OBSERVATIONAL STUDIES OF THE SOLAR INTENSITY PROFILE IN THE FAR INFRARED AND MILLIMETER REGIONS

R. W. NOYES

Smithsonian Astrophysical Observatory, Cambridge, Mass., U.S.A.

J. M. BECKERS

Sacramento Peak Observatory, Sunspot, N.M., U.S.A.

and

F. J. LOW

University of Arizona, Tucson, Ariz., U.S.A.

(Received 30 June, 1967)

Abstract. Observations of the intensity distribution near the solar limb at 2.43 and 22.5 μ, show the absence of limb brightening to within 1 or 2 arc sec of the limb. Observations at 1.2 mm indicate limb brightening at this wavelength. These results are compared with the Utrecht Reference Photosphere and with existing data on the solar flux in the millimeter range, and suggest that the temperature minimum is broad and extends above $T_{5000} = 2 \times 10^{-3}$. A sharp rise of temperature is required above $T_{5000} = 10^{-3}$.

In this paper we shall discuss a series of investigations that we have carried out during the past year to study the solar intensity distribution in the far infrared and millimeter regions. Part of the work has been reported previously (NOYES, GINGERICH, and GOLDBERG, 1966; NOYES, 1966; NOYES et al., 1966), but some of the results are new.

In February and March of 1966 we made preliminary measurements of the solar limb intensity at 24.3 μ in an attempt to see the brightening predicted by several current models of the solar atmosphere (e.g., NOYES, GINGERICH and GOLDBERG, 1966). The results were negative to within the 10-arcsec resolution limit of our measurements. This observation is described in Section 1.

Next we measured the infrared limb profile with higher spatial resolution during the November 12, 1966, total solar eclipse. This experiment has indicated that limb darkening at 22.5 μ persists to the limit of our resolution, about 1 or 2 arcsec from the limb. We discuss the experiment and preliminary results in Section 2.

At the same time, we have analyzed several drift curves of the sun made at a wavelength of 1.2 mm, and found definite evidence for limb brightening at this wavelength. We describe these data and their analysis in Section 3.

Finally, in Section 4 we discuss the implications of these various results for the temperature structure of the low chromosphere.

1. Measurements of the Solar Limit Profile at 24.3 μ

In February and March of 1966 we made several measurements of the solar limb intensity distribution, using the 5-foot f/14 telescope of the Lunar and Planetary
Laboratory of the University of Arizona. A carefully selected sheet of black polyethylene 0.004" thick was placed in front of the telescope to prevent excessive heating of the optics. The transmission of the polyethylene, while very low in the visible, was about 40% at 24 μ. Infrared scans of Venus with and without the polyethylene in place showed no noticeable degradation of the image. The infrared radiation passed through a narrow-band interference filter with its peak transmission at 24.3 μ and a halfwidth of 0.9 μ, and then through a 5-arcsec circular aperture at the detector. The detector was a germanium bolometer cooled by liquid helium to 4°K. The detectivity of such a system is actually far greater than the noise introduced by other sources, principally sky transmission fluctuations, but this equipment was already in use for stellar work and was readily available.

Fluctuations in the emission and transparency of the daytime sky were largely, but not completely, removed by chopping between two regions of the sun about

Fig. 1. Differential chopper scans of the sun at 24.3 μ, March 22, 1966. Chopper separation: 18 arcsec. (a): entire sun, (b) North limb, (c) South limb. (b) and (c) are at higher gain and higher dispersion. The scale for (b) and (c) is given in the figure.

18 arcsec apart, at the rate of 10 cps. Scans were made across the sun in the direction (N–S) of the line between the two regions being chopped, so that the signal approximated the spatial derivative of the intensity. Figure 1 shows a typical scan of the entire sun, with separate scans of the limb region at higher gain and time resolution. The flatness of the 25-μ sun is at once evident.

Reasonably good data were obtained for 18 sets of limb scans. After averaging
scans of the North and South limbs to remove the effects of an asymmetry in the instrumental profile, we were able to draw two conclusions:

(a) At a position 40 arcsec inside the limb, where the effect of the instrumental profile on the measurements is small, the slope of the intensity is $-0.06\% \pm 0.07\%$ arcsec. In terms of $\mu = \cos \theta$, at $\mu = 0.28$, $dI_d\mu = -0.16 \pm 0.20$.

