Observations of the selected astronomical objects using Polarization-Holographic Imaging Stokes Polarimeter

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Abstract

In this paper we present the innovative Polarization-Holographic Imaging Stokes Polarimeter which is developed based on a unique polarization-holographic diffraction element and allows one to determine full polarization of a light coming from a point or an extended space object in visual and near-infrared spectral ranges. Laboratory tests and first astronomical polarimetric observations show that the resulting errors are of the 10^{-4} order. As an example, the preliminary results of the polarimetric observations of some bright Algol-type variable stars and spicules are presented.

Keywords: *spectropolarimetry polarization-holographic diffraction element, Algol-type binaries, spicules*

1. Introduction

Polarimetry has become an indispensable tool in modern astrophysics, enabling the characterization of magnetic fields, circumstellar environments, interstellar dust, and exoplanetary atmospheres. However, the full scientific potential of astronomical polarimetry remains underexploited, largely because of limitations in instrumentation. Despite increasing demand across the electromagnetic spectrum, polarimetric measurements are often constrained by insufficient sensitivity, limited calibration accuracy and the complexity of integrating polarization analysis into multifunctional astronomical instruments (Kuhar, 2022; Sparks, 2012; Tinbergen, 2005; de Martino, 2023).

One of the most persistent problems in astronomical polarimetry is the presence of instrumental polarization and cross-talk in telescope and instrument optics. These effects, which arise from oblique reflections, optical coatings and asymmetries in beam paths, can introduce spurious polarization signals or alter the true polarization state of incoming light. For high-precision applications, such as detecting weak linear polarization signatures of exoplanets or the cosmic microwave background, instrumental contributions must be suppressed or modeled to a level below 0.01%. Achieving this level of sensitivity requires careful optical design, high-fidelity calibration procedures and real-time compensation techniques, all of which remain active areas of research (Compain et al., 1999; Tomczyk, 2008).

Another significant limitation is the lack of standardized calibration methods and reference sources. Polarimetric calibration depends on observations of stars with well-known polarization properties, but such sources are rare and often show temporal or spectral variability. Furthermore, specific instrumental effects such as detector nonlinearity, filter leakage, and beam asymmetry can make it difficult to transfer calibrations across different telescopes or even between observing runs. The absence of universally accepted calibration protocols impedes the development of widely compatible and reproducible polarimetric systems.

The integration of polarimetric capability into existing imaging and spectroscopic instruments also poses non-trivial engineering challenges. Most astronomical polarimeters are custom-built add-on or independent instruments, often requiring dedicated telescope time and complex alignment procedures. This isolation from mainstream observational pipelines limits their use in large-scale surveys and time-domain astronomy. The need for compact, robust, and modular polarimetric systems that can be seamlessly integrated with adaptive optics, integral field units, or fiber-fed spectrographs is therefore increasingly urgent.

Space-based polarimetry, while offering unique advantages in UV and X-ray bands, is also underdeveloped due to payload constraints and technological barriers. Instruments such as the Imaging X-ray Polarimetry

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doi: https://doi.org/10.52526/25792776-2025.72.1-48

Explorer (IXPE) and the proposed POLSTAR UV mission demonstrate the scientific potential of polarimetry beyond the ground-based optical domain. However, the complexity of polarization optics, the difficulty of in-orbit calibration, and the competition for limited satellite resources have slowed progress in this area. New designs must prioritize compactness, thermal stability, and radiation hardness while maintaining high polarimetric sensitivity (Donati & Landstreet, 2009; Keller, 2002; Snik & Keller, 2013; de Juan Ovelar, 2012).

In parallel, the advent of large-volume data from polarimetrically capable surveys, such as LSST in optical or SKA in radio, requires new instrument concepts that can deliver accurate polarization information at scale. This includes not only detector-level improvements, but also onboard data processing and smart calibration strategies using machine learning and predictive modeling. At present, few instruments are prepared for such challenges and polarimetric sensitivity is often sacrificed to favor spatial or spectral resolution.

Finally, there remains a gap between theoretical advances and experimental implementation. While optical modeling and polarization ray tracing have matured significantly, translating simulations into real-world polarimetric systems often reveals discrepancies due to unmodeled systematics, material inhomogeneities, and manufacturing tolerances. The development of experimental testbeds and calibration facilities for validating polarimetric components under realistic observing conditions is therefore essential.

