ON THE SUN'S LIMB BRIGHTENING IN THE VISIBLE

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Abstract. It is shown that in practice the method by Julius (1906) is incapable to determine the limb intensity drop. The brief intensity reversal near the extreme limb as derived from cinematography of flash spectra can be explained by diffraction.

1. Introduction

In a recent paper Rosen and Poss (1982) applied the method of Julius (1906, 1913) to derive the intensity profile of the extreme solar limb from the time variation of the monochromatic brightness of the crescents observed at two total solar eclipses. The altitude profile of the lunar limb was taken into account in order to improve the accuracy. The resulting intensity profiles of the Sun's extreme limb shows a 25% drop to a minimum near $r = 0.9970\ R_\odot$ followed by a 40% increase to a maximum near $r = 0.9988\ R_\odot$ before the steep drop at the limb. It is astonishing that this method is still used despite several warning notes. Evans (1947) already showed that Julius' method does not permit to even distinguish between a disk of uniform brightness and one with a linear limb darkening law. Hubenet and de Jager (1956) reevaluated the problem and concluded, that the method requires high accuracy in absolute energy measurements. To achieve this is rather questionable under eclipse conditions. Mädlow (1961) thoroughly discussed all methods for finding the solar limb intensity distribution. It will be shown, that the accuracy required in both contact time and photometry for determining a reliable limb profile is not met by the present observing techniques. It is however puzzling to see similar intensity reversals being derived from eclipse curves observed by the more accurate method of flash spectrum cinematography. Since direct observations never confirmed the intensity reversals, a critical discussion is in order.

2. The Problem of the Method by Julius

This is best demonstrated by a numerical integration experiment. The limb intensity profile of the standard photosphere and chromosphere, the Harvard–Smithsonian Reference Atmosphere (HSRA) (Gingerich *et al.*, 1971) serves as basis. It was calculated by Kurokawa *et al.* (1974) for $\lambda 4700$ and $\lambda 6690$ Å and compared with other model predictions. The limb intensity profiles derived by Rosen and Poss (1982) from the analysis of the entire light from crescents show a pronounced limb brightening near $r = 0.9988\ R_\odot$, which we will call a hump. We have calculated the intensity of the changing crescents as the Moon's limb moves across the Sun's limb for both limb

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profiles, the standard HSRA and that with the hump. For simplicity we assumed perfectly circular shapes for the limbs of the Sun and the Moon. The lunar limb relief is of minor importance for our discussion of the method. In Figure 1 we display the two limb profiles and show the difference between the two resulting eclipse curves of the crescents, permitting a shift of the limb position by 0.001 $R_\odot$ and an intensity scaling factor. As can be seen, the two curves differ in the region of interest by little more than one percent of the crescent intensity at 0.9960 $R_\odot$. This is not surprising since the limb intensity profile enters only as a higher order effect in the mainly geometrically determined integrated intensity variation of the eclipse curve.

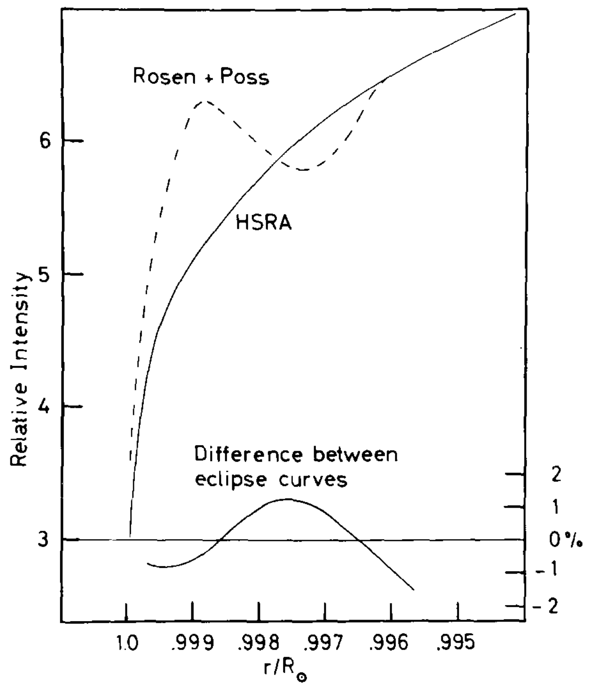

Fig. 1. The difference between the eclipse curves for the limb intensity distributions by Rosen and Poss (1982) and the Harvard Smithsonian Reference Atmosphere, HSRA (Gingerich *et al.*, 1971).

3. Limb Brightening in the Paschen Continuum?

The sensitivity of the observations to the limb intensity profile can be improved by restricting the measurement to a narrow section of the Sun's limb. At the cinematographic photometry of flash spectra (Schwarzschild, 1906) the brightness variation of selected Bailey beads is obtained. In the slit- or barren method the photographic photometry is replaced by photoelectric recording of the intensity restricted by a slit placed perpendicular to the Sun's limb, preferably oriented parallel to the motion of the

Moon. Both of these methods are influenced by the atmospheric seeing while Julius' method is not. It is strange, that eclipse curves of flash spectrum cinematography show a steadily decreasing slope until the last second of arc, where a brief inversion of the slope occurs. Consequently the derived intensity distributions show a maximum before the final drop off at the limb. But observations with the photoelectric slit- or barren method give no evidence for a change in slope.

