The BOES Spectropolarimeter for Zeeman Measurements of Stellar Magnetic Fields

KANG-MIN KIM,1 IN Woo HAN,1 GEN NADY G. VALYAVIN,1 SERGEI PLACHINDA,2 JEONG Gyun JANG,1 BE-HO JANG,1 HYEON Cheol SE ONG,1 BYEONG-Cheol LEE,1,3 DONG-IL KANG,1,4 BYEong-GON Park,1 Tae SeoG Yoon,1, and STEVEN S. VOGT3

Received 2007 April 11; accepted 2007 July 27; published 2007 September 27

ABSTRACT. We introduce a new polarimeter installed on the high-resolution fiber-fed echelle spectrograph (called BOES) of the 1.8 m telescope at the Bohyunsan Optical Astronomy Observatory, Korea. The instrument is intended to measure stellar magnetic fields with high-resolution (R ~ 60,000) spectropolarimetric observations of intrinsic polarization in spectral lines. In this paper we describe the spectropolarimeter and present test observations of the longitudinal magnetic fields in some well-studied F–B main-sequence stars (m < 8.8 mag). The results demonstrate that the instrument is able to detect the fields of these stars with high precision, with typical accuracies ranging from about 2 to a few tens of gauss.

1. INTRODUCTION

The presence of intrinsic linear and circular polarizations in spectra of stellar objects provides an important piece of information for diagnostics of their magnetism, wind surroundings, atmospheric inhomogeneities, and other properties. For example, nonzero continuum linear polarization due to Thomson and Rayleigh scattering demonstrates the presence of nonsymmetric patterns in the distribution of an atmospheric or wind medium. The broadband circular polarization, as well as circular and linear polarization, in spectral lines exhibits information on the magnetic fields. The spectropolarimetric observation is therefore one of the most important tools for experimental studies of stellar magnetism. To argue on behalf of this statement, we start our consideration with a brief presentation of the most important historical results that have come to us from stellar spectropolarimetry.

Magnetism of chemically peculiar main-sequence stars.—Strong magnetic fields up to several tens of kilogauss have been detected and studied on a large sample of chemically peculiar (CP) stars. In contrast to nonregular, localized magnetic fields of solar-type stars, the statistical properties of the fields in CP stars and the results of detailed modeling of field geometries in individual objects are generally consistent with the picture of a smooth, roughly dipolar magnetic field, inclined with respect to the stellar axis of rotation (Landstreet 2001).

Magnetism of early-type pulsating and hot O stars.—Recently, comparatively weak regular magnetic fields have also been found in hot, massive β Cep–type and some other pulsating stars (Hubrig et al. 2006) and O-type stars (Wade et al. 2006). The magnetic fields of these stars also have several morphological differences from the magnetic fields of the Sun and other late-type stars.

Magnetism of late-type, convective stars.—Practically all manifestations of solar activity (chromosphere and corona, plages and spots, flares, etc.) are related to magnetic fields and their interaction with differential rotation and convection. Spectropolarimetric studies of fragmented and global magnetic fields make it possible to extend our knowledge about these processes to another solar type and cooler convective stars.

At the moment, the presence of global magnetic fields from a few to some tens of gauss has been established in convective stars of spectral types F9–M3 among luminosity classes I–V (Plachinda & Tarasova 1999, 2000; Donati et al. 2003; Plachinda 2004a, 2004b; Petit et al. 2005).

This brief and, of course, incomplete presentation illustrates the importance of spectropolarimetry as an effective observational tool for studying stellar magnetism. Nowadays there is a large collection of portable (Eversberg et al. 1998 for instance) or stationary spectropolarimeters installed at different telescopes. The 2–3 m class telescopes equipped with stationary spectropolarimeters are

- 2.0 m telescope, Pic du Midi, France
- 2.6 m telescope, Crimea, Ukraine
- 2.6 m Nordic Optical Telescope, La Palma, Spain
- 2.6 m Hobby-Eberly Telescope, Texas, US
- 3.0 m Galileo Italian National Telescope, Italy
- 3.6 m Canada-France-Hawaii Telescope, US

Among the most known versions of spectropolarimeters in-
stalled at large telescopes are the imager/spectrograph/polarimeter FORS1 (Appenzeller et al. 1998) of the ESO, VLT; and spectropolarimeters at the AAT (Bailey 1989) and Keck (Goodrich et al. 1995). Very recently a low-resolution polarimeter was also installed at the 6 m Russian telescope (Naydenov et al. 2002). New magnetic weak-field main-sequence and degenerate stars have been detected/studied with these instruments (see, e.g., a review by Putney 1999; also Aznar Cuadrado et al. 2004; Valyavin et al. 2006; Wade et al. 2003 and references therein).

Recently designed high-resolution fiber-fed spectropolarimeters with intermediate-class telescopes such as the MUSICOS (Donati et al. 1999) or ESPaDOnS (Manset & Donati 2003) have demonstrated the best characteristics in obtaining polarization spectra and measuring stellar magnetic fields, which has led to a new generation of stellar spectropolarimeters. Typical accuracies of the field measurements with these instruments range from about 1 to a few tens of gauss depending on the spectral characteristics of the stars being studied. Here we present the structure of this polarimeter and the results of longitudinal magnetic field measurements for some well-studied magnetic stars. Observation of linear polarization is also available. However, due to poor weather conditions at the BOAO site and the presence of significant light pollution, observations of linear polarization are complicated and not quite as effective. Now, we are focused mainly on observations of circular polarization with this spectropolarimeter.

