AIRBORNE TOTAL ECLIPSE OBSERVATION
OF THE EXTREME SOLAR LMB AT 400 μm

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Abstract. The total solar eclipse of February 26, 1979 was monitored at far infrared wavelengths from the NASA Lear Jet Observatory flying at 12.9 km in the eclipse shadow. The resultant eclipse curve for radiation within a bandwidth of 20 cm⁻¹ centered upon 25 cm⁻¹ (400 μm) was measured and analysed at an equivalent angular resolution of 1 arc sec over a 100 arc sec region adjacent to the limb to provide information on the intensity distribution of continuum radiation close to this limb. The curve has been compared to predictions derived from models of the solar atmosphere for the specific geometry of this eclipse, and is shown to match most closely that derived from a uniform distribution of radiation across the disk. This is in distinct contrast to the result obtained in the only other comparable experiment, carried out over Africa in 1973 from a supersonic Concorde aircraft, in which an intense but narrow ‘spike’ of far infrared radiation at the extreme solar limb was inferred from the data. The absence also in the present observations of the significant limb brightening predicted by the HSRA model (in which homogeneity within the source region is assumed) is in substantial agreement with lower resolution results from mountain altitudes. This result is interpreted as further evidence for the presence in the Sun’s lower chromosphere of significant inhomogeneity with a scale size of at least 1000 km at this depth.

1. Introduction

A knowledge of the thermal and physical structure of the low chromosphere of the Sun is important in the evaluation of mechanisms of non-radiative energy transfer through this region and in the verification of theoretical models of the solar atmosphere. One technique which in the past has yielded important results pertaining to solar atmospheric structure is that of high angular resolution scanning of the solar disk from center to limb, in which the geometry of source path produces an equivalent depth scan within the solar atmosphere. At far infrared wavelengths, where such scans might be expected to yield important information about the crucial zone of the solar atmosphere from which they originate, namely the high photosphere and low chromosphere, two restrictions limit the effectiveness of the technique. Diffraction at these long wavelengths prevents a detailed examination of the extreme solar limb, even from the largest telescopes, and deconvolution techniques are difficult to apply to this type of scan. Furthermore, water vapor renders the Earth’s lower atmosphere almost totally opaque to far infrared radiation, and even in the limited windows which become available at high mountain altitudes, atmospheric emissions contribute thermal fluctuations which amount to restrictive noise on the solar disk scans.

These severe limitations have been simultaneously overcome in the present experiment by utilizing an airborne observation of a total solar eclipse. A simple multi-channel photometer was carried to an altitude of 12.9 km by the NASA Lear
Jet Observatory into the eclipse shadow on February 26, 1979, thereby placing the experiment above most of the absorbing water vapor of the atmosphere. In this way, the Moon was used as an essentially diffraction-free 'shutter' to provide in one dimension an equivalent high-resolution scan of the extreme solar limb region around totality. The only previous experiment of this kind, by Beckman et al. (1975) used the Concorde supersonic aircraft to extend the period of totality of the 1973 African eclipse, and thereby obtained a detailed but somewhat limited scan of the extreme solar limb. Interpretation of the data (Beckman and Ross, 1976) indicated that an intense but narrow 'spike' of limb brightening existed from 5 arc sec inside to 4 arc sec beyond the visible limb. These authors suggested that this enhanced emission, amounting to a surface brightness a factor of 2.16 above that at the solar disk center at 400, 800, and 1200 μm, was caused by the combined effect of the spicule field projected along the tangential line of sight at heights of several thousand kilometers. Evidence that these tenuous structures existed below about 3000 km had not previously been seen either on direct photographs or during eclipses. The geometry of the 1973 eclipse and the speed of the Concorde enabled the aircraft to remain within the shadow of the Moon for 70 min, but flight time limitation restricted the observations before second and after third contacts to only 19 arc sec on the solar disk.

The present experiment was an attempt to verify the existence or otherwise of this limb spike. The much slower Lear Jet aircraft could not be utilized to extend significantly the period of eclipse totality but allowed considerably more of the Sun's disk leading to the extreme limb at second contact (100 arc sec) to be observed, while providing much lower equivalent angular resolution than that available at supersonic speeds. The chosen flight path of the aircraft allowed observation of the Sun and Moon following fourth contact to provide adequate normalization to total solar intensity.

