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A NEW PRECISE MEASUREMENT OF THE CORONAL MAGNETIC FIELD STRENGTH

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ABSTRACT

Magnetism dominates the structure and dynamics of the solar corona. Current theories suggest that it may also be responsible for coronal heating. Despite the importance of the magnetic field in the physics of the corona and despite the tremendous progress made recently in the remote sensing of solar magnetic fields, reliable measurements of the coronal magnetic field strength and orientation do not exist. This is largely due to the weakness of coronal magnetic fields, previously estimated to be on the order of 10 G, and the difficulty associated with observing the extremely faint solar corona emission. Using a very sensitive infrared spectropolarimeter to observe the strong near-infrared coronal emission line Fe XIII λ10747 above active regions, we have succeeded in measuring the weak Stokes *V* circular polarization profiles resulting from the longitudinal Zeeman effect of the magnetic field of the solar corona. From these measurements, we infer field strengths of 10 and 33 G from two active regions at heights of $h = 0.12\ R_{\odot}$ and $h = 0.15\ R_{\odot}$, respectively. We expect that this measurement technique will allow, in the near future, the routine precise measurement of the coronal magnetic field strength with application to many critical problems in solar coronal physics.

Subject headings: Sun: corona — Sun: infrared — Sun: magnetic fields — techniques: polarimetric

1. INTRODUCTION

The Sun is a magnetic star. The solar magnetic fields are manifested in many magnificent forms, such as the photospheric sunspots and the large-scale coronal loop structures. Unfortunately, magnetic fields can only be measured reliably with Stokes polarimetry at photospheric and chromospheric heights ($h \approx 10^{-2}\ R_{\odot}$). But these layers comprise only a very small fraction of the entire solar volume. Direct measurement of the magnetic fields in the corona is very difficult, and past results are inconclusive because of large uncertainties. For example, the strongest field detected by early magnetograph observations of the Zeeman effect in the "green" Fe XIV λ5303 coronal emission line (CEL) was 13 ± 20 G (Harvey 1969). More recent spectropolarimetric measurements using the near-infrared line Fe XIII λ10747 could only set an upper limit of 40 G on the coronal field strength (Kuhn 1995). Linear polarization measurements of the Hanle effect in CELs were more successful in mapping the direction of coronal magnetic fields (Mickey 1973; Querfeld & Smartt 1984; Arnaud & Newkirk 1987); however, these measurements are not sensitive to the strength of the magnetic field (Casini & Judge 1999; Lin & Casini 2000). Observation of the Faraday rotation of linearly polarized radio signals emitted from natural sources and from interplanetary space probes (Stelzreid et al. 1970) during occultation by the solar corona has been used to infer coronal magnetic field strengths. These observations have not found wide use in solar physics because of the severe limitations of available observing geometries. In addition, radio observations of the spectral signatures of gyrosynchrotron (Gary & Hurford 1994; Lee et al. 1999) and thermal Bremsstrahlung radiation (Borovik, Medar, & Korzhavin 1999), as well as the combination of both (Brosius et al. 1997), have been employed to infer the strength of magnetic fields in the low solar corona. Unfortunately, these methods are highly dependent on model assumptions and suffer from uncertainty in the location of the source region.

Lacking reliable measurements of coronal magnetic fields, we are faced with the dilemma of believing that magnetic fields play a crucial role in almost all coronal activities in spite of the conspicuous absence of direct observational confirmation. Numerous theoretical and observational results from recent space-borne experiments (the *Solar and Heliospheric Observatory* [*SOHO*] and the *Transition Region And Coronal Explorer*) reinforce this deficiency. In order to advance further our knowledge of the solar corona, a direct measurement of the coronal magnetic field strength and configuration is indispensable.

