Revista Mexicana de Astronomía y Astrofísica Serie de Conferencias (RMxAC), **59**, 197–199 (2025)

https://doi.org/10.22201/ia.14052059p.2025.59.32

IMAGING STOKES PHOTOMETER-POLARIMETER FOR THE BOOTES GLOBAL TELESCOPE NETWORK

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RESUMEN

La idea principal y algunos detalles del fotómetro-polarímetro de Stokes se presentan en este artículo. El fotómetro-polarímetro está diseñado para observaciones muy tempranas de estallidos cósmicos de rayos gamma, seguimiento regular de objetos peculiares, de la coma de cometas, de asteroides activos y de Centauros (también en el Sistema Solar). Las observaciones polarimétricas se optimizarán para dos regiones espectrales: 400-550 nm y 550-1100 nm, haciendo así posible medir los parámetros de Stokes de dos maneras: mediante polarizadores con acimutes 0°, 60°, 120° y polarizadores con acimutes 0°, 45°, 90°, 135° y una placa de cuarto de onda. Esto proporcionará mediciones para polarizaciones lineales y circulares. Algunos detalles de este proyecto se presentan en este artículo.

ABSTRACT

The main idea and some details of Imaging Stokes photometer-polarimeter are presented. The photometer-polarimeter is designed for very early observations of gamma-ray bursts afterglows, regular monitoring of the peculiar objects, cometary comae, active asteroids and Centaurs. Polarimetric observations will be optimized for two spectral regions: 400-550 nm and 550-1100 nm, thus making possible to measure the Stokes parameters on two ways: by means of polarizers with azimuths 0°, 60°, 120° and polarizers with azimuths 0°, 45°, 90°, 135° and a quarter-wave plate. This will provide measurements for linear and circular polarizations. Some details of this project are presented in the paper.

Key Words: Imaging-Polarimetery — Stokes parameters — BOOTES — Robotic Telescope — GRB

1. INTRODUCTION

Polarimetry plays an increasingly important role in visible and infrared astronomical observations since it provides a wealth of information: on the nature of radiation sources, on the geometrical and velocity relationship between a radiation source, scatterer and observer, on the chemical and physical properties of the dust grains, on the direction of the magnetic field as projected on the plane of the sky (for the case where these are aligned).

Linear polarization dependencies on phase angle and wavelength also serve as reliable sources of information about the properties of dust particles in cometary comae and active asteroids and Centaurs. Analysing not only brightness measurements and their spectral dependencies but also the phase dependence of linear polarization, which is particularly sensitive to scattering object properties such as size, shape, structure, and refractive index, remains a relevant task for remote sensing of celestial bodies to investigate their origin and evolution. The past two decades have seen significant advancements in ground-based polarimetry of small solar system bodies. Notably, it has been observed that the negative polarization branch of scattered light (a 90° rotation of the plane of polarization at small phase angles) for distant comets significantly differs from comets at closer solar distances. The 2.0m Liverpool Telescope (+RINGO) already responded to two gamma ray bursts (GRBs): GRB 060418 in ≈200s imposing a 2-σ limit of polrization degree $< 8\%$ and detecting significant polarization (10%) for GRB 090102 in a 60s exposure taken 150s after the event (Steele et al. 2009). Support is given to a higher polarization which may be highly variable (as might have seen in γ-rays for GRB 041219A; (see also (Gtz et al. 2009)).

However, monitoring polarization observations in conjunction with photometric studies, feasible only

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with small telescopes, is required for a more detailed investigation. Additionally, monitoring polarimetric observations of Centaurs and asteroids is necessary for detecting activity. Only one active asteroid and two active Centaurs have been observed in polarimetric mode. Therefore, using small telescopes for polarimetric monitoring represents an essential tool in advancing our understanding of these celestial objects, shedding light on their physical properties, origins, and evolutionary processes.