It can be noted that ongoing innovation in instrument design, calibration methods, theoretical modeling, and data analysis is essential to unlock the full diagnostic power of polarimetry in astronomy.

This work addresses these challenges by developing innovative astronomical polarimeters capable of high-precision, scalable, and multiwavelength observations. We proposed an innovative polarimetric method for astronomy based on a polarization-holographic diffraction element.

Polarization holography was first proposed by Prof. Shermazan Kakichashvili (Kakichashvili, 1972, 1989). This method allows holographically recording a unique polarization holographic optical element providing an instant and complete analysis of the polarization state of an incoming light in the visual and near-infrared spectral ranges developed by Barbara Kilosanidze and George Kakauridze (Kakauridze & Kilosanidze, 2011; Kilosanidze & Kakauridze, 2007, 2009).

A brief description of the method, design of the spectropolarimeter, and its calibration is given. We present the first results of observations of some bright Algol-type variable stars and the test spectropolarimetric observations of the solar spicules in the Hα for different hights in the solar chromosphere using the Polarization-Holographic Imaging Stokes Polarimeter (PHISP).

2. Method, Design and Callibration

The method of Polarization Holography allows creating a unique polarization-holographic optical element capable to make a full analysis of polarization state in a real time and in a wide spectral range including near infrared. Based on such element we have developed the Polarization-Holographic Imaging Stokes Polarimeter for astronomy to determine an instant polarization state of a point source object and the distribution of a polarization on an extended object image for different spectral ranges (Kakauridze et al., 2019; Kilosanidze et al., 2015, 2023).

The polarization-holographic element decomposes incident light into circular and linear diffraction orders. As a result we get two orthogonal circularly polarized beams with intensities I_{+c} and I_{-c}, two linearly polarized beams with position angle $+45°$, two linearly polarized beams with position angle $+90°$ and with intensities I_{45} and I_{90} correspondingly and also none diffracted beam with a state of polarization identical to incoming beam and with intensity I_0. The measurements of intensities of diffracted orders allow to determine all four Stokes parameters through the following relations.

We have obtained formulas for all four Stokes parameters of a light source that is being analyzed through the intensities of the beams diffracted on the polarization-holographic element taking into account also the spectral dispersion of such an element:

$$\begin{aligned}
I_\lambda &= k_{+C,\lambda} I_{+C} + k_{-C,\lambda} I_{-C} \\
Q_\lambda &= (k_{+C,\lambda} I_{+C} + k_{-C,\lambda} I_{-C}) - 2k_{90,\lambda} I_{90} \\
U_\lambda &= 2k_{45,\lambda} I_{45} - (k_{+C,\lambda} I_{+C} + k_{-C,\lambda} I_{-C}) \\
V_\lambda &= k_{+C,\lambda} I_{+C} - k_{-C,\lambda} I_{-C}
\end{aligned} \tag{1}$$

Here λ is the wavelength from spectral range of the element, $k_{+C,\lambda}, k_{-C,\lambda}, k_{45,\lambda}$ and $k_{90,\lambda}$ are the corresponding coefficients connected with absorption of light in an element, the diffraction efficiency of an

doi: https://doi.org/10.52526/25792776-2025.72.1-48

element and the optoelectronic transformations by a photo detecting device. The values of these coefficients are determined experimentally during a calibration of the polarimeter.

These expressions show that the intensities of 4 orders I_{+C}, I_{-C}, I_{90} and I_{45} fully and unambiguously describe all four Stokes parameters through the corresponding coefficients. So if we know exactly the polarization state, i.e. the Stokes parameters of an incoming light and by simultaneously measuring the intensities of four diffraction orders, all four Stokes parameters can be determined using laboratory-derived formulas and specially developed software. This approach also makes it possible to obtain spatially resolved polarization maps of an object's image.

We have developed the Polarization-Holographic Imaging Stokes Polarimeter for astronomical observations based on the polarization-holographic diffraction element capable to make a real time full analysis of polarization state in an optical spectral range including near infrared. Such an Astropolarimeter enables to measure an instant polarization state of a point object and the distribution of a polarization on an extended object image for different wavelength ranges. It is very compact, lightweight and suitable to install on a large or small ground-based, airborne or space telescopes (see Figure 1).

A schematic picture of diffraction orders of a polarization-holographic element and the principal schema of a proposed Astropolarimeter are shown in the Figure 2 (Kakauridze et al., 2019).

