equation in this case is $sin(A) = (k\lambda g)/(n-1)$, where k is the diffraction order, λ is the central wavelength where we make the calculation, g is the number of grating grooves per millimeter, and n is the refractive index of the prism. For example, working in the first diffraction order (k=1), using

[5] We note that this precision is defined arbitrarily, that is, without a clearly defined scientific goal and precision that is optimal for the corresponding observation on the Milanković telescope. However, this precision may represent the maximum precision we want to achieve with this spectrograph design.

a 50x50 mm^2 grating with g=350 grooves/mm, and a glass prism with a refractive index n=1.54 (glass), we can calculate that the A is about 25 degrees.

Characteristics of the collimator lens system, the focal length and its diameter, is determined from two conditions for photon conservation mentioned above: a) the focal ratio of the collimator lens must be equal (or less) to the focal ratio of the telescope, that is, $F_{col}/D_{col} \leq F_{tel}/D_{tel}$, and b) the diameter of the light beam behind the collimator lens, D_{col}, must not be greater than the physical size of the dispersion element, that is 50mm in our case. From these two conditions, it can be calculated that $F_{col} \leq 400mm$ and $D_{col} \leq 50mm$.

By differentiating the grating equation by the dispersion angle, the angular dispersion of the grating can be determined, and the reciprocal linear dispersion can be directly determined from it, $d\lambda/dx = ((n-1)cos(A))/(kgF_{cam})$. On the other hand, the spectral resolution element, $d\lambda$, must be sampled with at least two pixels of the CCD camera, $d\lambda/dx \leq d\lambda/(2e)$, where e is the pixel size. For CCD camera with pixel size $13\mu m$, it can be calculated that the camera lens focal length is $F_{cam} \leq 165mm$. In general case, anamorfic factor is given by $r = cos(\alpha)/cos(\beta) = D_{col}/D_{cam}$. Therefore, the diameter of the camera beam is $D_{cam} \leq 50mm$.

At this point we have the characteristics of all optical elements for the low resolution spectrograph. Installed on the Milanković telescope (focal length 12000mm and primary mirror diameter 1400mm) and with the spectrograph slit opened to 1.2" (median seeing value on the ASV), we can calculate that the spectral resolution power is $R \approx 2900$ and spectral resolution $d\lambda \approx 2.3\mathring{A}$, which is very close to the values we have defined at the beginning of this example. It can be shown that the flux density for an A0V star of magnitude 16 for such a spectrograph is about 1 e^-/s/pix [6]. Using CCD camera with readnoise about 10e^- and negligible dark noise, 300s of exposure time provide SNR $\approx$ 14.

Case study for the polarimeter. Assuming that the double Wollaston prism has the same effective surface area as the grism (50mm), we can calculate photon statistics for polarization measurements as well. In the case of linear polarization, we measure three Stokes parameters, Q, U and I. In practice, it is common to calculate the degree of polarization and the angle of polarized light via the normalized Stokes parameters, $q = (I_0 - I_{90})/(I_0 + I_{90})$ and $u = (I_{45} - I_{135})/(I_{45} + I_{135})$, where I denotes total counts of stars measured in the aperture, and subscripts denote four different polarization angles. The degree and angle of polarization are then calculated using simple formulas: $P = \sqrt(q^2 + u^2)$ and $\theta = 0.5 \times arctan(u/q)$. The errors of these parameters are calculated in the usual way by error propagation.

Ramaprakash et al. (1998) derived an approximate formula that is useful for photon statistic calculation. For the polarization degree $\sigma_p \approx 100 \times \sqrt(I + I_B)/I$, where $I = I_e + I_o$, that is, sum of number of photo-electrons in ordinary and extraordinary star images, and I_B is the background flux. By using the same conditions described in the footnote 3., it can be shown that for $\sigma_p = 0.1\%$ we need about 10 minutes exposure time for a 15 magnitude star in V band.

Regarding polarimetry, attention should be paid to several things, of which we will mention only the two most important: 1). In Nasmith telescopes, the tertiary mirror

[6] For the calculation this values were used: atmospheric transparency 0.80, total instrumental efficiency 0.20, effective collection area of the telescope 13700cm^2, and the sky brightness of 20 mag/arcsec^2

can produce instrumental polarization (IP) of about 5%, and this parameter depends on the telescope position, therefore IP must be corrected (e.g. Tinbergen, 2007), and 2). none of the listed parameters used to calculate the degree/angle of polarization have a normal distribution, so this must be taken into account, especially if the SNR is low (e.g. Wardle and Kronberg, 1974).

3. SUMMARY

In this paper, we presented the idea for the design of a multi-functional instrument, which will be optimized for the 1.4m Milanković telescope. Taking into account the real conditions of observation on the ASV, as well as some real parameters of the optical elements of the instrument, we have shown that the future instrument is suitable for the set tasks. With a collimator lens with aperture ratio ≈f/8 and a camera lens with aperture ratio ≈f/3, it is possible to obtain a spectrum with spectral resolution power R≈3000 and a spectral resolution element in the vicinity of the H_α emission line of around $2.2\mathring{A}$. For the reference, with about 5 minutes of exposure time, that is, time period where the Milanković telescope is very precise in tracking stars on the whole sky, a spectrum with a signal to noise ratio per pixel of around 14 can be obtained. With the same parameters, a polarimetric precision of 0.1% for a 15 magnitude star in the V band can be obtained in less than 10 minutes of observation. These results encourage us to continue building this multi-functional instrument in cooperation between AOB and SAO RAS.

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