(b) At a distance 10 arcsec from the limb ($\mu = 0.14$), which lies within the instrumental profile of the apparatus, the instrumentally smoothed profile is asymmetric, even after averaging the North and South limbs. This presumably is caused by an asymmetry in the original unsmoothed derivative of the intensity about the limb position. The direction of the asymmetry at 10 arcsec from the limb is such as to imply limb darkening at that position. Thus we have somewhat indirect evidence that the darkening persists to within at least 10 arcsec of the limb.

2. Eclipse Measurement at 22.5 $\mu$

In order to attain better spatial resolution near the limb, we attempted a similar observation during the November 12, 1966, total solar eclipse. This eclipse had the appeal of passing over the Andes, where high-altitude sites are reasonably accessible. We set up a 12-inch $f/8$ cassegrain telescope at an elevation of 14000 feet on the centerline of the eclipse north of Arequipa, Peru. A prefilter of high-quality black polyethylene, similar to that described above, was stretched over the entrance aperture of the telescope. At the cassegrain focus we placed a rectangular slit, 1 arcmin by 3.5 arcmin, with its long axis parallel to the apparent motion of the moon. A rotating two-level mirror displaced the image by 4.2 arcmin in the direction of the long axis of the slit, at a frequency of 12 cps. This allowed us to chop between a region including a 1-arcmin slice of the solar crescent and a region on the dark lunar disk. The chopping eliminated sky-emission fluctuations, but not transparency fluctuations. The solar radiation passed into a liquid helium dewar through a window of Irtran 6, then successively through the focal plane slit, through a 22.5-$\mu$ interference filter (Figure 2), and through a KRS-5 Fabry lens, which finally imaged the objective onto the detector. The detector was a germanium bolometer especially constructed for the experiment at the Lunar and Planetary Laboratory of the University of Arizona, and had a noise-equivalent power of $1.6 \times 10^{-12}w$ at 4°K.

The entire slit-filter-lens-detector assembly was cooled to 4°K by a liquid helium bath.* The signal from the detector was fed into a low-noise parametric amplifier, a phase-lock differential amplifier, an integrating digital voltmeter, and a digital printer.

On the morning of the eclipse thin clouds covered the sky, gradually thinning out as totally approached. At totality, the sun appeared to be uniformly covered by very thin cirrus, although examination of a large-scale photograph of the sun obtained by

* The liquid helium, as well as liquid nitrogen for precooling, was airshipped from the United States, then transported by train and truck to the site, which was 40 miles horizontally and 6000 feet vertically from the nearest paved road. It was only through the efforts of many people, especially the Smithsonian Observing Station in Arequipa, Peru, that the logistic difficulties were overcome.
a Kitt Peak National Observatory expedition at the same site does not show the cirrus. Shortly after totality the sky became very cloudy.

Before second and third contacts, we attempted to set the slit on the lunar limb at those position angles that were calculated by one of us (Beckers, 1966) to cause a minimum of resolution loss due to irregularities of the lunar limb and distance off axis from the sun–moon centerline. Unfortunately, flexure in our guide telescope caused an error in positioning the slit, and we missed these optimum positions. Even more serious, at third contact the limb was placed quite close to the end of the slit, where the sensitivity drops rapidly with position. Calibration curves of the variation of slit sensitivity with position were obtained the previous day; these indicate that at third contact a sizeable correction to the data is necessary.

The data near second and third contacts are shown in Figures 3 and 4. Figures 3a and 4a show the raw data, i.e., the integrated intensity $I(x)$ between the lunar and solar limbs, as a function of the distance $x$ in arcsec between the lunar and solar limbs. There is considerable noise in the data, consisting of two types: (a) high-frequency ($>1$ cps) noise, which is proportional to the signal $I(x)$ and is almost certainly due to rapid transparency fluctuations, and (b) low-frequency ($\leq 0.1$ cps) variations, which are presumably due to slower drifts in sky transparency. Fortunately, during the few seconds preceding second contact and following third contact, there is no evidence for drifting in sky transparency.

