A Photometer for Measurement of Sky Brightness Near the Sun

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Measurement of the brightness of the sky near the sun is difficult because instrumental scattered light originating in the solar disk is usually many times brighter than light from the sky. An optical system for eliminating this scattered light and providing means for a visual photometric comparison between the sky and the sun has been constructed and tested. The principles of the instrument are explained in sufficient detail to permit the design of similar instruments for a wide range of applications.

In connection with research on the solar corona, the High Altitude Observatory of Harvard University and the University of Colorado (hereafter abbreviated to HAO) has been using a simple visual photometer for determining the brightness of the sky immediately surrounding the sun. Its performance has been very satisfactory. Since such a photometer has many interesting applications, including the meteorological, a short description of it is given below.

The principal difficulty in measuring sky brightness very near the sun is the elimination of the sun's light itself from the measuring instrument. Somewhere, either in the instrument or in the eye of an observer, an image of the sun must be formed, undiluted by stray light from the sun. Since, in a really clear atmosphere the sun is of the order of $10^4$ times as bright as the neighboring sky, the problem of scattered light is acute. The scatter by diffraction from the edge of an aperture diaphragm fully illuminated by direct sunlight is, by itself, many times brighter than the image of the clear sky near the sun. Added to this is the scattering from dust and film on lenses and the multiple reflections between lens surfaces.

Several possible devices for the elimination of scattered sunlight would doubtless be satisfactory. The HAO photometer consists essentially of a rudimentary Lyot coronagraph of 3 mm aperture equipped with an external occulting disk which shades the entrance aperture, and a photometric comparison surface illuminated by direct sunlight through an adjustable optical wedge. Its satisfactory operation depends both on careful adjustment and cleanliness of the optical parts.

The optical system is shown schematically in Fig. 1.

The external occulting disk, $O_1$, completely shades the 3 mm aperture, $a_1$, so that no point on the sun can be seen from any point in the aperture. (Distance $O_1$ to $a_1$ is 100 cm.) If an observer looks through $a_1$, however, he sees the edge of $O_1$ brilliantly illuminated by diffraction. The main function of the remainder of the optical system is to eliminate this diffracted light. Behind $a_1$ is a simple telescope consisting of the objective, $l_4$, ($f=25$ cm) and eyepiece, $l_5$, ($f=10$ cm). The telescope is folded by reflection from an uncoated black glass mirror, $m$, into a compact unit with the eyepiece in a comfortable position. (Direct vision solar instruments are definitely neck wringing at lunch time in the summer.) A second occulting disk, $O_2$, is set in the focal plane of $l_4$. It is large enough to intercept the somewhat out of focus image of the brilliant edge of $O_1$, and the narrow ring of the sky around the sun which suffers from vignetting due to the fact that the sky and $O_1$ cannot be simultaneously in focus. The second occulting disk stops the bulk of the diffracted light, but not all. In passing the edge of the aperture $a_1$, the light diffracted originally at $O_1$ is diffracted a second time. As seen from a point in the field near $O_2$, the edge of the aperture appears very bright, and it constitutes a source which scatters light over the whole field quite comparable in intensity with the image of a clear sky near the sun. To suppress this source of scatter, a second aperture diaphragm, $a_2$, is mounted concentric with the exit pupil where $a_1$ is imaged by lens $l_5$. The opening in $a_2$ is slightly

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smaller than the image of the bright edge of \(a_1\), and effectively prevents the diffracted light from that edge from entering the observer's eye.

For photometric purposes, the back surface of \(O_2\) is painted a diffuse white. Direct sunlight illuminates it after passing through the optical wedge, \(w\). When the observer looks into the eyepiece he sees \(O_2\) surrounded by an image of the sky. Measurement consists in adjusting the wedge until the two appear equal in brightness. From the known density of the wedge, then, the sky brightness in terms of the average brightness of the sun is readily calculated. It is

\[
B = B_0 \frac{\varphi^3 r_s \cos \theta}{t_w r_m}
\]

where

- \(B = \text{brightness of sky}\)
- \(B_0 = \text{brightness of sun}\)
- \(\varphi = \text{angular radius of sun (0.0047 radian)}\)
- \(\theta = \text{angle of incidence of sun light on } O_1\)
- \(t_w = \text{transmission of } t_w\)
- \(t_m = \text{transmission of wedge at balance}\)
- \(r_s = \text{diffuse reflecting power of white surface on } O_1\)
- \(r_m = \text{reflecting power of mirror, } m.\)

