

PART 2

INFRARED OBSERVATIONS OF THE 1991 TOTAL SOLAR ECLIPSE

ECLIPSE OBSERVATIONS OF THE EXTREME SOLAR LIMB AT SUBMILLIMETER WAVELENGTHS

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Abstract. This paper will review the use of solar eclipses in the study of the extreme solar limb at sub-millimeter and millimeter wavelengths. This approach has been used to overcome the severe limitation imposed by diffraction upon the resolution attainable by direct solar limb scans at these wavelengths. Strong absorption by water vapor in the Earth's lower atmosphere has necessitated the use of telescopes at high altitude sites or in jet aircraft. Data from several of these experiments will be reviewed, including those from the recent James Clerk Maxwell Telescope observation at a wavelength of 1.3 mm of the eclipse of 11 July 1991. In view of the success of recent measurements in improving the spatial resolution with this technique, several of the ultimate limitations placed upon it by lunar surface roughness and by diffraction at the lunar limb are outlined.

These observations have demonstrated the inadequacy of present phenomenological solar atmospheric models at sub-millimetric source heights. Newer models have been developed to fit the observed extension, brightening and detailed structure of the solar limb by attempting to include the structure of the chromospheric network and its spicular field, and their relative success in doing so will be discussed.

Key words: eclipses – infrared: stars – Sun: atmosphere – Sun: chromosphere

1. Introduction

This review covers one specific technique for the study of the solar chromosphere, the detailed examination of the solar limb at millimeter and sub-millimeter wavelengths from mountain altitudes or aircraft during solar eclipses. The reasons for this specific approach can be summarized briefly.

Observations made at the extreme solar limb can provide a direct and precise attribution of height to measured parameters within the solar atmosphere. Disk-center measurements which are utilized in the construction of atmospheric models such as far IR and UV brightness temperatures are averages over relatively broad source functions. Furthermore, attribution of height to such disk-center measurements is model-dependent and most models (*e.g.*, VAL models, Vernazza *et al.*, 1976, 1981) assume gravitational-hydrostatic equilibrium and an unstructured atmosphere, conditions which appear not to hold in the chromosphere. Height above some reference level is measured directly in limb observations, even though the measurements are also averages, this time along a tangential path. In the case of eclipse experiments, this height measurement is provided by careful timing of the occultation.

Sub-millimeter and millimeter radiation is measured since this radiation originates from heights which bracket the important temperature minimum and the 6000 K plateau regions within the chromosphere. This predominantly continuum radiation is almost certainly formed in LTE, the main opacity sources, H^- and H free-free processes, are well understood, and the source functions are directly related to electron temperature. These factors are in distinct contrast to those for the UV radiation which also originates in this region. In this case, the radiation is primarily line emission, and source heights for these lines are more difficult to determine.

These observations must be made from high mountain or aircraft altitudes since moisture in the Earth's lower atmosphere almost totally absorbs radiation from about 20 to 300 μm . Even in windows beyond this, at 350, 450, 850 and 1100 μm , and at high and dry mountain sites, transmission is low, spectrally structured and highly variable. For eclipse observations, this situation leads to the requirement for upper-atmospheric observations where one has careful control over the location of the instrumentation. This effectively rules out balloon-borne or spacecraft experiments but this requirement can be met by jet aircraft and, for longer wavelengths at least, high mountain sites. An added bonus for fast aircraft platforms, whenever the geometry is favorable, is the possibility of extension of eclipse observing time by flying in the direction of motion of the Moon's shadow.

Observations are made in eclipses in order to overcome the severe resolution limit placed upon solar limb-scanning techniques by diffraction even at the world's largest millimeter telescopes. Spatial resolution for these telescopes is still only on the order of supergranular cell dimensions or of the depth of the chromosphere. Thus, direct single-dish limb scans cannot provide high resolution information. Interferometric techniques can increase this scanning resolution significantly, but these methods are difficult, particularly at shorter wavelengths, and resolution still falls short of that attained by eclipse methods. In contrast, even with modest time resolution, observation of a solar eclipse can enhance this resolution to the point where detailed structure can be inferred within the chromospheric layers. This advantage becomes particularly significant where one is forced by atmospheric transmission to consider aircraft observations, for which the telescope diameter restriction is much more severe.

