International Symposium on Solar Physics and Solar Eclipses (SPSE) 2006
R. Ramelli, O. M. Shalabiea, I. Saleh, and J.O. Stenflo, eds.

EKPOL: LIQUID CRYSTAL POLARIMETER FOR ECLIPSE OBSERVATIONS OF THE K-CORONA

LUCA ZANGRILLI, SILVANO FINESCHI, GIUSEPPE MASSONE,
GERARDO CAPOBIANCO and FRANCESCO PORCU
INAF - Osservatorio Astronomico di Torino, Strada Osservatorio 20, I-10025, Pino Torinese, Italy

and

PAOLO CALCIDESE
Osservatorio Astronomico della Regione Autonoma Valle d'Aosta, Nus, Saint-Barthélemy, Italy

Abstract.
The EKPol experiment is a K-corona imaging polarimeter, designed to measure the linear polarized radiation coming from the solar corona, during the total solar eclipse of March 29^{th}, 2006, in Waw an Namous - Libya. The EKPol polarimeter is based on Liquid Crystal Variable Retarders, allowing a polarimetric optics configuration without mechanically rotating retarders. This instrument is also thought as a proof of concept for a polarimeter to be placed along the visible light path of the UltraViolet and Visible-light Coronal Imager (UVCI) of the Sounding-rocket Coronagraphic Experiment (SCORE).

Key words: solar corona, K-corona

1. Introduction

The total solar eclipses offer a great opportunity to observe the faint solar corona, expecially its inner portions, which are not easily accessible by coronagraph telescopes, owing to the instrumental scattered light. As during eclipses, the corona is directly observed, those kind of observations benefit of a great reduction of instrumental scattered light, particularly in the inner solar corona close to the limb.

The continuum coronal emission in the visible light arises from Thomson scattering of the solar disc radiation by free electrons in the coronal medium (K-corona), and from the radiation scattered by coronal dust particles (F-corona). The brightness of the K-corona is directly proportional to the electron column density along the line of sight. By adopting proper geometrical assumptions (see e.g. van de Hulst, 1950), we can obtain information on the coronal medium electron density.

The K-corona emission turns out to be partially linearly polarized, as light scattered by coronal electrons is incident from a particular direction: unpolarized light is emitted isotropically from the solar disc and electrons scatter it. For a sufficient distant position of the scattering electrons, the Sun can be considered as a point source and an observer will see radiation with the electric field vibrations in a plane parallel to the solar limb.

In the following we describe the EKPol experiment, which is a K-corona telescope for the observation of the total solar eclipse of March 29th, 2006, in Waw an Namous, Libya. It consists of a Liquid Crystal Variable Retarder (LCVR) based polarimeter, and produces images of the linearly polarized radiation of the K-solar corona. The choice of using LCVRs allows replacing mechanically rotating retarders with electro-optical devices, without moving parts.

The experiment purposes can be summarized as follows:

- study the linearly polarized component of the K solar corona between 1.2 and 4 solar radii;
- observe the morphology of the coronal structures in the visible light;
- obtain the coronal electron density distribution, from the measured polarized brightness (pB);
- proof of concept and LCVRs test for a polarimeter due to be assembled in a sounding rocket instrument (SCORE; Launch: end 2006 - beginning 2007 (after STEREO launch).

The absence of mechanically rotating retarder, makes the EKPol concept suitable for being implemented in space-borne coronagraphs, such as the SCORE sounding rocket experiment, a set of two UltraViolet Coronagraph Imager (UVCI) with co-aligned and co-registered fields of view. UVCI is an externally occulted, off-axis Gregorian telescope, designed to provide full images of the extended corona and optimized for the HeII λ 30.4 nm and HI λ 121.6 nm narrow-band coronal emission (see e.g. Fineschi, 2003, Romoli, 2003).

EKPol has been designed and assembled in the Optics Laboratory of the Astronomical Observatory of Torino, in collaboration with the Osservatorio Astronomico della Regione Autonoma Valle d'Aosta.