The instrumental constants of the HAO photometer give:

\[
B = 494 \times 10^{-6} B_0 \varphi w
\]

This instrument is restricted to measurements of sky less than 500 millionths as bright as the sun. Since skyls of this brightness are completely useless for coronal observation, the range is adequate. But for other studies, the range can be extended as far as seems desirable, preferably by increasing the illumination of \(O_2\) with a simple lens system. The alternative of putting an absorbing screen in the sky beam should be used with caution as it is necessary that the absorber be completely specular to avoid damaging scattered light. A second reflection from a black glass mirror might be the safest device.

When the HAO photometer was first tested, it was found, surprisingly, that at levels of less than 100 millionths the sky near the solar limb was still very blue. Comparisons with the white surface of the occulting disk were troublesome and their interpretation was doubtful. The difficulty was overcome by mounting a green filter (Wratten No. 58) over the exit aperture, \(a_2\)—a satisfactory remedy in this instance since the corona is observed chiefly in the light of a green emission line at \(\lambda 5303\).

Mention has been made of the vignetting of an area of the sky adjacent to the limb of the sun. This vignetting is a necessary evil in any instrument with a non-zero entrance aperture and an external occulting disk at a finite distance. Instruments of this type are unsuitable for measuring sky brightness right up to the solar limb. The HAO instrument was made with the second occulting disk large enough to cover up the vignetted area, which was, in this case, a circle of 1.6 solar diameters. The minimum sizes of the occulting disks which assure freedom from vignetting in the visible image are given by the following relations:

\[
\begin{align*}
\psi &= 2 \varphi + \alpha, \\
\theta &= \psi + \alpha,
\end{align*}
\]

where

- \(\psi = \text{angular diameter of } O_1 \text{ seen from } a_1\)
- \(\alpha = \text{angular diameter of } a_1 \text{ seen from } O_1\)
- \(2 \varphi = \text{angular diameter of the sun (0.0094)}\)
- \(\theta = \text{angular diameter of area of sky covered by } O_2, \text{ or angular diameter of } O_1 \text{ seen from } l_1.\)

If we let \(O_1, O_2 \text{ and } a_1\) represent diameters; \(d_1\), the distance between \(O_1 \text{ and } a_1\); and \(f_1\) the focal length of \(l_1\), we find for the minimum linear
diameters of the occulting disks:

\[ O_1 = 2 \sqrt{d} + a_1 \]

\[ O_2 = 2 f_i \left( \varphi + \frac{a_1}{d} \right) \]

As the diameter of \( O_1 \) and \( O_2 \) are made slightly larger than these minima, the instrumental adjustment naturally becomes less critical.

A rather rough experimental study indicates that when the instrument is properly adjusted and clean, the HAO photometer still has detectable scattered light superposed on the image of the sky. It amounts to about 1 millon of the brightness of the sun, and appears to originate in the rather serious surface imperfections in the objective lens, \( l_i \). The scattered light could presumably be reduced to a fraction of its present level by use of an undamaged lens, or better, a specially polished lens similar to the lens of a coronagraph.

The accuracy of the photometer in its present form is not high, but is quite adequate for its intended use. The accidental mean error of repeated settings is about \( \pm 5 \) percent for most observers. Personal differences between observers usually appear smaller than the accidental errors of an individual observer.

The systematic errors of the sky photometer depend largely upon the method and accuracy of calibration. If the density curve of the wedge is measured independently and combined with \( r_s \), \( r_m \), and \( l_i \) to calculate \( B \), then obviously the accuracy of the result depends upon the precision with which these constants are known. Furthermore, unless the wedge is quite specular, its density curve is dependent upon the particular manner in which it is used. In view of the numerous possibilities of error in the determination of the constants, a direct calibration on an artificial sky of controllable brightness is to be recommended if systematic errors are to be reduced to a minimum.

Because of the excellent performance of its visual photometer, the HAO now has a photoelectric instrument under construction. It will use the same type of optical system for the elimination of scattered light and is designed to be mounted equatorially, either on a mounting of its own or on a telescope. It will keep a continuous record of sky brightness on a Micromax recorder.