Long-Term Monitoring Studies of the Sun at the National Astronomical Observatory of Japan

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Abstract. Long-term monitoring studies of the sun being conducted at the National Astronomical Observatory of Japan by using ground-based optical telescopes are described. A future plan for further strengthening the long-term studies of the sun, called the Solar Cycle Telescope, is presented.

1. Introduction

Observations of the Sun at the National Astronomical Observatory of Japan (NAOJ since 1989, formerly Tokyo Astronomical Observatory, University of Tokyo) started in the 1920’s. This article reviews long-term studies of the sun being conducted at NAOJ by using ground-based optical instruments. The sources of data are the instruments at Mitaka (Tokyo), Norikura, and Okayama. The accumulated data cover the following items.

1) sunspots (Mitaka)
2) faculae (Mitaka)
3) Hα flares (Mitaka)
4) active region vector magnetic fields (Okayama, Mitaka)
5) full-disk magnetic fields (Mitaka)
6) coronal green line intensities (Norikura)
7) He 10830 Å spectroheliograms (Norikura)
8) solar diameter (Mitaka)

In the following sections, brief descriptions of the instruments and the obtained data are given. At the end we will present our future plan to further strengthen the long-term studies of the sun at NAOJ.

2. Sunspots

Sunspot observations by taking sketches started at Mitaka in 1926, and the sunspot relative numbers were recorded since 1928 (Natori 1991). Before 1938, the telescopes were changed several times, and the sketches are more like observation log and are not accurate enough to obtain the precise location of sunspots. Since 1938, the same telescope (20 cm refractor of Zeiss) has been used for sunspot observations. The size of the solar diameter on the sketches was fixed to 24 cm in 1955. Photographs have been taken on sheet film, too.
The coordinates of sunspots recorded in the sketches since 1943 were read by a digitizing tablet (Kamby 1991). Fig. 1 shows the butterfly diagram constructed from these data. Differential rotation (Kamby & Nishikawa 1990) and meridional flows (Kamby et al. 1991) were studied by using these data.

![Butterfly diagram](image)

Figure 1. Sunspot butterfly diagram based on the observations at Mitaka, 1943–1991.

Now a transition to a new system based on a 2K×2K pixel CCD on a 10 cm telescope is under way. The new system will yield sunspot areas and coordinates automatically. In 1989 Nishikawa (1990) conducted a high precision 2-D surface photometry of the sun at Mitaka, and showed that the solar irradiance can be tracked by observing darkening by sunspots and brightening by faculae and network elements. This was one of the earliest attempts to study the solar irradiance variation from the ground. The new telescope will continue this surface photometry with higher (2K×2K instead of 500×500 pixels) spatial resolution.

On the same equatorial mounting, another telescope of 15 cm in aperture is installed for He 10830 Å observations. This telescope will use a Lithium Niobate etalon fabricated by CSIRO, Australia. The etalon has a diameter of 75 mm and a thickness of 200 μm. With the finesse of about 25, it will give an effective passband of 1 Å when used in a telecentric beam of F/30. The passband can be tuned on and off the line by changing the applied voltage.

3. Faculae

On the sunspot sketches described in the previous section, faculae in active regions and polar areas are also recorded (sunspots in black pencil, faculae in red pencil). The numbers of polar faculae are counted for three latitude bands (λ =50–60, 60–70, 70–90 degrees, respectively). Individual observations take 30 minutes or so, and faculae have life times of similar length, so that our facular counts represent snap shots at the time of observation.

Fig. 2 shows the seasonal variation of polar facular counts derived from observations over the period of 1951–1991. The annual variation is mostly due to the tipping of the solar rotation axis with respect to the earth. The north pole is most visible in September when \( B_0 = +7^\circ \), and the south pole is most
visible in March when $B_0 = -7^\circ$, where $B_0$ is the latitude of the center of the visible solar disk. Superposed on these is probably a seasonal variation of seeing, which is better in summer and poorer in winter. If we represent the number of observed faculae as $N(B_0, \lambda)$, we found

$$\frac{N(B_0 = \pm 7^\circ, \lambda = 70-90^\circ)}{N(B_0 = 0^\circ, \lambda = 70-90^\circ)} = 3-4,$$

$$\frac{N(B_0 = \pm 7^\circ, \lambda = 60-70^\circ)}{N(B_0 = 0^\circ, \lambda = 60-70^\circ)} = 1.5-1.7,$$

$$\frac{N(B_0 = 0^\circ, \lambda = 70-90^\circ)}{N(B_0 = 0^\circ, \lambda = 60-70^\circ)} = 1.4-1.6.$$

Here $+$ or $-$ sign should be used if $N$ is for north or south polar facular count, respectively.