2. Early Observations

Early work in the far IR and sub-millimeter by limb scanning produced mixed results. These experiments showed in general that the Sun showed far less limb brightening than was predicted by the single-stream phenomenological chromospheric models which had been assembled to account for the available data in a self-consistent way (*e.g.*, HSRA; Gingerich, 1971). This discrepancy between model and observation was attributed to "roughness" in the chromosphere on a scale of about 1 scale height (Simon and Zirin, 1969), and was generally related to the spicules within the chromospheric network, since spicules had already been identified and characterized from $\text{H}\alpha$ photographs as existing above the far IR source height regions.

Much of the early millimeter work, both eclipse-related and scanning, notably by Shimabukuro and colleagues at Aerospace Corporation, (Shimabukuro, 1975), Zirin and his group (*e.g.*, Marsh *et al.*, 1981; Horne *et al.*, 1981; Wannier *et al.*, 1983), Kundu and his team at Maryland, (Ahmad and Kundu, 1981), Labrum and colleagues in Australia (Labrum *et al.*, 1978), the Queen Mary College, London group (*e.g.*, Newstead, 1969, Beckman *et al.*, 1973, Ade *et al.*, 1974), and Lindsey and others (Lindsey and Hudson, 1976, Lindsey *et al.*, 1981, 1984), led to discordant results, but some consensus emerged for weak limb brightening which increased with wavelength at sub-millimeter wavelengths.

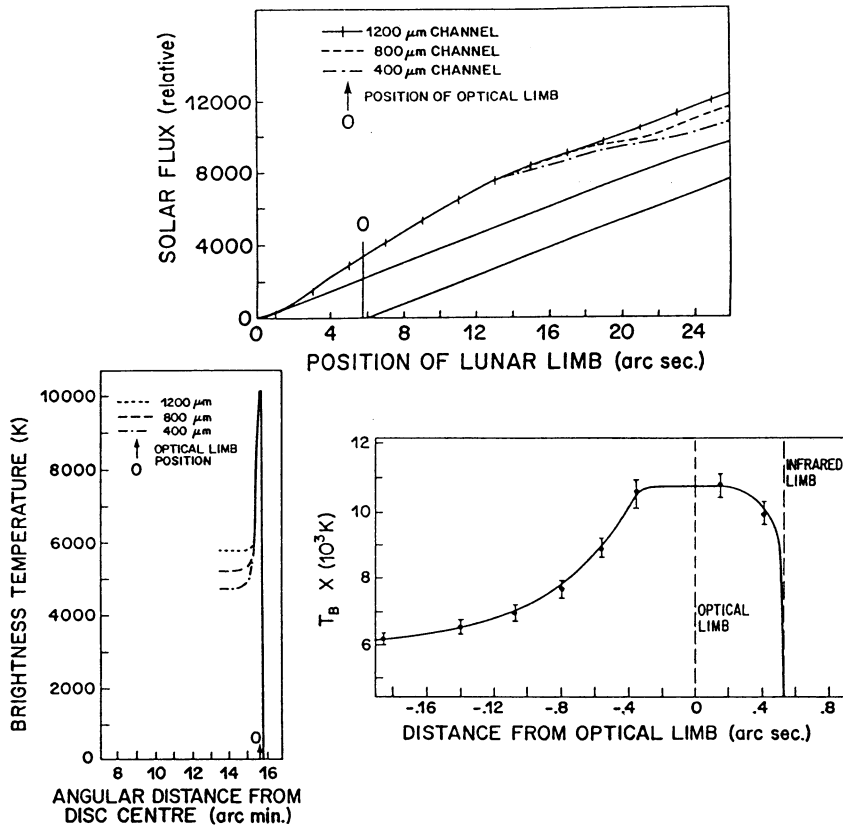


Fig. 1. (a) The eclipse curve for the 3 wavelengths as a function of time at 4th contact during the 30 June 1973 total solar eclipse, as measured from the Concorde aircraft by Beckman *et al.* (1975). (b) Derived limb profiles for the 3 wavelengths, showing the same brightness temperature at each wavelength, (c) Expanded limb brightness profile for 1.2mm. (From Beckman *et al.*, 1975)