2. EKPol description

The EKPol assembly essentially consists of:

- an achromatic doublet with 600 mm of focal length and 50 mm of aperture acting as objective lens;
- a LCVR based polarimeter, without moving retardance plates;
- a CCD camera detector, Pixel Vision, back illuminated, triple Peltier cooling;
- a Losmandy G11 telescope mount, with Gemini computer guide system.

The EKPol field of view is about 2°, and the solar corona can be detected up to 4 solar radii. The CCD camera pixel size is 24 μm, with a angular resolution of 8.6 arcsec per pixel. A design showing the EKpol mechanical structure is shown in Figure 1. As can deduced from Figure 1, the project of the structure is modular, allowing to test separately in the laboratory the collimator and camera lenses and the polarimetric optics complex. Moreover, the light baffles can be removed and replaced with other stops, defining the effective telescope aperture.

2.1. EKPOL OPTICAL DESIGN

The construction specifics of EKPol are summarized in the table shown in Figure 2, and a scheme of the optical assembly of the EKPol instrument is shown in Figure 3. It essentially consists of off the shelf elements: the primary lens is an achromatic doublet from Melles-Griot; the collimating and camera triplets are from Optec; the polarimetric optics are from Meadowlark Optics, and the color filter is from Andover.

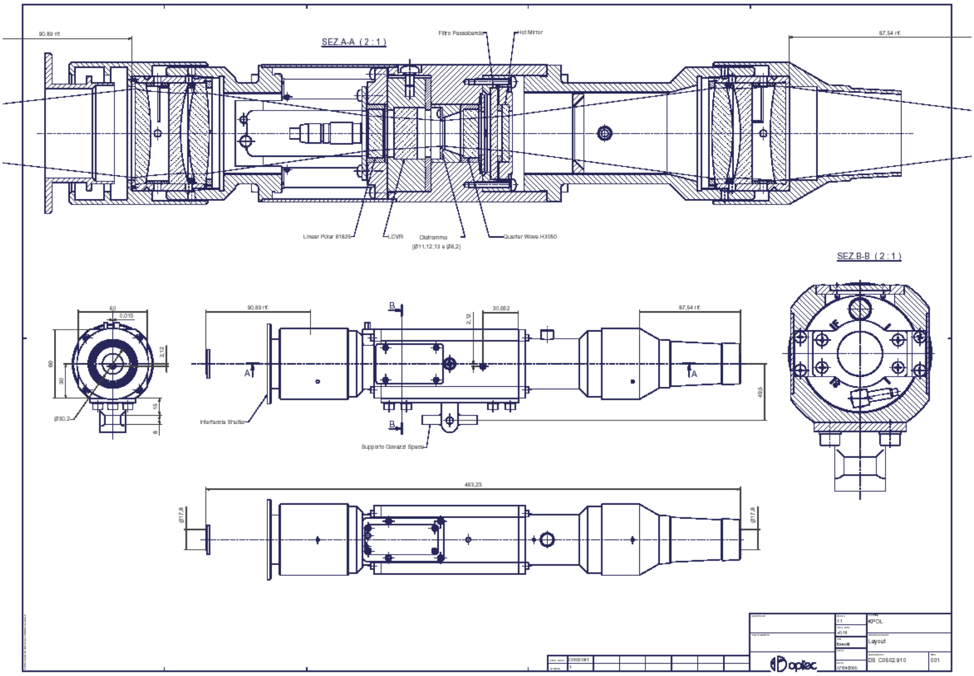
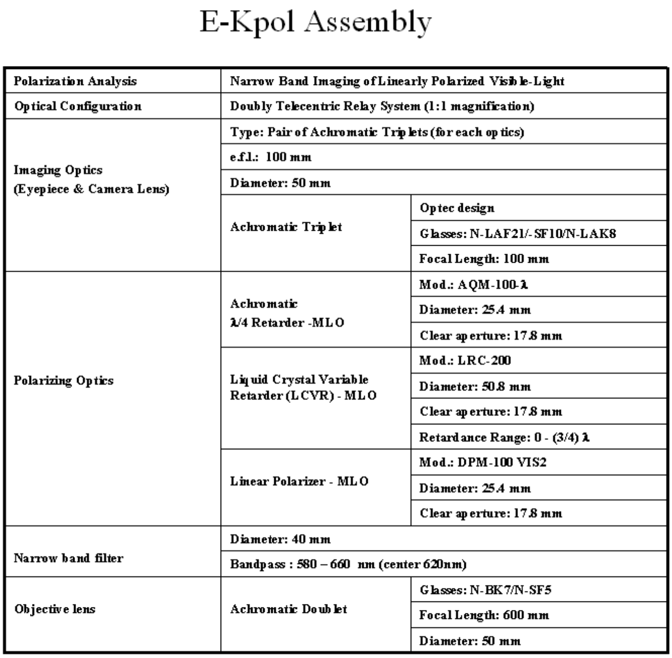