In Figures 3b and 4b we have plotted the ‘average remaining intensity’ $J(x) = I(x)/x$. The run of these points itself should be an index of whether the limb region shows brightening or darkening. The fluctuations in these data make clear the difficulty of deriving a very precise estimate of the limb darkening from them. Actually, the data for $J$ suffer from other uncertainties, which are not evident in Figures 3b.
and 4b: (a) there is an uncertainty of about ±0.1 arcsec in the location of the limb, which causes a fractional uncertainty of about 0.1/x in \( \bar{I} \) at a distance x arcsec from the limb, (b) the third contact data have been corrected for the variation of sensitivity with position in the detector slit, described above. This makes these data considerably less reliable than the second contact data.

Nevertheless, there does appear a tendency for the mean remaining intensity \( \bar{I} \) to drop slightly toward the limb. This tendency may be followed to within about 3 arcsec of the limb before second contact, where the apparent influence of irregularities of the lunar profile becomes noticeable, and to within about 1 or 2 arcsec of the limb in the less reliable third contact data. We must emphasize, however, that noise in the data, uncertainties in the calibration, and possible transparency drifts make such a conclusion a probability rather than a certainty.

Several curve-fitting procedures have been applied to the data in Figures 3 and 4 in an attempt to get the function \( I(x) = dI(x)/dx \) directly. These include least-squares

![Graph](image)

**Fig. 3.** (a) Integrated intensity \( I(x) \) before second contact. (b) Average remaining intensity \( \bar{I} = I(x)/x \), where \( x \) = distance remaining to limb. Solid line is the prediction of the Utrecht Reference Photosphere (Heintze, Hubenet, and De Jager 1964).
fits of polynomials directly to the entire data string near each contact, and polynomial fits at each point to those points in its immediate neighborhood. We also tried other numerical techniques that suppress the high-frequency noise relative to the lower frequency components of the signal.

For the second contact data, the various methods concur in yielding either a flat distribution or slight darkening near the limb. (Further than 10 arcsec inside the limit some apparent brightening occurs, but we believe that this is due to a slow drift in sky transparency; for the last 10 arcsec, the time of about 25 sec remaining until contact is sufficiently short to make the sky drift less important.) The amount of darkening near the limb is rather sensitive to the fitting technique used. None of the techniques used produced a brightening at the limb, although the data are not good enough to rule out a very small brightening. The amount of brightening predicted by the Utrecht Reference Model (Heintze, Hubenet, and De Jager, 1964) seems
outside the limits of error, however. The measured darkening for $x<10$ arcsec is $(1/J) (dJ/dx) = -0.005 \pm 0.005$/arcsec, where the uncertainty simply includes the spread among different curve-fitting techniques.

The third contact data give identical results, but are unfortunately less reliable, due to the calibration problem mentioned above. However, they can be followed to within about 1 arcsec of the limb, in distinction to the second contact data, and yield no evidence of a brightening even this close to the limb.

3. Millimeter Region

The millimeter data consist of three drift curves of the sun obtained in February 1965 at the National Radio Astronomy Observatory, using a 5-foot spun plastic antenna with a conical feed into a germanium bolometer. The effective wavelength was 1.2 mm. In addition, both drift curves and North–South scans of the full moon were obtained. The intensity scans of the moon in the North–South and East–West directions appeared very similar.

Figure 5 shows drift curves of the sun and the moon and their derivatives, with the East and West limbs averaged. Although the solar drift curves do not explicitly show limb brightening, we may infer its presence from the asymmetry of the drop-off of the smoothed intensity at the limb. If the intensity distribution were flat, we would expect its derivative to be symmetric about the limb position. The lower left curve of Figure 5 shows the observed derivative for the sun. We see that: (a) the tail to the

![Fig. 5. Upper left: Solar drift curve at 1.2 mm, averaged over East and West limbs. Upper right: Lunar drift curve at 1.2 mm, averaged over East and West limbs. Lower curves are the spatial derivatives of the upper ones.](image-url)
derivative is smaller on the side toward the disk center, and (b) the peak of the derivative is moved outward somewhat from the limb position. Both effects are easily explained by the presence of limb brightening which, while not large enough to survive as explicit brightening after instrumental smoothing, does slow down the drop-off of the instrumentally smoothed profile at and just inside the limb.