2. THE BOES SPECTROPOLARIMETER: BASIC PRINCIPLES AND DESIGN

The BOES (BOAO Echelle Spectrograph) is a high-throughput, versatile, fiber-fed prism cross-dispersed echelle spectrograph installed at the 1.8 m telescope of the BOAO. Using a 2k $\times$ 4k CCD, the BOES can obtain spectra simultaneously over a wide wavelength range of 3500–10,500 Å with a throughput (resolution times slit width in arcseconds) around 125,000. It has nine fibers with core diameter from 80 to 300 μm; corresponding fields of view and resolutions ($\lambda/\Delta\lambda$) are 1.1”–4.3” and 30,000–90,000, respectively.

The block diagram of the BOES is presented in Figure 1. The instrument consists of three main parts: (1) polarization optics (BOESP; Fig. 2) containing a rotatable quarter-wave plate (QWP) and a Savart plate (SVTP) as a beam splitter, (2) CIM (Cassegrain interface module; Fig. 3) with a light-transmitting fiber set (Fig. 4), and (3) a spectrometer (i.e., a bench-mounted...
echelle spectrograph; Fig. 5). The 18.5 m length optical fibers transmit the starlight accumulated at the Cassegrain focus to the spectrometer room, where the temperature and humidity are maintained at 20°C ± 0.5°C and below 50%, respectively.

In addition to the high-resolution echelle mode, BOES is equipped with a medium-dispersion long-slit spectrograph (called LS) in the CIM (Fig. 3). The LS can obtain a spectrum of a linear reciprocal dispersion of 19–217 Å mm⁻¹ (0.45–5.2 Å pixel⁻¹) with 3.6′ slit length. The device switching between BOES (ordinary spectroscopic mode), BOESP (spectropolarimetric mode), and LS (long-slit spectroscopic mode) can be done within 10 s.

As shown in Figure 1, the BOES uses three CCDs: a slit-monitoring CCD (called SMCCD), LS CCD, and the BOES CCD. For the SMCCD, we use the Quantix 57 camera, which has an EEV 57-10 CCD chip (530 × 526, 13 μm pixel) with 2.7′ field of view. The LS CCD has a Tek 1024 chip (1024 × 1024, 24 μm pixel) with readout noise of 7.4 e⁻. The BOES CCD is a grade zero class E2V CCD 44-82 chip (2048 × 4096, 15 μm pixel) with 4.0 e⁻ readout noise.

Three personal computers (PCs) are used to control the instrument. PC 1 connected to the CIM through RS232C controls the CIM. The observer can monitor the slit image and control the CIM by PC 2 connected to PC 1 by network. And the data acquisition from the BOES CCD or LS CCD is performed by Linux-based PC 3.

2.1. Polarimetric Optics

The polarimetric analyzer that we use in the spectropolarimetric mode consists of a rotatable QWP for polarimetric modulation and a Savart plate as a beam splitter. In the present design we have decided to use a polymer QWP (Samoylov et al. 2004) instead of the frequently used quartz/MgF₂ crystal wave plate or Fresnel rhombs. It is a well-known fact that the quartz/MgF₂ QWP produces significant artificial polarization ripples of 0.05%–2% (Harris & Howarth 1996; Donati et al. 1999) due to the interference within the cemented layers of the
retarder. And the well-known solution based on Fresnel rhombs cannot easily be used in our design due to the considerable size of this optics. At the same time, the polymer QWP that we used retards the wave at a rate of $0.25 \pm 0.007\lambda$ in the 4000–8000 Å range (Samoylov et al. 2004), and the ripple is below 0.1% (Ikeda et al. 2003). Such good parameters of the plate make it possible to use it instead of other available plates. With these optical elements the available working wavelength range of the polarimeter is 4000–8000 Å.

The optics is installed at the Cassegrain focus in front of the fiber input as shown in Figure 2. It is mounted on rotary stages to be removable from the optical axis in case of ordinary spectral observations. The spectropolarimetric observations are available with a resolving power of 45,000 or 60,000.

Before each run of the polarimetric observations, the adjustment of the polarimeter is examined using a laboratory source of light (for example, a similar procedure is described in detail by Plachinda 2005). Some important examples of these tests are presented in Figure 6, where the upper plot illustrates the analyzer assembled for measurements of the modulation by the QWP in observations of circular polarization. Artificial circularly polarized light is created by the combination of an additional QWP (QWP1) and polarizer (polarizer 1) as shown in the figure. The efficiency of the modulation is better than 99.7%. The lower plot (graph) illustrates the results of cross talk measurements obtained at different orientation angles (the horizontal axis) of polarizer 1 (QWP1 is removed in this case). As one can see, the maximum cross talk (vertical axis in the figure), which characterizes artificial circular polarization from linearly polarized light, is not higher than 5.5%. To our knowledge, this result is practically standard for modern polarimeters.

2.2. The CIM and the Fiber Assembly

As the design concept of the CIM and the fiber assembly was described in Kim et al. (2002), we do not mention it here in detail. Since then, we have revised the flat-fielding lamps and the fiber assembly that was adopted for polarimetric observations. For the white balance of the flat fielding, we use three tungsten halogen lamps with an integration sphere—a 10 W lamp with a half-inch diameter aperture for the red wavelengths, a 100 W with 1 inch diameter filters (3 mm KG3 + 1 mm BG24A + 1 mm BG39) for the medium wavelengths, and a 100 W with 2 inch diameter filters (3 mm KG3 + 1 mm UG5 + 1 mm S8612) for the blue region (see the cube-type integrating sphere in Fig. 3).

