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High temporal resolution multimode panoramic photospectropolarimeter. State and prospects

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ABSTRACT

We describe the final stage of developing the hardware and software complex of the MANIA experiment (Multichannel Analysis of Nanosecond Intensity Alterations) to search and study the brightness variations of astrophysical objects with extremely high temporal resolution. The main instrument of the complex is a panoramic photospectropolarimeter with remotely mounted optical blocks that feed light beams to the photo-receiving devices (PRD) with position-sensitive detectors (PSD), the individual quanta of which are registered by chronometric devices with a 30 ns cadence and with each quantum linked to universal time. We present some scientific results obtained through observations with the 6-meter telescope of SAO RAS, as well as plans of further hardware development and its application.

Key words: relativistic astrophysics, optical observations, photometry, high temporal resolution, black holes, pulsars, flare stars, astronomical instruments

1 Introduction

The work, named the MANIA experiment, was initiated by Viktorii Favlovich Shvartsman in 1971 (Shvartsman, 1971). It is based on the method of searching for black holes by studying the statistics of quanta emitted by flickering plasma halos around them. This idea was further developed by him for high temporal resolution studies of other X-ray sources, flare stars, optical pulsars, lineless objects, hypothetical laser stars, and signals from extraterrestrial civilizations.

The point of the experiment is to register photon fluxes from the objects under study along with high-precision measurements of the arrival time of each quantum, as well as its spatial, polarization, and energy characteristics with subsequent analysis of these data using any conceivable methods. For the practical implementation of the MANIA experiment, a set of basic mathematical methods for the analysis of rapid variability was generated, and devices for registering photon fluxes based on position-sensitive detectors were developed, as well as methods for digitizing and timing the obtained counts. Photospectropolarimetric instruments that allow one to study the physical characteristics of the registered quanta were also created. These components, together with specialized software (Plokhotnichenko et al., 2020a), formed the observational complex of the MANIA experiment (Plokhotnichenko, 2020a). Its main feature is operational multifunctionality, which allows changing its structure in accordance with research tasks and observational conditions.

Some adjustments have been made to the design and material support of the complex, described in Plokhotnichenko et al. (2020a). In particular, the control system has been modernized: a computer for working with the instrument kinematics through COM ports is installed on its body, which improved the mobility of the photopolarimeter and simplified the installation at the telescope focus. Continuous exposure throughout the entire observation night has been ensured, which is necessary for searching for the optical companions of sources detected in other ranges, for example, fast radio bursts.

