HIGH-CADENCE Hα IMAGING OF SOLAR FLARES

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ABSTRACT

The Hα observation is a powerful tool to study the high-energy aspect of solar flares. Spiky brightenings of flare kernels at the Hα center reflect the rapid fluctuation in particle acceleration; linear polarization of Hα emission might be evidence of accelerated protons; red-shifts of the Hα line are caused by the chromospheric evaporation. To study the spiky brightenings of flare kernels with high-cadence imaging at the Hα center, a high-speed Hα camera for the Solar Flare Telescope at Mitaka, NAOJ, had been developed and it started the regular observation in 2001 July. However, the polarimetry and the Dopplermetry are also important and they are required to be carried out in parallel with the high-cadence imaging at the Hα center. Then, we upgraded the original high-speed Hα camera to a new Hα camera system for the multi-aspect Hα observations, which performs all of the high-cadence imaging, the linear polarization measurements, and the off-band imaging for velocity measurements. The new system started the observation in 2002 July. In this paper, the multi-aspect Hα imaging system is described and sample Hα images are presented.

INTRODUCTION

Hα observations of solar flares provide us plenty of information about the high-energy aspect of solar flares. Firstly, imaging observations at the Hα center realize a high spatial-resolution ($\sim 1''$) and a high time-resolution (< 1 s) simultaneously, which are required to observe the rapid evolution of flare kernels. Although such high resolutions are important to study the acceleration of high-energy electrons, it is difficult for hard X-ray imaging observations to realize these resolutions simultaneously. Therefore, collaborations between hard X-ray telescopes on board spacecrafts and ground-base telescopes observing in the Hα line are essentially important to study the high-energy aspect of solar flares. For this reason, various attempts to develop high-cadence Hα imaging systems for solar flare observations have been carried out for long time (e.g., Wülser, 1987; Kiplinger et al. 1989). Our high-speed Hα camera (Hanaoka et al., 2003), which attached to the Solar Flare Telescope (Sakurai et al., 1995) of National Astronomical Observatory of Japan (NAOJ), also aims at the high-cadence imaging of solar flares at the Hα center. We started the regular observation with the high-speed Hα camera in July 2001, expecting collaborative observations with the RHESSI satellite, which was launched in 2002 February.

Not only the high-cadence imaging, but also the measurements of linear polarization and velocity field using the Hα line also provide important information about the high-energy aspect of flares. The linear polarization of flare kernels is considered to be produced by impact polarization, which is caused by the bombardments of high-energy particles to the chromosphere. Particularly, protons are presumed to be a dominant cause of the impact polarization. Therefore, the observations of the polarization of flare kernels might show the behavior of protons in flares. Some observations have shown polarization signals in Hα images (Hénoux et al., 1990; Vogt and Hénoux, 1999), but observations are still not enough. While the observable value is the linear polarization only, there are various factors affecting the polarization — the amount and the spectrum of the high-energy particles, the magnetic field configuration which guide the particles, etc. Therefore, statistical analyses based on routine observations of the linear polarization of solar flares are required to study the behavior of the high-energy particles, especially protons.

Mass motions in flare kernels are another important clue to study the behavior of the high-energy particles. Downward motions of the chromospheric plasma in flare kernels are observed as a 'red-asymmetry' of the spectrum in Hα, etc. This is considered as a reaction to the chromospheric evaporation caused by the bombardments of high-energy particles, and it is a measure of the energy input into the chromosphere during flares (e.g., Ichimoto and Kurokawa, 1984; Canfield et al., 1990).

For the above reason, we upgraded the high-speed Hα camera to a multi-aspect Hα imaging system, which performs the linear polarization measurements, and the off-band imaging for the Doppler velocity measurements, as well as the high-cadence imaging. For the polarimetry, we added a polarization modulator, which includes a rotating 1/2-λ plate. For the Dopplermetry, the Lyot-filter is tuned to $\pm$0.5 Å to take off-band images. To accommodate three types of observations, we need to sacrifice the time-resolution of the high-cadence imaging at the Hα center, which was 0.5 s in the original system. The data acquisition rates of the new system are as follows.

