A New Imaging System of the Corona at Norikura

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Abstract

A new imaging system of the coronal green line (Fe XIV 5303 Å) was constructed at the Norikura Solar Observatory. The system consists of a 10-cm coronagraph, a tunable Lyot filter, and a cooled CCD camera. The transmission curve of the Lyot filter can be modulated by two liquid-crystal variable retarders. This scheme provides quick wavelength tuning and efficient subtraction of sky background. Two-dimensional distributions of the intensity and Doppler shift of the coronal green line can be obtained within 30 seconds with accuracies of better than 10⁻⁶Iₖ and 1 km s⁻¹. Regular operation was started in 1997 September. The aim of the new system is to investigate plasma motions associated with the magnetic field reconnection and waves in the solar corona.

Key words: Instruments: coronagraph — Sun: corona — Sun: spectra

1. Introduction

Owing to successful operations of X-ray imagers aboard Yohkoh (Ogawara et al. 1991, SXT: Tsuneta et al. 1991), SoHO (EIT: Delaboudiniere et al. 1995), and TRACE (Tarbell et al. 1994), the dynamical nature of the solar corona has been revealed, and it is now widely known that the solar corona is never a stationary atmosphere; dynamic phenomena, such as re-structuring of the magnetic field configurations, energy releases, and plasma ejections are taking place ubiquitously in the solar corona. Of particular importance for the next step is understanding the physical processes that cause the variety of active coronal phenomena.

Magnetic field reconnection is suggested to be a fundamental mechanism that drives these phenomena (e.g., Shibata et al. 1995; Tsuneta 1996). The observational evidence for reconnection is, however, more or less based on the morphological nature of the observed phenomena. A more direct proof should be obtained by quantitatively measuring plasma flow associated with the magnetic field reconnection.

On the other hand, detecting waves or oscillatory phenomena in the corona is another observational interest in the sense that they may transport energy for heating the corona or disturbances for triggering instabilities, or that they may provide a clue for diagnosing magnetic field configurations in the corona. So far, a number of observations suggest the existence of oscillatory phenomena in the corona; some of them were found in Doppler signals of spectral lines, as expected for the case of Alfvén waves (Tsubaki 1987, and references therein). The nature of such oscillations, however, is not yet well known due to the lack of spatial information.

Thus, measurements of plasma motions in the corona are of vital importance for further understanding the physical processes in coronal phenomena. So far, Doppler measurements of the corona have been widely made using spectrographs on ground-based coronagraphs (e.g., Ichimoto et al. 1995) or space observatories (e.g., SUMER instrument aboard SoHO, Wilhelm et al. 1995), in which two-dimensional images are taken by scanning the coronal image with the slit of the spectrograph. Though spectrographic observations can provide accurate information about the Doppler shifts of coronal emission lines, it is difficult to achieve a high temporal resolution that is sufficient to resolve transient phenomena with a large enough coverage of the field-of-view. A more efficient instrument is highly desired that has the capability to measure two-dimensional coronal velocity fields with a high time cadence.

Since 1950 the Norikura Solar Observatory had been performing routine observations of the intensities of the coronal emission line of Fe XIV 5303 Å (the so-called coronal green line) with a direct visual spectrograph (Notuki 1951; Miyazaki et al. 1982; Sakurai et al. 1999) and publishing the results in Quarterly Bulletin on Solar Ac-
tivity (1950–1997). The measurements were made at 72 points around the sun at a height of 50° above the solar limb with a detection limit of about $4 \times 10^{-6} I_\odot$ on a very clear day. A new observing system of the coronal green line was constructed to replace the classical observation system and to realize efficient measurements of two-dimensional Doppler images of the coronal green line. The system utilizes a tunable birefringent filter and a cooled CCD camera.

In this paper, the details concerning the instrument and its performance are described. The new system is called NOGIS (NOrikura Green-line Imaging System).

2. Optical Configuration

The optical layout of NOGIS is shown in figure 1. The telescope is an ordinary Lyot-type coronagraph with a singlet objective lens of 100 mm effective aperture and 1490 mm focal length at 5300 Å. The occulting disk is supported by a metallic pole attached at the center of the field lens, which has a focal length of 240 mm and makes a pupil image at the subsequent Lyot stop. The occulting-field lens unit is mounted on a two-dimensional linear stage and is controlled so as to achieve the best occultation of the sun; this mechanism is necessary because another coronagraph is mounted on the same equatorial mount with NOGIS, and a gradual change in the mutual alignment between the two coronagraphs is unavoidable.