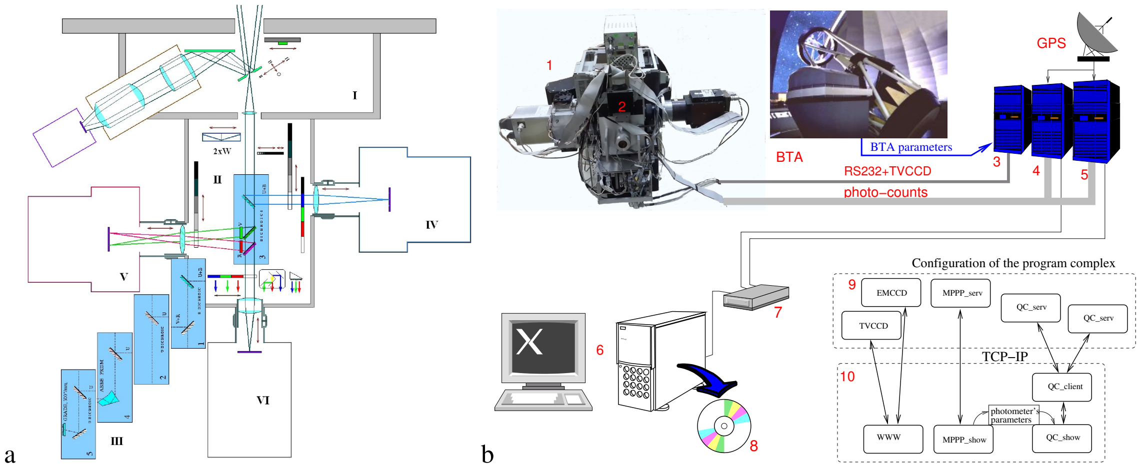

Fig. 1. (a) MPPP block diagram. (b) Structure of the observational complex, namely: 1 – MPPP; 2 – multiplexer of data streams from two PSDs, which forms a single sequence from them; 3 – computer for TV monitoring and kinematics control; 4, 5 – computers for data acquisition from the Quantochron 4–48 chronometric grabber; 6 – control computer; 7 – network switch of the selected line; 8 – accumulated data; 9 – hardware components; 10 – software modules of interface computers.

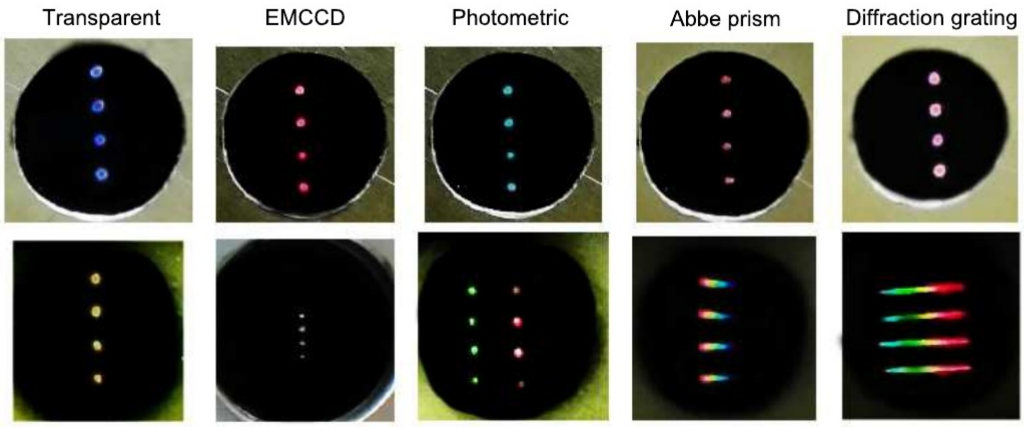

Fig. 2. Images of polarized beams on frosted glasses installed instead of photodetectors. The "blue" (upper row) and the "red" channel (lower row).

2 Observational complex

The hardware basis of the complex is a multimode panoramic photometer-polarimeter (MPPP), the functioning version of which is described in Plokhotnichenko et al. (2021), and the optical scheme is shown in Fig. 1a. It consists of: a focal platform (I) with a mirror-slit unit for viewing the working field and an input lens of the collimator of radiation from the studied sky area; a unit of optical blocks (II) with a linear polarization analyzer at the input of the optical beam in the form of a double Wollaston prism (Oliva, 1997); a device (III) for remote installation of five optical blocks in the working position; two photodetector devices (IV, V) based on PSDs (Debur et al., 2003; Plokhotnichenko et al., 2020b) for operation in the "blue" and "red" channels with a chronometric registration system (see the next section), which accumulate arrays of codes corresponding to the registered quanta with a 30 ns cadence; an EMCCD camera (VI), capable of capturing up to 10 frames/s.

The structure of the complex is shown in Fig. 1b. Its operation is illustrated in Fig. 2.

The instrument is controlled using a graphical interface in the form of its stylized optical scheme with movable elements.