The BOES is furnished with nine fibers of 80, 100, 150, 200, and 300 μm in core diameters that provide corresponding spectral resolutions $\lambda/\Delta\lambda \sim 90,000, 75,000, 60,000, 45,000,$ and 30,000, respectively (Fig. 4). Five of them are used for ordinary spectroscopy, and two pairs of 150 and 200 μm fibers, for spectropolarimetry. At the fiber input, fibers in each pair are separated by 500 μm distance that corresponds to the separation of the beams split by the polarimetric analyzer. At the fiber exit, these are separated to 380 μm to avoid overlapping of spectral orders. All the fibers except the 80 μm one (STU; Schötz et al. 1998) are FBP, the transmission of which is improved relative to STU fiber, especially in the blue region.

2.3. The Spectrometer Part

The spectrometer (BOES) was designed by S. S. V. and is shown in Figure 5. It is a quasi-Littrow configuration in the dual-white-pupil (DWP) configuration pioneered by the UV-Visual Echelle Spectrograph (UVES; Dekker et al. 1992) on the VLT. Other similar-style DWP spectrometers are FOCES (Pfeiffer et al. 1998) of the 2.2 m telescope at Calar Alto Observatory, HRS (Tull 1998) on the Hobby-Eberly Telescope (HET), and FEROS (Kaufer & Pasquini 1998) at ESO.

In the BOES design, the f/8 beam exiting the fiber is collimated by the main off-axis collimator into a 136 mm diameter beam, which is then dispersed by a 41.59 groove mm$^{-1}$ R4 echelle of size 203 × 813 mm. This echelle is a replica of the master ruled for the blue side of UVES. The dispersed light from the echelle returns in quasi-Littrow mode (0.6° out of plane) back to the main collimator and, via the folding mirror, to the transfer collimator. The transfer collimator is identical.
Fig. 7.—Measured efficiency of the (BOES + telescope + air extinction) for different single fibers without the correction of the light cutoff at the fiber input while the star was at 1.13 air mass with the seeing around 2.3" on 2003 November 3.

to the main collimator, and the optical axes of both are collinear. The transfer collimator corrects, to a high degree, the aberrations introduced by the main collimator and provides a white pupil near the cross-disperser to minimize the required clear apertures of the prisms and camera. Both collimators are cut from a common f/1.8 parent parabola of 600 mm diameter. All the mirrors have durable high-reflectance silver coatings.

Most if not all previous versions of DWP spectrometers incorporated a toroidal rear surface in the optical train (near the focal plane) to counteract astigmatism introduced by the quasi-Littrow white pupil collimation combination. However, we found that slightly pistoning the transfer collimator provides an equally viable solution that eliminates the need for this aspheric optics.

For the cross-disperser, we adopted the use of a pair of 55° prisms instead of a grating. Prisms provide more uniform order separation and higher efficiency across the very wide spectral bandpass of BOES. We used S-BSL7Y, a BK-7–like glass with enhanced ultraviolet transmission available from Ohara, Inc. It was selected on the basis of its unusually high ratio of red to blue dispersion, creating a more uniform order separation across the echelle format and thus more efficient order packing. The f/1.6 camera has an effective focal length of 389 mm and consists of six spherical lenses in three groups. It works over about a 9.5" diameter field of view and spans the entire 3500–10,500 Å range with adequate image quality. All prisms and camera lenses were treated with wideband antireflection coatings, which provide reflectance below 1.5% across the 3500–10,500 Å range. Overall, 86 spectral orders, from the 46th to the 131st, are captured on the CCD. Interorder stray light appears to be at least less than 2% of the intensities of the neighboring orders.

2.4. Efficiency and Stability of the BOES

Figure 7 illustrates the typical efficiency of the BOES measured on 2003 November 3 with different (300, 200, and 80 µm in diameter) single fibers. This shows that maximum efficiency is up to 12% including the light loss due to the atmospheric extinction, the reflectance of the telescope, and the light cutoff at the fiber input. While the efficiency was measured, the target star was at an air mass of 1.13 with the seeing size around 2.3". The small efficiency of the 80 µm fiber comes from the light cutoff at the fiber input due to the small diameter (Kim et al. 2002).

Good mechanical stability of the spectrograph makes it possible to use the instrument in a wide range of observational programs, for example, asteroseismology as well as Zeeman observations. Figure 8 illustrates the typical accuracy of the stellar radial velocity measurements achieved in observations with the BOES equipped with an iodine cell. The standard star τ Ceti (G8 V) does not exhibit any variations in radial velocity within a typical accuracy of about 9 m s⁻¹ on a 3 yr time base.

3. MEASUREMENTS OF STELLAR MAGNETIC FIELDS WITH THE BOES

3.1. Preliminary Remarks

Directly, stellar magnetic fields are detected mainly through the observations of the Zeeman effect in spectral lines. According to basic physical principles (for more details see, for example, Landstreet 1980), if an atom is placed in a magnetic field \( B \), its individual energy levels are split into \( 2J + 1 \) sublevels separated by energy \( \Delta E = g\mu_B B/2mc \), where \( g \) is the Lande factor. As a result, stellar magnetosensitive spectral lines are split into a number of \( \pi \)- and \( \sigma \)-components, which are polarized depending on the orientation of the magnetic field relative to the observer.

In a longitudinal (parallel to the line of sight) magnetic field the \( \sigma \)-components, which are generally displaced symmetrically...
BOES SPECTROPOLARIMETER FOR ZEEMAN MEASUREMENTS

Fig. 9.—Stokes V spectra (from top to bottom) of the stars HD 215441, HD 32633, HD 40312, and the star HD 61421 (Procyon) at the Hβ line region.