From these annual modulation of polar facular counts, one can derive information on the distribution of polar faculae. We assume that
(1) the number of faculae per unit area is represented as $\exp(-\theta/\theta_0)^2$ or $\cos^m(\theta)$, where $\theta$ is the angular distance from the pole,
(2) faculae too close to the limb (angular distance from the limb smaller than $\theta_{\text{lim}}$) are not visible.

Then, for a given value of $B_0$, one can calculate a relative number of observable faculae. We found that the model fits the observation if we take $\theta_{\text{lim}} \simeq 12^\circ$, and $\theta_0 = 20-30^\circ$ or $m = 8-12$. In the source surface model of global solar magnetic fields, it is often assumed that the distribution of the polar magnetic flux is modeled by $\cos^8 \theta$. Although our analysis cannot strongly constrain the model parameters, our results are consistent with the $\cos^8 \theta$ distribution.

After removing the seasonal variation of facular counts by taking one-year running mean, we can plot yearly variation of facular counts. Fig. 3 shows north and south polar facular counts for the two latitude ranges (60–70 and 70–
90°); the data from 50–60° bins are mixtures of polar and active region faculae and therefore are omitted here. In Fig. 3, counts of active region faculae are also shown in the form of a butterfly diagram. Active region faculae are not as isolated as polar faculae, and are much more numerous. Therefore, active region facular counts are approximately obtained by counting 5 × 5° areas on the sun which are fully (weight = 1) or roughly half (weight = 0.5) populated by faculae. Fig. 3 was generated by assuming, rather arbitrarily, that one polar facula has a weight of 1/25. The counting process of active region faculae was carried out only on the data of December, where \( B_0 \approx 0 \). Active region faculae show essentially the same distribution as sunspots, while polar faculae are most numerous near the sunspot minima.

![North Polar Faculae](image)

![South Polar Faculae](image)

Figure 3. Polar facular counts (top and bottom two panels) and the butterfly diagram in which active region and polar faculae are combined. Polar facular counts shown are for the latitude ranges of 60–70° (dashed) and 70–90° (solid).

4. \( \text{H}\alpha \) Flares

\( \text{H}\alpha \) flare patrol observations at Mitaka started in 1948 by using a visual spectrohelioscope (Yamaguchi 1991). The sunbeam from a coelostat was fed to a 13 cm objective lens and the image was made on the slit of a spectrograph. In front of the slit was a rotating prism which moved the solar image, and at the
spectrograph exit was another prism which was rotated in synchronization with
the first prism. An observer could see Hα images visually, and recorded notable
events. Sketches of this kind have been obtained from 1948 to 1967. In 1957, a
14 cm refractor made by Cecasi, France, equipped with a Lyot filter was installed
and the photographic flare patrol observations started. In 1991, an automatic
system using a 4 cm objective lens, a CCD camera and a personal computer
with a video frame memory was introduced. In the present system, digital Hα
images are recorded periodically, and when a flare is detected, the light curve is
plotted and the area and the brightness are measured automatically (Suematsu
et al. 1994).

5. Vector Magnetograms of Active Regions

At Okayama, the 65 cm Coude-type solar telescope was built in 1967, and a
photoelectric vector magnetograph was installed in 1982. The spectral line used
is Fe I 5250 Å (Landé factor g_L = 3.0). A typical observing run of about an
hour covers an area of 500″ × 450″ with 10″ steps (Makita et al. 1993).

From 1992 we have been operating a video vector magnetograph at Mitaka.
The magnetograph, attached to a 20 cm refractor, is one of the four component
telescopes (2×20 cm, 2×15 cm) on the Solar Flare Telescope (Sakurai et al.
1995). The spectral line used is Fe I 6302.5 Å (g_L = 2.5), and a birefringent
filter with a bandwidth of 1/8 Å is used to isolate the wing of this spectral line.
The field of view is 400″×300″, covered by a CCD of 512×480 pixels. The Solar
Flare Telescope takes vector magnetograms every 3 minutes, and also measures
the Doppler shifts and records Hα and continuum images.

Magnetic vector maps of active regions have been published since 1982. The
publications are based on the Okayama magnetograph up to 1995, and on the
Solar Flare Telescope at Mitaka from 1996. Routine operation of the Okayama
magnetograph was stopped at the end of 1995.

