The Rotation Period of the Sun As Determined from the
Motions of the Calcium Flocculi

Hale George Ellery
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THE CALCULUM FLOCCULI

BY

GEORGE E. HALE AND PHILIP FOX

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THE ROTATION PERIOD OF THE SUN AS DETERMINED FROM
THE MOTIONS OF THE CALCIUM FLOCCULI.

The rotation period of the Sun has been determined by three independent
methods: (1) from measurements of the motions of the spots in longitude;
(2) from measurements of the motions of the faculae in longitude; and (3)
from spectroscopic measurements of the motion in the line of sight of the
approaching and receding limbs. The first series of monochromatic photo-
graphs of the Sun, made with the spectroheliograph of the Kenwood Observa-
tory in the years 1892-94, has provided material for a new determination of
the rotation period, based upon the motions in longitude of the calcium
flocculi. Through a grant from the Carnegie Institution it became possible
to undertake the measurement of these plates at the Yerkes Observatory.
The results of this investigation are contained in the present paper.

THE KENWOOD SPECTROHELIOGRAPH.

The spectroheliograph employed in the present investigation is shown in
plate 1, attached to the eye-end of the Kenwood refractor of 12 inches
(30.5 cm.) aperture and 18 feet (5.49 m.) focal length. It consisted of a
large grating spectroscope, with collimator and camera of 3.25 inches (8.4
cm.) aperture and 42.5 inches (108 cm.) focal length, inclined to each other
at an angle of 25°. The collimator and camera objectives were corrected
for the K line. A 4-inch (10 cm.) Rowland plane grating, having 14,438
lines to the inch (5,684 lines to the cm.), stood at the intersection of the
collimator and camera axes. The spectroheliograph was provided with two
movable slits, one at the focus of the collimator (in the focal plane for
K light of the Kenwood refractor), the other in the focus of the camera lens.
Both slits, which were 3.25 inches (8.4 cm.) in length, were adjustable in
width by means of micrometer screws. They were attached to carriages
mounted on steel balls, movable across the axes of the tubes, at right angles
to the spectral lines. A photographic plate-holder was supported just beyond
the camera slit and, after drawing the slide, the plate-holder could be pushed
forward by means of a cam until the surface of the plate almost touched the
jaws of the slit. A small 90° reflecting prism was attached to the slit carriage
on the side toward the grating, and by a suitable combination of lenses a
portion of the spectrum could be viewed without disturbing the plate-holder.
This was not used in practice, the K line (in the fourth-order spectrum)
being brought on to the slit by observing lines in the green of the overlapping
third order with a low-power, positive eye-piece. The motive power was
supplied by a specially designed clepsydra, mounted within the braced frame of the spectroscope. It consisted of a brass cylinder of 3 inches (7.6 cm.) bore and 6 inches (15.2 cm.) stroke, supplied with a three-way valve, permitting the liquid to flow in at one end of the cylinder and out at the other. The piston had a cup-shaped leather packing, and the phosphor-bronze piston-rod passed through a stuffing-box in the upper head. At the end of the rod a system of bell-crank levers was attached, which conveyed the motion to the slit at the focus of the camera objective. An extension of the piston-rod passed through a guide in the upper frame of the spectroscope, and connected with the first slit by another lever system. It will be seen that when the piston was set in motion, the two slits would move simultaneously, and in opposite directions, the first slit across the solar image, the camera slit, containing the K line, across the photographic plate. Water pressure was supplied to the clepsydra from a tank, in which the pressure was kept constant by means of an automatic pump. In winter, alcohol or glycerin was mixed with the water to prevent freezing.¹

This spectroheliograph, though it gave satisfactory photographs of the prominences and flocculi, had one important disadvantage: the distortion of the image resulting from the motion of the slits.

In the equation for the plane reflection grating

$$\lambda = \frac{d}{n} (\sin \theta \pm \sin \omega)$$

θ = angle of diffraction,
ω = angle of incidence,
λ = wave-length of line observed,
n = order of spectrum employed,
d = distance between adjacent lines of grating.

Then

$$\sin \theta = \frac{n\lambda}{d} \pm F \sin \omega$$

Differentiating, we have

$$d\theta = \frac{\cos \omega d\omega}{\cos \theta}$$

\(\frac{n\lambda}{d}\) being a constant for a given line.²

In the case of the Kenwood Observatory spectroheliograph, when used in photographing an image of the Sun 51 mm. in diameter, we have

θ (maximum) = 14° 36' \hspace{1cm} \theta (minimum) = 13° 42'
ω (maximum) = 40° 54' \hspace{1cm} \omega (minimum) = 38° 42'

\(d\omega = 51\) mm.

¹ For a more complete description of this spectroheliograph, in its original form, see Astronomy and Astro-Physics, May, 1892, p. 407.
THE SPECTROHELIOPHOT OF THE KENWOOD ASTROPHYSICAL OBSERVATORY, CHICAGO.
FROM THE MOTIONS OF THE CALCIUM FLOCCULI.