I would like to discuss the works by Heintze (1965) and by Kurokawa *et al.* (1974). The spread of the intensity measurements of the flash spectra observed by Kurokawa *et al.* (1974) is about the same as that found by Heintze (1965), i.e. about 17%, although it appears larger in the figures of the latter. Let me first state that a limb brightening in the Paschen continuum has never been noticed in direct observations by visual observers, or during Stratoscope observations, or even in the extremely fine resolved limb observations, which are aimed at solar diameter measurements (Rösch, 1983). It is therefore necessary to look for possible origins of the strange behavior of the light curves of Bailey beads in flash spectrum cinematography.

4. Calibration

I checked the work by Heintze (1965) shortly after its appearance during a visit at Utrecht and found the calibration performed very carefully and the entire procedure perfectly alright. There is however a possibility that the Eberhard effect may indeed have increased the photographic density of narrow stripes from Bailey beads. Scheffler (1957) has developed a correction procedure. It has not been applied to this problem. But it is unlikely, that the effect influenced both investigations in the same way.

5. Seeing

Image motion and defocussing in the direction of dispersion cannot affect the result as long as there are no chromospheric emission lines near the continuum window. All observers have carefully avoided this situation. A washing out of Bailey bead structure *perpendicular* to the direction of dispersion however will always decrease the peak intensity, resulting in a smaller slope with approach of the contact time.

6. Shadow Bands

These are mostly reported to move faster over the telescope apertures than could be resolved. The overall effect should make the data noisier, but not increase the average.

7. Photospheric Inhomogeneities and the Lunar Limb Relief

These two items can be treated together. The solar 'surface' roughness and the relief of the lunar valleys can be considered as 'dirty' spectrograph slit jaws. In principle this can be treated as decreasing slit length. Considering for simplicity a flat intensity distribution,

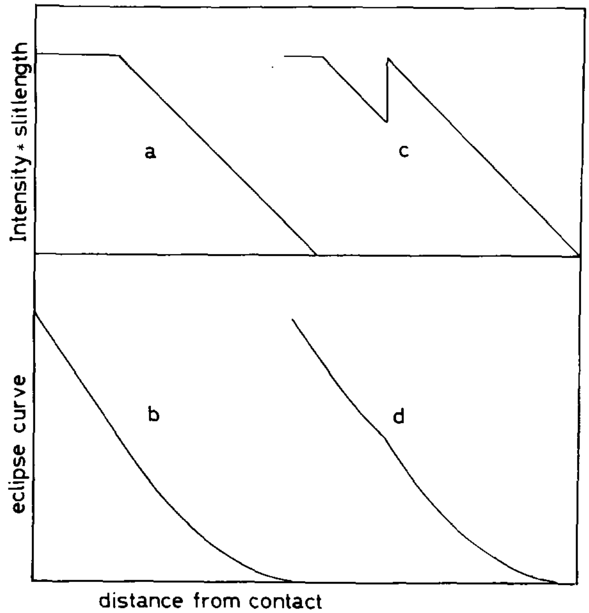

Fig. 2. (a) and (c): idealized limb profiles (intensity * slit-length). (b) and (d): the resulting eclipse curves.

it is easy to see that the 'dirty' slit will decrease the slope of the eclipse curve but not increase it, as observed. In Figure 2 we show the shape of the illuminated areas and the corresponding eclipse curves. We see that near contact time the illuminated area becomes very small also in its length. Only if there is a sudden increase in that length or in intensity (c) does a reversal of the slope result (d).