- High-cadence images at the Hα center: every 1-2 s
- Polarization image sets: every 4-5 s
- Hα off-band image sets: every 1 min

The instrumentation of the multi-aspect Hα imaging system is described in the next section. Sample flare images taken with this system are presented in the last section.

MULTI-ASPECT Hα IMAGING SYSTEM

Figure 1 shows a schematic diagram of the multi-aspect Hα imaging system. This system is installed in the Solar Flare Telescope of NAOJ. The target of the observation of the Solar Flare Telescope is the magnetic activity in solar active regions such as flares. It consists of four refractors, which are used for a vector magnetograph, a white-light imager, an Hα imager, and an Fe I 6337 Å imager (currently under the replacement with another system), respectively. The Solar Flare Telescope had started the regular observation in 1990. The old Hα imager system had been replaced with the high-speed Hα camera described in Hanaoka et al. (2003), and now upgraded to the multi-aspect Hα imaging system.

The optical system of the Hα imager consists of a 15cm refractor and a Zeiss Lyot filter, of which passband is 0.25 Å. The final focal length is about 2.4 m. The digital camera, TAKEX FC-300, has a CCD which is a 1/3 inch type and has 660$\times$494 pixels. The depth of the A/D conversion of the camera is 10 bits, and the frame rate is 30 frames s^{-1}. The field of view is $6' \times 4.5'$, which covers a typical single active region on the Sun. The data from the camera are received by a frame grabber, which installed in a Windows PC. To perform the linear polarization measurements, a rotating waveplate is placed in front of the Lyot filter as the polarization modulator. The waveplate is a polymer type fabricated by Meadowlark Optics, and its retardation is 1/2-λ of 6563 Å. The polarization analyzer is a polarizer located at the entrance of the Lyot filter. In the normal setting of Zeiss Lyot filters, a fixed polarizer is located at the exit of the filter, and the entrance polarizer rotates with the wavelength tuning. Therefore, we set the filter in the opposite direction to the normal one, so that the fixed exit polarizer becomes a polarization analyzer at the entrance of the filter.

The waveplate rotates continuously. The rotation of the waveplate and the exposures of the camera should be synchronized. For this reason, the stepper pulses for a stepping motor, which rotates the waveplate, are produced from the vertical synchronizing pulse of the digital camera (30 Hz) by a PLL synthesizer. Furthermore, exposures should start when the waveplate comes at certain fixed phase angles. The rotation of the waveplate is controlled such that the signal from an origin sensor and the exposure timings of the camera are locked on to each other. The modulation period of Stokes Q and U is a 90-deg rotation of the 1/2-λ waveplate, and four exposures cover a 90-deg rotation. Therefore, a complete rotation of the