Fig. 1. EKPol mechanical structure; details of the optical mounts and polarimeter module are shown. In the configuration used during the eclipse campaign, the light baffle on the right has been properly replaced with another field stop.

The improvement of the optical design has been developed with the ZEMAX ray tracing program. The geometrical spot size, evaluated with ZEMAX is shown in Figure 4. Different spots for six fields (the remaining five fields are symmetric) are shown, corresponding to heliocentric distances of 0, 1.9, 2.1, 2.6, 3.2, and 4.4 solar radii. The fields relevant to the corona observations correspond to rms spot diameters between 5 and 13 μm, well within the 25 μm detector pixel size.

2.2. EKPol polarimeter design

The innovation of the EKPol polarimetric group consists of using a nematic Liquid Crystal Variable Retarder plate (LCVR), in a rotator configuration, allowing to replace mechanically rotating retarders with electro-optical devices without moving parts (for an analogous solar corona polarimeter design see also Elmore, 2000). Nematic liquid crystals are optically anisotropic media, acting locally as a uniaxial retarders and exhibiting optical birefringence. The effective birefringence can be changed by varying an applied voltage, producing different values of the retardance. The external applied variable voltage, ranging from 0 to 10 mV, with retardance values going from about λ to 0. The LCVR is constructed using precision polished, optically flat fused silica windows spaced a few microns apart, with the cavity filled with nematic liquid crystal material and sealed. The assembly ensures excellent transmitted wavefront quality and low beam deviation. The extraordinary (or slow)



E-Kpol Assembly

Polarization Analysis	Narrow Band Imaging of Linearly Polarized Visible-Light	
Optical Configuration	Doubly Telecentric Relay System (1:1 magnification)	
Imaging Optics (Eyepiece & Camera Lens)	Type: Pair of Achromatic Triplets (for each optics)	
	e.f.l.: 100 mm	
	Diameter: 50 mm	
	Achromatic Triplet	Optec design
		Glasses: N-LAF21/-SF10/N-LAK8
		Focal Length: 100 mm
Polarizing Optics	Achromatic λ/4 Retarder -MLO	Mod.: AQM-100-λ
		Diameter: 25.4 mm
		Clear aperture: 17.8 mm
	Liquid Crystal Variable Retarder (LCVR) - MLO	Mod.: LRC-200
		Diameter: 50.8 mm
		Clear aperture: 17.8 mm
		Retardance Range: 0 - (3/4) λ
	Linear Polarizer - MLO	Mod.: DPM-100 VIS2
		Diameter: 25.4 mm
		Clear aperture: 17.8 mm
Narrow band filter	Diameter: 40 mm	
	Bandpass : 580 – 660 nm (center 620nm)	
Objective lens	Achromatic Doublet	Glasses: N-BK7/N-SF5
		Focal Length: 600 mm
		Diameter: 50 mm

Fig. 2. EKPol construction specifics for the different instrumental modules.