The Lyot stop is followed by a relay lens unit and a collimating lens, which creates a 28-mm pupil image in the following optics. A polarizing beam-splitter (PBS-1) after the collimating lens separates the beam into two observing paths; one is the green-line observing path and the other the Hα observing path.

The green-line path includes a tunable Lyot filter, the details of which are described in the next section. The pupil image created by the collimating lens is located at the center of the Lyot filter. The second polarizing beam-splitter (PBS-2) is placed at the exit of the Lyot filter and a camera lens unit in one of the exiting beam forms the solar image on the CCD camera. The two beam-splitters work as the entrance and exit polarizers of the Lyot filter.

The CCD camera is the model MCD 1200 (Spectra Source), which uses the TC 215 chip (Texas Instruments) with a pixel size of 12 μm that spans 2"75 on the sky.
With 1024 × 1024 pixels, the field of view of the camera is 47′ × 47′. The CCD chip is cooled to a temperature of −30°C and data are digitized in 12 bits with a speed of 200 kHz.

In the Hα observing path, another polarizing beamsplitter (PBS-3) sends a small fraction of light to the guiding sub-system. The light level for the guiding system can be adjusted by changing the angle of a polarizer located between PBS-1 and PBS-3. A lens (150 mm focal length) makes a full-disk image of green-continuum on a 2/3-inch video camera mounted there. The images taken by this camera are used to monitor the guiding status of the coronagraph and to control the linear stage of the occulting disk unit to compensate the long-term guiding error of the telescope. A personal computer digitizes the guiding images, calculates the brightness distribution of the sky around the occulting disk and sends control signals to the linear stage.

An Hα interference filter (DayStar filter with a passband width of 0.45 Å) follows PBS-3, with the solar image formed on a 35-mm film camera by an imaging lens unit. When the solar image is focused on the film, the image of the occulting disk is not in focus due to the chromatic aberration of the objective lens of the coronagraph. However, by adopting a relatively narrow-band Hα filter, prominences can be observed even though the solar disk is not completely occulted.

There is another lens unit mounted on a one-dimensional linear stage between the relay lens and the collimating lens. This lens unit is occasionally inserted into the optical axis to make an image of the objective lens on the CCD camera. This system enables us to evaluate the scattered light that is produced by dust on the objective lens, and is used to monitor the instrumental background level.

An anti-reflection coating optimized for 5300 Å is applied to most of the lenses and the beam splitters, except for the objective lens of the coronagraph. The entire system, including the field lens unit and following components, is connected to the telescope by a draw tube and can be moved along the optical axis to focus the solar image on the occulting disk. The first two elements of the relay lens unit are moved by a helicoid to focus the occulting disk image on the CCD camera.

3. Lyot Filter

To measure the intensities of the coronal emission lines with a ground-based coronagraph, it is important to eliminate the scattered light produced by the sky. To perform two-dimensional subtraction of the scattered light efficiently, we developed a new tunable birefringent filter. The configuration of the filter is shown in figure 2. The core birefringent unit of the filter consists of 4 calcite...
blocks which produce sinusoidal modulations of transmission in wavelength corresponding to 1, 2, 4, 8 Å full-width at half maximum, respectively. All calcite blocks are combinations of two calcite pieces with a half waveplate in-between them, thus providing a wide field of view. The 1 Å block is placed at the entrance, and the 2 Å block is at the exit windows. These elements are fabricated at the Nanjing Astronomical Instrument Factory.

For the purpose of modulating the transmission curve of the Lyot filter, two liquid-crystal variable retarders (LCVR) are attached at the entrance and exit surfaces of the calcite elements using Dow Corning Q2-3067 optical couplant. The fast axes of the LCVRs are aligned 45° to the axes of the adjacent calcite elements. The LCVRs (Meadowlark Optics, Boulder, Colorado) are nematic-type liquid crystal variable retarders with a compensation waveplate; the retardance is adjustable in a range from −180° to 360° at 5300 Å by changing the amplitude of the applied AC voltage on the liquid crystal in the range of 1–10 V. The relationship between the produced retardance and the applied voltage was calibrated in the laboratory for various temperatures of the liquid crystal. The temperature of each liquid crystal is monitored by a thermosensor attached on a side of the cell and is taken into account to determine the desired voltage for producing a certain amount of retardance. The core birefringent components are located in a thermal oven stabilized at 40 ± 0.1°C.

With the two polarizing beam-splitters (PBS-1 and PBS-2) at both windows of the birefringent unit, the system forms a Lyot filter which has a passband width of 1 Å and a clear aperture of 30 mm. An interference filter with a full width at half maximum of 10 Å (Andover Corp.) is placed at the entrance window and blocks the undesired periodic side peaks of the birefringent unit.