3 Photon flux detectors and their chronometry

Electro-vacuum PSDs are used as photodetectors. Electrons knocked out of the cathode by incoming light quanta are accelerated in a strong electrostatic field and multiplied due to secondary electron emission on microchannel plates (MCP). Avalanches of electrons hit the anode elements, then the resulting current pulses enter charge-sensitive amplifiers, are measured by analog-to-digital converters (ADC) and recorded by chronometric devices for storage and processing. We use a PSD for the ultraviolet-blue range with an S20 cathode and a quadrant collector (Debur et al., 2003) and a PSD for the green-red range with a GaAs cathode and a 16-anode collector (Plokhotnichenko et al., 2020b). The appearance and principles of measuring the signals obtained by PSDs are shown in Figs. 3 and 4. The quantum efficiency is about

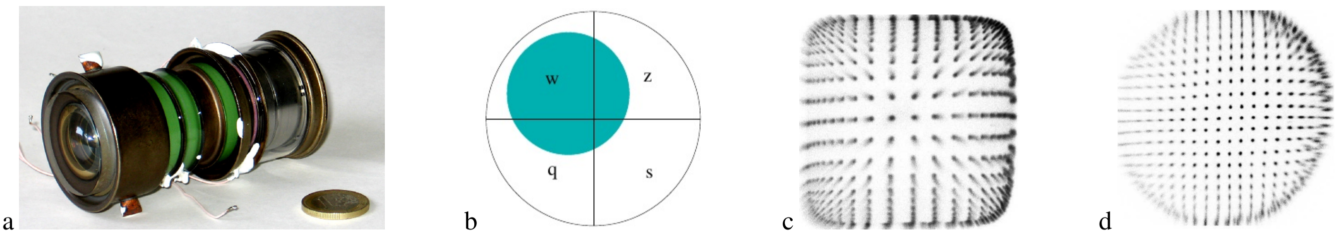

Fig. 3. (a) PSD with an S20 cathode. (b) 4-element anode (quadrant) with a wide avalanche of electrons from one photon count. (c) Field of luminous points obtained by direct summing of quanta in coordinates of their registration. (d) Field after correcting position of each photon. The gaps between points are 3′′.

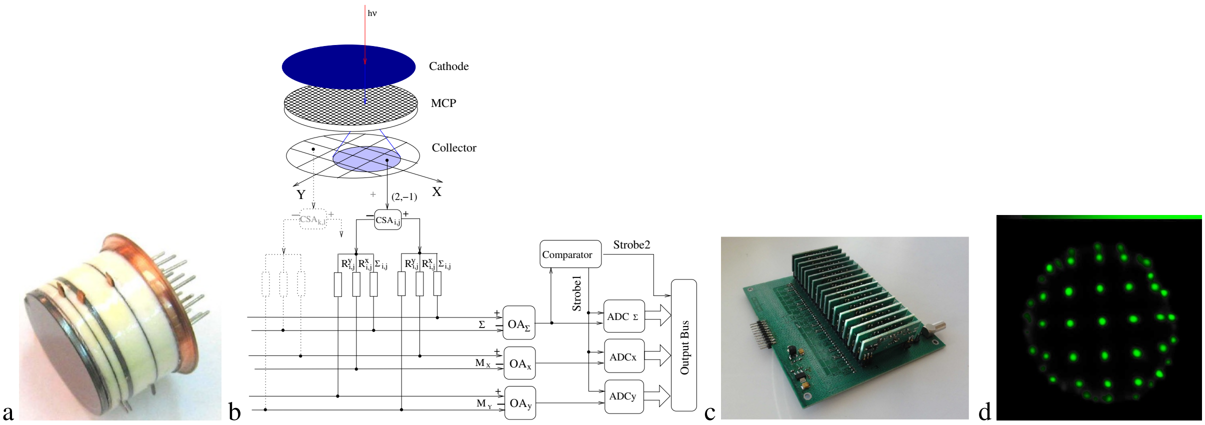

Fig. 4. (a) 16-anode PSD with a GaAs cathode. (b) Functional scheme of analog charge encoding, with charges collected by a collector as the sums of avalanche charges and their momenta along the axes. (c) A set of 16 amplifiers on the encoding board. (d) Detector field with 1 minute exposure. The gaps between points are 12′′.

