Observation of the 1997–03–09 total eclipse at 8.6 mm† *

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Abstract: Analysis of the total eclipse observation of 1997 March 9 at wavelength 8.6 mm, shows that, at this wavelength, the solar radius is 1.012 \( R_\odot \), the total flux density is 2540 sfu, the mean brightness temperature of the solar disk is 9632 K, and the brightness temperature distribution shows limb brightening at the inner edge of the solar disk, the average brightness at 0.936–0.992 \( R_\odot \) being 9.7% above the central brightness.

Key words: total eclipse—mm wavelength—brightness temperature distribution

1. INTRODUCTION

Solar eclipse is a rare phenomenon, it provides opportunity for medium- and small-size solar radio equipment to make high resolution observation, with resolutions as high as a few or a few tens of arcsecond\(^1\). With this opportunity and by means of some model we can determine the radial profile of the solar brightness temperature, thereby providing important observational basis for constructing models of the atmosphere of the quiet sun. Also, we can measure the scale (one- or two-dimensional) of active regions, and this is important for the theoretical study of the solar radio quiet and burst components. Flux spectrum of active regions provided by multi-wave observations can be used when searching for evidence of current sheets on the sun’s surface and so providing observational basis for the current sheet model of solar flares.

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The brightness temperature radial profile is different at different wavelengths. For the optical and radio cm ranges we have clear conclusions: limb darkening in the optical, and limb brightening in the radio cm waves. As for the mm waves in between the two, it has been a debatable point. According to available data, results from high resolution equipment tend to zero limb brightening, while eclipse observations tend to finite limb brightening\cite{2}. In order to settle this question we carried out observations at 8.6 mm of both the 1980 total eclipse at Ruili, Yunnan Province and the 1987 annular eclipse in Nanjing region, and we found limb brightening in both cases\cite{3,4}.

2. OBSERVATIONS IN BRIEF

2.1 Eclipse Conditions

The 1997-03-09 total eclipse occurring in the Mohe Region in our northern frontier province of Heilongjiang is the last eclipse of this century visible in China. As early as September 1996 we sent experts to the region to select and construct site, paying due regard not only to good observing condition but also to logistics and service, particularly electricity supply. The site selected (at Sanzhong, Mohe) proved to be good, contributing to the successful observation. Its geographic coordinates are Longitude -122°32' 33", Latitude +52°58' 26", Height 425 m. The circumstances of the optical eclipse are: First Contact 00:02:38.9 UT, Eclipse Maximum 01:07:46.3-0.1::10:12.4 UT, Last Contact 02:19:21.5 UT, Altitude at Maximum 22°02', Maximum eclipse Factor 1.01. The conditions were better than on the previous occasions in China\cite{5}. Table 1 compares the circumstances of the three eclipses in China.

<table>
<thead>
<tr>
<th>Data</th>
<th>Site</th>
<th>Start</th>
<th>Maximum</th>
<th>Factor</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980-02-16</td>
<td>Ruili</td>
<td>09:27:12</td>
<td>10:32:26</td>
<td>1.03</td>
<td>10°49' 47‖</td>
</tr>
<tr>
<td>1987-09-23</td>
<td>Nanjing</td>
<td>00:33:36</td>
<td>02:01:17</td>
<td>0.943</td>
<td>48°02'</td>
</tr>
<tr>
<td>1997-03-09</td>
<td>Mohe</td>
<td>00:02:38.9</td>
<td>01:07:46.3</td>
<td>1.01</td>
<td>22°02'</td>
</tr>
</tbody>
</table>

2.2 Equipment

Our 8.6 mm radio equipment consists of antenna-feed, microwave, receiving and recording, and tracking systems. The antenna is a parabolic dish, aperture 40 cm, main lobe width 90'. To ensure the telescope pointing exactly at the centre of the sun for more than 2 hours during the eclipse, we used a high precision step motor drive. Our receiver is a K factor receiver. The main instrumental parameters are: a Dicke Type receiver, observing frequency 34884 MHz, bandwidth 43 MHz, time constant 1 s, sensitivity 0.3 K, nonlinearity ≤ 0.5%, gain fluctuation 0.3% per hour. With this high-stability, high-sensitivity equipment we obtained a complete, almost ideal eclipse curve. See Fig.1. Recording was made in two ways: analog and digital.
3. ANALYSIS AND TREATMENT OF DATA