6. Full-Disk Magnetic Maps

In the framework of the Solar Terrestrial Energy Program (1990–1997), a full
disk video magnetograph was constructed in 1993 (Sakurai et al. 1995). The
spectral line used is that of Fe I at 5324.2 Å (g_L = 1.5), and a birefringent filter
with a bandwidth of 1/5 Å was used. The pixel size corresponds to 5″ on the
sun. In order to increase the sensitivity of magnetic field measurement, in 1996
we upgraded the filter passband to 1/10 Å. We still have some problem with the
performance of the filter and the adjustment is now under way.

7. Coronal Emission-Line Intensities

At Mt. Norikura, 2876 m above sea level, a coronagraph station was established
in 1949 (now the Norikura Solar Observatory). By using a 10 cm coronagraph,
photographic observations of coronal structures and prominences have been car-
ried out, and the intensities of the coronal emission line of Fe XIV at 5303 Å
Figure 4. Coronal green-line intensities from Norikura (top) and from a unified data set of Sykora (1992) (bottom). The ordinates are in $10^{-6}$ of the disk center intensity.

have been measured. The measurements are made every five degrees of the position angle along the perimeter of the sun, at a height of 50'' above the limb, and the intensities are represented as millionths of the intensity of the disk center in a nearby continuum. The measured intensities have been published in the Quarterly Bulletin on Solar Activity of IAU since 1951, and are plotted in Fig. 4.

In the same figure, a reference curve taken from Sykora (1992) is also plotted. He cross-calibrated the data from all of the available coronagraph stations and reduced the data into a unified scale originating from the Pic-du-Midi Observatory. By comparing the two curves one may notice that the intensity scale of Norikura in the earlier data (up to nearly 1963) might be different from the rest of the period. Fig. 5a shows the ratio Norikura/reference, which is nearly constant after 1964 but is larger before. Fig. 5b shows the sky intensities (intensities of a continuum just next to the green line) simultaneously measured at Norikura, and there seems to be a correlation between the two curves in the period 1955–1963. This seems to indicate a long-term drift in the standard of intensity measurement which uses a neutral density filter and an optical step wedge.

As it is not possible to definitely locate the source of errors now, we will try to re-scale the data empirically.

\[
I_{\text{rescaled \ (year)}} = 0.5 \times I_{\text{original \ (year)}} \quad (1951-1954, 1964-\text{present})
\]

\[
I_{\text{rescaled \ (year)}} = 0.5 \times \frac{I_{\text{sky \ (year)}} - I_0}{I_{\text{sky \ (1964)}} - I_0} I_{\text{original \ (year)}} \quad (1955-1963)
\]
Figure 5. Top: ratio between the Norikura green-line intensities and the reference data from Sykora (1992). Bottom: Sky intensities measured at Norikura. The ordinate is in $10^{-6}$ of the disk center intensity. The dotted horizontal line in the bottom panel shows the level of $I_0 = 30$. The vertical lines indicate the period where the re-scaling to the data is to be applied.

Here 0.5 is the average ratio between Norikura intensities and reference data in the period of 1964–present. $I_0$ is taken to be 30, which maximizes the correlation between the green-line intensities and sky intensities. The results, i.e. the re-scaled Norikura green-line intensities are plotted in Fig. 6, together with the butterfly diagram of the green-line corona.

The instrument was upgraded in 1997 and now we can obtain 2-D images of the green-line corona by using a birefringent filter. It will take one or two years to establish the intensity scale of the new system.

8. He 10830 Å maps

The 25 cm coronagraph at Norikura, built in 1971, is equipped with a spectrograph and a CCD camera, and the mapping of the sun using the Helium 10830 Å line is conducted on an almost routine basis since 1991 (Hiei et al. 1991). A single pixel of the CCD covers $1'' \times 0.2$ Å, and spectral strips of 2 Å width are recorded. A raster scan of the full-disk, made of four swaths of 500'' wide, is completed in 30 minutes. This synoptic program will be soon transferred to the instrument based on the Lithium Niobate etalon described in section 2.
9. Solar Diameter

The photoelectric meridian circle (the Tokyo PMC) was constructed in 1982. The main objective of this instrument is to construct a catalog of star positions. In addition the instrument has been used to observe solar system bodies, and in particular the diameter of the sun has been measured since 1985. The initial results reported by Yoshizawa (1997) indicates a variation of about 0.05" in amplitude, with the tendency that a smaller diameter is found in the period of activity maximum. This is in qualitative agreement with the results from CERGA, France (Delache & Krall 1994), but the amplitude is smaller by a factor of four or so.