The limb scan technique for investigating solar parameters was thought earlier to be equivalent, at least in this spectral region, to the measurement of brightness temperature over a range of wavelengths, in which source depth for this predominantly continuum radiation can be related directly to wavelength. Over the past decade it has become apparent that some mechanism, probably inhomogeneity within the source region, effectively hides the expected effect of temperature gradient upon center-to-limb distribution. The need for caution in interpreting limb scans was pointed out as early as 1969 by Simon and Zirin (1969), and recent work has shown that the discrepancy becomes apparent even at the relatively low angular resolutions available at ground-based infrared telescopes. Recent submillimeter (Righini and Simon, 1976; Lindsey and Hudson, 1976; Lindsey, 1980) and millimeter observations (Shimabukuro, 1971; Lantos and Kundu, 1972; Ade et al., 1974; Kundu and Liu, 1975; Labrum et al., 1978) have found less limb brightening than predicted by recent solar atmospheric models and have shown no evidence of the limb spike. Thus, it seemed necessary to explore this situation to the highest possible angular resolution, albeit with less than perfect geometry, and attempt to
observe a total solar eclipse from above most of the atmospheric water vapor, with a view to evaluating further the level of inhomogeneity within the low solar chromosphere.

2. Experimental Design

The relatively small Lear Jet aircraft imposed severe size and weight limitations upon the instrumentation, and the final configuration chosen for this experiment was a four-channel filter photometer. The system was designed to provide adequate signal-to-noise ratio within a time constant chosen to match the required spatial resolution on the solar disk during the passage of the eclipse. Spatial chopping and phase-sensitive detection removed from the signals the effects of thermal emissions from the aircraft and the remnant atmosphere above the aircraft. Provision of adjustable chopping speed and the narrowband electronics were also useful in reducing the effect upon the signals of the severe vibrational environment within the aircraft. A primary consideration in the overall design was the need to minimize fluctuations in measured intensity caused by aircraft motions, accounting particularly for the diffraction effect at the relatively small entrance apertures available in the optics. Thus the design criterion was that the photometer field of view should include the diffraction-degraded images of both Sun and Moon at all stages of the eclipse. In practice, this criterion was not fully met, but was sufficiently close to satisfy the demands of the experiment in reducing signal fluctuations caused by aircraft motion to acceptable levels.

3. Optical Design

The schematic diagram of one of the two identical telescopes is shown in Figure 1. Radiation entered the aircraft through a specially constructed 25 mm thick low-density polyethylene window mounted in the emergency exit door of the aircraft. A gyroscopically controlled mirror on the heliostat provided by the Airborne Sciences Office of NASA Ames Research Center guided this radiation onto the plane mirror M1 which was adjustable in height to compensate for changes in solar elevation angle during the eclipse. The reflective aluminum chopper C with adjacent blades machined with an angle of 0.84° between them, reflected alternately the Sun’s radiation and that of an adjacent portion of sky into the telescopes. This alternating technique and the attendant phase-sensitive detection removed the effect of radiation from the sky and the window from the measured signal.

Each f/8 Newtonian telescope (M2 and M3) was designed to image the Sun and the adjacent sky within 64 arc min onto an aperture directly in front of an f/1 field lens, L1, which in turn focussed the primary mirror onto the relevant detector (D1) (Infra Red Laboratories Inc.). A Mylar beamsplitter provided the adjacent beam into the second detector, D2, via the field lens L2. Filters F1, F2, and F3 restricted the different channels to the required bandpasses. The system was designed to
provide about ±5 arc min of tolerance in steering precision before producing a change of 1% in signal level from an uneclipsed Sun. The primary mirror aperture diameter which satisfied this criterion within the system was thus 55 mm.