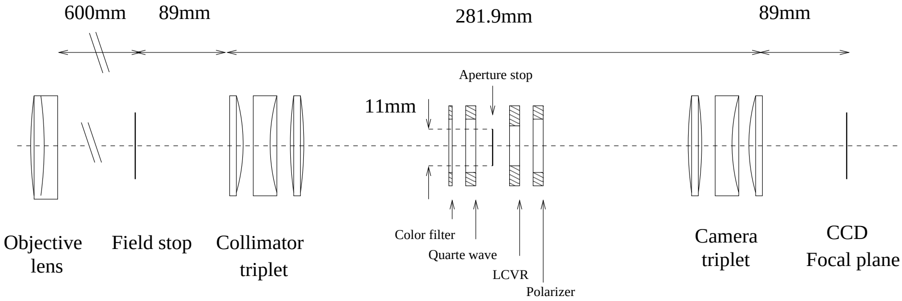


Fig. 3. EKPol optical diagram, showing the system sizes and the different groups of optics.

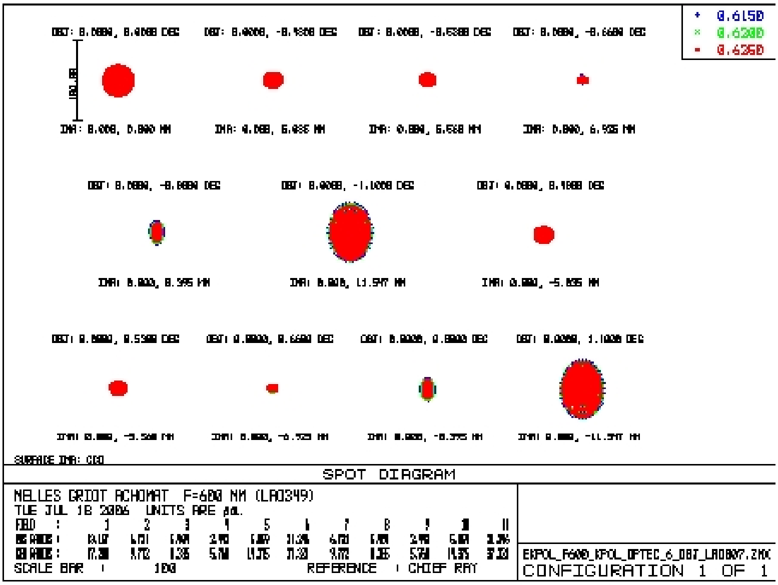


Fig. 4. Spot diagrams for different fields. The rms spot radii are reported.

index is defined by the long axis of the liquid crystal molecules. When no voltage is present, the molecules lie parallel to the windows and maximum retardance is obtained. When voltage is applied across the liquid crystal layer, the molecules tip parallel to the applied electric field. As voltage increases, the effective birefringence decreases, causing a reduction in retardance. These liquid crystal retarders are sensitive to temperature and wavelength changes, and stability of performances are obtained by a constant heating control and a narrow band selection.

The LC low-voltage electro-optical modulation of the polarization signal is accurate, reproducible, and - most important - fast, i.e., up to 100 Hz. Moreover, the control hardware is compact, light-weight, with limited power consumption. This is a clear advantage over more classical methods of mechanical modulation by rotation of polarizing elements, or of piezo-elastic modulation which require high driving voltages (i.e., kilovolts), while in the case of LCVRs large retardance intervals are obtained without requiring very high voltages. Using LCVRs, errors caused by moving parts, unavoidable when using mechanical rotation (inertia with its acceleration and brake times, misalignments of the signal on the detector, etc.), are eliminated. Precise rotation stages, stepper motors and accessories such as a gearbox are avoidable.