Figure 1. The Celestron SCT-14 telescope of Georgian National Astrophysical Observatory (Abastumani, Georgia) equipped with the PHISP and the Starlight Express SX-36 CCD

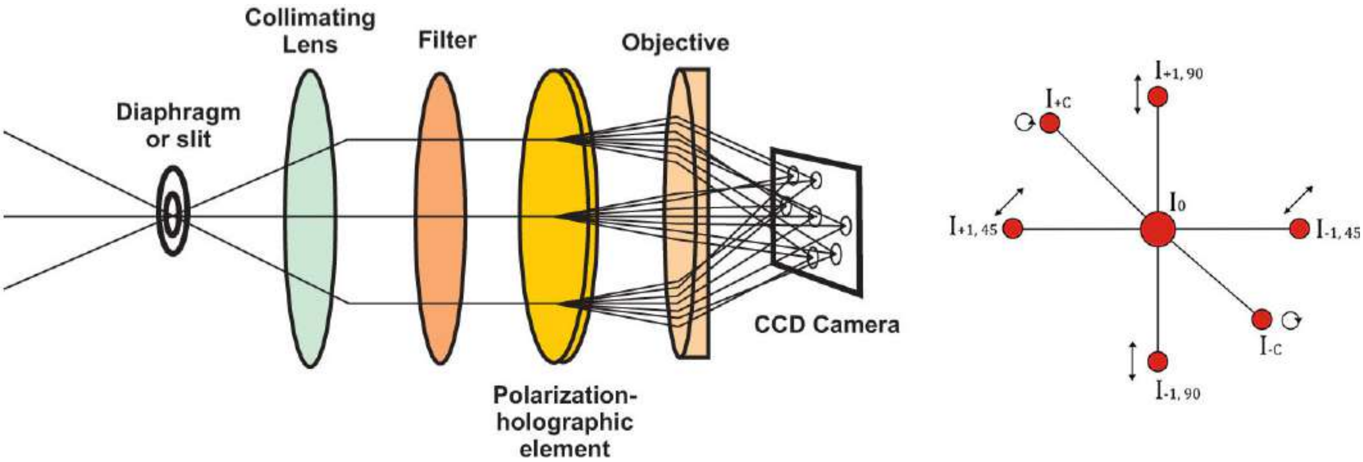

Figure 2. A schematic view of diffraction orders of a polarization-holographic element and the principal schema of a proposed Astropolarimeter.

The operating spectral range of an element varies between 500-1600 nm with reciprocal spectral dispersion of 714 Å/mm and diffraction efficiency equal to 20% at 532 nm, 16% at 635 nm and 2% at 1550 nm.

For calibration of the PHISP, observations of Vega were carried out through the standard V filter. The polarimeter was mounted on a refractor with 10 cm aperture and 1 m focal length. The large diameter polariser

doi: https://doi.org/10.52526/25792776-2025.72.1-48

was attached at the front of the telescope and rotated with fixed angle equal to 15°to get a sequence of CCD images with known linear polarization and position angles. The CCD images were processed for bias, dark and flat field calibration. Than the total intensities of all orders were measured and used to estimate coefficients in the relations (1). The normalized Stokes parameters were calculated for the same measurements. Figure 3 shows the variations of calculated (circles) and theoretical (solid lines) normalized Stokes parameters with position angle of linearly polarized light (left) and residuals of calculated and theoretical Stokes parameters. The RMS errors for these residuals are the following: $\sigma_{i-I} = 0.003; \sigma_{q-Q} = 0.004; \sigma_{u-U} = 0.004; \sigma_{v-V} = 0.0001$.