3.1 Data Treatment

During an eclipse the signal received by the radiometer consists of three portions, the emissions from the sun, moon and the background. Hence, at any instant $t$, the flux received can be expressed as

$$S(t) = \frac{8\pi k}{\lambda^2 KG}(T_\odot(t) + T_M(t) + T_\varphi(t))e^{\frac{T_\odot}{\eta} \sec Z} \cdot M,$$

where $k$ is the Boltzmann constant, $K$ is the correction factor of the directivity pattern, $G$ is the antenna gain, $\Gamma_\odot$ is the atmospheric absorption in the direction of the sun, $Z$ is the zenith distance, $M$ is the correction factor for the sun-earth distance, and $T_\odot(t), T_M(t), T_\varphi(t)$ are the effective antenna temperatures of the sun, moon and the background, respectively.

As we use the technique of aperture calibration, the antenna efficiency $\eta$ is automatically removed by the calibration[6], and the last three quantities are the temperature for the corresponding emissions. To find the radial profile of solar brightness temperature we must isolate the solar signal from all three, then normalize the isolated signal by the total solar radiation before the eclipse, to get the normalized solar antenna temperature at any time $t$, $T_\odot'(t)$. At $t$, the solar antenna temperature is

$$T_\odot(t) = L(t)(R_\odot(t) - R_T(t)) - T_M(t) - T_\varphi(t) + T(t),$$

where $R_\odot(t)$ and $R_T(t)$ are the record readings (in mm), at $t$, of the eclipse curve and the ambient temperature, $L(t)$ is the calibration factor (K/mm) and $T(t)$ is the ambient temperature. The background temperature at $t$ was obtained by interpolation of two series of measurements made before and after the eclipse, and $T_M(t)$ was also obtained from

Fig. 1 Normalized eclipse curve at 8.6 mm wavelength
measurement. We also measured the atmospheric absorption before and after the eclipse, and the absorption factor at Zenith $T_0$ was 0.0402. The total flux at 8.6 mm we found is 2540 sfu, corresponding to a brightness temperature of 9632 K, in agreement with the result of Ref. [3].

3.2 Calculation of the Radial brightness Temperature Profile

Hagen et al. [7] making use of eclipse observations, gave a method of calculating the radial profile of brightness temperature for mm and short cm waves. They used a circularly symmetric model, divided the solar disk into a series of rings and assumed within each ring the brightness temperature is uniform. The brightness temperature at radial distance $r-1/2$ was then calculated according to the formula,

$$T_{r-1/2} = [S_{r-1/2} - C \sum_{n=r}^{R_1} (A'_{r-1/2,n+1} - A'_{r-1/2,n})T_{n+1/2}g_{n+1/2}] \times 1/(CA'_{r-1/2,n}g_{r-1/2}), \quad (3)$$

where $S_{r-1/2}$ is the flux variation as a function of the sun-moon distance when the limb of the moon is at $r-1/2$, in $A'$, the first suffix is the position of the limb of the moon, the second suffix is the radial distance of the ring, $g_{r-1/2}$ is the correction factor of directivity pattern at radial distance $r-1/2$, $C$ is the brightness temperature-flux conversion factor, $R_1$ is outer radius of the outermost ring (from the eclipse curve, we measured $R_1 = 1.012 R_\odot$).

From the normalized eclipse curve, we used a 7-point filter [3] and obtained the gradient curve shown in Fig. 2 (the dotted curve corresponds to quiet solar background). Then, by suitably dividing the solar disk into a series of rings and using (3) we obtained the radial temperature profile and normalized it with the average brightness at the centre.

![Normalized gradient curve](image)

Fig. 2 Normalized gradient curve.

