# Planetary Fiber-Fed High Spectral Resolution Spectrograph-Polarimeter for the BTA

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**Abstract.** We present the first results of pilot operation of a high spectral resolution fiber-fed spectrograph (R = 20000 - 100000) of the SAO RAS 6-m BTA telescope. The spectrograph is designed to carry out complex studies of exoplanets, astroseismological studies, studies of stellar magnetism, stellar atmospheres, active nuclei of bright galaxies, the interstellar medium, etc. Its operating range is from 4000 to 7500 Å. The first observations of radial-velocity variability in stars have been carried out. As a result, we obtained the characteristic measurement accuracies from several m/s to several tens of m/s. Over the next 1-2 years we are planning bring the accuracy of radial velocity measurements in stars up to 1 m/s.

**Keywords:** instrumentation: spectrographs; planetary systems

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# 1 Introduction

Since the fall 2015, a high spectral resolution fiber-optic echelle spectrograph has been constructed at the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS). The tool is designed for high-precision measurements of radial velocities in stars in order to search for and study their exoplanets, and conduct magnetometric studies. The primary study of the instrument is presented in the papers by Valyavin et al. (Valyavin et al. 2014, 2015). The first spectra, obtained in laboratory conditions, the final version of the optical-mechanical layout and the evaluation of the efficiency of the instrument are presented in the following papers: Valyavin et al. (2019, 2020). The spectrograph was mounted on the 6-m telescope of the SAO RAS BTA in 2018. In 2019, immediately after the completion of the planned activities on the reinstallation of the 6-m mirror of the BTA, the first pilot observations of stars with exoplanets have began. In this study, as well as in the papers of Burlakova et al., Gadelshin et al. (2020, in the same edition) we present the current version of the opto-mechanical layout of the spectrograph and the first results of its exoplanetary observations.

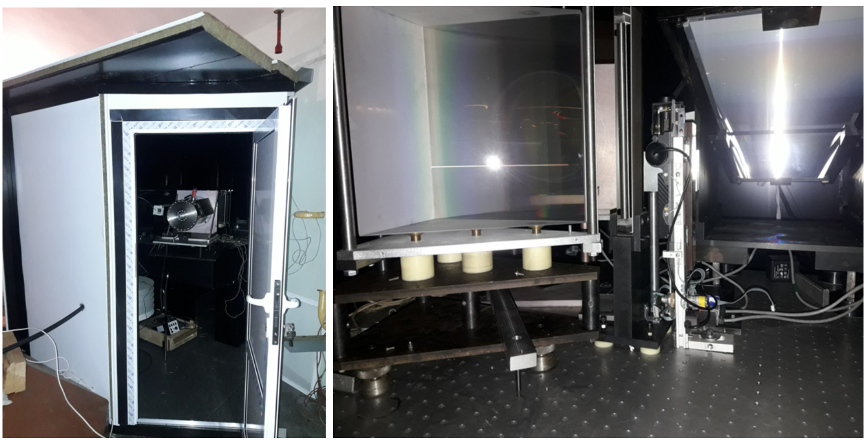

**Fig. 1.** General view of the spectrograph. The left plot shows the spectrograph in a protective envelope on the heel of the BTA telescope; the right plot demonstrates its diffractive optics.

## 2 Optical-Mechanical Layout

We have modified the layout of the fiber-optic spectrograph several times during its creation, nevertheless retaining its general concept, known as the white pupil design (Dekker et al. 2000). The requirement for a certain positional stability of the tool has forced us to abandon the use of the UV wavelength range. A convenient place of mount for the spectrograph on the BTA telescope foundation implies using a more than 60-m long optical fiber (see Valyavin et al. (2020)). In this case, at wavelengths shorter than 4000 Å light absorption becomes so significant that any attempts to consider this range in the present project lose their meaning. This circumstance determines the choice of the working spectral range from 4000 to 7500 Å.

The optical layout of the spectrograph is presented in Valyavin et al. (2014, 2015). In contrast to the traditional design, the white pupil concept uses two off-axis collimators. One of the collimators operates with an echelle grating in the autocollimation mode, the other (the 'transfer collimator') forms the pupil plane, constructing in its focus an image of the echelle grating. A cross-dispersion unit is placed at this point followed by the focusing optics with a CCD chip. The main advantage of the chosen spectrograph layout is its compactness, which allows minimizing the size of the optics mounted next to the transfer collimator.