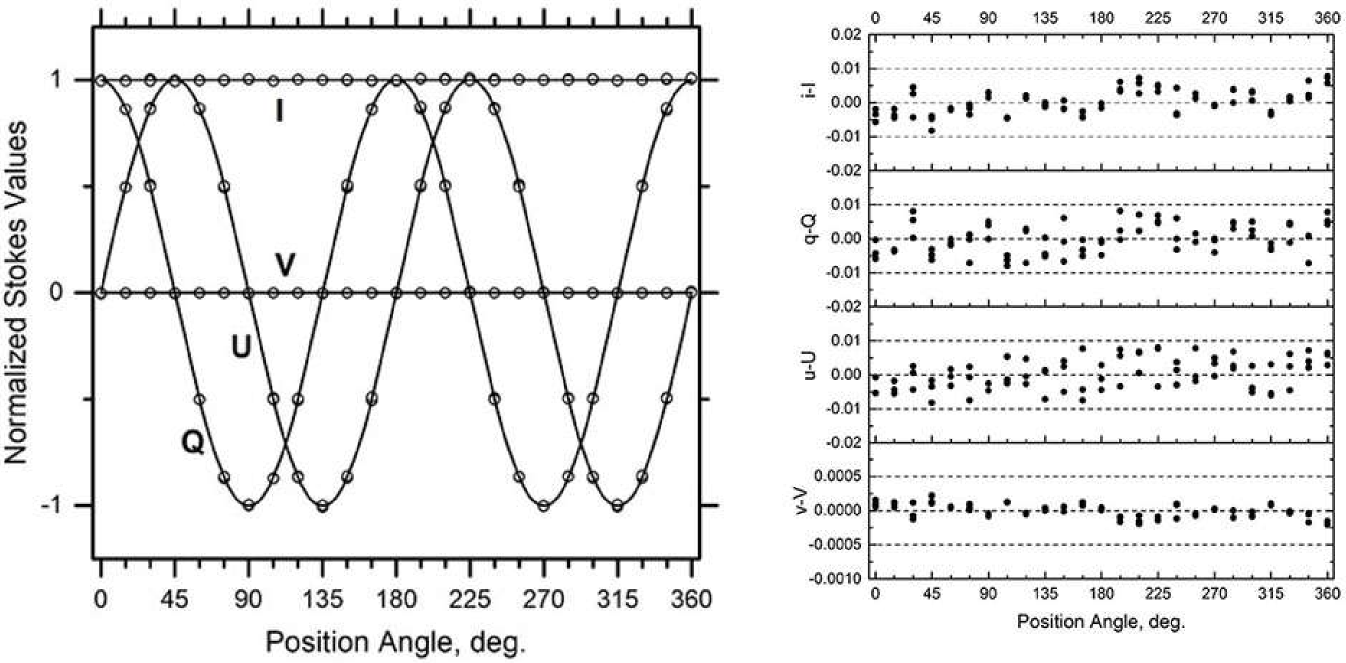

Figure 3. The variations of calculated (circles) and theoretical (solid lines) normalized Stokes parameters with position angle of linearly polarized light (left) and their residuals (right).

These results show that the errors are better than 10^{-3} and prove the great potential of such astropolarimeter for observations of various space objects including variable stars and spectropolarimetric observations of the solar active formations like the solar spicules and prominences. The PHISP is very compact, lightweight and suitable to be installed both on ground-based large or small and airborne telescopes.

3. Test Observations and Experimental Results

We present the preliminary polarimetric observations of some bright Algol-type variable stars using the Polarization-Holographic Imaging Stokes Polarimeter (PHISP).

The Algol-type binaries are the semidetached interacting binary systems in which the cool secondary star have expanded to its Roche lobe and is transferring material through a gas stream onto the hot primary star. The Algol-type binaries show polarization variability due to scattering in mass transfer streams and circumstellar discs, as well as Thomson scattering in the photospheres of their hot stars and Rayleigh scattering due to irradiation of their cooler stars.

The measurements of polarization variability of Algol-type binaries are neglected so far, which poses instrumental and data processing challenges.

The series of polarization-holographic images in the standard V filter of a β Lyr Algol-type variable were obtained during 2017 using the Celestron 14 inch Schmidt-Cassegrain telescope of the Georgian National Astrophysical Observatory (Abastumani, Georgia). The intensities of each diffraction order were transformed to the Stokes parameters using the calibration coefficients. The Stokes parameters calculated for each CCD frame were used to calculate the degree of polarization. The polynomial fitting of the trend lines clearly show the variation of the polarization. The standard deviations estimated for each observational day show that the errors are near 10^{-4}.