Choice of infrared filters in each beam was determined by matching the predicted energy flux from the Sun at the relevant times close to second and third contacts to the desired signal-to-noise ratio while maintaining adequate time resolution. The final bandwidths for each channel were determined by the combined transmissions of the 25 mm low density polyethylene aircraft window, a 25 μm black polyethylene filter (F1), the reflection or transmission properties of the 25 μm Mylar beamsplitter, the 2.5 mm TPX Dewar window, the quartz field lenses with diamond scatter filter, an additional 150 μm black polyethylene filter, and low-pass metal mesh filters (Cambridge Physical Sciences Ltd.) in three of the channels with cut-off wavenumbers of 110, 67, and 33 cm⁻¹, respectively. The effective central wavenumber in Channel 1, the analysis of data from which will be described later in this paper, was 25 cm⁻¹ with a FWHM of 20 cm⁻¹.

The final choice of parameters in the system was thus made such that the signal-to-noise ratio would reach unity at a time when the angular separation between lunar and solar limbs was less than 1 arc sec for a time constant of 1 s, the angular motion of the Moon across the Sun being about 0.3 arc sec in the same time interval. The experimental values proved to be close to these criteria in practice.

The gyro-controlled heliostat was equipped with manual control for initial acquisition and for subsequent control of slow image drifts. An auxiliary visible light optical system aligned with the infrared beam was used to monitor the progress of the eclipse via two further photometers at visible and near IR wavelengths and to
produce a projected solar image on a screen for use in visual monitoring of the heliostat steering. A small optical window adjacent to the main polyethylene aircraft window provided this auxiliary light.

4. Electronics and Data Recording

The spatial chopping system produced alternating signals at each detector, the precise frequency of which was chosen during test flights to minimize interference from aircraft vibration. In practice, this frequency was fixed at 43 Hz and detector signals at this frequency, after preamplification and amplification by switchable gain amplifiers, were passed to phase-sensitive detectors along with reference signals provided by photo-interrupters on the chopper system. Each DC signal from phase-sensitive detection was subsequently offset by a switchable amount and amplified before being multiplexed and converted to digital format by a 32 word, 8 bit PCM system at a frame rate of 16 Hz. The resulting serial bit stream was recorded on an analog tape recorder along with precise time information from a time code generator. A second small instrumentation tape recorder was used as a back-up duplicate recorder, upon which voice comments and time information were also collected.

5. Flight Path

The limited flight time of the Lear Jet 24 aircraft was such that the whole of the eclipse from first to fourth contact could not be covered in a single flight. It was therefore necessary to design the flight path to cover both the period bracketing totality and a period beyond fourth contact in order to normalize the observed eclipse curve during the totality section. Furthermore, the small window available in the aircraft, and the movement of the aircraft during the eclipse required that a curved path be flown to ensure that the incoming beam was not vignetted by the window in the azimuthal direction. The mirror M1 was adjustable in height to avoid the same vignetting as the Sun’s elevation angle changed during the eclipse.

The first section, spanning 30 min centered on totality was flown at a small angle to the eclipse shadow line and covered the observation of second and third contacts. The second section was flown against the direction of motion of the shadow to maximize the apparent speed of the eclipse and hasten the onset at the aircraft of fourth contact. The final section, again flown at a small angle to the shadow track, was used for observation of this contact and subsequently the uneclipsed Sun and the attendant Moon. Since Minot Air Force Base was utilized for aircraft refuelling, the flight pattern was located over the northern U.S.A. and southern Canada and was chosen to avoid interference with ground-based eclipse observations at the main population centers. Figure 2 shows the final flight path for the totality phase with respect to the shadow path center-line at the aircraft altitude of 12.9 km, along with the positions of the lunar shadow at second and third contacts.
6. Flight Performance