8. Diffraction

Kurokawa *et al.* (1974) estimated the effect of diffraction to be less than one percent by using a straight-edge approximation. We propose a different treatment. As long as the Sun's limb is far enough away from the lunar valleys, roughness is inconsequential, but spectral purity will increase as the eclipse progresses. As soon as the Sun's limb moves into a lunar valley, however, the size of the valley becomes important. Depending on the aperture of the telescope there will be a moment when the monochromatic continuum radiation must be considered as coherent. For this case the amplitudes of the electromagnetic radiation must be integrated over the aperture. Therefore, the central intensity of a monochromatic source as a function of 'slit' size behaves like the square of the sine-integral. A well-pronounced maximum, just before the slit is closed, is preceeded by a less-pronounced minimum (van Cittert, 1930). This closely resembles the intensity distributions derived from eclipse curves. It is important for the interpretation of the data, that the radiation must be coherent. This requires, that the radiation from the various parts of the photosphere, limited by the lunar relief, must arrive in phase at the various parts of the telescope aperture. This is the case if the bundle is sufficiently narrow. It is fulfilled for the last 500 km of the Sun's edge. The observations of Heintze (1965) and of Kurokawa *et al.* (1974) were obtained with telescope apertures below 2 cm. Since the coherency condition is better fulfilled for longer wavelengths, the larger effect found in the red is understandable. Let us estimate at which limb position we would have to expect the maximum intensity. According to Figure 5 of the article by van Cittert (1930)*, the maximum occurs for an angle $\psi' = \lambda/D$, where D is the telescope aperture. For 6000 Å and $D = 2$ cm we get $\psi' = 6''.5$. Assuming $1''$ for the depth of the lunar valleys and $8''$ for their extent a linear relation would place the $6''.5$ length at a distance of 600 km from the Sun's limb. This is about the region where the eclipse curves of Heintze (1965) invert their slope. For estimating the degree of coherence we have to compare the path difference from the extreme points of the origin of radiation with the wavelength of light. The telescope aperture is seen from the source at an angle $u = 2\ \text{cm}/1.5 \times 10^{13}$ cm. The path difference from a 600 km wide area of the Sun is then $6 \times 10^5\ u = 8 \times 10^{-6}$ cm, which is a factor 1/8 smaller than the wavelength. Thus the condition for coherence is fulfilled.

We may then ask for the reason, that the slit- or barren method does not lead to limb brightening? The spread of the photoelectric signal variation hardly differs from that of Bailey bead intensities. The slit, which crosses the Sun's limb, is oriented parallel to the lunar motion. In the case of Weart (1968) the slit was fortuitously placed at a position where the lunar limb had a rather flat relief. Also de Groot (1962) mentions little structure. But even more important seems to be, that these investigations were using much larger telescope apertures, thereby shifting the condition for coherence undetectably close to the contact times. None of these photoelectric recordings of eclipse curves indicate an inversion of the slope.

In flash spectrum cinematography one always uses a large number of Bailey beads, and therefore one should expect, that in some of these the lunar relief must be flatter than in others. The proper method of averaging of eclipse curves would therefore be, to shift them in such a way as to obtain a minimum of scatter at larger distances from the limb position, thereby allowing a greater scatter near contact, where the influence of diffraction can be expected. I have tried this procedure with the data of Heintze (1965) for λ5700 Å. Averaging four of the seven Bailey beads observed at second contact is shown in Figure 3. The inversion of the slope does not completely vanish. A similar diagram was obtained for three of the six Bailey beads of the third contact. Checking the locations of these Bailey beads on the tracings across the flash spectra, it is puzzling that those near the center of the crescents show steeper slopes than those near the edges.

* In Figure 3 of the paper by van Cittert (1930) J_c must increase steadily with $\psi_0 d$, since Equation (1) gives for $\varphi d = 0$ the expression: $J_c = (2/\pi)[Si(2\psi_0 d) - \sin^2(\psi_0 d)/(\psi_0 d)]$. The second term in the bracket was omitted in the original paper.

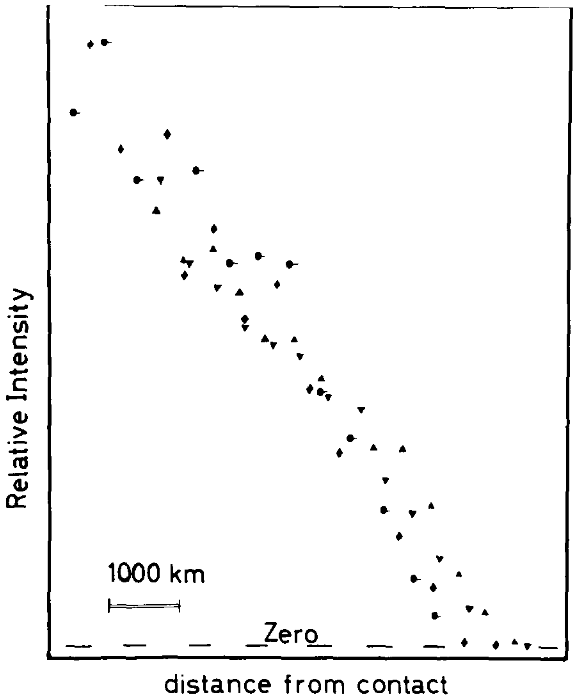

Fig. 3. Average eclipse curve using four out of seven of the Bailey beads at second contact observed by Heintze (1965), but using different horizontal shifts.

Achieving less scatter of the average eclipse curve further away from contact time produces a larger scatter near contact time, which makes the inversion of the slope much less striking.

9. Conclusion

I hope to have successfully demonstrated that the method of Julius is unfit for determining the limb intensity profile, and that the limb brightening derived from flash spectrum cinematography can be explained by diffraction. It is clear, that direct observations of the intensity drop near the extreme limb, obtained from space, will settle the problem. Special attention must then be paid to the measurement of the instrumental scattered light.

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