2. INSTRUMENTATION AND TECHNIQUE FOR PRECISION CORONAL POLARIMETRY

We designed an experiment aimed at obtaining definitive spectroscopic measurements of the strength of the coronal magnetic field using the 40 cm aperture coronagraph of the Evans Solar Facility of the National Solar Observatory at Sacramento Peak (NSO/SP), New Mexico. A new spectrograph using a 1200 line mm^{-1} echelle grating (42°.5 blaze angle) optimized for the line pair Fe XIII λ10747 and λ10798, which are among the strongest CELs in the near-IR (Judge 1998; Kuhn, Penn, & Mann 1996), was built for this experiment. A liquid-crystal variable retarder (LCVR)–based polarimeter and the Michigan State University NICMOS 3 IR camera were used to analyze and record the Stokes spectra.

The measurement of the Stokes *V* signal that is due to the

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longitudinal Zeeman effect in coronal magnetic fields is one of the most challenging experiments in observational solar astronomy. Under the weak-field (10 G) and high-temperature (10^6 K) coronal conditions, the expected Stokes V amplitude is only $10^{-3}I_L$ or smaller, where I_L is the intensity of the CEL. Furthermore, the linear polarization amplitude of the CELs is typically 2 orders of magnitude larger than that of the circular polarization, so that a small instrumental Q-to-V cross talk is sufficient to render the coronal Stokes V signal unrecognizable. Therefore, measurement of the coronal Stokes V signal is only feasible with a very sensitive polarimeter and extremely small instrumental (telescope and polarimeter) polarization cross talk. Numerical simulations indicate that a noise of $1 \times 10^{-4}I_L$ or better and a Q-to-V cross talk coefficient of 1×10^{-3} or smaller are required to detect the Stokes V signature of Fe XIII λ10747 with a 10 G field strength. To achieve the required noise level in our measurement, we typically integrate 2560 1 s exposures, cycling through four retardation settings (0, λ/4, λ/2, and 3λ/4) repeatedly, for one set of measurements of the Stokes I, Q, and V parameters. The resulting noise in a single exposure is typically $4 \times 10^{-4}I_C$ under good sky conditions, where I_C is the continuum intensity of the spectrum. The total integration time for the Q and V spectra are both approximately 22 minutes, while the total observing time required to obtain such a measurement is approximately 70 minutes.

The strongest source of polarization cross talk in a telescope is usually the reflecting surfaces of the mirrors in the optical train. This is eliminated from our experiment by mounting the polarimeter directly behind the primary focus and the occulting disk of the coronagraph, before all the reflecting optics. The second source of instrumental polarization cross talk is the polarimeter itself. A LCVR-based polarimeter capable of measuring the full polarization state of the incident radiation typically consists of two LCVRs and a linear polarizer (Lin, Penn, & Kuhn 1998). Errors in the retardation settings and alignment between the LCVRs and polarizer all contribute to produce nonzero polarization cross talk. Since we are primarily concerned with measuring the Stokes V parameter of the CEL, only one LCVR (with its fast axis rotated 45° with respect to the polarization axis of the exit linear polarizer) is required in the polarimeter (Lin 1995). This configuration can only measure three of the four Stokes parameters (I, Q, and V; Q is in the direction of the polarization axis of the exit linear polarizer). Nevertheless, its simplicity allows a simple calibration procedure to reduce the Q-to-V cross talk to a very low level, limited only by the stability of the LCVR and the calibration light source, and the photon noise. In this configuration, the Stokes V state is measured by differencing two measurements with the retardation setting of $\phi_1 = +\lambda/4$ (for $I+V$) and $\phi_2 = -\lambda/4$ (equivalent to 3λ/4, for $I-V$), where λ is the wavelength of the observed CEL. To first order, the Stokes Q-to-V cross talk arises only from the difference $\delta\phi = \phi_1 - \phi_2$ between the two retardation settings. The Stokes U-to-V cross talk depends on both $\delta\phi$ and the misalignment (deviation from 45°) between the LCVR and the exit linear polarizer. It is a second-order effect and can be neglected. Therefore, we can minimize the Q-to-V cross talk by balancing the two retardations, setting $\phi_1 = -\phi_2$. Notice that the retardations need not be exactly λ/4 since deviation from λ/4 only decreases the efficiency of the polarimeter. We balanced the retardation settings by mounting a linear polarizer oriented along the Q-direction in front of the polarimeter and by iteratively adjusting ϕ_2 while keeping ϕ_1 constant (which is set approximately equal to λ/4) until the measured Stokes V amplitude met the cross talk criteria (10^{-3} or smaller). The smallest cross talk coefficient we achieved in the laboratory with a stable light source was 1×10^{-4}. When mounted in the coronagraph, we used the sky as our calibration light source. Under good sky conditions, the variation of the sky brightness is small, and the Q-to-V cross talk is typically 1×10^{-3} or smaller after calibration. During exceptionally good coronal sky conditions, a cross talk coefficient of 5×10^{-4} has been achieved.