Test flights over California and a full test flight to Minot A.F.B. from NASA Ames Research Center served to optimize the operational aspects of the flight, such as liquid helium filling and pumping in the detector assembly, and aircraft refuelling. Only one of the four infrared channels produced satisfactory data during the crucial phases of the eclipse. An unfortunate misalignment occurred following the final test flight which went undetected until the aircraft turned onto its final eclipse track, while a fourth detector developed an extreme sensitivity to aircraft vibration on the eclipse flight. Aircraft motions and steering problems plagued the early part of the eclipse run but became tolerable during the period from 300 s before second contact until 120 s into totality, covering a separation span between lunar and solar centers of about 100 arc sec. Heliostat drift during the remainder of totality made reacquisition of the initial thin crescent at third contact difficult and the vital section of data was thus lost at this contact. The data beyond fourth contact for this channel proved excellent and were used in subsequent normalization. The visible light and near IR monitors provided a good record of the eclipse and, along with the voice record on the auxiliary tape recorder, provided confirmation of the precise time of second contact.
7. Data Analysis

The section of the data outlined above required averaging to reduce the remaining noise, and several short sections of the data were removed because poor heliostat steering as judged by examination of the signal from the optical channel had produced unacceptable departures from the eclipse curve. This averaging was performed over 1, 2, 5, and 10 s to determine the best compromise between noise and spatial resolution. The 1 s averaged data are shown in Figure 3, along with predicted curves for the particular geometry of this eclipse for three intensity distributions across the solar disk: a uniform (‘flat’) Sun; the limb brightening predicted at this wavelength by the homogeneous HSRA model; and a model incorporating a ‘spike’ of brightness extending from 4 arc sec outside to 5 arc sec inside the optical limb, similar to that observed by Beckman and Ross (1976) in.
the 1973 eclipse. The inset shows the visible eclipse curve for the same time span with the periods of poor steering indicated on this graph.

The infrared eclipse curve was normalized to the intensity of the uneclipsed Sun taken beyond fourth contact, after correction for loss of part of the lunar radiation which was calculated to be out of the field of view, and which amounted to approximately 1% of the solar signal, with an uncertainty small compared to the noise on the data. A 'zero-level' intensity consisting of contributions from the Moon, thermal gradients in the window, and all sources other than the Sun was reached after second contact and was subtracted from the remainder of the data before normalization.

8. Results and Discussion

Figure 4 shows the data averaged over 10 s intervals, with the sections removed for which the steering was poor. The error bars represent standard deviations.
obtained from the averaging process and are larger than expected from detector noise alone. The origin of the component of noise which is signal dependent is unknown, but could be related either to high frequency atmospheric transmission fluctuations or to vignetting of the beam during small steering changes, although the latter explanation is thought unlikely.

Comparison of the data with the predicted eclipse curves from the three intensity distributions already discussed shows that the intensity distribution across the solar limb during this eclipse was closer to that of a uniform Sun than that of either the homogeneous HSRA model or to a model with a sharp increase in intensity at the limb. A statistical $\chi^2$ test on the data yields values for the probability of obtaining the present data from models of solar intensity distribution shown in the figure. These values are $>0.99$ for a ‘flat’ Sun, 0.18 for the HSRA model, $<0.001$ for a limb spike model and 0.71 for a model with limb brightening amounting to one-third of the amount predicted by the HSRA model at all positions on the disk. It can thus be stated with some certainty that no limb spike was present during this eclipse and that the amount of limb brightening was considerably less than that predicted by HSRA or equivalent models of the solar atmosphere.

The statistical test is slightly misleading in that it provides a measure of agreement over the entire curve, while visual examination suggests that the data could be represented more closely by different curves over different sections of the eclipse. In particular, the early data are consistently higher than the predicted curve for a uniform disk, while later data appear closer to if not slightly below this predicted curve. Interpretation of individual features is not straightforward, since the curve is derived from the integral of the intensity distribution, but the observed data would represent changes in intensity distribution within 40 arc sec of the limb. With the observed noise level, however, detailed interpretation of the slope changes cannot be justified.