To shorter and longer wavelengths relative to the nonshifted central π-components of spectral lines, have opposite circular polarizations. Thus, by observing circular polarization in the spectral lines we are able to measure the longitudinal component of the stellar magnetic field. To reconstruct the full vector of the field, additional observations of linearly polarized π- and σ-components are needed. These observations allow us to estimate a transverse field component that, together with observations of the longitudinal component, gives a full vector magnetic field averaged over the stellar disk. In this paper, we discuss observations of the longitudinal fields only.

The averaged circularly polarized σ-components are displaced relative to the rest wavelength λ₀ of a spectral line by a factor of

$$\Delta \lambda_\sigma = \pm 4.67 \times 10^{-13} \lambda^2 B_l,$$

where $B_l$ is the longitudinal field component in gauss, $\lambda$ is the effective Lande factor, and $\lambda$ is the wavelength in angstroms. Due to the fact that these displaced components have opposite circular polarizations and are shifted relative to each other, in the stellar circular polarization spectra (Stokes V spectra, or V spectra) they form nonzero features within magnetosensitive spectral lines. In most cases of spectropolarimetric observations these features show well-known S-shaped features (Fig. 9) at the cores of spectral lines. Their amplitudes and forms depend on magnetic field strengths, Lande factors, gradients of the line profiles, and the spectral resolution of the spectrograph:

$$V \sim \frac{d}{d\lambda} (dI/d\lambda),$$

where $dI/d\lambda$ describes the gradient of a spectral line convolved with the instrumental function of a spectrograph (e.g., Landstreet 2001). The mean longitudinal magnetic field can be estimated by applying model methods of Doppler-Zeeman spectropolarimetric tomography to the analysis of the Stokes V spectra (e.g., Euchner et al. 2002), or the LSD method (Donati et al. 1997). Alternatively (and traditionally), longitudinal magnetic fields can simply be measured via analysis of the displacement (eq. [1]) between the positions of spectral lines in the spectra of opposite circular polarizations split by the analyzer.

3.2. Obtaining Circular Polarization Spectra: Observations and Data Reduction

Each exposure in observations of circular polarization with the BOES yields two spectra on the CCD—one from the ordinary beam and the other from the extraordinary beam split by the analyzer. In the case of an ideal spectropolarimeter (which has no intrinsic distortion factors), this single exposure obtained at one of the orthogonal orientations of the quarter-wave plate would practically be enough to build V Stokes spectra and to measure the magnetic field. However, due to the presence of a large number of instrumental biases such as pixel-to-pixel inhomogeneity, slightly different dispersion relation-

ships at each of the split beams, and other factors, it is recommended to obtain an additional exposure with inverted sign of the polarization effects by rotating the quarter-wave plate by 90°. Such a technique makes it possible to reconstruct the Stokes V spectra in a pixel coordinate system separately for the spectra of the ordinary and extraordinary beams that significantly increases the quality of the output results (for details see, e.g., Plachinda & Tarasova 1999, Bagnulo et al. 2002, or Aznar Cuadrado et al. 2004).

Due to the above-mentioned reasons and in order to increase the reliability of our observations of circular polarization, one observation with the BOES consists of four short, consecutive exposures at two orthogonal orientations of the quarter-wave plate (the sequence of its position angles is $+45^\circ$, $-45^\circ$, $-45^\circ$, $+45^\circ$). Assuming a priori that the timescale of possible physical variability of polarization features in spectra of nondegenerate stars would be as short as a few hours, we usually set the integration time for each of the individual exposures from a few minutes to 0.5 hr depending on stellar magnitude and sky conditions.
The data reduction was processed with IRAF. The procedures are mostly standard, including the following steps: cosmic-ray hit removal, electronic bias subtraction, flat-fielding, 2-D wavelength calibration, sky background subtraction, and spectrum extraction. As an output result we obtained a series of pairs of left and right circular polarized spectra that we used to build V Stokes spectra and measure stellar longitudinal magnetic fields. We obtained the individual Stokes V spectra for each of the echelle spectral orders by applying the technique presented by Bagnulo et al. (2002).

In order to illustrate the results of the reduction in our first polarimetric observations with the BOES, we present fragments of circular polarization spectra of the magnetic stars HD 215441, HD 32633, HD 40312, and the star HD 61421 (Procyon) in Figures 9 and 10. We have chosen these stars as the remarkable cases of typical magnetic stars (HD 215441, HD 32633, HD 40312) having polarization features of different intensities (details on these stars are also presented below) and a zero-field star (Procyon). As one can see (Fig. 9), the circular polarization of different intensities can easily be resolved and studied with our polarimeter.

Examination of the zero-field star Procyon has not revealed any artificial circular polarization features at a characteristic level of about 0.5% within the working wavelength region from 4000 to 8000 Å. The bottom plot in Figure 9 demonstrates zero polarization of Procyon at the Hβ region. An example of another wavelength region is presented in Figure 10.

### 3.3. Linear Polarization

Finally, before presentation of the results of the longitudinal magnetic field measurements in the standard stars, we would also like to briefly discuss the possibility of obtaining Stokes Q/U (linear polarization) spectra, which is necessary for measurements of the transverse magnetic fields. It should be noted that linear polarization features in spectral lines due to the Zeeman effect are intrinsically weaker than the corresponding circular polarization features. This strongly complicates observations of linear polarization with 2 m class telescopes. To simplify the solution, special methods of data reduction (Donati et al. 1997) and the LSD method for obtaining linear polarization measurements that are averaged over all spectral lines (Donati et al. 1997) should be applied. In this paper we do not discuss these details, leaving them for future investigations for application to the BOES data. Here we just briefly present and illustrate test observations of the Stokes Q/U spectra with the BOES.