In addition to instrumental cross talk, image motion during the observations can produce spurious signals that can mask the Stokes V signature. Experience from high spatial resolution observations on the solar disk has shown that image motion can couple with strong velocity variations (e.g., the flows associated with solar granulation) across the field of view (FOV), to generate Stokes V–like spectra when measuring small-scale photospheric magnetic fields. Image motion can also couple with intensity gradients to produce polarization cross talk (Lites 1987) in vector magnetic field measurements. The usual solution to these problems is to measure the two orthogonal polarizations (e.g., $I+V$ and $I-V$) simultaneously using a polarizing beam-splitter setup (Elmore et al. 1992; Penn & Kuhn 1995; Lin & Rimmele 1999) and to perform a large number of measurements in order to minimize the seeing effect through temporal averaging. While we did not use a dual-beam setup to measure the two orthogonal polarizations simultaneously, our long integration times and the lack of significant velocity or intensity gradients across the FOV (see Fig. 2 below) were sufficient to mitigate the effects of seeing. We did not see any significant evidence of seeing-induced cross talk in our data.

3. THE MAGNETIC FIELD STRENGTH OF THE SOLAR CORONA

The first positive detection of the Zeeman effect in a coronal Stokes V signal was obtained in 1999 October 14 by observing a region with strong (110 millionths of disk-center intensity) green-line emission at a height of 0.15 $R_\odot$ above the east solar limb. The IR Fe XIII line intensity was 14 millionths, with a sky brightness of 56 millionths. Figure 1 shows the Fe IX λ171 image of October 14 taken by the EUV Imaging Telescope (EIT) on board the *SOHO* spacecraft and the coronal green-line intensity at $h = 0.15\ R_\odot$ obtained with the NSO/SP coronal photometer (Smartt 1982). Some large-scale loop structure near the target region is clearly visible. Kitt Peak full-disk magnetograms taken on the following days revealed that the strong green-line emission was due to the limb passage of a bipolar active region (NOAA 8736). Figure 2 shows the Stokes I, Q, and V spectral images from this observation. The strong Fe XIII λ10747 and λ10798 emissions are clearly visible in the Stokes I image. The Stokes Q profile of Fe XIII λ10747 changes sign in the middle of the FOV, indicating a change in the magnetic field orientation. Fe XIII λ10798 does not show appreciable linear polarization. The antisymmetric Stokes V signal is only barely discernible in the Stokes V spectral image because of the noise in the data. We averaged all the Stokes V profiles along the slit in order to generate an averaged V profile for this measurement.

The noise in this averaged V profile is $7 \times 10^{-5}I_C$. The averaged Q and V profiles are shown in Figure 3. Here the characteristic antisymmetric signature of the Stokes V profile is clearly visible. We derived a magnetic field strength of 33 ± 0.7 ($3\ \sigma$) G from this V profile using the standard magnetograph formula. The alignment-effect correction (Casini & Judge 1999; Lin & Casini 2000) was not applied since we did not measure the full Stokes vector. Note that a line-of-sight field strength