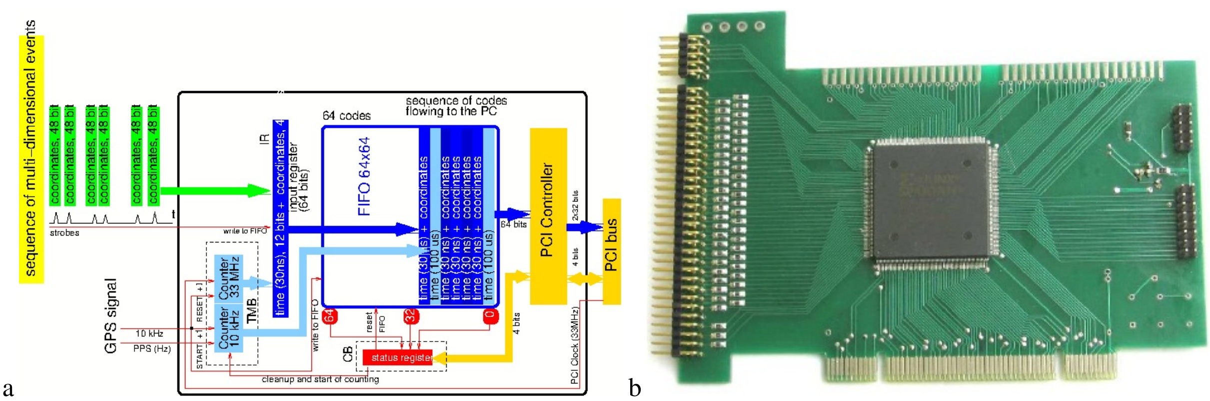

Fig. 5. (a) Functional scheme of the chronometric grabber. (b) Its PCI board.

20 % for the former and 30 % for the latter. The multiplication of electron avalanches is $\sim 10^6$ times, which determines the long-term operability of the devices (for about 20 years now) on the one hand and a fairly good spatial resolution of about 0′′.2 on the other. The maximum measurable fluxes recorded by detectors are of the order of 2×10^6 pulses/s. The dead time is ~ 0.1 μs.

Receiving of the observational data, namely digitized photopulses from PSDs, is performed by the Quantochron 4–48 chronometric grabber developed by us (Plokhotnichenko et al., 2009), installed in the PCI bus slot of the computer (see Fig. 5). Interfacing to the PCI bus controller is carried out with data buffering in the device memory, which is organized according to the FIFO (first in, first out) principle, that is, in the form of a simple non-priority queue. Synchronization with GPS/GLONASS has an accuracy of 100 ns. In real time, the readings from the coordinate detectors and the arrival time of each quantum are collected in the form of a vernier reading after the next clock pulse in the reference frame of the navigation system sync signals and are recorded in the computer's memory. Readings from detectors are merged into a single stream by a stochastic signal mixer, in which they receive marks of their place of origin. Data arrays stored in the memory of one of the receiving computers during one second with the prohibition of all interrupts of its single-core processor are transferred via the TCP/IP protocol to the accumulation computer during the next second, and the continuity of data acquisition at this time is ensured by the operation of the same device in another receiving computer, forming a Flip-Flop mode. Due to the organization of work with data, the continuity of the total exposure can be maintained for any duration for which the volume of the disk memory of the accumulation computer is sufficient. The stream of counts recorded without losses is more than 5×10^5 digitized counts/s. Data collection is controlled using an intuitive graphical interface that allows one to quickly view the flux intensities in the form of light curves both from selected sites and from all sensitive surfaces of the detectors. The result of the collection system operation is the so-called photon sheets, the rows of which contain the registration times of quanta, the coordinates of their hit on the detector cathode, as well as the mark of the detector on which the given quantum was registered. The statistical properties of the accumulated counts from illumination of constant intensity are compatible with mathematically expected ones.