When calculating the radial profile we must remove contributions by the slowly varying components from active regions. As Fig. 2 shows, the eclipse gradient curve is quite noisy with fluctuating structures. By comparing individual structures with the times of immersion and emersion of active regions, useful information on the active regions may be extracted.
Strictly speaking, it is only when a structure is 5 times above the noise level, that is, only when 
\[ |T_a - \dot{T}_a\theta| \geq 5|\dot{T}_a - \dot{T}_a\theta| \], (second suffixes \( s \) and \( \theta \) respectively referring to source and quiet sun) that the detection of signal can be said to be on a high confidence level. Otherwise misidentification and confusion may result. Of course, the main criterion here is still correspondence between a given structure and the eclipse phase. Let us first estimate the detectability of source from the viewpoint of brightness temperature. For the whole disk and from the known sensitivity of our instruments, the smallest detectable brightness temperature is \( \sim 9 \) K. The average fluctuation in Fig. 2 is \( \sim 3 \times 10^{-5} \) K/s, and with an average half-power width of the structures of \( \sim 30 \) s, smallest detectable brightness temperature is

\[
T_{b\min} = S_{\min} \frac{\lambda^2}{2k\Omega} \sim 2.3 \times 10^5 \text{ K},
\]

where the smallest detectable flux is

\[
S_{\min} = \frac{8\pi k}{D_0 K_0 \lambda^2} \int |\dot{T}_a - \dot{T}_a\theta|\,dt = \frac{8\pi k}{D_0 K_0 \lambda^2} \int \dot{T}_a - \dot{T}_a\theta \, dt
\]

where \( \lambda \) is the observing wavelength, \( T_{a0} \) is the antenna temperature before the eclipse, \( \Omega \) is the solid angle corresponding to the half-power width, \( D_0 \) is the antenna gain, \( K_0 \) is the directivity pattern correction factor, and \( K_i \) is the correction factor in the direction of structure \( i \). As Fig. 3 shows, during the eclipse there were only two small sunspots, NOAA serial numbers 8020 and 8021 on the disk. No. 8021 was too small to be instrumentally resolved. So we estimate only for No. 8020. From the optical data, its angular size is \( \sim 21'' \), hence we estimate \( T_{b0} \sim 1.1 \times 10^5 \), which is less than \( T_{b\min} \), so detection is not possible. More importantly, at the instants when the limb of the moon began to cover the two sources (Fig. 3), there was nothing unusual in the gradient curve of Fig. 2. Hence we can neglect any possible contribution from these two sunspots.

![Fig. 3 Moving path of the moon’s center](image)

Let us now consider the detectability of limb brightening. Here, we have to address two issues, the one-dimensional spatial resolution of our observation \( \Delta l \) and the amplitude
of brightening, $\Delta T_b/T_{b0}$. The step length taken in the data treatment was 15 s. Now, $\Delta l \propto f(V_D, \delta T_{\text{min}}, T_a)$, $V_D$ being the average velocity of the centre of the moon relative to the centre of the sun, $\delta T_{\text{min}}$, the telescope sensitivity. We found $\Delta l \sim 5''$, and this is less than the estimated size of the region of brightening of $\sim 28''$, estimated from the half-power width. Therefore, the region of brightening was resolvable. As to the amplitude of brightening, we need only consider the fluctuations in the brightness temperature at the centre of the solar disk. From calculation we know this fluctuation relative to the average brightness temperature to be $\sigma T_b \sim 1\%$. But our calculated limb brightening had an amplitude of $\sim 10\%$, or more than 5 times $\sigma T_b$. Hence, in regard to both spatial resolution and amplitude, our result of the limb brightening should be regarded as reliable.

Our result of the radial profile of brightness temperature, calculated for a division of the solar disk into 21 rings is shown in Fig. 4 (Fig. 4a is based on the first contact data, Fig. 4b is the average result for the first and third contact). The profile in numerical form is given in Table 2.