There are several designs of polarimetric optics for obtaining all Stokes parameters including Stokes Q/U. Due to technical limitations, for linear polarization measurements we have chosen the simplest configuration of polarimetric optics, similar to that presented by Naydenov et al. (2002). According to their scheme, the Stokes Q/U spectra can simply be obtained by using the beam splitter only (without the QWP). In this case, the necessary observational basis is achieved by rotation of the Cassegrain assembly to obtain four consecutive exposures at different position angles of the beam splitter relative to the sky plane (for details see Naydenov et al. 2002). Applying this method, we observed the magnetic star α2 CVn, which shows rotationally modulated linear polarization in its spectral lines.

According to Wade et al. (2000) net linear polarization of this star varies from about −0.2% to about +0.6%. We observed α2 CVn at two phases of the star’s rotation when the polarization is nearly zero (φ ≈ 0.03) and at one of the extrema (φ ≈ 0.2) where the star’s spectrum exhibits nonzero positive linear polarization (Stokes Q ≈ +0.6% and Stokes U ≈ +0.3%; see Fig. 6 in Wade et al. 2000). Such a weak polarization level cannot simply be registered within consideration of one individual spectral line. However, the problem can be resolved if several spectral lines are considered together. For instance, considering net polarization as a function of the distance from the line cores (in the radial velocity scale), the LSD method of obtaining polarization that is averaged over all available spectral lines can be applied (Wade et al. 2000). To illustrate this, in Figure 11 we present Stokes Q/U spectra of α2 CVn that are averaged over all available Balmer lines. The
Monin et al. 2002 and references therein). This technique, if lines in the spectra of opposite circular polarizations (see, e.g.,
of the displacement (eq. [1]) between the positions of spectral
with the BOES we measured longitudinal fields via analysis
Fields with the BOES
3.4. Measurements of Stellar Longitudinal Magnetic
the longitudinal magnetic field measurements only.
ourselves to presentation of the polarimeter and consideration of
left two plots illustrate zero polarization at the rotation phase
φ ≈ 0.03. The right plots present nearly maximum positive
polarization level can also be registered with our polarimeter, which enables us to measure the transverse magnetic field. This problem, however, deserves an additional special paper where we will present all the necessary tools for these measurements and details on linear polarization observations of the standard stars including α² CVn that we briefly touched on here. In this paper we limit ourselves to presentation of the polarimeter and consideration of the longitudinal magnetic field measurements only.

3.4. Measurements of Stellar Longitudinal Magnetic Fields with the BOES

In our first Zeeman observations of stellar magnetic fields with the BOES we measured longitudinal fields via analysis of the displacement (eq. [1]) between the positions of spectral lines in the spectra of opposite circular polarizations (see, e.g., Monin et al. 2002 and references therein). This technique, if

applied to all selected spectral lines in a spectrum with further statistical averaging of the result, is quite robust for the determination of longitudinal magnetic fields averaged over the stellar disks. The atomic data necessary for the identification of spectral lines and their Lande factors were taken from the VALD database (Piskunov et al. 1995; Ryabchikova et al. 1999; Kupka et al. 1999).

Measurements at individual spectral lines were carried out in a pixel coordinate system separately for spectra obtained at the ordinary and extraordinary beams split by the analyzer to avoid uncertainties in the wavelength calibration. In this case, Zeeman displacement between σ-components of opposite circular polarizations can be measured as a shift between the centers of gravity of a spectral line extracted from the same pixels of two neighboring CCD frames obtained at two orthogonal orientations (+45° and −45°) of the quarter-wave plate. The longitudinal magnetic field \( B_l \) based on these measurements can be found as an averaged mean of \( B''_l \) and \( B'_l \) estimates of the magnetic field obtained from spectra of the corresponding ordinary and extraordinary beams. It is clear that \( B''_l \) and \( B'_l \) are not free of any biases due to the influence of mechanical instabilities from exposure to exposure. Their averaging, however, significantly reduces them as we now illustrate.

Denoting the center of gravity of spectral lines from the ordinary/extraradial spectrum obtained at the +45° or −45° position of the quarter-wave plate as \( \lambda_{+45°} \) or \( \lambda_{-45°} \), the \( B''_l \) and \( B'_l \) estimations have the following forms:

\[
B''_l = \frac{\lambda_{+45°} - \lambda_{-45°}}{2} = \frac{k(\pm 2\Delta\lambda_g \pm \Delta\lambda_h)\lambda_{45°}}{2}, \quad (3)
\]

\[
B'_l = \frac{\lambda_{+45°} + \lambda_{-45°}}{2} = \frac{k(\pm 2\Delta\lambda_g \mp \Delta\lambda_h)\lambda_{45°}}{2}, \quad (4)
\]

where \( k = 1/(4.67 \times 10^{-11} \lambda^2) \); \( \Delta\lambda_g \) is Zeeman displacement between the σ-components in the spectral line; and \( \Delta\lambda_h \) and \( \Delta\lambda_l \) are instrumental shifts between spectra of the ordinary/extraordinary beam obtained at different moments in time due to the requirement of having two consecutive exposures at +45° and −45° orientations of the QWP. The sign inversion in \( B'_l \) estimation appears due to the inverse polarimetric properties of the extraordinary beam relative to the ordinary one. Averaging the data, we have

\[
B_l = B''_l/2 + B'_l/2 = \frac{k(\pm 4\Delta\lambda_g \pm \Delta\lambda_h \mp \Delta\lambda_l)}{4}. \quad (5)
\]

In equation (5), the instrumental shift is taken with opposite sign due to the polarimetric inversion in the beams. In practically all cases of any instrumental effect these shifts are equal in linear guess approximation and eliminated each other in the applied method.