4 Software

The software includes tools for obtaining and analyzing time series. It allows one to receive digitized quantum fluxes from detectors: photon sheets in the form of time counts, coordinates, polarization and energy characteristics of light quanta; analyze accumulated images, compensate for jitter using software microguiding, and perform photometry of extended and point objects; construct and analyze light curves, perform smoothing, calculate residuals, make convolutions and Fourier analysis; analyze stochastic signals, perform dispersion analysis, and study the statistics of intervals between counts; analyze periodic signals, perform barycentric corrections of time series (correct for Doppler effects), search for periods, fold light curves with periods taking into account their observed first derivatives, analyze and compensate for phase shifts. A description of the algorithms of the current stage of software development is given in Karpov (2007).

5 Some results

5.1 Search for black holes

The method consists in studying the distributions of time intervals between quanta in candidate objects for isolated black holes, selected by a combination of their peculiar characteristics. A search was made for differences in these distributions on short time scales in the studied sources and standard stars, which would be evidence of the generation of microsecond flares of radiation in the accreting plasma near the event horizon of a black hole. Figure 6 shows the result of such a study of a candidate for possible microlensing black hole with a mass of several solar masses, MACHO-1999-BLG-22. In this case, no ultrafast variability of the radiation from this object was registered (Beskin, 2012).

5.2 Studies of flare stars

Starting from the 1980s, several series of observations were carried out. A detailed description of the studies can be found in Beskin et al. (1988) and Beskin (2012). The features of the fine structure of flares were investigated, and the absence of microsecond variability was shown. Polarized flares of subsecond duration were detected in the UV Ceti star, which proves the assumption of the 1960s about the realization of the synchrotron mechanism of radiation in (some!) flares of red dwarfs (Beskin et al., 2017).

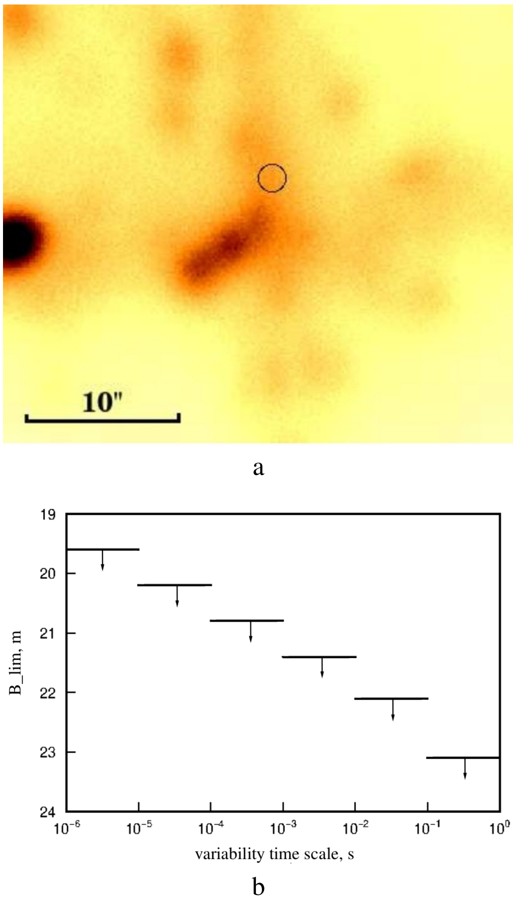

Fig. 6. (a) BTA/PSD image of the MACHO-1999-BLG-22 field. The exposure is one hour. The localization of the object is indicated with the black circle. (b) Radiation variability level of the area of the object localization, obtained from power spectrum integration.

5.3 Studies of the pulsar in the Crab Nebula

In 1980, using the method of digital synchronous detection, a phased light curve of the pulsar was obtained with the world's best cadence of 6 μs (Beskin et al., 1983). In the 1990s, light curves in the UBVR bands were investigated (Komarova et al., 1996). In high-precision observations of 2005–2006, a short-term change in the shape of the main pulse was detected, as well as the instability of its profile after the next glitch (Karpov et al., 2007).