Meanwhile, a unique and innovative airborne eclipse experiment at millimeter and sub-millimeter wavelengths produced a somewhat perplexing result. Beckman and his colleagues from Queen Mary College, London, mounted a Michelson interferometer and optics on the prototype supersonic Concorde aircraft in 1973 and, along with several other groups, were able to enjoy the remarkable extension of eclipse totality to 70 minutes over Africa (Beckman, 1973). Their eclipse curve shown in Figure 1, apparently to good signal-to-noise level, was interpreted to indicate that an intense “spike” with peak intensity of more than 2 times that of the solar continuum extended from 4” inside to 6” outside the optical solar limb, with the same brightness temperature at each of the 3 wavelengths.

This somewhat surprising result from an admittedly very difficult experiment, prompted a more modest airborne experiment (Clark and Boreiko, 1982) to confirm

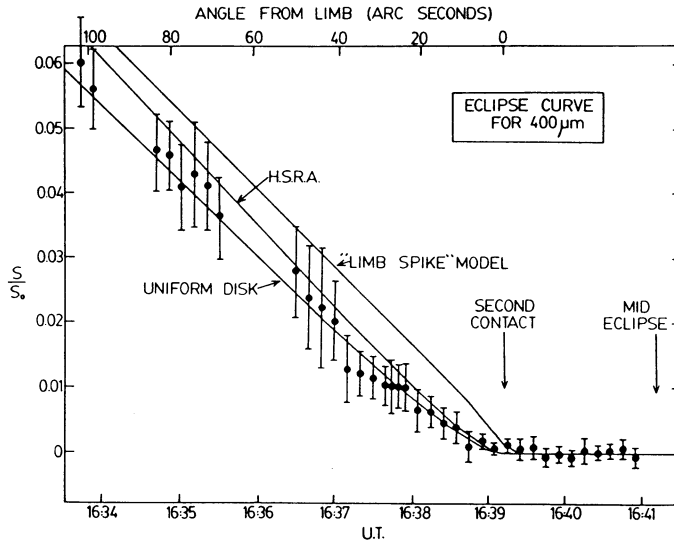


Fig. 2. Eclipse curve from the $400\ \mu\text{m}$ photometer within $100''$ of second contact in the 26 Feb 1979 eclipse, observed from the NASA Lear Jet Observatory. This curve is compared to model curves for a uniform disk (with no limb extension), an HSRA disk and a disk containing a limb "spike" (From Clark and Boreiko, 1982).

or test the result, using the NASA Lear Jet Observatory. A multichannel photometer was used in which individual optics focussed the Sun and adjacent Moon during the eclipse onto several separate detectors, to reduce the effect of steering jitter and beam pattern upon the observed eclipse curve. Though the $400\ \mu\text{m}$ data shown in Figure 2 were somewhat noisy, no evidence was seen of an intense limb spike. This eclipse curve was best fitted to a solar profile with about $1/3$ of the limb brightening predicted by the HSRA model (Gingerich *et al.*, 1971). A subsequent annular eclipse experiment (Clark and Boreiko, 1980) was flown on the NASA Galileo II aircraft with a similar $400\ \mu\text{m}$ photometer and confirmed this result, though the somewhat noisy data demonstrated again the severe restriction of this small-optics full-sun-imaging approach.

3. Kuiper Airborne Observatory Experiments

Then began a remarkable series of very careful airborne experiments by a team headed by Becklin and Lindsey, in which the 0.9 m telescope of the NASA Kuiper Airborne Observatory was pressed into service to observe both the 1981 and 1988 eclipses over the Pacific Ocean (Lindsey *et al.*, 1983, 1986; Roellig *et al.*, 1991). The telescope was screened with polyethylene and equipped with a 4-detector filter photometer (extended to 7 detectors in 1988), to measure individual bands in the far IR and sub-millimeter range. The major advantage of this technique over whole-sun imaging was the ability to observe the points of eclipse contact with the