The principle of operation is as follows: by changing the retardance of the entrance and exit LCVRs, the phases of the sinusoidal transmission curve of the 1 Å and 2 Å elements are shifted independently in wavelength. If both peaks are at the center of the green line, the filter provides a single-peak transmission. If the phase of the 2 Å element is shifted by 180°, the filter provides a double-peak transmission in which the two peaks are separated by 4 Å. The latter mode can be used for measuring the continuum of the scattered light. When the phase shifts of the 1 Å and 2 Å elements are varied, while keeping a ratio of 2:1, we obtain a single-peak transmission shifted over the range of −1 Å + 1 Å, while a secondary peak grows at the other side when the amount of the shift becomes large. Figure 3 shows the theoretical transmission curves for various combinations of the retardances of the LCVRs.

It is noticed that the two beams emerging from PBS-2 provide coronal images in different transmission curves. When one path provides an image in the single-peak transmission, the other path provides an image in the double-peak transmission. Thus, we are able to obtain the green line and the sky images simultaneously, provided that two CCD cameras are equipped (at this moment only one CCD camera is in operation).

4. Control System and Observation Scheme

Figure 4 (Plate 18) shows a view of the instrument. A block diagram of the computer control system is shown in figure 5. Both the Lyot filter and the CCD camera are controlled by a personal computer. The desired voltages for the two LCVRs in the Lyot filter are calculated each time by referring to the LCVR temperatures, and are sent via a 12-bit digital I/O interface to the control unit that produces 2 kHz AC voltages with the requested amplitudes. The response time of the LCVR is about 20 ms. After exposure of the CCD with a mechanical shutter, the data are digitized with 12-bit accuracy and sent to the computer at a rate of 200 kpixels s⁻¹. Any rectangular area can be selected for reading-out by the software at
any locations, the on-chip binning factor being selectable from 1, 2, 4, and 8. A typical exposure time for coronal observation is, in case of no binning, 1–2 s depending on the brightness of the sky.

The main observing program is written in IDL (Interactive Data Language, Research System Inc.), while basic functions for controlling the hardware are provided using Dynamic Link Library coded in C-language. The sequence of exposures is defined in an observation table and regular operation is fully automated. Prior to starting a continuous observing sequence, a set of full-frame images of the green-line and the sky is taken. Then, regions of interest of the day (partial-frame images) are selected with up to two rectangular boxes on the computer screen. In a typical observation, images in the single-peak, the double-peak, –0.45 Å and +0.45 Å, are taken subsequently and repeated 4 times to improve the signal-to-noise ratio. A complete set of partial frame observations, is completed in about 1 minute or less. Full-frame images with 1 k x 1 k pixels are taken once every 20 sets of the partial-frame images, while dark images are taken every 40 sets of the partial-frame observations.

The transmission curves of the four filter modes used in the observation are shown in figure 6 together with the sky spectrum and a typical green-line profile. These profiles are obtained with the spectrograph of the 25-cm coronagraph at Norikura. It is evident that the measured transmission curves reproduce the theoretical ones quite well.

A photo-diode cell is attached on a side of the telescope for the purpose of monitoring the solar brightness in the green continuum. The output voltage from the sensor is digitized by a 12-bit A/D converter installed on the computer and used later for obtaining the absolute intensity of the green-line emission.

The linear stage of the lens unit for imaging the objective lens on the CCD is controlled through an RS 232C interface with a control unit for the stepping motor. Once a day, the unit is inserted into the optics axis and an im-
age of the objective lens is taken by the CCD camera. The image is immediately analysed and the level of the instrumental scattering is evaluated and informed to the observer.

The size of the occulting disk is selectable with a step of 5″ in radius. The typical height of occultation is 25″−35″ above the solar limb, depending on the guiding condition on the day. The data are taken continuously through the day as long as the sky permits observations.

5. Calibrations of Data

Figure 7 (Plate 19) shows a set of full-frame images taken with the four modes of transmission profiles of the Lyot filter. The observed intensity can be written as follows:

$$I_i = \int [I_{\text{sky}}(\lambda) + I_{5303}(v, \lambda)] T_i(\lambda) d\lambda = S_i + E_i. \quad (1)$$

where $I_{\text{sky}}(\lambda)$ is the scattered-light spectrum, $I_{5303}(v, \lambda)$ is the green-line spectrum with a Doppler shift of $v$, $T_i(\lambda)$ is the transmission curve of the Lyot filter, and $i$ stands for the mode of the filter. $S_i$ and $E_i$ are thus the sky and emission-line contributions to the observed intensity, respectively. A set of exposures gives four intensities in different modes of the filter transmission as follows:

$$I_0 = S_0 + E_0,$$
$$I_{\pm 2} = S_{\pm 2},$$
$$I_{-0.45} = S_{-0.45} + E_{-0.45},$$
$$I_{+0.45} = S_{+0.45} + E_{+0.45}, \quad (2)$$

where suffixes, 0, ±2, −0.45, +0.45 denote the single-peak, double-peak, −0.45 Å, and +0.45 Å modes of the filter transmission. We assume here that the intensity obtained with the double-peak mode has no emission-line contribution. The quantities, $S_0/S_{\pm 2} = r_0$, $S_{-0.45}/S_{\pm 2} = r_{-0.45}$, and $S_{+0.45}/S_{\pm 2} = r_{+0.45}$ are constants that do not depend on the intensities of the emission line and the scattered light, but are determined by the profiles of the scattered-light spectrum and the filter transmission. By using the transmission profiles of the filter and the sky spectrum measured with the spectrograph of the 25-cm coronagraph (figure 6), we obtained these values as $r_0 = 1.074$, $r_{-0.45} = 0.963$, $r_{+0.45} = 1.153$. We define the following quantity as a measure of the green line intensity (I-index):

$$I'_{5303} = (E_0 + E_{-0.45} + E_{+0.45})/3. \quad (3)$$

From the above relations, we obtain

$$I'_{5303} = (I_0 + I_{-0.45} + I_{+0.45})/3$$
$$- (r_0 + r_{-0.45} + r_{+0.45}) \cdot I_{\pm 2}. \quad (4)$$

Thus the I-index can be calculated from the 4 observed quantities of NOGIS.

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On the other hand, ratios of intensities observed with different filter modes vary with the Doppler shift of the green line. Figure 8a shows the calculated intensity responses for the four filter profiles against the Doppler shift of the green line. The solid curve is for the single-peak mode, dashed curve for the double-peak mode, and dotted curves for ±0.45 Å modes. The peak intensity of the emission line is assumed to be the same as the continuum level of the scattered light. (b) The calculated relation between the line shift, $V_{5303}$ (km s$^{-1}$), and the $V$-index, $V'_{5303}$.
using the following expression:

\[
V'_{5303} = \frac{(E_{+0.45} - E_{-0.45})/I'_{5303}}{\left[ I_{+0.45} - I_{-0.45} - (r_{+0.45} - r_{-0.45}) \right] \cdot I_{\pm 2}/I'_{5303}}.
\]

(5)

Figure 8b shows the calculated relation between the actual velocity \(V_{5303}\) (km s\(^{-1}\)) and the \(V'\)-index. For small values of \(V_{5303}\), we obtain

\[
V_{5303} = 22.89 \times V'_{5303} \quad \text{(km s}^{-1}).
\]

(6)

The coefficient does not depend on the intensity of the emission line. It is found from the figure that the sensitivity of NOGIS to Doppler shift saturates at velocities of about ±50 km s\(^{-1}\) for the current set of observing sequences.

In order to determine the absolute scale of the green-line intensity, we performed simultaneous observations with NOGIS and the spectrograph of the 25-cm coronagraph in 1998 October 28–30. With the 25-cm coronagraph, the same coronal region was scanned by the spectrograph slit simultaneously with a spatial resolution of 2′′ (in the slit direction) \(\times 4″\) (scan step), while disk-center spectra were taken before and after the scan in the same configuration of the spectrograph, but with a well-calibrated neutral-density filter. The emission-line component was extracted from the spectrum of each coronal position and fitted with a Gaussian profile. The peak values of the Gaussian profile were compared with the continuum intensity of the disk-center spectra and, thus, the intensity distributions of the green-line were obtained in unit of \(10^{-6}I_\odot\) from the spectroscopic observations \((I_\odot\) is the disk center brightness).

Figure 9 (Plate 20) shows an example of a co-aligned set of green-line images and Dopplergrams obtained with the two observing systems. The scale and orientation of the two images are adjusted by referring to characteristic features of the corona. It is worth noting that NOGIS obtained quite similar intensity and velocity maps within 50 s, while the spectrograph took more than 15 min, though the accuracy of the measurement looks better for the spectroscopic observation. Figure 10a shows the correlation plot of two intensities; the abscissa is the \(I\)-index of NOGIS defined by equation (4) and the ordinate is the peak intensity of the green-line in \(10^{-6}I_\odot\) obtained by the 25-cm coronagraph. Here, the NOGIS’s \(I\)-index is normalized by the solar brightness monitored by the photo-diode cell, the exposure time (s) and the number of integrations. A fairly well-defined linear relation is found between the two quantities. From several sets of such analyses, we obtained the relation

\[
I_{5303} \sim 290 \times I'_{5303} \quad \text{\(10^{-6}I_\odot\)}
\]

(7)

for the absolute intensity scale of the NOGIS data.