Owing to the chromaticity of LCVRs, for a given applied voltage different retardance values are produced within the visible band in corona (about $400 - 650$ nm), diminishing the contrast while modulating the polarized signal in a polarimeter. Hence, in principle, it would be necessary to characterize the LCVR chromatic response when observing non-monochromatic radiation. In EKPol, the bandpass is restricted by a narrow band filter, and the effect of integrating over the transmission band results in a negligible loss of contrast. For a discussion about the chromaticity of LCVRs, see (Fineschi, 2003), where the results of first tests on the LCVR's chromatic response in a polarimeter assembly are presented.

The polarimeter concept is illustrated in Figure 5. It is constituted of a fixed achromatic $\lambda/4$ retarder with the fast axis aligned with the 0° axis of the system, a LCVR with the fast axis at 45°, which allows the modulation of the polarized signal from the corona, and a linear polarizer with its transmission axis at 0°. This polarimetric configuration does not suffer from the possible presence of circularly polarized radiation. The polarimetric elements are placed in a telecentric beam, so transmission and polarization dishomogeneities are averaged across the field of view. The signal modulation, which is required to determine the Q and U Stokes coefficients, is obtained by varying the voltage applied to the LCVR, and taking exposures at four different retardance values. A narrow band color filter, centered about λ 620 nm, is placed in front of the polarimetric complex and selects the polarimeter bandpass, in order to minimize the pollution effect of the sky brightness.

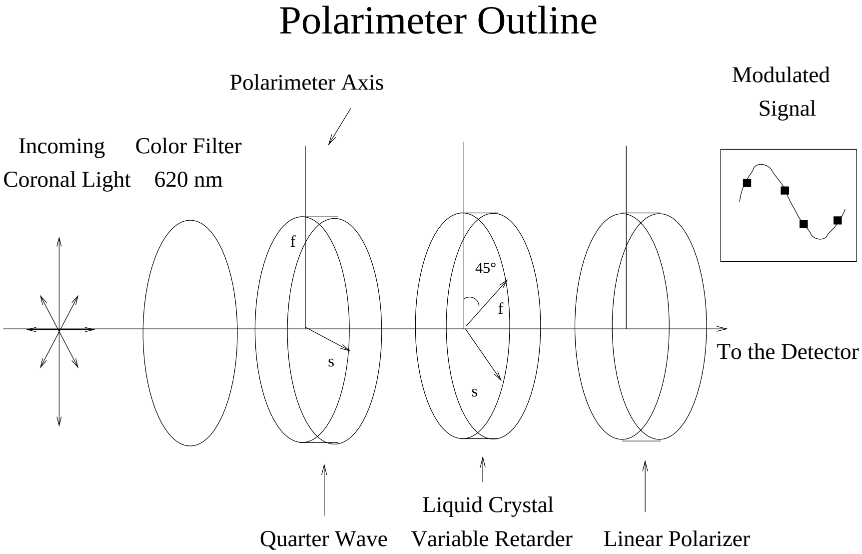


Fig. 5. Illustrating scheme of the EKPol polarimeter, with the essential optical components.

In the configuration above described, the four measured signals m_i from the polarized corona are given by equation 1:

$$m_i = g(I + Q\cos\delta_i + U\sin\delta_i) + b \tag{1}$$

where I, Q, U are the input Stokes parameters, δ_i are the LCVR retardances, g is a constant factor containing the transmission of the polarimetric optics and the detector quantum efficiency, b is the detector bias and dark current. Linear combinations of the four measures for each pixel are used to obtain I, Q and U, and the polarized brightness is given by

$$pB = \sqrt{Q^2 + U^2} \tag{2}$$

Details about the instrument calibration procedure and data analysis will be given in a forthcoming paper, describing the results from this eclipse campaign.

2.3. INSTRUMENT CONTROL SETUP

The EKPol operation control has been made with a Compaq Evo workstation with Windows/NT operating system, for the CCD camera, and a Asus laptop with Windows/98, for the LC voltage and temperature settings. The LCVR output voltage was driven by a programmable digital controller, by LPT port, generating a 2 KHz frequency square wave. We acquired 16 bit, 1024x1024 pixel frames, from the CCD camera, connected by optical fibers from the digital converter to the PC board. The CCD camera properties are summarized in Table I:

TABLE I
CCD camera parameters.