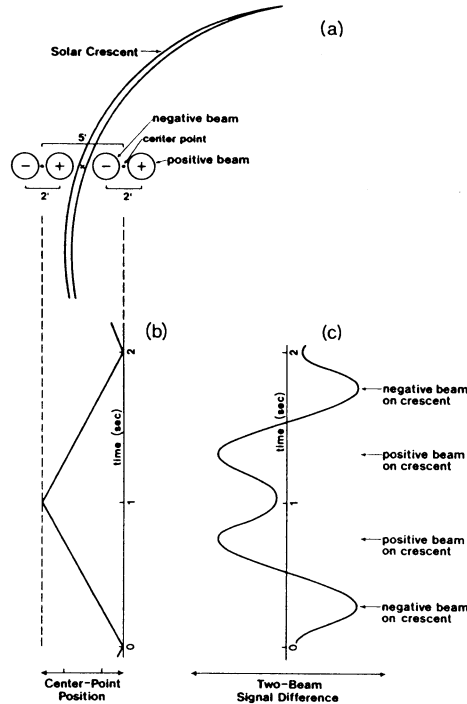


Fig. 3. (a) Schematic depiction of the 2-beam chopping-scanning geometry used by Lindsey *et al.* (1983, 1986) to observe the 1981 and 1988 eclipses from the Kuiper Airborne Observatory. (b) The 0.5 Hz triangular scan-pattern of the center-point of the 2-beam chop. (c) The resulting 2-beam difference signal profile as the positive and negative beams pass over the solar crescent. (From Lindsey *et al.*, 1983)

100'' diffraction-limited beam of the telescope. However, a direct "staring" mode would carry with it a significant disadvantage. Telescope tracking errors across the diffraction-limited beam would result in significant intensity variations unrelated to the eclipse, even when two-beam chopping from one beam on the solar limb to an adjacent sky area 2' away was used to remove atmospheric and telescope emission. A special observing technique was therefore developed and used both in these 2 flights and subsequently on the James Clerk Maxwell Telescope (JCMT) on Mauna Kea in the 11 July 1991 eclipse. The telescope was linearly scanned back and forth across the remnant solar crescent in a manner outlined in Figure 3, to produce the typical eclipse signal shown in Figure 4. The envelope of peaks represents the center-sample of the beam-pattern across the remaining solar crescent, or the equivalent integral eclipse curve.

Careful removal of the remnant Moon radiation and reconstruction of the eclipse curve produced the initial indication of significant limb extension at these wavelengths, of about the same magnitude as that measured by Beckman and Ross

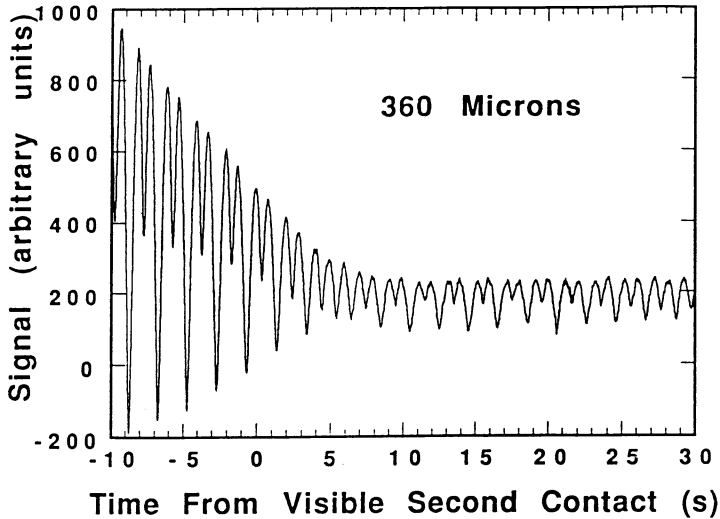


Fig. 4. Typical second-contact eclipse signal curve at 360 μm , uncorrected for moon emission, from the 1988 eclipse. (From Roellig *et al.*, 1991)

(1975), but with no indication of the intense limb spike (Figure 5). There is evidence of some limb brightening in these records, of the order of 2% at 30 μm and 22% at 200 μm between -3000 and $+350$ km from the visible limb, normalized to disk center.