Obtaining an estimate of the averaged mean longitudinal magnetic fields and error bars within one observation of a star (consisting of four consecutive exposures) was done by weight-

---

**Fig. 11.**—Stokes Q/U parameters of the star α² CVn that have been averaged over basic Balmer lines, shown at those rotational phases where the star exhibits zero (φ ≈ 0; left) and maximum (φ ≈ 0.2; right) linear polarization. The data are presented in the radial velocity scale as functions of the distance from the spectral line cores.
Results of the Longitudinal Magnetic Field Measurements

Determination of the Mean Longitudinal Field

Table 1

| Name     | JD          | Exposure Time | N_{obs} | S/N | WC     |
|----------|-------------|---------------|---------|-----|--------|
| HD 32633 | 2,454,006.0665278 | 8400          | 1       | 350 | Moderate |
| HD 40312 | 2,454,006.256944 | 3840          | 3       | 400 | Poor    |
| HD 61421 | 2,454,006.3333333 | 395           | 1       | 600 | Poor    |
| HD 215441| 2,454,005.981944 | 7200          | 1       | 180 | Moderate |

Note.—Col. (1): name of an observed star; col. (2) Julian date (JD) of the midpoint of the observation; cols. (3) and (4): total exposure time and corresponding number of observations N_{obs}; col. (5): total signal-to-noise ratio (S/N) at λ5500; col. (6): weather conditions (WC): good, moderate, or poor.

Table 2

| Name     | Spectral Class | Exposure Time | B_l | σ |
|----------|----------------|---------------|-----|----|
| HD 32633 | B9p            | 7.1           | 8400 | 0.13 | −2616 | 56 |
| HD 40312 | A0p            | 2.6           | 3840 | 0.61 | +310  | 28 |
| HD 61421 | F5             | 0.34          | 395  | −3.8 | 2.2   |
| HD 215441| B9p            | 8.8           | 7200 | +10500 | 330 |

Determination of the Mean Longitudinal Field

The observations were carried out in the course of one observing night on 2006 September 27. Three well-known magnetic Ap/Bp stars, HD 215441, HD 32633, and HD 40312 (θ Aur), were observed, together with Procyon as a zero-field standard. Table 1 gives an overview of the observations.

Results of the longitudinal magnetic field measurements are summarized in Table 2, where column (1) is the name of a star, column (2) is the spectral class, column (3) is the visual magnitude, column (4) is the exposure time, column (5) is the rotational phase of a magnetic star if known (throughout this study we use ephemerides presented by Wade et al. 2000), and columns (6)–(7) report the measurements and uncertainties, respectively, of the longitudinal magnetic fields obtained as explained above. We briefly discuss these results.

HD 215441, or the famous Babcock’s star, is known to have the strongest magnetic field among the main-sequence stars. The longitudinal field of this star varies with the rotational period P = 9.4871 days about the mean value of +15,000 G with an amplitude of about 4.5 kG (Bychkov et al. 2005). Our result (B_l = +10,500 ± 330 G; see Table 2), which is consistent with the data presented by Bychkov et al. (2005), was measured as the average mean of individual Zeeman measurements obtained from all 68 available spectral lines (including hydrogen lines) in the region between 4100 and 8000 Å. Unfortunately, due to uncertainties in the determination of the magnetic ephemeris of this star (Bychkov et al. 2005), we are unable to compare our result with those of other authors. Besides, measurements of B_l by using only metal lines compared to measurements using hydrogen lines exhibit a very large discrepancy (much larger than corresponding scatter due to Poisson noise), which suggests the presence of a very complicated magnetic field morphology in this star. For example, measurements of the magnetic field by using only the Balmer lines give B_l = +17,000 ± 700 G, which is significantly larger than the field averaged by individual measurements of all the other spectral lines. In this study we do not discuss this well-known effect (Bychkov et al. 2005 and references therein), presenting HD 215441 only as an illustration.

HD 32633 and HD 40312, or θ Aur, are well-known broad-lined B9p and A0p magnetic stars that we used as standards to compare our measurements with the best measurements given by other authors. To our knowledge, the most extensive high-precision measurements of their variable magnetic fields were performed by Wade et al. (2000).

According to Wade et al. (2000) the longitudinal magnetic field of HD 32633 varies with a period of 6.4300 days and demonstrates smooth, nonsinusoidal variation with two extremes at B_l ≈ −4200 and ≈ +1800 G. Our single observation of this star was carried out at the rotation phase φ = 0.012 under moderate weather conditions. At this phase the longitudinal magnetic field of this star is located at a rising branch of the field variation between the negative extremum and crossover. With our polarimeter, the measured longitudinal field at this phase (B_l = −2616 ± 56 G; see Table 2) has demonstrated very good agreement with the results of other authors. In Figure 12 (bottom) our observation (filled triangles) is illustrated in comparison with the data (open circles) taken from Wade et al. (2000). The obtained field value and small error bar (in Fig. 12 the error bar is smaller than the triangle size) suggest high quality of our polarimeter in measurements of stellar magnetic fields. In particular, the previous best estimates of the mean longitudinal magnetic field of this star demonstrated the same or twice lower accuracy (Wade et al. 2000).