Manufacturing of the spectrograph was launched in 2015 and its laboratory prototype was completed by 2017 (Valyavin et al. 2019). The optomechanical workshop of the SAO RAS (design of frames and assembly of the spectrograph) took part in the construction in cooperation with the Vavilov State Optical Institute (GOI, St. Petersburg), and the Optics Research and Manufacturing Association (NPO Optics, Moscow). Diffractive optics were manufactured at the GOI. The collimation system was manufactured by NPO Optics. Some of the folding mirrors and the cross-dispersion prism were created for our project at the Main (Pulkovo) Astronomical Observatory of the Russian Academy of Sciences (GAO RAS, St. Petersburg).

Figure 1 shows the appearance of the spectroscopic part of the spectrograph mounted at the BTA foundation. The features of the instrument and its basic circuit arrangement are described in Valyavin et al. (2020). The general concept of the spectrograph is as follows:

The optical fiber path forms 5 independent channels:

- a zero-point control channel used to transmit light with the interference pattern obtained using a Fabry-Perot standard or a Th-Ar hollow cathode lamp;
- two data channels providing observations in high spectral resolution mode (R $>$ 70 000);

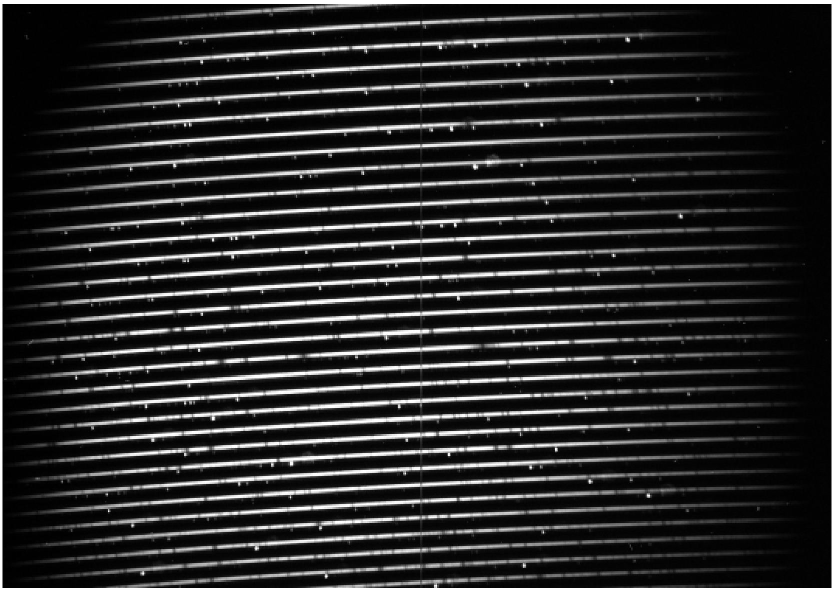

**Fig. 2.** Example of an echelle image, obtained with the spectrograph.

– two data channels for the low spectral resolution mode observations (R = 35 000).

In this configuration, observations are organized in either high or low spectral resolution modes with simultaneous registration of spectra from two corresponding data channels and a reference spectrum. In the case of polarization observations, two data channels form the spectra of 'ordinary' and 'extraordinary' rays, spatially separated by a polarization analyzer (see Valyavin et al. (2014, 2020)). In the case of spectroscopic observations with no polarization analysis, one of the two data channels forms the object spectrum, while the other channel forms the background spectrum. Formation of all these channels takes place in the primary focus of the BTA using the mounted instrumentation unit Valyavin et al. (2020).

A projection camera is still in production (Vasilyev et al. 2016) it is expected to help reach the limiting spectrograph characteristics. However, due to the availability on the optical market of simpler, though still suitable for operation in combination with our spectrograph standard lens objectives, we have launched pilot operation of the constructed spectrograph and its experimental study. Its first results are presented in the present paper.

## 3 Observations

Pilot spectroscopic observations of several solar-type stars with and without confirmed exoplanets were carried out on the 6-m telescope from April to June 2020. The observations were conducted using a high-resolution fiber-optic spectrograph with resolution from R45000 to R65000. The purpose of the observations was to test the instrument for characteristic accuracy in measuring radial velocities of stars from their spectra.