4. Modeling

Modeling of this extended and limb-brightened limb by Lindsey and his colleagues have explored several avenues. Initially, a “stretched” VAL (Vernazza *et al.*, 1973) model was fitted to the profiles (Hermans and Lindsey, 1973) by stretching the entire chromosphere by a factor of 2.4 in height while maintaining the vertical temperature-optical depth relationship, thereby violating gravitational hydrostatic equilibrium in a “smooth” atmosphere. Electron densities were lowered to maintain the $T - \tau$ relation, while other densities were lowered in a commensurate manner to maintain ionization equilibrium. This density change would also affect Lyman- α and Lyman continuum emission however, and is probably unacceptable as a realistic model, even though the model fits the observed far IR data.

Lindsey (1987) and Braun and Lindsey (1987) used techniques developed for LTE calculations in a “rough” atmosphere to compute a model chromosphere consisting of a plane-parallel temperature minimum region out to 1000 km and randomly distributed cylindrical spicules interspersed within transparent coronal material above this height. This model was able to fit both the limb-brightened far-IR eclipse data and the relatively flat limb distribution at 2.6 mm, measured interferometrically by Wannier *et al.* (1983), by using a constant spicular temperature of

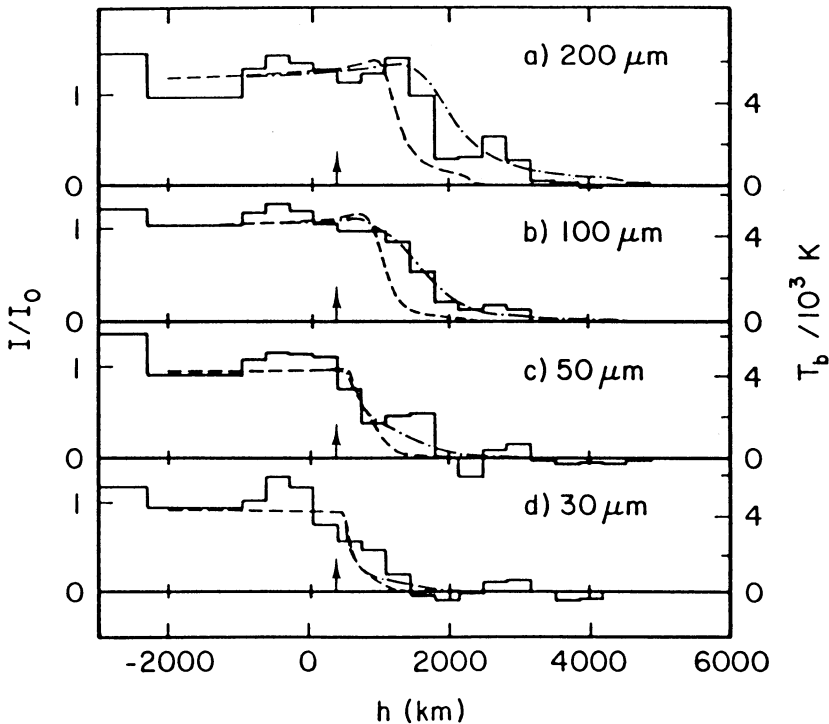


Fig. 5. Far IR solar limb distributions from the 1981 eclipse, compared to limb brightness profiles for an unperturbed VAL model (1973) (dashed curve), and a “stretched” VAL model, (From Hermans and Lindsey, 1986).

about 7000K and a selected spicular distribution with height. This lack of significant brightness enhancement at the limb at 2.6 mm [and also at 1.3 mm, (Horne *et al.*, 1981)] is a significant argument in favor of the conclusion that the temperature of spicular material must be significantly lower than that derived by Beckers (1972).

Other analysis (Jefferies and Lindsey, 1988, and Lindsey and Jefferies (1990)) has provided statistical methods to account for spicule distributions within the chromosphere, and to generate an equivalent “smooth” atmosphere with appropriate opacity and source functions to fit both the submillimeter eclipse measurements and the 2.6 mm profiles of Wannier *et al.* (1983).

Roellig and his colleagues (Roellig *et al.*, 1991) have recently published the analysis of the 1988 eclipse flight and have used a modified Braun and Lindsey (1987) spicule model with slightly lower electron density, to match their solar limb profiles, as shown in Figure 6. There is still disagreement between the modeled limb profiles and the observed results at the extreme limb at these wavelengths, the model predicting a small limb spike. This is probably a consequence of the abrupt transition in the model between a smooth atmosphere below 1000 km and the assumed spicular structure above this altitude, and the power law assumption for spicular number density.