The star HD 40312 exhibits a weak variable longitudinal magnetic field, the behavior of which is currently well studied (Wade et al. 2000). Our observations of HD 40312 were carried out under poor weather conditions that made us observe this star for quite a long time (about 1 hr; Table 1). We have observed this target at the rotation phase φ ≈ 0.6 of the field variation. Similar to the previous star, our estimate of the field is quite consistent with the results given by Wade et al. (2000) (see Table 2 and Fig. 12, top).
Finally, HD 61421 (or α CMi, Procyon) was used as a zero-field star. This star has been observed polarimetrically by a number of authors (see an overview in Table 3). In their observations a magnetic field has not been found, with typical accuracies from about 1 to 7 G. Formal averaging of these results produces no traces of magnetic field at a level of about 0.5 G, which makes it possible for us to use this star as a well-studied zero-field standard. Our result also showed a very accurate zero with error bar of about 2 G (see Table 2). This result was obtained during only about 6 minutes of integration, in contrast to the hours of typical exposure times in the previous observations of this star (see Table 3). About 100 nonblended spectral lines were used to obtain this result.

It should be noted here that such a high accuracy of the field measurement becomes critical to the adopted methods of data reduction and the measurements. In our measurements, for example, different methods of statistical analysis in the applied line-by-line technique gave us some differences in the final result. Obtaining statistical weights of the measurements at individual spectral lines using their residual intensities and signal-to-noise ratios, we initially derived an uncertainty of about 2.7 G. However, from the measurements weighted by the Monte Carlo simulation method (Plachinda 2004a), the final error bar was determined with significantly better accuracy of about 2.2 G. This fact can easily be understood because there are more than the above-mentioned two factors (Poisson noise and residual intensities) influencing the statistical weights. The Lande factors (their values) and shapes of spectral lines also play roles. The applied Monte Carlo method takes them all into account.

At the same time, methods of weighting do not play such a significant role in the determination of strong mean longitudinal fields in chemically peculiar magnetic stars. In these stars the main contribution to the uncertainty comes from the inhomogeneous distribution of the magnetic field over the surface and chemical peculiarities that may demonstrate local field intensities at chemically overabundant spots (such as in our example with HD 215441).

Different methods of data reduction also play a role (extraction of spectral orders, for example). In this paper, however, traditional standard methods were adopted for the spectropolarimetric analysis to demonstrate the pilot workability of the BOES spectropolarimeter.

5. SUMMARY

We have presented the new stationary spectropolarimeter mounted on the high-resolution fiber-fed echelle spectrograph BOES of the 1.8 m telescope at the BOAO. At the moment, the instrument is ready for regular observations of stellar longitudinal magnetic fields and demonstrates good transparency and precision of the measurements. Typical accuracies of the field measurements in bright stars (brighter than 9th stellar magnitude) range from about 2 to a few tens of gauss depending on spectral class, rotation of the star, and integration time. In this regard, further improvements to the polarimeter concern mainly the software for the data reduction and methods of the measurements. We expect that, applying more advanced technologies of data reduction connected, for example, with optimal extraction of spectral orders (Donati et al. 1997) or the LSD

### TABLE 3

| Author                  | Aperture (m) | Polarimeter                  | Exposure (hr) | $B_{\parallel}$ (G) | $\sigma$ (G) |
|-------------------------|--------------|------------------------------|---------------|---------------------|--------------|
| Landstreet (1982)       | 2.6          | Magnetometer                 | ?             | 7                   | 7            |
| Borra et al. (1984)     | 2.5          | Multislit magnetometer       | ?             | −7.5                | 5.9          |
| Glagolevsky et al. (1991)| 6.0          | Magnetometer                 | ?             | 17                  | 7.1          |
| Bedford et al. (1995)   | 1.9          | Triple magneto-optical filter with a potassium cell | 8            | −1.86               | 0.9          |
| Plachinda & Tarasova (1999) | 2.6          | Stokesmeter + CCD            | 2.2           | −1.34               | 1.0          |
| Shorlin et al. (2002)   | 2.0          | Stokesmeter + CCD            | ?             | 2.0                 | 5.0          |
method for measurements of weak magnetic fields (Donati et al. 1997), the instrument will demonstrate even better results. Further examination of these points will be among the goals of our final study on the final upgrade of the polarimeter.

This work was supported by the Korea Astronomy and Space Science Institute (KASI) under grant 2007-1-310-A0. We wish to thank our anonymous referee for comments on the first draft of this paper, which led to considerable improvement of this paper. K. M. K. thanks A. Kaufer, J.-L. Lizon, and H. Dekker of ESO, D. Fabricant of SAO, J. Zajac of Oak Ridge Observatory, H. Epps of UCO/Lick Observatory, J. Lee of Chong Ju University, and D. Shakhovskoy of CrAO for their kind help while manufacturing the BOES process. I. Han acknowledges partial financial support by KFICST through grant 07-179. G. V. is grateful to the Korean MOST (Ministry of Science and Technology; grant M1-022-00-0005) and KOFST (Korean Federation of Science and Technology Societies) for providing him an opportunity to work at KASI through the Brain Pool program. B. C. L. acknowledges his work as part of the research activity of the Astrophysical Research Center for the Structure and Evolution of the Cosmos (ARCSEC, Sejong University) of the Korea Science and Engineering Foundation (KOSEF) through the Science Research Center (SRC) program.