One of the most significant factors limiting the accuracy of ground-based polarization observations is the influence of Earth's atmosphere. Simple changes in transparency in the case of a two-beam polarization measurement scheme have little effect on the accuracy of normalized Stokes parameter measurements. However, variations in radiative transfer parameters in the atmosphere lead to changes in the depolarization coefficient D = Io/Ie in different exposures. The primary cause of depolarization is selective scattering on microparticles whose size is smaller than the wavelength of the observed radiation and non-selective scattering on aerosols. Moreover, the characteristic times of rapid depolarization changes in the atmosphere are comparable to the freezing time and can vary depending on the atmospheric conditions during observations, typically ranging from 10 to 30 ms. Usually, schemes with fast modulation or switching of polarization channels are used to suppress depolarization effects, which are referred to as flickering effects. We need to measure linear polarization with an accuracy of not less than 0.10.2 %. Also important to have a detector that allows fast acquisition of images, which is necessary for suppressing atmospheric flux scintillation in polarized light.

It is crucial to conduct obsevations during photometric nights with low values of seeing, absence of clouds, and dark nights with no moonlight or preferably during gray nights (during the small phases of the Moon). During data processing, proper consideration of the background (e.g., using histogram methods) and the correct removal of stars from the field is essential, especially for extended objects like comets and active asteroids.

2. BURST OBSERVER AND OPTICAL TRANSIENT EXPLORING SYSTEM

The Burst Observer and Optical Transient Exploring System (BOOTES), started in 1998 as a Spanish-Czech collaboration devoted to study optical emissions from gamma ray bursts (GRBs). The BOOTES global network of robotic telescopes is constantly watching the sky for astronomical transients, from its seven locations spread across both hemispheres. With them, Spain celebrated the beginning of a transformative era in ground-based observations with the successful completion of the BOOTES Network (Castro-Tirado 2023). Studies of astrophysical transients, such as GRBs and other high-energy phenomena, have long been hindered by their elusive and unpredictable nature. BOOTES can track and monitor suspected neutrino sources and gravitational wave emitters, as well as nearby objects like fireballs, comets, asteroids, or trans-Neptunian objects in the Solar System, variable stars in our Galaxy, supernovae in distant galaxies or blazars. Moreover, BOOTES may diligently commit to space debris monitoring and may survey the sky to identify potentially dangerous objects posing a threat to humanity. Very few telescopes can obtain polarimetric observations on a regular basis. In our case, we can very simply and without much expense add the ability to do polarimetric observations using BOOTES network telescopes. Thus, we have designed a photometer-polarimeter optimised for very early observations of gamma-ray bursts afterglows, regular monitoring of the peculiar objects, cometary comae, active asteroids and Centaurs.

3. INSTRUMENTATION

The optical wavelength range of the BOOTES telescopes is determined by the sensitivity of the detector. It spans from 350 to 1000 nm, with all six 0.6 m telescopes (100 deg/s slewing speed) being equipped with identical high-speed, highly sensitive electron multiplying EMCCD cameras iKon-L. These cameras offer a 10 arcmin field of view and employ Sloan ugri and ZY WFCAM filters, enabling seamless data fusion from various observation sites (Hu et al. 2023). Sloan Digital Sky Survey (SDSS) is one of the most common and important photometric systems in modern astronomy. The filters are placed in the holes of the rotateing wheel (Fig. 1.a). Five u, g, r, i, z band filters are for cover camera spectral range. Sixth hole place quartz window (to compensate optical ray path in filters for no defocusing when changing wheel position).

To provide polarization measurements, it is planned to add an additional wheel with 8 holes into the telescope path. The first three holes is for linear polarizers with optimal set of azimuths of 0°, 60° and 120°. These will allow determining the linear polarization of the input scene in the 400-550 nm spectral range. The next four holes is for three linear polarizers with azimuths of 0°, 45°, 90° and one for a circular polarizer, built of sequence of achromatic quarter-wave plate and a 135° linear polarizer.

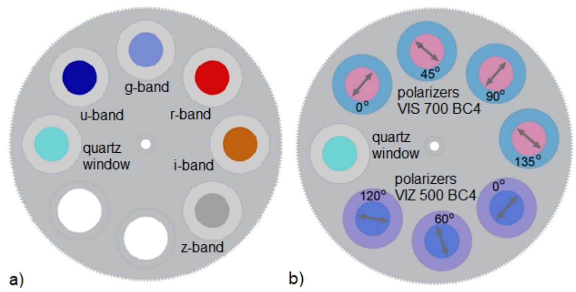

Fig. 1. a) Filter wheel of BOOTES telescope; b) additional polarizer wheel.