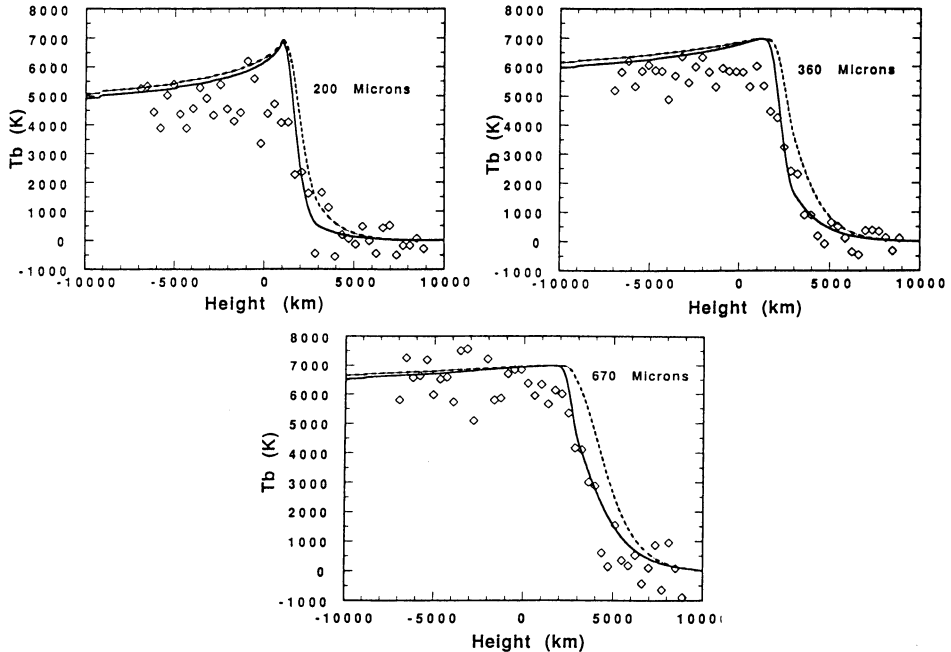


Fig. 6. The observed and model limb profiles at 200, 360 and 670 μm , with the Braun and Lindsey model shown by the dashed lines and the modified Roellig model shown by the solid lines. (From Roellig *et al.*, 1991)

5. 11 July Eclipse Results

The 11 July 1991 total eclipse provided a unique opportunity to utilize the two large sub-millimeter and millimeter telescopes, the 10 m California Submillimeter Observatory (CSO) and the 15 m JCMT in Hawaii for extreme solar limb observations since the eclipse shadow passed almost directly over Mauna Kea. Ewell *et al.* (these proceedings) describe their observations at 850 μm on the 10-m CSO in which they find an extension of the limb and 10% limb brightening at this wavelength. They account for these results without invoking complex spicular structure by using a non-hydrostatic equilibrium model chromosphere with higher electron density than that predicted by the VAL model.

The 15 m JCMT was used by an international collaboration to monitor the solar limb occultation at 1.3 mm (Lindsey *et al.*, 1992) during this eclipse. Here, the advantage of a large and stable telescope within the eclipse path was exploited, using a similar scanning technique to that developed for the airborne observations but without beam chopping to avoid beam-pattern effects. The secondary telescope mirror was scanned in a 40'', 1 Hz triangular wave across the remaining solar crescent to sample it at equivalent spatial intervals of 0.26'', providing unprecedented resolution at this wavelength.