Substituting in (1), we find $d\theta = 39.8$ mm. That is, the diameter of the photographed solar image which is parallel to the length of the spectrum will be reduced by the distortion from 51 mm. to 39.8 mm. The diameter parallel to the lines of the spectrum will of course remain undistorted. This result, however, is only approximate, as the distortion for equal values of $d\omega$ increases from one side of the image to the other. Thus if we make $d\omega = 1$ mm., and calculate the values of $d\theta$ for one side, the center and the other side of the solar image, we obtain the respective values

$$d\theta = 0.78 \text{ mm. (for maximum value of } \theta)$$
$$d\theta = 0.79 \text{ mm. (for mean value of } \theta)$$
$$d\theta = 0.80 \text{ mm. (for minimum value of } \theta)$$

In measuring photographs distorted in this way the necessary correction for a point at a given distance from the Sun's limb might be taken from a table, readily constructed for a given position of the Sun's image with respect to the axis of the collimator. To define this position, means were provided for making the solar image concentric with the axis of the collimator. Care was always taken to orient the image so that the distorted axis should be parallel to the solar equator in the photograph. For this purpose the whole instrument could be rotated about the axis of the collimator, the direction of the slit being read off on a position circle. The parallel lines on the photograph (due to dust on the slit, which can not be altogether avoided in any form of spectroheliograph when the slit is narrow) were made to serve a useful purpose in the orientation of the image.

After a considerable number of distorted photographs had been taken with the instrument, a simple device was attached for the purpose of making the images practically circular in form. This consisted of a lever arm which moved the photographic plate, during the exposure, in a direction opposite to that of the motion of the second slit, and through a distance equal to the difference between the major and minor axes of the distorted image. It will be observed that this correction, though not perfect, is very nearly so. The modified instrument yielded photographs which were very nearly circular in form.\(^*\)

The Kenwood spectroheliograph and all the optical parts of the Kenwood refractor were constructed by Brashier, whose valuable services and cordial cooperation greatly facilitated the investigations of the Observatory. Warner & Swasey also gave much useful assistance, in addition to their work of constructing the telescope mounting and dome.

During the years 1892-94 there were obtained with the Kenwood spectroheliograph 2,295 photographs of the Sun showing the calcium flocculi. In 1,408 of these photographs the image was elliptical (or approximately so)

\(^*\)A mechanical device for copying distorted photographs, in such a way as to obtain a circular image, was also constructed at the Kenwood Observatory.
in form. These were obtained before the device for correcting the distortion of the image had been applied to the spectroheliograph. By means of the apparatus devised for the purpose, these negatives might have been copied in such a way as to give circular images, in which case they would have been available for the present investigation. But in view of the much greater excellence of the photographs which were being obtained with the 40-inch Yerkes Observatory telescope, when the present reduction of the Kenwood plates was undertaken, it was decided to confine the work to the measurement of the circular images, 887 of which were available. Mention has not yet been made of the slight distortion of the Sun’s image, caused by the curvature of the spectrum lines in the Kenwood spectroheliograph. Since the motion of the photographic plate, which served to transform the elliptical image into a nearly circular one, did not also furnish the means of correcting for the curvature of the slit, precautions had to be taken, while making the photographs, to eliminate the effect of this curvature. For this reason, the plates were made in two series, in one of which the slits were made parallel to the Sun’s axis, while in the other they were placed in a position angle 90° from this. For the present investigation the plates of the first series were employed, since the displacement (due to curvature) of the flocculi in longitude would be, in this case, only a second-order effect, too small to be appreciable in photographs no sharper than those available. In order to avoid errors in the identification of the flocculi measured, no attempt was made to employ plates separated by two or more cloudy days. The best plate, corresponding to each day in a series of two or more clear days, was selected for measurement. In this way the number of plates to be measured was reduced to 138, covering the period 1893 July 31 to 1894 September 29.

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\[ \text{Radius of curvature} \approx \text{about} \ 1 \ \text{m.} \]

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**FIG. 1. PLAN AND ELEVATION OF THE GLOBE MEASURING MACHINES**
METHOD OF MEASUREMENT.

Two causes made it undesirable to adopt the ordinary method of measurement in the reduction of these photographs. In the first place, the high degree of precision attainable in measuring very sharp direct photographs of the Sun, such as those comprised in the Greenwich series, is out of reach in the case of photographs taken with such an instrument as the Kenwood spectroheliograph. In the second place, the measurement and reduction by the ordinary process of the numerous positions required would have been a larger task than could be undertaken in the intervals of work with the Rumford spectroheliograph. Accordingly a new method of measurement was devised by Mr. Hale, which is at once exceedingly rapid in execution and, at the same time, sufficiently precise for the immediate object in view.¹

The photographs are projected by means of the light of an electric arc lamp upon a globe accurately ruled with a series of meridians and parallels. The details of the arrangement are described below. The greater part of the apparatus was constructed in the instrument shop of the Yerkes Observatory (see fig. 1). References to this apparatus will be used as follows:

\( A = \) Arc lamp, fed by clock-work so as to keep the arc at a fixed point.
\( C = \) Condensing lens, 10 inches (25.4 cm.) in diameter.
\( P = \) Plate-holder, which carries the solar negative.
\( L = 12\text{-inch (30.5 cm.)} \) objective of 18 feet (5.49 m.) focal length, which forms an image of the photograph upon the globe, \( G \).
\( M = \) Plane mirror inserted in the path of the rays, to secure the necessary distance of the globe from the lens, in the limited space available. The globe must subtend an angle of 32' as seen from the lens.

THE GLOBE.

The globe is of cast-iron, accurately turned to form a sphere 9.53 inches (24.21 cm.) in diameter. It was enameled white to receive the ruling, and afterwards reworked to a spherical form. In order to rule the parallels of latitude, centers were drilled at points corresponding to the north and south poles, and the globe was mounted in a Brown & Sharpe milling machine, between the spindle and the overhanging arm. A support for a ruling-pen was clamped to the spiral head, the pen resting on the globe. The position of the equator was determined by

¹ For an improved form of globe-measuring machine (the Helomicrometer), capable of giving results of the highest precision, see Contributions from the Solar Observatory, No. 16; Astrophysical Journal, June, 1907.