Pixel size	24 μm
CCD op. temp.	237 K
Field of view	1024 x 1024 px
RO frequency	454 KHz
Dark Current	0.49 e^-/px/sec

3. Instrument characterization and observations

During the days preceding the eclipse, several tests on the control software and calibration operations where performed. The calibration procedures, included flat fielding, electronic bias and dark current measurements, absolute calibrations and polarimeter response. Focusing tests were made on star images and during the partiality phase of the eclipse on the lunar edge on the solar disc. Absolute calibration data has been taken by putting an opal in front of the telescope, on uneclipsed Sun at the same elevation as totality, taking exposures for each of three exposure times selected for the observations. A first choice of exposure times were made during preliminary working tests of EKPol, performed at the beginning of March at the Osservatorio Astronomico della Regione Autonoma Valle d'Aosta (Italy), on the full moon.

The polarization calibration setup included a prepolarizer plus an opal, and we took exposures at five positions of −90°, −45°, 0°, 45°, 90°, and for each of the the

LCVR voltages of 10, 7, 5.4, and 4.5 V, which were used during coronal observations, and corresponding to an approximate LCVR retardance (after a first data analysis) of 66°, 144°, 242°, 323°, (referred to the polarimeter 0° axis).

Owing to keep the image registration error within the telescope resolution, the telescope mount was accurately stationed by using a standard Bigourdan procedure and a STV monitoring station with CCD camera. We got an error of 10 arcsec (about one detector pixel) during the 4 minutes of totality, on the night preceding the eclipse. Major difficulties where encountered with the ground solidity (the telescope mount tended to sink in the sand and suffered from vibration transmission), and the structure vibrations induced by the wind. However, during the totality phase the wind calmed down, and a first image inspection told us that the instrument maintained the coronal images in the required position.

The stability of the LCVR response has been ensured by keeping the crystal temperature constantly at about 30 °C, by means of a electric resistance heater.

The scheme of the observing sequence is given in the following Table II.

TABLE II
Observing sequence scheme adopted during eclipse observations; exposure times and LCVR voltages are given.

Exp (ms)	LCVR (V)	Seq.	Exp (ms)	LCVR (V)	Seq.	Exp (ms)	LCVR (V)	Seq.
250	10	first img.						
250	10	1	1000	10	2	4000	10	3
250	7	1	1000	7	2	4000	7	3
250	5.4	1	1000	5.4	2	4000	5.4	3
250	4.5	1	1000	4.5	2	4000	4.5	3

To get a further calibration and an idea of possible instrumental variations, polarization response, absolute calibration, bias and dark current measurements have been repeated immediately after the totality phase.

4. Conclusions

The EKPol experiment adopts the innovative technology of LCVRs, in a polarimeter assembly for the K-corona observation during the total solar eclipse of March 29th, 2006, in Waw an Namous - Libya. A first lookup to the data we obtained, confirms the validity of the instrument approach, which, in the next future, will be implemented in a polarimeter for the HERSCHEL/SCORE sounding rocket mission.

References

D. F. Elmore, et al.: 2000, in *Instrumentation for UV/EUV Astronomy and Solar Missions*, Proc. *SPIE*, **4139**, 370

S. Fineschi, et al.: 2003, in *Innovative Telescopes and Instrumentation for Solar Astrophysics*, Proc. *SPIE*, **4853**, 162

S. Fineschi, et al.: 2005, in *Solar Physics and Space Weather Instrumentation*, Proc. *SPIE*, **5901**, 389

M. Romoli, et al.: 2003, in *SOLAR WIND TEN; AIP Conference Proceedings*, **679**, 846

van de Hulst, H., C.: 1950, *Bulletin of the Astronomical Institute of the Netherlands*, **11**, 135