We carried out the test spectropolarimetric observations of the solar spicules in the H_α for different hight of chromospheric altitudes using the innovative Polarization-Holographic Imaging Stokes Spectro-Polarimeter

doi: https://doi.org/10.52526/25792776-2025.72.1-48

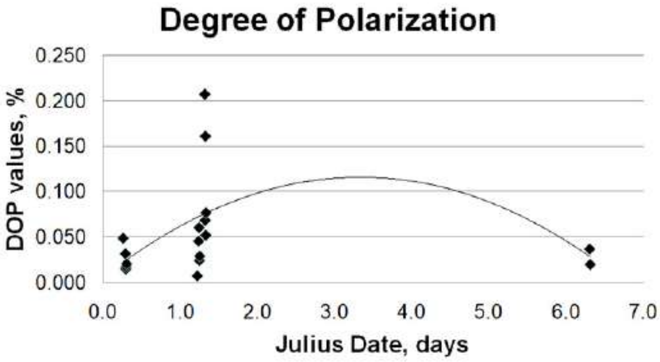

Figure 4. Time series variations of degree of polarization of β Lyr

(PHISP) mounted on the 53-cm coronagraph of the Georgian National Astrophysical Observatory (Georgia).

Figure 5 shows the polarization-holographic images of H_α spicules which were observed using 53-cm coronagraph equipped with spectrograph having spectral dispersion of $0.96/mm$ on different heights from the solar photosphere: 5000 (a), 6000 (b), 6500 (c) and 7000 (d) km.

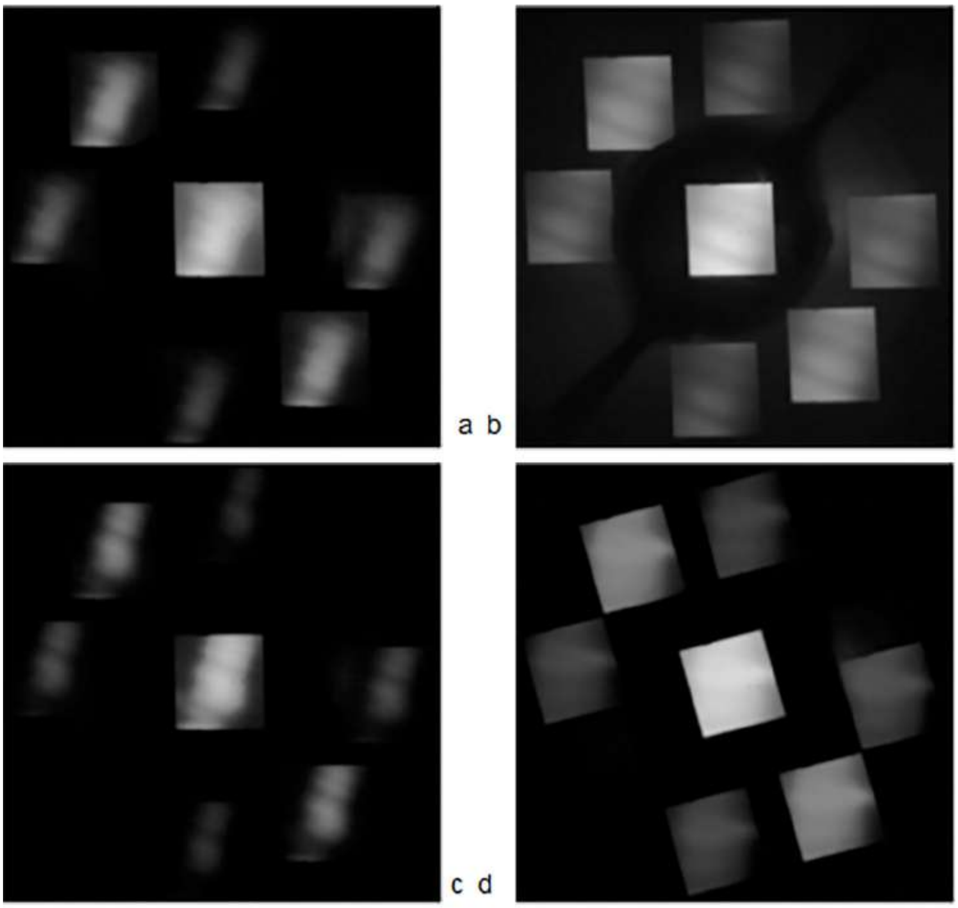

Figure 5. Polarization-holographic images of H_α spicules which were observed using 53-cm coronagraph equipped with spectrograph having spectral dispersion of 0.96 Å/mm on different heights from the solar photosphere: 5000 (a), 6000 (b), 6500 (c) and 7000 (d) km.