REFERENCES

Appenzeller, I., et al. 1998, Messenger, 94, 1
Aznar Cuadrado, R., Jordan, S., Napiwotzki, R., Schmid, H. M., Solanki, S. K., & Mathys, G. 2004, A&A, 423, 1081
Bagnulo, S., Szeifert, T., Wade, G. A., Landstreet, J. D., & Mathys, G. 2002, A&A, 389, 191
Bailey, J. 1989, in Spectropolarimetry at the AAT (The AAT User’s Manual No. 24) (Epping: Anglo-Australian Obs.)
Bedford, D. K., Chaplin, W. J., Davies, A. R., Innis, J. L., Isaak, G. R., & Speake, C. C. 1995, A&A, 293, 377
Borra, E. F., Edwards, G., & Mayor, M. 1984, ApJ, 284, 211
Bychkov, V. D., Bychkova, L. V., & Madej, J. 2005, A&A, 430, 1143
Dekker, H., Delabre, B., Hess, G., & Kotzlowski, H. 1992, in ESO Conf. and Workshop Proc., Progress in Telescope and Instrumentation Technologies, ed. M.-H. Ulrich (Garching: ESO), 581
Donati, J.-F., Catala, C., Wade, G. A., Gallou, G., Delaigue, G., & Rabou, P. 1999, A&AS, 134, 149
Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E., & Cameron, A. 1997, MNRAS, 291, 658
Donati, J.-F., et al. 2003, MNRAS, 345, 1145
Euchner, F., Jordan, S., Beuermann, K., Gänssicke, B. T., & Hessman, F. V. 2002, A&A, 390, 633
Eversberg, T., Moffat, A. F. J., Debruyne, M., Rice, J. B., Piskunov, N., Bastein, P., Wehlay, W. H., & Chesneau, O. 1998, PASP, 110, 1356
Glagolevsky, V., Romaniiuk, I., Naidenov, V. G., & Shtol, V. G. 1991, Bull. Spec. Astrophys. Obs., 27, 32
Goodrich, R. W., Cohen, M. H., & Putney, A. 1995, PASP, 107, 179
Harris, T. J., & Howarth, I. D. 1996, A&A, 310, 533
Hubrig, S., Briquet, M., Schöller, M., De Cat, P., Mathys, G., & Aert, C. 2006, MNRAS, 369, L61
Ikeda, Y., Akitaya, H., Matsuda, K., Kawabata, K. S., Seki, M., Hirata, R., & Okazaki, A. 2003, Proc. SPIE, 4843, 437
Kaufu, A., & Pasquini, L. 1998, Proc. SPIE, 3355, 844
Kim, K. M., et al. 2002, J. Korean Astron. Soc., 35, 221
Kupka, F., Piskunov, N. E., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, A&AS, 138, 119
Landstreet, J. D. 1980, AJ, 85, 611
———. 2001, in ASP Conf. Ser. 248, Magnetic Fields Across the Hertzsprung-Russell Diagram, ed. G. Mathys, S. K. Solanki, & D. T. Wickramasinghe (San Francisco: ASP), 277
Manset, N., & Donati, J.-F. 2003, Proc. SPIE, 4843, 425
Monin, D. N., Fabrika, S. N., & Valyavin, G. G. 2002, A&A, 396, 131
Naydenov, I. D., et al. 2002, Bull. Spec. Astrophys. Obs., 53, 124
Pettit, P., et al. 2005, MNRAS, 361, 837
Pfeiffer, M. J., Frank, C., Baumuller, D., Fuhrmann, K., & Gehren, T. 1998, A&AS, 130, 381
Piskunov, N. E., Kupka, F., Ryabchikova, T. A., Weiss, W. W., & Jeffery, C. S. 1995, A&AS, 112, 525
Plachinda, S. I. 2004a, in Photopolarimetry in Remote Sensing, ed. G. Videen, Y. Yatskiv, & M. Mishchenko (NATO Sci. Ser. II, 161; Berlin: Springer), 351
———. 2004b, in IAU Symp. 223, Multi-Wavelength Investigations of Solar Activity, ed. A. V. Stepanso, E. E. Benevolenskaya, & A. G. Kosovichev (Cambridge: Cambridge Univ. Press), 689
———. 2005, Astrophysics, 48, 9
Plachinda, S. I., & Tarasov, T. N. 1999, ApJ, 514, 402
———. 2000, ApJ, 533, 1016
Putney, A. 1999, in ASP Conf. Ser. 169, 11th European Workshop on White Dwarfs, ed. J.-E. Solheim & E. G. Miiis (San Francisco: ASP), 195
Raychbochka, T. A., Piskunov, N. E., Stempels, H. C., Kupka, F., & Weiss, W. W. 1999, Phys. Scr., T83, 162
Samoylov, A. V., Samoylov, V. S., Videmchenko, A. P., & Perekhod, A. V. 2004, J. Quant. Spectrosc. Radiat. Transfer, 88, 319
Schötz, G. F., Vydra, J., Lu, G., & Fabricant, D. 1998, in ASP Conf. Ser. 152, Optics in Astronomy III, ed. S. Arribas, E. Mediavilla, & F. Watson (San Francisco: ASP), 20
Shorlin, S. L. S., Wade, G. A., Donati, J.-F., Landstreet, J. D., Petit, P., Sigut, T. A. A., & Strasser, S. 2002, A&A, 392, 637
Tull, R. G. 1998, Proc. SPIE, 3355, 387
Valyavin, G., Bagnulo, S., Fabrika, S., Reisenegger, A., Wade, G. A., Han, I., & Monin, D. 2006, ApJ, 648, 559
Wade, G. A., Bagnulo, S., Szeifert, T., Brinkworth, C., Marsh, T., Landstreet, J. D., & Maxted, P. 2003, in ASP Conf. Ser. 307, Solar Polarization, ed. J. Trujillo Bueno & J. Sanchez Almeida (San Francisco: ASP), 569
Wade, G. A., Donati, J.-F., Landstreet, J. D., & Shorlin, S. L. S. 2000, MNRAS, 313, 851
Wade, G. A., Fullerton, A. W., Donati, J.-F., Landstreet, J. D., Petit, P., & Strasser, S. 2006, A&A, 451, 195

2007 PASP, 119:1052–1062