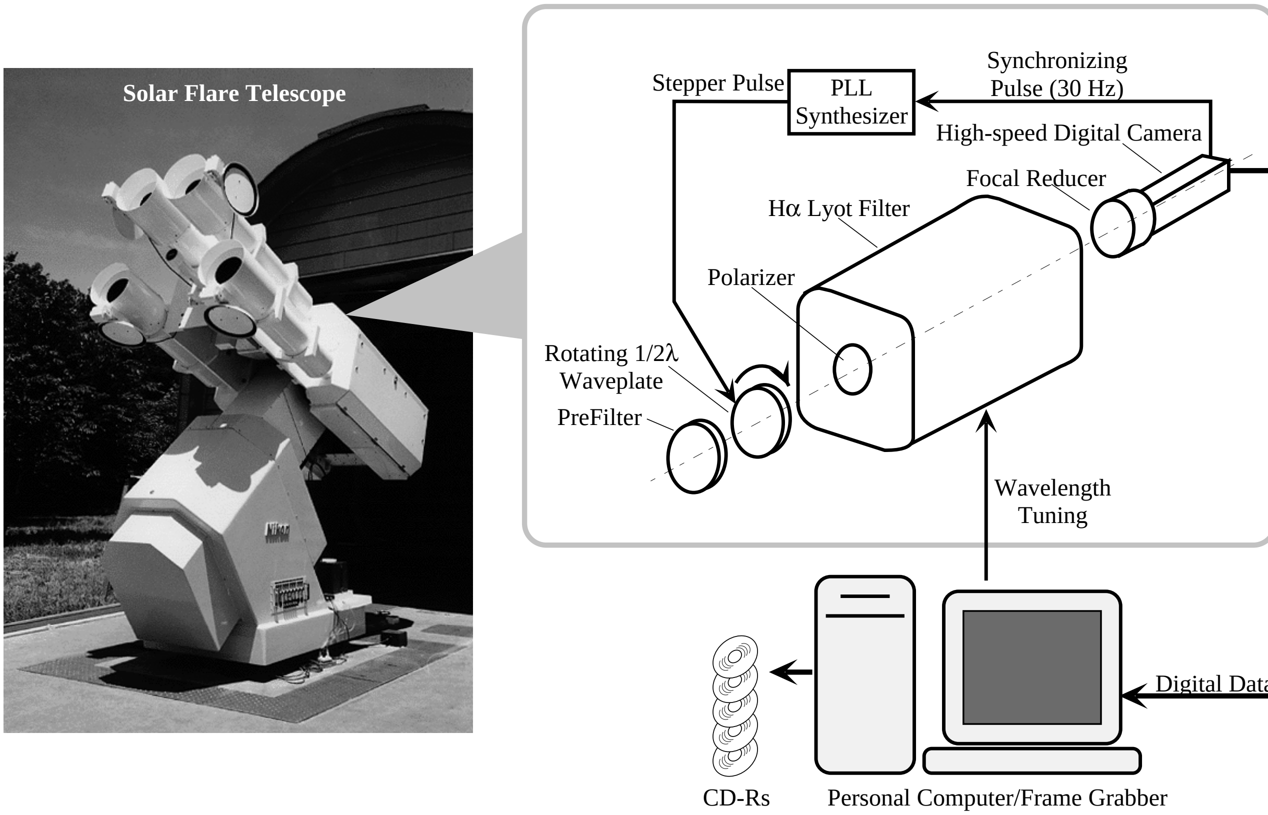

Fig. 1: Schematic drawing of the multi-aspect Hα imaging system. A polarization modulator, a Lyot filter, and a digital camera are installed in one of the refractors of the Solar Flare Telescope of NAOJ, Mitaka.

waveplate corresponds to 16 exposures of the camera, or a complete rotation takes $16/30 (\simeq 0.53)$ s, and the waveplate rotates by 22.5 deg during a single exposure (in the current optical configuration, a 1/30 s exposure gives an overexposed image, and therefore, we set the efficient exposure time to be 1/250 s with an electronic shutter control. Then the waveplate rotates by 2.8125 deg during an exposure).

To take off-band images of the Hα line, the transmission wavelength of the Lyot filter is shifted by the wavelength tuning controlled by the computer.

The data acquisition control of this system is based on a flexible real-time data processing system for solar observations described in Hanaoka et al. (2003). A time chart of the data acquisition sequence, which accommodates the high-cadence imaging at the Hα center, the polarization data acquisition, and the off-band imaging for Dopplermetry, is shown in Figure 2. The basic sequence including the polarization data acquisition and the high-cadence Hα imaging, and the detail of the polarization data acquisition are shown in Figure 2a. An off-band imaging sequence is inserted once in a minute, and the sequence in such a case is shown in Figure 2b. The basic period in these sequences is two rotations of the waveplate or 32 exposures, which take $32/30 (\simeq 1.07)$ s. Figure 2c shows a set of images taken with the high-cadence imaging, the off-band imaging, and the polarization data acquisition.