By way of comparison, the lower right-hand curve of Figure 5 shows the analogous curve for the moon, which is known to have considerable limb darkening at 1.2 mm. Here the effects are just the opposite: the increased slope on the side toward the center of the moon due to the lunar limb darkening is clearly evident, as well as a shift of the position of maximum slope inside the limb.

A rather crude attempt has been made to correct for the effects of instrumental smoothing, using Bracewell's (1955) chord-construction technique. This method suffers from our lack of detailed knowledge of the antenna pattern. We use the equation

\[ I_{\text{corr}}(x) = 2I_{\text{obs}}(x) - \frac{1}{2} \left[ I_{\text{obs}}(x - \frac{a}{2}) + I_{\text{obs}}(x + \frac{a}{2}) \right], \]

where \( I_{\text{obs}} \) and \( I_{\text{corr}} \) are the observed and corrected intensities, respectively (Bracewell, 1955). This equation assumes that the antenna profile looks like a single-slit diffraction pattern of halfwidth \( a \). Although we do not know the 'best' value for \( a \), it certainly is at least as large as the halfwidth of the lower left curve in Figure 5, which gives a crude measure of the instrumental profile. (Assuming that the true intensity near the solar limb is nearly a step function. Note that limb brightening can only serve to decrease the apparent halfwidth over the true antenna profile halfwidth.) This minimum halfwidth is \( a = 4.9 \) arcmin. Figure 6 illustrates the effect of applying Equation (1) to the data for several values of \( a \), and shows explicit brightening for values of \( a \) greater than 4.0 arcmin. Thus we have further evidence that the inferred brightening is real.

Calculations were made of the area under the upper left curve of Figure 5, compared with the area under a step-function distribution extending to the white light limb, where we assume circular symmetry in both distributions. The ratio of these areas should equal the excess flux emitted by the 1.2-mm sun over that of a uniform disk of emissivity equal to that at the solar disk center. We find this ratio to be \( 1.14 \pm 0.03 \), where the last figure gives the internal consistency of the three drift curves. Systematic errors due to the lack of circular symmetry of the sun or the antenna patterns are possible, but hard to estimate. In addition, the ratio would be an overestimate if the antenna smoothing lowered the intensity at the center of the disk, but the spread of the inferred antenna profile seems too narrow to allow this.

4. Discussion

The persistence of darkening at 22.5 \( \mu \) to within 2 arcsec of the limb requires that the temperature minimum in the low chromosphere lie above \( \tau_{5000} = 2 \times 10^{-3} \). The pres-
Fig. 6. 1.2-mm limb profile as restored from the original data using Bracewell's (1955) technique: (a) original data; (b) restoration with $a = 4.0$ arcmin; (c) restoration with $a = 4.6$ arcmin; (d) restoration with $a = 5.1$ arcmin; (e) restoration with $a = 5.7$ arcmin.

ence of limb brightening at 1.2 mm requires that the temperature minimum lie below $\tau_{1\text{mm}} = 1$, or $\tau_{5000} \sim 1.5 \times 10^{-5}$. The present data do not place any further restrictions on the model. However, it is interesting to consider this data in the light of our knowledge of the solar intensity distribution with wavelength in the millimeter region. Figure 7 (see also Table I) shows the various published measurements of brightness temperature $T_B$ in the far infrared and millimeter range, plotted versus wavelength in millimeters. The solid curve in Figure 7 is the prediction of the Bilderberg continuum atmosphere* (Gingerich and de Jager, 1968), and is only one of many plausible fits to these rather widely scattered data, but any fit will have to show a rather sharp rise in the 1 to 10-mm range. In order to fit the brightness temperatures observed in the visible and infrared, a rather broad low-temperature region is necessary.

* Extrapolated upward according to $T(\tau_1) = 4820 + 215/\sqrt{\tau_1}$ above $\tau_1 = 10^{-3}$, where $\tau_1$ is the optical depth at 1 mm. Since the millimeter data alone determined the model in this height range, the agreement between the model and the data is good.
Fig. 7. Data from Table I on solar brightness temperature $T_B$ in the sub-millimeter and millimeter regions, plotted against wavelength $\lambda$. The solid line is the predicted brightness temperature from the Bilderberg model (GINGERICH and DE JAGER, 1968).