Active regions would be expected to produce changes in the shape of the submillimeter eclipse curve, since calcium plage regions can have temperatures approximately 200 K or 4% above that of their surroundings at these wavelengths (Beckman and Clark, 1971). The Sun was relatively active at the time of the eclipse, with several major sunspot groups and plage regions. However, only the latter are of interest because all major sunspot regions were already covered at the beginning of the data run. The increase in integrated intensity expected from a plage region depends on the area of any given arc covered by the plage, and also on the distribution of such regions over the solar surface, since the technique is essentially differential in nature. Since the plage regions were reasonably uniformly distributed over the Sun at the time of the eclipse (see Figure 5), the fractional area of the remaining crescent of the Sun covered by plage regions was essentially constant through the eclipse. The maximum increase in slope of the eclipse curve attributable to a plage region is estimated to be less than 0.5%, and hence active regions would not have had a significant effect on the eclipse curve.
9. Conclusions

The intensity distribution which best represents the present data is essentially uniform, with the possibility of very slight limb brightening of magnitude certainly less than half of that predicted by the HSRA model, over the region 100 arc sec from the limb. Other workers who earlier measured small or no limb brightening interpreted this as indicating a flat temperature minimum region within the chromosphere of the Sun. However, the shape of this temperature minimum is now sufficiently well determined from brightness temperature measurements at disk center that such a conclusion would entail an inconsistency between center-to-limb variations and disk center measurements. The alternative proposed explanation has been the suppression of limb brightening by the effect of inhomogeneities whose
scale height increases with height above the photosphere (a feature which is necessary in order to retain the observed degree of limb darkening at visible wavelengths). If these inhomogeneities were to be related to the observed spicules at higher chromospheric levels, evidence for this should appear in the form of a bright spike extending outside the solar limb, as seen by Beckman and Ross (1976). There is no evidence in the present data for the existence of such a spike. Of special importance to the detectability of such a spike is its extension beyond the limb, since it contains a significant amount of energy due to the large arc length, and, to a high level of confidence, any extension of total energy greater than 0.5% of that of the full Sun can be ruled out in the present case.

Inhomogeneities existing in the chromosphere are expected to have observable effects apart from possible contribution at the limb from spicules, the most noticeable of these being the suppression of the predicted limb brightening of homogeneous models. Lindsey and Hudson (1976) have calculated the expected center-to-limb curves from various shapes of irregularities assuming that an intrinsic angular dependence of radiation intensity exists in the inhomogeneity. Their curves, derived for an angular dependence of the form \( \ln(\sec(\Psi)) \), where \( \Psi \) is the angle from normal to the surface, show a suppression of brightening over most of the disk in general, with a minimum followed by a bright spike at the limb.

Spicula models have been shown not to be useful for the explanation of a lack of significant limb brightening at millimeter wavelengths, since such models inevitably predict higher limb brightening than the homogeneous models. However, Beckman et al. (1973), by ray tracing through a model chromosphere, have shown that this absence can be explained by a vertically disturbed model, in which surfaces of constant electron temperature and number density are randomly displaced, representing rising and falling gas. These authors suggest the possibility of determining the scale of chromospheric roughness from measurements of the amount of residual brightening at various wavelengths. The absence in this perturbed model of effects due to spicules can be explained either by their merging into the remainder of the chromosphere at heights below 2000 km, or by the presence of optically thicker, cooler material shielding the spicules from observation. Whether spicules are observable directly at submillimeter wavelengths has not yet been determined conclusively, but the foregoing discussion indicates that they should not be expected to appear solely at the limb, but rather to produce apparent brightening extending over a large part of the solar disk and increasing toward the limb. The present data suggest that spicules are not observable either at the limb or as a contribution to limb brightening, to within the accuracy of the measurement, although the known non-uniform distribution of spicules and their association with supergranular boundaries might mean that the density of spicules at the limb for the specific geometry of second contact during this eclipse was statistically much lower than the equivalent situation over Africa in 1973. This explanation for the apparent discrepancy between the two results seems somewhat unlikely, however. The effects of inhomogeneities can clearly be seen in the suppression of the expected limb
brightening, and a scale size for these cannot be significantly below 1000 km (Beckman et al., 1973). More precise measurements at other wavelengths might serve to determine the scale size more accurately. It is hoped that analysis of data taken in a repeat of the present experiment during the annular eclipse over the Pacific Ocean in the summer of 1980 will provide more information of relevance to this question. It is obviously of some importance to resolve the discrepancy between the results of the present experiment and those of Beckman et al. with respect to the existence or otherwise of a general spike of far infrared radiation at the solar limb.

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