Because four exposures cover a modulation period of the Stokes Q and U parameters or 90 degree, a period of 32/30 s includes 8 sets of polarization modulated images. The eight images for each polarization state are integrated in real time, and four integrated images are saved on a hard drive. The polarization modulated images are taken every four periods, and therefore, the standard time resolution of the polarization data sets is about 4.27 s.

The high-cadence images at the Hα center are taken in every period except for the period to take the off-band images. The first image of each period is saved as a high-cadence image. The first image of the period for a polarization data set is also saved as a high-cadence image. Therefore, all the high-cadence images are taken at an identical polarization state. The standard time-resolution of the high-cadence images at the Hα center is 1.07 s.

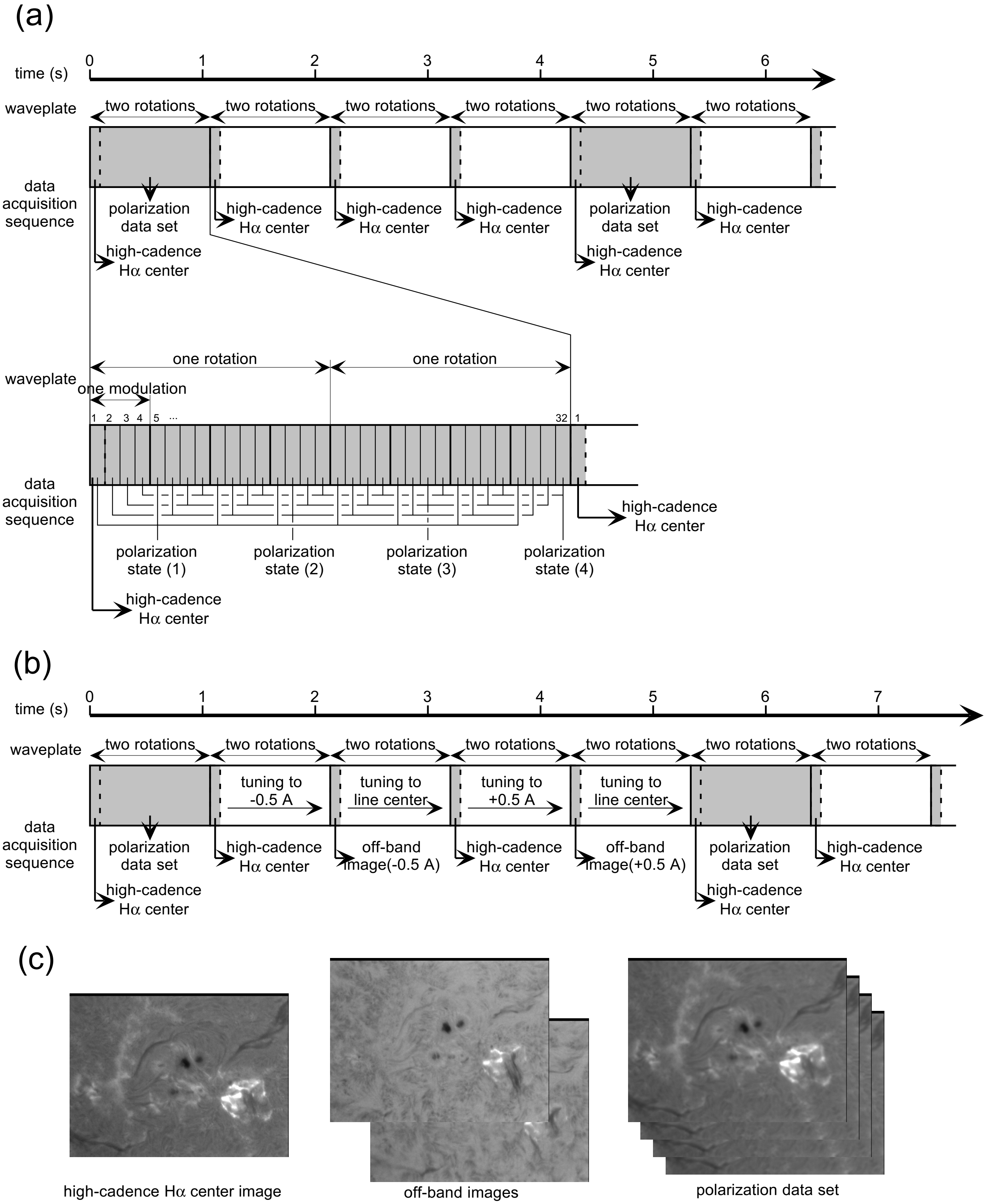

Fig. 2: Time-chart of the data acquisition sequence of the multi-aspect Hα imaging system. (a) Basic sequence of the high-cadence Hα center imaging and the polarimetry data acquisition. The detail of the polarimetry data acquisition is also shown. (b) Sequence including the off-band imaging for Dopplermetry. (c) Sample images taken with the Hα center imaging, the off-band imaging, and the polarimetry data acquisition, respectively.