Figure 10b shows a correlation plot of the Doppler shift obtained with the two systems; the abscissa is the \(V\)-index of NOGIS defined by equation (5) and the ordinate is the Doppler shift of the green-line in km s\(^{-1}\) obtained with the 25-cm coronagraph, where the plot includes only the coronal points where the \(I\)-index is larger than 0.2. In the figure, the relation of \(V_{5303} = 22.89 \times V'_{5303}\) is shown to be a straight line. Though the scatter of points is relatively large compared with the intensity plot, the two quantities show a clear correlation that follows the same slope indicated by the theoretical line; thus, the adequacy of equation (6) is confirmed.

Figure 11 (Plate 21) shows an example of a calibrated green-line intensity map and intensity distribu-
tions around the sun at heights of 50, 100, 200, and 300" from the solar limb. It is now possible to record the intensity distribution of the coronal green-line around the sun with much higher accuracy and cadence than before.

6. Discussions

Since a single-exposure image contains random photon noise of approximately 0.6% RMS, 4-times summation of images achieves about 0.3% random noise of the measurement. If the sky brightness is $5 \cdot 10^{-8} \, I_\odot$ (typical value on a fine day at the Norikura Solar Observatory), the detection limit of the green line is about $5 \cdot 10^{-7} \, I_\odot$ when it is defined as 3σ noise-level. With similar assumptions, the V-index defined by equation (5) contains random noise of about $2 \cdot \sqrt{0.003^2 + 0.003^2}$ RMS when the green line has the same intensity as the scattered light level. Thus, the sensitivity of NOGIS to the Doppler shift of the green line is estimated to be about 0.6 km s$^{-1}$ for regions where the line intensity is comparable with the scattered-light.

Random noise also arises from fast fluctuations of the images during a sequence of exposures. The sources of such fluctuations can be short-term guiding errors of the telescope or image jitter produced by scintillation, and scattered light by dust or insects flying across the line of sight. These effects sometimes cause a significant error in the measurements, while the amount is highly dependent on the observing conditions. It is expected that such noise can be greatly reduced if simultaneous exposures of images in the different wavelengths are made with a secondary CCD camera. We have designed NOGIS to provide such capability and this is our future plan for improving the system performance.

Systematic errors can arise from variation of the wavelength of the filter transmission and of the sky spectrum across the field-of-view. The former is caused by position-dependent ray angles in the collimated beam that passes through the Lyot filter and the polarizing beam-splitters, and the latter is caused by solar rotation and the different contributions to the sky spectrum from different parts of the solar disk; i.e., the sky on the western limb shows a slightly red-shifted spectrum compared with that on the eastern limb. Misalignments of the optical elements can also produce an additional offset of the wavelength. These effects lead to changes in the quantities $r_0$, $r_{-0.45}$, and $r_{+0.45}$, defined in section 5, and cause a bias on the reduced data. We have not yet evaluated these effects exactly, and neglected them in our current data analysis. A linear trend found in the reduced full-frame image and a constant bias in the Doppler signal were subtracted, however. A careful analysis of these effects and a further adjustment of optical elements are desired.

It is highly possible that flares produce a broader emission-line, or a fairly large Doppler shift ($\geq 50$ km s$^{-1}$), if magnetic field reconnection takes place there as expected. Our current observing procedure may, however, not be compatible with such large velocities. NOGIS has the capability to measure larger Doppler shifts and line widths, with a slight modification of parameters in the observing table. The development of appropriate software that take the change of the line width into account is also planned.

So far we have been obtaining a number of time series of the coronal intensities and Doppler images for active regions in the corona. It is remarkable that we frequently notice obvious signatures of propagating disturbances in the Dopplergram movies obtained under good observing conditions, even though the intensity images show no time variations. These phenomena will be described in our future papers. We expect that NOGIS will be able to provide valuable information on plasma flows associated with the magnetic field reconnection and the coronal waves.

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Fig. 4. Outside view of NOGIS.

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Fig. 7. Example of full-frame images taken in the four modes of the filter.

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Fig. 9. A co-aligned set of green-line images and Dopplergrams obtained by NOGIS (right) and the spectroscopic observation with the 25-cm coronagraph (left). The upper panels are the intensities and the lower panels are the line shift images.

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Fig. 11. An example of full-frame green-line image and corresponding intensity distributions around the sun at the heights of 50, 100, 200, and 300'' from the solar limb.

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