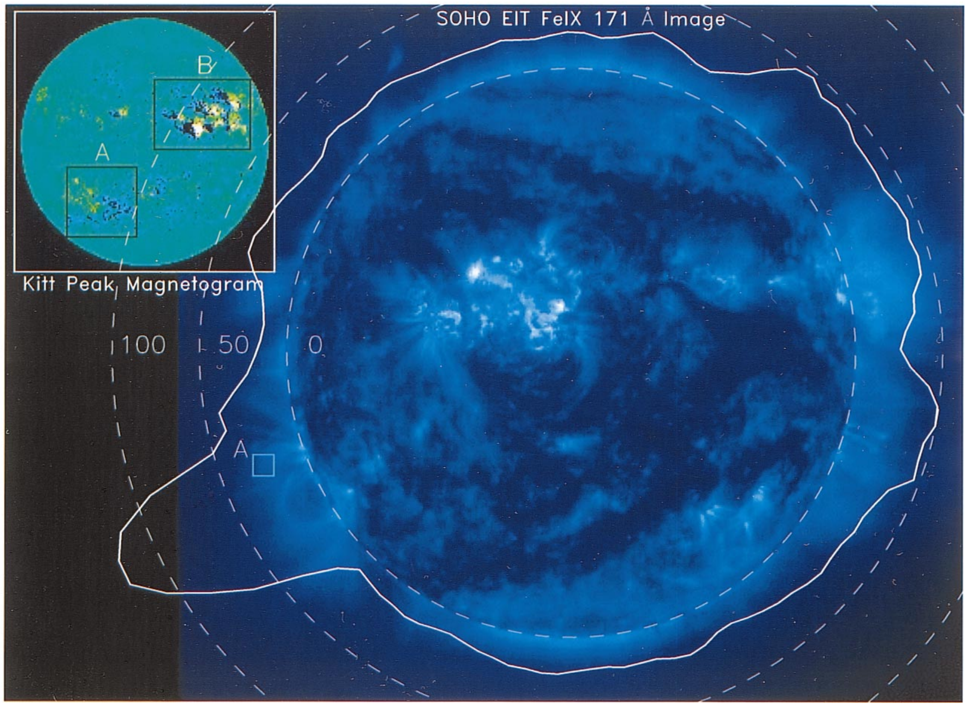

FIG. 1.—*SOHO* EIT Fe IX λ171 image of the structure of the solar corona near the time of the 1999 October 14 IR observation. The region marked by the square box A is the target area observed by the IR polarimeter. The solid contour line shows the green Fe XVI λ5303 line intensity measured by the NSO/SP coronal photometer at height $h = 0.15\ R_\odot$. The three dashed lines mark the contours of 0, 50, and 100 millionths disk-center intensity. The insert in the upper left-hand corner shows the Kitt Peak magnetogram taken in 1999 October 18. The active regions in the magnetogram (boxes A and B) were the target regions of the October 14 and 23 observations, respectively.

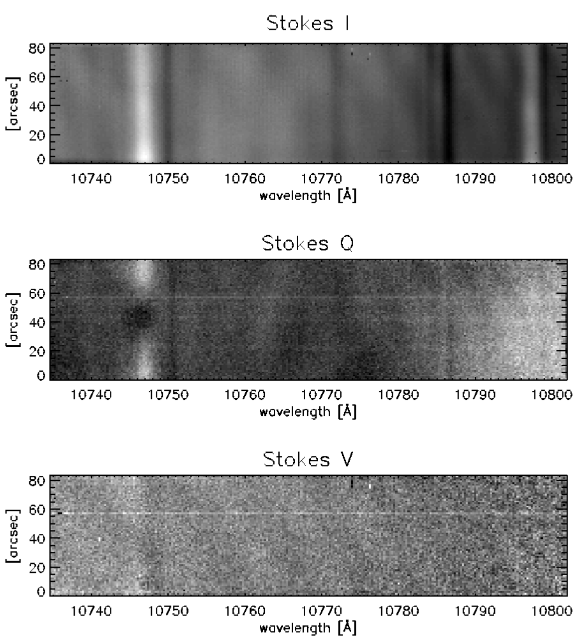

FIG. 2.—Stokes *I*, *Q*, and *V* spectral images from the 1999 October 14 observation. The Stokes *Q* spectra show variation across the FOV, indicating magnetic field spatial variation. The Stokes *V* spectra show a faint antisymmetric structure across the FOV at the location of Fe XIII λ10747. The averaged Stokes *Q* and *V* spectra are shown in Fig. 3.