### TABLE I

<table>
<thead>
<tr>
<th>$\lambda_{\text{mm}}$</th>
<th>$T_B$</th>
<th>$\Delta T_B$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0086</td>
<td>5160</td>
<td>40</td>
<td>SAIEDY, 1960</td>
</tr>
<tr>
<td>0.0111</td>
<td>5040</td>
<td>30</td>
<td>SAIEDY, 1960</td>
</tr>
<tr>
<td>0.0120</td>
<td>5050</td>
<td>80</td>
<td>SAIEDY, 1960</td>
</tr>
<tr>
<td>1.0</td>
<td>5900</td>
<td>500</td>
<td>LOW and DAVIDSON, 1965</td>
</tr>
<tr>
<td>1.3</td>
<td>5800</td>
<td>500</td>
<td>BASTIN et al., 1964</td>
</tr>
<tr>
<td>2.0</td>
<td>5670</td>
<td>230</td>
<td>WORT, 1962</td>
</tr>
<tr>
<td>2.15</td>
<td>5430</td>
<td>500</td>
<td>TOLBERT and STRAITON, 1961</td>
</tr>
<tr>
<td>2.5</td>
<td>6700</td>
<td>500</td>
<td>BASTIN et al., 1964</td>
</tr>
<tr>
<td>2.73</td>
<td>5500</td>
<td>700</td>
<td>TOLBERT and STRAITON, 1961</td>
</tr>
<tr>
<td>3.0</td>
<td>5870</td>
<td>950</td>
<td>TOLBERT and STRAITON, 1961</td>
</tr>
<tr>
<td>3.2</td>
<td>6400</td>
<td>200</td>
<td>SIMON, 1965</td>
</tr>
<tr>
<td>3.2</td>
<td>8000</td>
<td>560</td>
<td>TOLBERT, 1966</td>
</tr>
<tr>
<td>4.3</td>
<td>6200</td>
<td>310</td>
<td>TOLBERT, 1966</td>
</tr>
<tr>
<td>4.3</td>
<td>7000</td>
<td>700</td>
<td>COATES, 1958</td>
</tr>
<tr>
<td>8.6</td>
<td>6500</td>
<td>260</td>
<td>TOLBERT, 1966</td>
</tr>
<tr>
<td>8.6</td>
<td>8500</td>
<td>1200</td>
<td>COATES, 1958</td>
</tr>
<tr>
<td>11.8</td>
<td>9800</td>
<td>300</td>
<td>STAELIN, 1968</td>
</tr>
<tr>
<td>12.8</td>
<td>10700</td>
<td>500</td>
<td>STAELIN, 1968</td>
</tr>
<tr>
<td>13.5</td>
<td>11000</td>
<td>500</td>
<td>STAELIN, 1968</td>
</tr>
<tr>
<td>14.3</td>
<td>10800</td>
<td>400</td>
<td>STAELIN, 1968</td>
</tr>
<tr>
<td>15.8</td>
<td>10800</td>
<td>400</td>
<td>STAELIN, 1968</td>
</tr>
</tbody>
</table>
If we accept a homogeneous model of the chromosphere, then, it is clear that a sharp temperature rise must occur above about $\tau_{1, \text{mm}} = 1$, or $\tau_{5000} \sim 10^{-5}$. In view of the known inhomogeneous structure (spicules, etc.) above this level, however, such a conclusion seems unwarranted. For instance, the increased brightness temperature past 1 mm could be caused by the increased optical thickness of the hot chromospheric structures, while the mean atmosphere, i.e., the interspicular regions, remain rather cool.

Acknowledgements

We are grateful to Mr. Arnold W. Davidson for construction of the 22.5-µ bolometer, and for the major effort in securing the 1.2-mm solar drift curves. We thank Mr. James M. Percy for outstanding assistance in the eclipse expedition. The DuPont Company of Wilmington, Delaware generously supplied the special polyethylene prefilters for the infrared work.

References