These will allow determining the linear polarization of the input scene in the 550-1100 nm spectral range (Fig. 1.b). We plan to use a highly efficient CODIXX polarizers. One set of VIS 500 BC4 polarizers to cover the g band. Second set of VIS 700 BC4 polarizers with achromatic quarter-wave plate to cover the r - band, I - band, z - band. The principle of design an imaging polarimeter for BOOTES telescope is shown in Figure 2.

4. MEASUREMENT AND CALIBRATION APPROACH

Above set of polarization elements will make it possible to determine Stokes parameters of the input scene in the spectral range 550-1100 nm. For example, an expression for determining the first three Stokes parameters I, Q, U of radiation in the first case is given below:

$$\begin{bmatrix} I \\ Q \\ U \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & \cos(\theta_1)a_1 & \sin(\theta_1)a_1 \\ 1 & \cos(\theta_2)a_2 & \sin(\theta_2)a_2 \\ 1 & \cos(\theta_3)a_3 & \sin(\theta_3)a_3 \end{bmatrix}^{-1} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{1}$$

where θ_n - azimuth of polarizers; I_n intensity at the output of polarizer with azimuth θ_n; $a_n = (e_n - 1)/(e_n + 1)$ polarizations scale factor, e_n extinction ratio of n-th polarizing film; "-1" inversion of matrix.

From eqn. 1 it is clear that the above mentioned parameters of polarizert (as well as the parameters of wave plate) are not mandatory, although they are optimal from the point of view of minimizing the measurement error. Therefore, some dispersion of extinction ratio of polarizing films and birefringence of wave plate are acceptable. The eighth hole of the additional wheel will be free of optical elements to ensure optical observations with the telescope in normal mode at the appropriate angle of rotation of the wheel.

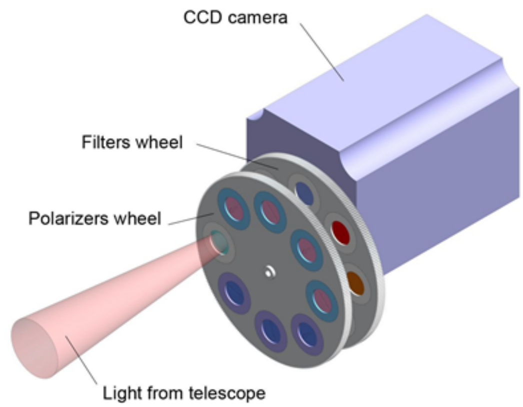

Fig. 2. The principle of design an imaging polarimeter for BOOTES telescope.

Each cycle of linear polarization measurements consists of a series of images obtained at fixed positional angles of polarisation wheel, for instance, 0°, 60° and 120°. Instrumental polarization is determined through observations of standard stars with low polarization (Heiles (2000): 9286 Stars: An agglomeration of Stellar Polarization Catalogs./ Heiles C(2000): standard s, rs should deviate from catalog values by an average of 0.1-0.3 % and the position angle of the polarization plane should shift by 0.5-0.7°. These values are considered the accuracy of a comet's integral polarimetric data. Binning 2×2 pixels is applied to the polarimetric images to enhance the measured signal's signal-to-noise (S/N) ratio.

5. CONCLUSION

In our project we showed how, with simple means and little funding, can upgrade existing photometers with the using of an additional wheel with polarizer films. This Photometer-polarimeter designed for BOOTES telescopes network for very early observations of gamma-ray bursts (afterglow), regular monitoring of the peculiar objects, cometary comae, active asteroids and Centaurs. Polarimetric observations will be on the two spectral regions 400-550 and 550-1100 nm, using two set of polarizers and one quarter-wave plate. This will provide measurements circular and linear polarizations in considered bands correspondingly.

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