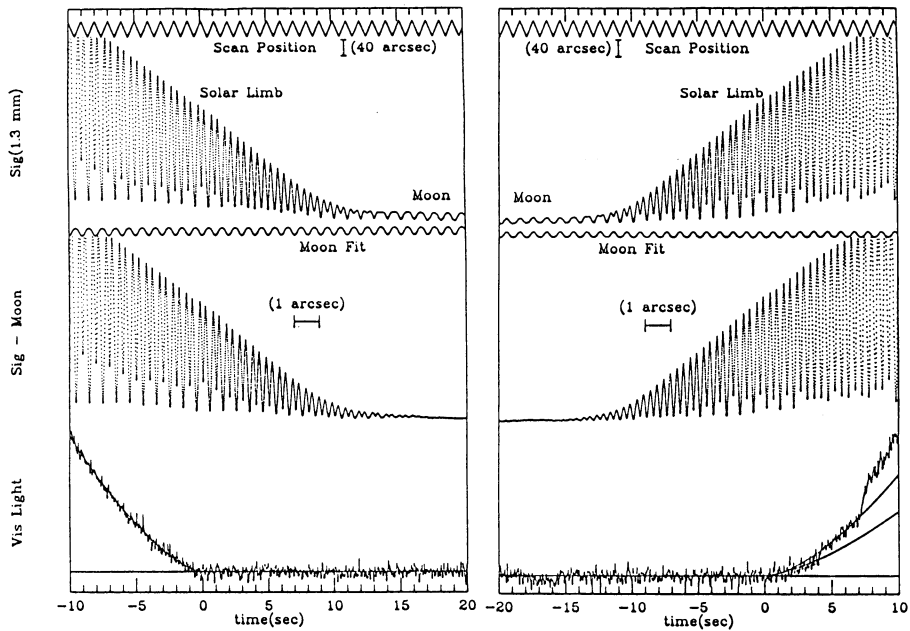


Fig. 7. JCMT scans of the disappearing solar crescent during 2nd and 3rd contacts of the 11 July 1991 solar eclipse at 1.3mm. The secondary mirror scan pattern is shown above these scans, while the visible light occultation, measured from the same site, is shown below each millimeter scan. The signal from the Moon was extracted from these scans before deriving the limb profiles.

Figure 7 shows the eclipse scans for 2nd and 3rd contacts, along with simultaneous visual scans from the same site. Again, these profiles indicate significant extension of the solar limb beyond the visible limb, in this case by about $5''$, with faint emission existing up to $8''$ from the visible limb. The second and third contact limb profiles of Figure 8 were derived from these occultation curves using the method outlined in Lindsey *et al.* (1986), with intensity normalized to disk center intensity. The limbs are seen to be extended, and the intensity at this limb is about 50% brighter than the quiet sun at disk center and falls off slowly beyond the millimeter limb, with an equivalent intensity scale height of about 1900 km.

6. Limits Imposed by Lunar Limb Shape and Diffraction.

The calculated limit placed upon the resolution of the occultation technique for this specific eclipse by the irregularity of the lunar limb at the position of each contact is shown in Figure 8 – Lindsey *et al.*, 1992. This amounts to a broadened “scanning function” with a width of about $0.3''$. Also shown in Figure 8 is the calculated Fresnel diffraction pattern for solar radiation diffracted by the lunar limb. While representing fundamental limits to this technique, neither of these effects play any significant role in the interpretation of the present data.

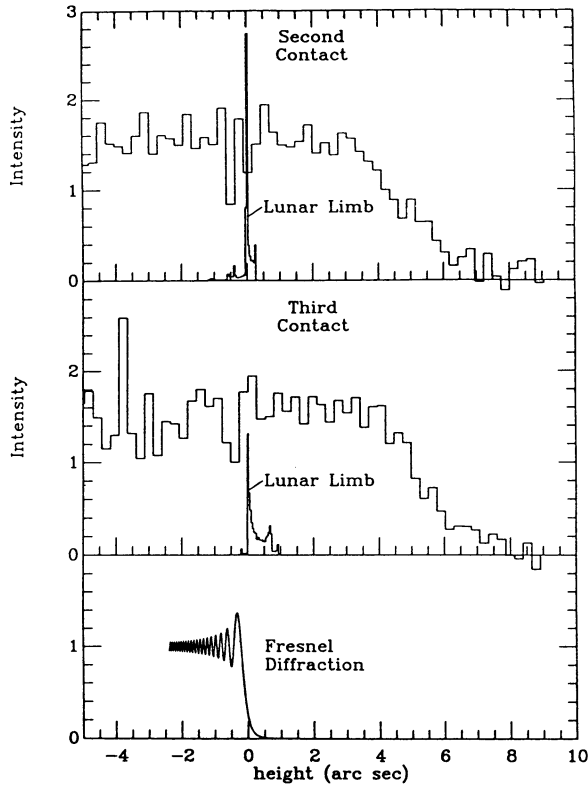


Fig. 8. Brightness profiles of the 1.3 mm solar limb at 3rd contact, computed from the occultation record of Figure 7, showing the extension of the limb beyond the visible limb and the slow decay of intensity at the millimeter limb. Also shown are the effects on the equivalent beam pattern of the rough lunar limb and Fresnel diffraction at that limb.