The residuals show that the resulting uncertainties are estimated to be of the order of 10^{-4}.

4. Conclusions

Based on the polarization-holographic diffraction element, a universal polarization-holographic Stokes spectropolarimeter has been developed in the laboratory for astronomical applications. It enables the deter-

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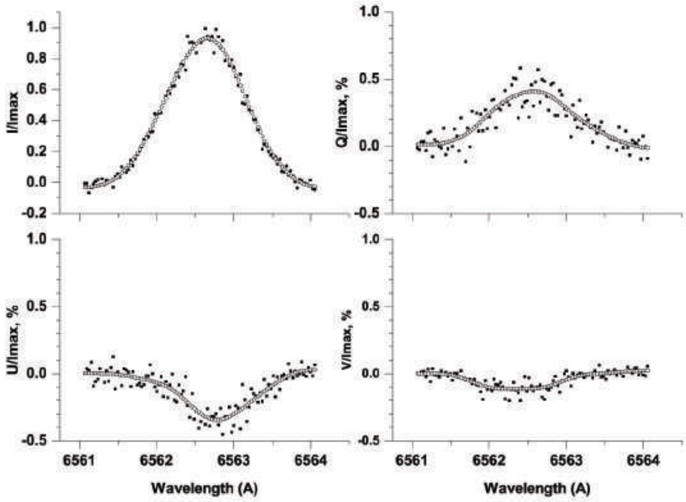

Figure 6. Stokes profiles of solar spicules in the H_α spectral line. The dispersion is 0.017 Å/pixel.

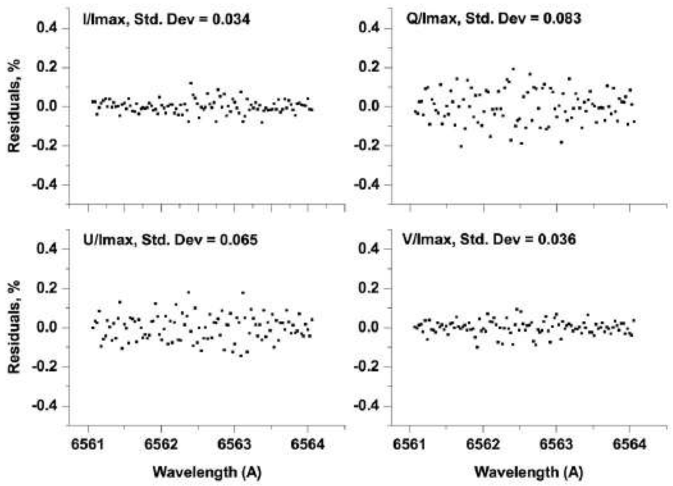

Figure 7. Residuals of observed and FFT smoothed of solar spicules in the H_α spectral line from Figure 7.

mination of the polarization state of radiation (i.e., all four Stokes parameters) at each point in the image of an astronomical object, across different spectral regions. This represents a significant advancement in astrophotometry, providing new insights into both point-like and extended astronomical sources, and is of clear scientific importance and relevance.

In this context, imaging spectropolarimeters based on polarization-holographic diffraction elements offer a promising solution. These elements can be designed to encode both spectral and polarization information into a single diffracted pattern, allowing simultaneous retrieval of the full Stokes vector without mechanical modulation. This passive, motionless approach enables:

- High temporal resolution, limited only by the detector frame rate,
- Elimination of moving parts, reducing mechanical noise and improving stability,
- Compact integration with high-speed cameras for transient polarimetry.

Such a system is particularly well-suited for observations of:

- Solar flares and chromospheric events, where polarization can change on timescales of seconds or less,
- Rapidly rotating magnetic stars or pulsars with phase-resolved polarimetric signals,
- Time-variable scattering environments (e.g., comet outbursts, microlensing polarization events),
- Polarization reverberation mapping in AGNs, where delayed polarized light traces spatial structure.

doi: https://doi.org/10.52526/25792776-2025.72.1-48

Furthermore, real-time polarization data can be critical for adaptive exposure control, triggering follow-up observations, or onboard decision-making in space telescopes with limited data bandwidth. Coupling a PHDE-based spectropolarimeter with real-time image processing pipelines (e.g., FPGA-based demodulation or GPU-assisted Stokes reconstruction) could open a path to autonomous polarimetric monitoring of variable sources.

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