of 33 G at $h = 0.15\ R_\odot$ is significantly higher than the empirical formula of the field strength expected from the potential field extrapolation (Dulk & McLean 1978). In the days that followed, several observations with reduced coronal limb activity yielded weak Stokes *V* signals that were barely above the noise level. A second definitive detection was obtained in 1999 October 23, a day after a complex of large active regions (including NOAA 8731, 8732, 8728, and 8729) crossed the west limb of the Sun, at a height of $h = 0.12\ R_\odot$. This region has a complicated photospheric magnetic field structure, with several polarity reversals within the region. It also generated strong (140 millionths) green-line emission. The Fe XIII λ10747 line intensity was 9 millionths. The *Q* and *V* amplitudes are $2.2 \times 10^{-2} I_L$ and $4 \times 10^{-4} I_L$, respectively. A magnetic field strength of 10 ± 0.5 ($3\ \sigma$) G was derived for this region.

4. CONCLUSIONS AND FUTURE PROSPECTS

Magnetic field strength measurements are important for testing coronal magnetic field models. Early statistical studies found that the coronal magnetic field strength falls off as a function of height *h*, with an exponent of -1.5, for $0.02\ R_\odot \le h \le 9\ R_\odot$. Moreover, modern modeling efforts by extrapolation of the observed photospheric magnetic field, assuming either potential or force-free field configurations, have been successful in generating realistic coronal magnetic field models matching observed coronal structures (Lee et al. 1999; Falconer et al. 2000; Oliver et al. 1999). However, except in

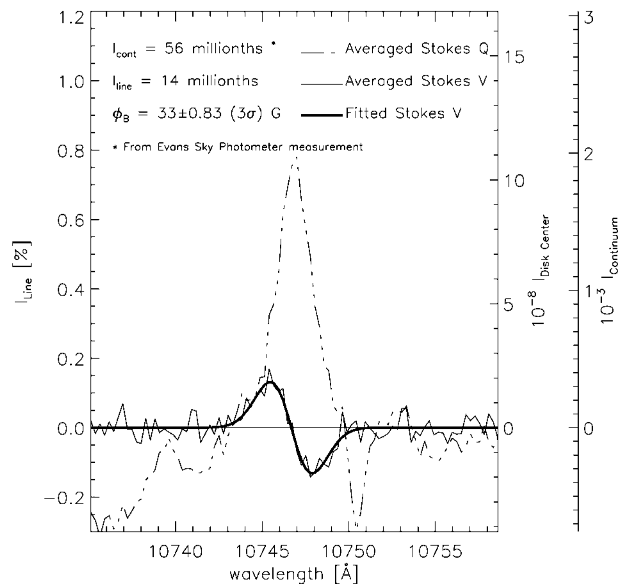

FIG. 3.—Stokes Q and V profiles averaged over the entire FOV in Fig. 2. The magnetic antisymmetric profile of the Stokes V spectrum is clearly shown. The calibration to disk-center intensity was obtained from a sky brightness measurement using the Evans' sky photometer.

the case of a potential field configuration, the mathematical problem associated with the extrapolation techniques is, in general, an ill-posed boundary value problem in which small errors in the photospheric magnetic field measurement grow exponentially (Low & Lou 1990). Usually, additional observational constraints (e.g., loop structures measured in UV or X-ray intensity) are used a posteriori to check if the computed magnetic field structure matches the observed one. With our new capability to measure the magnetic field strength in the corona, the magnetic field derived from a model calculation can be compared directly with observation. For example, with measurements of the magnetic field strength variations as a function of height for the active regions, the potentiality of the magnetic field configuration (i.e., whether it is potential or force-free) can be determined and directly compared with the extrapolation results.

The observations presented in this Letter demonstrate that the coronal magnetic field strength, albeit weak, can be measured by observing the longitudinal Zeeman effect of coronal emission lines. Our experiment is currently limited by photon noise and thus by the aperture of the available coronagraph. New coronagraphs with larger apertures will provide data with improved spatial and temporal coverage as well as higher magnetic field sensitivity that will allow a comprehensive comparison with models. These measurements will provide important new insights into the physics of the solar corona.

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