7. Conclusions

The use of the relatively sharp edge of the Moon's limb as a shutter to examine the distribution of brightness of the solar limb at submillimeter and millimeter wavelengths during solar eclipses has produced solid evidence of an extension of the solar limb, well beyond that predicted by homogeneous models at these wavelengths, which increases with wavelength as shown in the summary diagram of Figure 9. If spicules are the cause of this extension, then the increase is probably an indication of increasing opacity within the cooler (6000–7000K) spicular material, since the tangential line of sight intersects more than 1 spicule on average below a height of 3000 km above the visible limb (Michard, 1974). This tangent height occurs at a wavelength of about 1 mm. The extension beyond this wavelength and the slow fall-off of intensity at the limb is probably governed by the scale height of the number density of spicules and, at the longer wavelengths, by the increasing emission of coronal material.

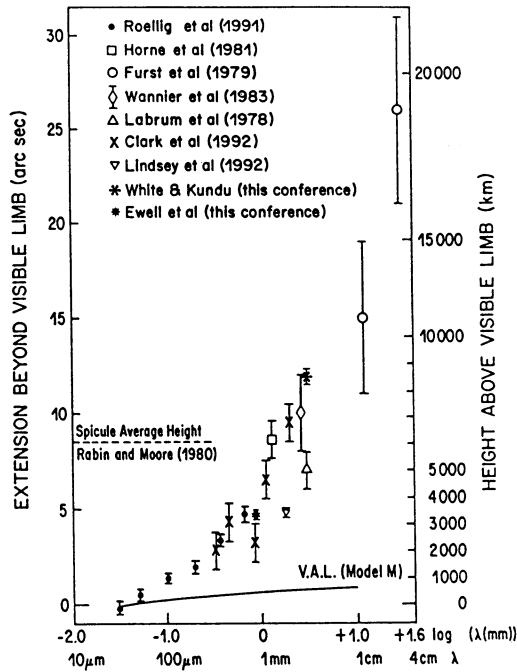


Fig. 9. Summary of measurements of limb extension as a function of the logarithm of wavelength, including recent limb-scan observations with the JCMT (Clark *et al.*, 1992).

The variability of the size of the extension at a wavelength of about 1 mm in Figure 9 might be due to experimental and systematic error in the individual measurements but is much more likely to be due to the clumpiness of spicules on the solar surface and the resultant variability of the number of spicules in a particular line of sight, a conclusion also reached by Wannier *et al.* (1983) on the basis of interferometric scans of the solar limb at different solar position angles at 2.6 mm.

Puzzling features in these data which have recently been discussed by Foukal (1992) are that there appears to be no significant millimeter emission above the heights to which the Balmer- α -emitting spicules reach, and that the millimeter temperature of this spicular material appears to be so low. This indicates that the mechanism which propels the spicular material upwards does so with little dissipation of energy and heating, and that, once at this maximum height, the plasma ceases to emit both Balmer- α and millimeter radiation. Foukal concludes that this observation is important in judging the effectiveness of certain proposed models for chromospheric heating by the release of spicule potential energy within this layer (*e.g.*, Athay and Holzer, 1982).

Thus, these latest measurements on the extended and weakly limb brightened millimeter solar limb place important constraints upon model development for this solar atmospheric layer. This is the important region from which the majority of

the solar UV radiation arises and in which so-far unidentified non-radiative mechanisms are providing the source of heating, at least in the chromospheric network surrounding supergranular cells. These results will have to be included in a self-consistent manner along with the extensive disk-center and strong-line and UV eclipse measurements in more refined models of the chromosphere.

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