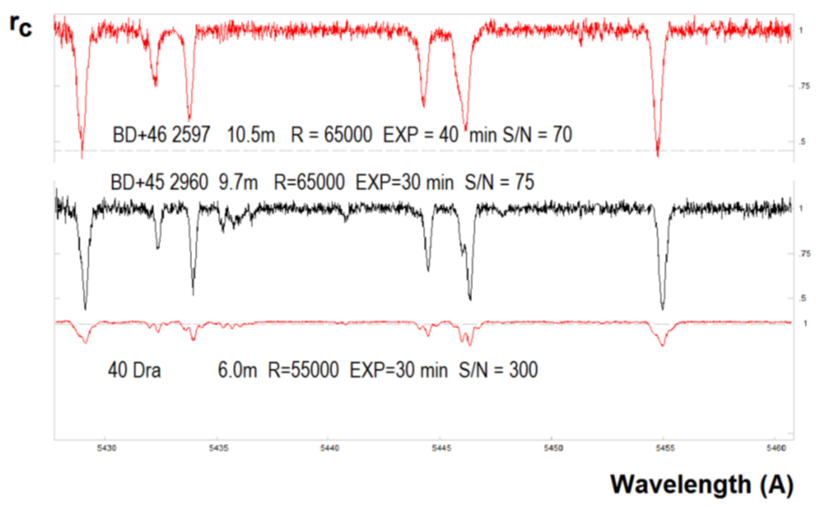


**Fig. 3.** Examples of spectra of different spectral types of stars obtained with the spectrograph.

Figure 2 shows an echelle image obtained with the spectrograph. Every spectral order is represented by two strobes spaced apart in distance, one of which gives the spectrum of a star, and the other shows the spectrum of a Th-Ar lamp. The reduction of such an image by the standard method is reduced to getting two extracted spectra obtained in one image: the spectra of the star and a spectrum of the Th-Ar lamp (a comparison spectrum). Simultaneous measurements of radial velocities from the spectral lines of the star and the comparison spectrum, carried out over the entire series of observations of a particular star make it possible to estimate the Doppler variability amplitude of stellar radial velocity corrected for mechanical instability of the instrument, which is controlled by the comparison spectrum.

Figure 3 shows the fragments of spectra of different spectral types of stars, obtained using the spectrograph. As you can see, the current configuration of the instrument, that uses the temporary projection camera already allows to study the stars significantly fainter than 10m and up to 13m with the S/N 50 per hour of exposure. When the standard camera is put into operation, we shall be able to observe stars up to $m_v = 14^m$.

## 4 Results of Star Radial Velocity Testing

Details on the radial-velocity measurements for tested stars from the spectral lines in their spectra are presented in the same proceeding book of Burlakova et al., as well as in Burlakova et al. (2020). We hence omit here the description of measurement procedures. Let us only briefly illustrate and summarize the main result presented in Fig. 4.

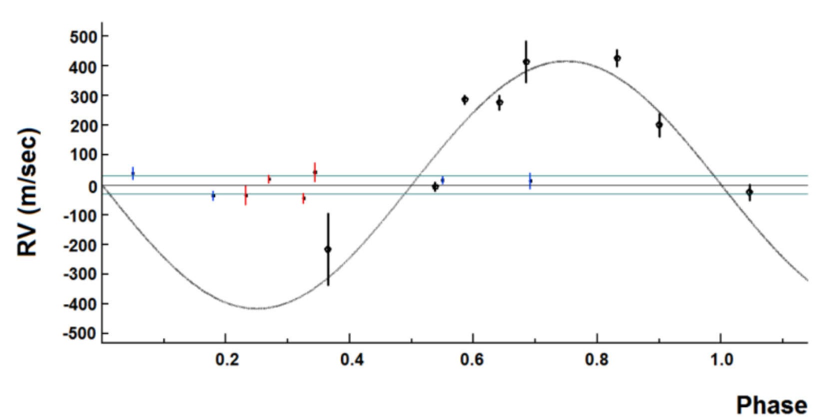


**Fig. 4.** Results of radial-velocity variability measurements in stars with exoplanets.

In Fig. 4 the solid line describes the radial velocity curve of the exoplanet Mascara-3b. Black circles with dashes indicate the results of radial velocity measurements of this exoplanet and the associated error bars according to our observations. The symbols of other colors denote the results of radial velocity measurements in other solar-type stars that did not reveal any significant radial velocity variations. The radial velocity measurement accuracy in stars depends on their spectral type, brightness and seeing, and varies from 4.7 m/s to 20 m/s for solar-type stars.

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