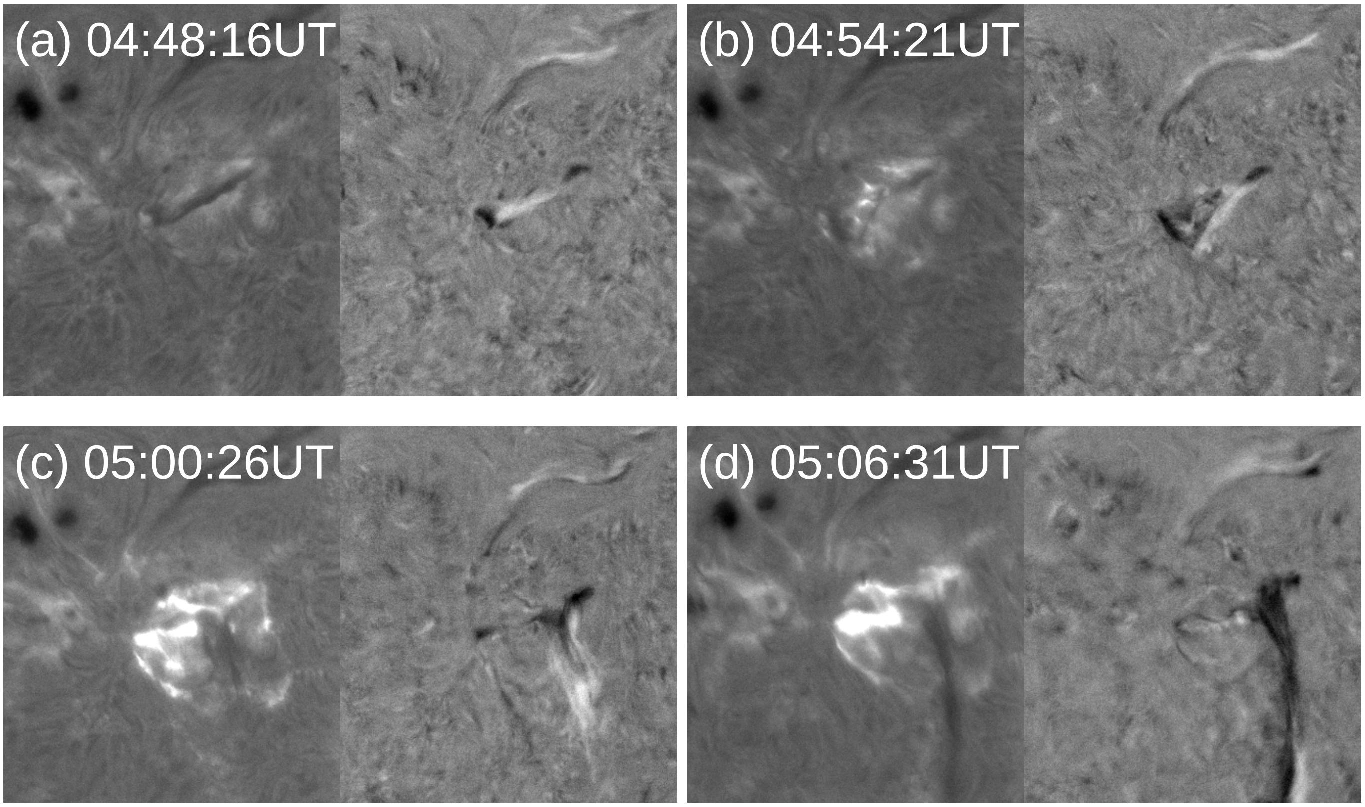

Fig. 3: A flare on 2002 July 4. This figure shows an example of flares observed with the multi-aspect Hα imaging system. Left-hand panels show sample pictures of the high-cadence Hα images. Right-hand panels show Dopplergrams produced from H$\alpha \pm 0.5$ Å images, of which acquisition times are closest to the Hα center images. In the Dopplergrams, white stands for blue-shifts, and black stands for red-shifts. A flaring seen in the Hα center images follows a filament eruption seen in the Dopplergrams.

Once in a minute, three successive imagings at the Hα center shown in Figure 2a are replaced with an off-band imaging sequence as shown in Figure 2b. An H$\alpha - 0.5$ Å image and an H$\alpha + 0.5$ Å image are taken between Hα center images. The period of 32/30 s is kept in the case of the off-band imaging. The filter tuning can be done within a period, and the off-band images are also taken at the first exposure of each period. When the off-band imaging is inserted, the interval of the polarization modulated image acquisition becomes 5 periods or 5.33 s, and that of the high-cadence imaging at the Hα center becomes 2.13 s.

The amount of the polarimetry data and that of the high-cadence Hα center images are about 20 GB each for a daily observation. Such an amount of data are too huge to keep all of them, and furthermore, the high-time resolution data only during flare time periods are needed for analyses. Therefore, we record the Hα center images every 30 s and the polarization data sets every 2 min in parallel with the high-cadence data recording. All of these lower cadence data as well as all of the off-band image sets are written on CD-Rs after the observation. On the basis of the 30-s data at the Hα center, a post-facto flare detection is carried out after the observation. The method of the flare detection is the same as that