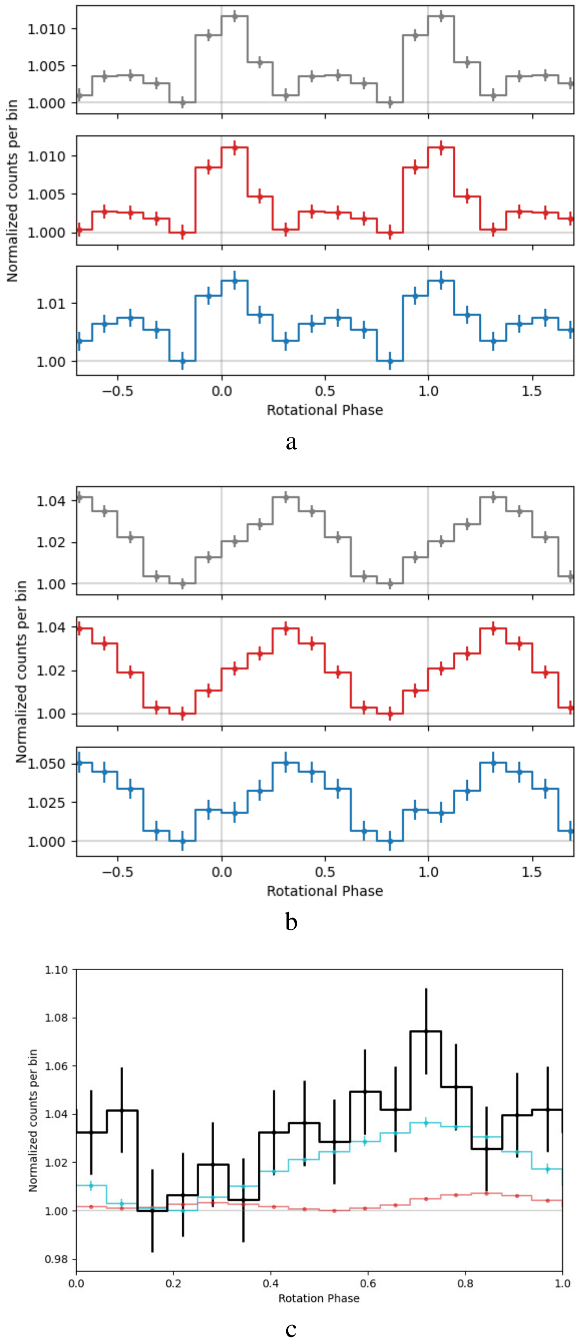

Fig. 7. (a) Typical double-peaked pulse profiles of the J1023+0038 pulsar, observed in the majority of data. (b) Pulse profiles obtained when folding a "unique" 230-second interval with the pulsar period. (c) A light curve of the 10-second interval during a change of the pulse profile shape (black), the entire "unique" interval (turquoise), and the standard double-peak profile (red). All the profiles are brought to a unified initial phase.

5.4 Observations of the millisecond pulsar PSR J1023+0038

In October 2017, observations of a millisecond pulsar in the binary system with a rotation period of 1.69 ms were carried out. On the night of November 15, 2017, flare activity was observed in the system, and for the first time, a transition from a double-peak structure to a single-peak structure of the pulsar pulse and back was recorded on a time scale of a few minutes (Fig. 7a and b; Tanashkin et al., 2022). During this event, the amplitude of single-peak pulsations was increased several times (Fig. 7c).

6 Conclusions

The developed observational complex allows one to effectively solve the tasks posed by Viktorii Shvartsman and naturally fits into the framework of a new direction of science – high temporal resolution astrophysics (Phelan et al., 2008).

The complex is conceptually complete. It remains to improve the quantitative characteristics of the optical elements, detectors, and registration system used.

Works on creating a new generation of PSDs (larger working field and higher quantum yield) and a new chronometric registration device are currently being carried out; the conceptual design of the latter is described in Plokhotnichenko (2020b). It will be suitable for using with any modern computer and available for manufacturing in a small series, which will open up the possibility of installation on other telescopes, including for joint synchronous observations.

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