In order to strengthen our systematic, long-term observations of the solar activity, we are proposing to construct a new facility, the Solar Cycle Telescope. The aims of this facility are twofold. The first is to observe the solar magnetic field with high precision, at an infrared wavelength where the Zeeman splitting is larger than in the visible wavelengths. Ambiguities in the magnetic field measurement arising from the existence of unresolved flux elements are more easily disentangled in the infrared than in the visible. The second is to measure the differential rotation and large-scale convective flows on the sun, which drive the solar dynamo, with an accuracy of a few meter per second.
This facility is made of an infrared Stokes polarimeter working at the wavelength of 1.56 μm, and a Doppler telescope measuring the line profile and Doppler shift of a Zeeman-insensitive spectral line (Fig. 7). In the following, we will describe our current design for the facility.

10.1. Infrared stokes polarimeter

A Makustov telescope of 30 cm aperture with a focal length of 2 m will be put onto an equatorial mounting. After the first solar image, a polarimeter made of a rotating waveplate and a Wollaston prism are located. A Littrow spectrograph by using the Cassegrain configuration is attached onto the telescope. The telescope tube and the spectrograph are evacuated. The detectors can be either a PtSi camera or a HgCdTe camera, with 1000×1000 pixels. A single pixel corresponds to 2″, and the detector covers the full solar diameter. Stokes profiles of Fe I line at 1.56 μm ($g_L = 3.0$) are recorded for eight intervals of waveplate rotation, each spanning 22.5 degrees. The exposure time necessary in achieving $10^{-3}$ polarimetric accuracy is about 0.1 s for a single waveplate position. A raster scan of the full solar disk in 2″ steps will take about 17 minutes. In terms of the field strength, the sensitivity is about 1 G for longitudinal fields, and about 100 G for transverse fields.

10.2. Doppler telescope

A heliostat mirror feeds the light through the polar axis of the telescope onto a refractor of 15 cm aperture with a focal length of 1 m. By using an image rotator, either equatorial or meridional slice of the sun is projected onto the slit of the spectrograph. In order to suppress five-minute oscillations and to focus on steady-state flows, each measurement has to be completed in one minute or so. Therefore we give up scanning the sun with high spatial resolution. Instead, about 20 strips which are parallel to the equator, and only one meridional strip will be observed. The profile of Fe I 5576 Å line (which has no Zeeman sensitivity, $g_L = 0$) is recorded with a CCD camera of 1000×1000 pixels. A single pixel corresponds to 2″, and the detector covers the full solar diameter. The telescope tube and the spectrograph are evacuated. For wavelength standards, a stabilized laser is simultaneously observed by the spectrograph, and for calibration an iodine vapor cell is inserted into the light beam. The goal of the stability of the wavelength standard is $10^{-9}$.

In addition to these, a fiber bundle is attached to the focal plane of the second Makustov telescope on the equatorial mounting and feeds the light into a spectrograph designed for visible wavelengths. This spectrograph is used for general spectroscopic observations, including a two-dimensional mapping of the Doppler shift which is not supported by the Doppler telescope. A zero-dispersion spectrograph is attached before the main spectrograph for order-sorting.

The facility will be operated continuously over at least one solar cycle, and the accumulated data will be used for the study of the driving mechanism of the solar activity cycle.

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Figure 7. A schematic diagram of the Solar Cycle Telescope.
Figure 7. (continued)
and to Dr. M. Yoshizawa for providing his new publications to the author. Finally, the author acknowledges the organizing committee for financial support.

References

Kambry, M. A. 1991, thesis, The University of Tokyo
Yoshizawa, M. 1997, in Dynamics and Astrometry of Natural and Artificial Celestial Bodies, IAU Colloq. 165, in press

Group Discussion

Demidov: Could you please tell us about characterics of the full disk magnetograph telescope: (1) spatial resolution, (2) value of the instrumental noise?
Sakurai: Our full-disk video magnetograph is made of a 6 cm objective lens, a birefringent filter (5324 Å, 0.2 Å passband), and a CCD camera. One pixel corresponds to 4", and the solar disk is covered by 512(H) × 480(V) pixels. The noise level is about 10 G. The details can be found in J. Geophys. Geoelectr. 47, 1035, 1995.
Jones: How long will it take to obtain a full-disk observation with your proposed vector magnetograph? How often do you plan to obtain these data?
Sakurai: The polarization modulation will be made by a rotating waveplate. Eight exposures of about 0.1 second each will be made for a 180° rotation of the waveplate. By assuming a 1000 pixel detector which covers the slit length of 2000", the full disk will be scanned in 2" step (1000 scan positions in east-west). Therefore a full disk mapping will take at least 1000 seconds. The observing cadence depends on the data storage capacity, but one map per hour will be a reasonable cadence.