of the original high-speed Hα camera described in Hanaoka et al. (2003). According to the flare detection results, polarization data sets and high-cadence Hα center images during flare time periods are cut out, and only the flare data are written on CD-Rs. Besides the raw data recorded on CD-Rs, daily Hα images and movies, lists of the observation time periods and detected flares, and quick-look pictures of the flares are produced automatically. They are open on the WWW page of NAOJ to promote collaborations with the researchers outside NAOJ.

SAMPLE OBSERVATIONAL DATA

The multi-aspect Hα imaging system with the polarization modulator and the filter tuning control started the regular observation in July 2002. Figure 3 shows an example of observed flares, which was observed on 2002 July 4. A filament eruption is seen in Dopplergrams clearly, and a flare follows it. The linear polarization signal is not remarkable in this particular flare.

In our polarimetry observations, the seeing-induced error dominates in the polarization error, particularly at flare kernels, where the gradient of the brightness is steep. However, the polarization error can be reduced to much less than 1 % even in flare kernels with appropriate integrations. In spite of the high precision of the polarimeter, most of the observed flares, including one in Figure 4, do not show the polarization signal. However, we found polarization exceeding 1 % in a gradual flare (Hanaoka, 2003) among several tens of flares observed. Results of a statistical analysis of the observed flares will appear in a forthcoming paper.

ACKNOWLEDGMENTS

We are grateful to the staff of the Advanced Technology Center of National Astronomical Observatory for their help to develop the Hα imaging system.

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Manuscript received 5 November 2002; revised 20 July 2004, accepted 21 July 2004