![Fig. 4](image)

**Fig. 4** The radial brightness temperature distribution at 8.6 mm (a) based on the first contact data and (b) mean result from the first and third contact observations

**Table 2** The Calculated Radial Profile of Brightness Temperature

<table>
<thead>
<tr>
<th>$r_i/(R_\odot)$</th>
<th>1.006</th>
<th>1.000</th>
<th>0.992</th>
<th>0.984</th>
<th>0.976</th>
<th>0.968</th>
<th>0.960</th>
<th>0.952</th>
<th>0.944</th>
<th>0.936</th>
<th>0.917</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{bi}/T_{b0}$</td>
<td>0.7115</td>
<td>0.9531</td>
<td>1.0967</td>
<td>1.1883</td>
<td>1.0782</td>
<td>1.0946</td>
<td>1.0925</td>
<td>1.0859</td>
<td>1.0367</td>
<td>1.0312</td>
<td>1.0587</td>
</tr>
<tr>
<td>$r_i/(R_\odot)$</td>
<td>0.887</td>
<td>0.857</td>
<td>0.827</td>
<td>0.797</td>
<td>0.752</td>
<td>0.692</td>
<td>0.632</td>
<td>0.572</td>
<td>0.512</td>
<td>0.241</td>
<td></td>
</tr>
<tr>
<td>$T_{bi}/T_{b0}$</td>
<td>0.9881</td>
<td>1.0041</td>
<td>0.9868</td>
<td>0.9876</td>
<td>0.9866</td>
<td>0.9920</td>
<td>0.9831</td>
<td>0.9971</td>
<td>1.0041</td>
<td>1.0157</td>
<td></td>
</tr>
</tbody>
</table>

The figure and table show that limb brightening is clearly present. The region of brightening is between $0.936-0.992 R_\odot$, and the amplitude of brightening is about 9.7% of the central brightness;— a value intermediate between the results of Ref. [3] and Ref. [4].

**4. DISCUSSION**

1) The results from the 8.6 mm data at the two total eclipses (1980 and 1997) and one annular eclipse (1987) are collected in Table 3. The limb brightening is given in the
last column. Although there are numerical differences in the three eclipses, there is definite evidence for a finite limb brightening.

<table>
<thead>
<tr>
<th>Year</th>
<th>$R_0(R_\odot)$</th>
<th>$S$ (sfu)</th>
<th>$T_b$ (K)</th>
<th>$\Delta T_b/T_{b0}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980-02-16</td>
<td>1.014</td>
<td>2568</td>
<td>9727</td>
<td>18</td>
</tr>
<tr>
<td>1987-09-23</td>
<td>1.014</td>
<td>2346</td>
<td>9032</td>
<td>5.1</td>
</tr>
<tr>
<td>1997-03-09</td>
<td>1.012</td>
<td>2540</td>
<td>9632</td>
<td>9.7</td>
</tr>
</tbody>
</table>

2) The different amplitudes of limb brightening on the three occasions seem to be related the total solar flux (or $T_b$), resulting from different activity levels in the solar cycle.

3) Formula (3) shows that the calculated value of the brightness temperature of a given ring is affected by the value calculated for the previous ring: if the result of the previous ring is too large, then the result for the current ring tends to be too small, and vice versa. This behaviour is entirely caused by the direction of the smoothed gradient curve, accuracy of the datapoints and the method itself. Especially at the four contact epochs, a small sampling error will cause jumps in the calculated brightness temperature. The spikes or sawtooth structures in the brightening at the limb may all be due to measuring errors. Hence in such cases we must use smoothed values and discard wildly discrepant values.

4) As pointed out by Belkora et al. when discussing the brightness profile at 3 mm, observations using the same instruments but made during and outside eclipses give different results and this is due to different resolutions and observing paths. Here, in this paper, we found the region of brightening at 8.6 mm to have a size of $\sim 28''$. Now, the highest spatial resolution of the best equipment for observing brightness distribution is $\sim 27''$, so it is incapable to detect the limb brightening. It is only during an eclipse, when the spatial resolution is as high as $5''$ that evidence for the limb brightening can be obtained.

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