A HIGH-RESOLUTION STUDY OF THE RADIO SOURCE 3C273

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SINCE the first detailed study of 3C273 by the "method of lunar occultations" and its subsequent identification with a stellar object[1,2] which led to the recognition of a new class of astronomical objects, it has proved to be one of the most interesting and puzzling objects in the entire sky. The early occultation observations which were made using the 210-ft. radio telescope at Parkes at frequencies of 136, 410 and 1,420 Mc/s showed that basically the source consists of two components (called *A* and *B*). A preliminary analysis of the records showed that the majority of the radiation from *B*, which is associated with a 13th magnitude star-like object, arises in a source of angular size less than or equal to 0·5″ while component *A* appeared to consist of a central core about 2″ wide embedded in a halo about 7″ wide and to be associated with a jet extending outwards from the stellar object. The jet which lies along a position angle of 43° starts at about 11″ from this object and terminates abruptly at a distance of 20″, while it was estimated that the two radio components were oriented along a line at position angle 44° and separated by 19·5″. A more detailed analysis of the 1,420 Mc/s observations[3] using the convolution procedure of Scheuer confirmed these general conclusions but indicated the presence of additional weak sources near *B* and a faint extension extending from *A* towards *B*. It also appeared that *B* was resolved with an angular size of about 0·6″, a conclusion confirmed by a similar analysis of the same data by Scheuer[4]. Later observations by Hughes[3,5] confirmed the conclusion that *A* is elongated along the direction of the jet, a conclusion also reached by Von Hoerner[6] from a series of occultation observations at Green Bank. A comparison of the observations at different frequencies showed a marked difference in spectral index between the two components, that of *A* being about $-0·9$ compared with a value for *B* of about 0·0.

Since the foregoing series of observations the extremely interesting observation has been made by Dent[7] that at 8,000 Mc/s the flux of 3C273 has increased over a period of 3 years by about 40 per cent. Because of the difference between the spectral indices of the source components this increase in flux must be due to component *B* and it sets an upper limit to its angular size of about 0·001″. However, the absence of any evidence of a cut-off in the spectrum of *B*, at least down to a frequency of 410 Mc/s, shows that if the emission from *B* is due to synchrotron radiation the angular size must be greater than about 0·2″, which is in better agreement with the occultation observations. This suggests either that the emission is not synchrotron radiation or that there is a genuine change in apparent angular size between 1,420 Mc/s and 8,000 Mc/s.

Because of the seriousness of the discrepancy in the estimates of angular size we have taken advantage of an accultation visible from the Arecibo Ionospheric Observatory in Puerto Rico to make a more accurate measurement of the diameter of component *B* and at the same time a more detailed comparison of the optical and radio brightness distributions. In addition we have re-analysed the earlier 1,420 Mc/s observations, as in this case the resolution limit set by the time constant and the bandwidth was about 0·5″, so close to the estimated size of *B* that there must be some doubt as to whether it had really been resolved.

* The Arecibo Ionospheric Observatory is operated by Cornell University with the support of the Advanced Research Projects Agency under a research contract with the Air Force Office of Scientific Research.

Observations of the occultation which occurred on June 7, 1965, were made using the 1,000-ft. aperture telescope of the Arecibo Ionospheric Observatory which has been described in detail by Gordon[8]. The main primary feed of this instrument consists of a line feed 96-ft. long operating at 430 Mc/s and designed to correct the spherical aberration of the reflecting surface and to fill the full 1,000-ft. aperture. However, it was decided not to use this feed but to construct a special set of simpler feeds operating at 41 Mc/s, 195 Mc/s and 430 Mc/s, feeding 1,000 ft., 500 ft., and 350 ft. of the aperture respectively. There were several reasons for this decision. First, it was decided to attempt a resolution of 0·1″ and, as pointed out by Hazard[3], the finite size of the aperture sets a limit to the resolution and for an aperture of 1,000 ft. this limit is about 0·2″. Secondly, it was desired to investigate the source spectrum in more detail. Finally, the occultation occurred near the edge of the field of view of the telescope and there was some danger that part of the occultation curve would be missed using the line feed, while with the simpler feeds the field of view could be extended by mounting them offset from the main feed support. It was estimated that the apertures illuminated by the simple feeds would be adequate to achieve the desired resolution.

Because of low-level interference and the higher background noise at the lower frequencies, the 430-Mc/s record is the only record which permits a detailed study of the source structure down to a resolution of the order of 0·1″ and we will confine our attention to the observations made at this frequency. The spectral measurements have turned out to be very complex and will be discussed later.

At 430 Mc/s, a Dicke-type receiver was used with two separate channels, one channel having a bandwidth of 125 kc/s and the other 1 Mc/s. The observations were made by directing the telescope beam to the position of the source and recording the received power with the telescope in automatic motion tracking the source. The received power was recorded on magnetic tape using a time constant of 0ˢ1. With this time constant the limit to the resolution is set only by the receiver bandwidth and the signal-to-noise ratio. The effect of the bandwidth on the source distribution when restored using the method of Scheuer is to convolve the source distribution with a beam of half-power width about equal to 0·62 $(\Delta\lambda/D)^{1,2}$, where $\Delta\lambda$ is the width between half-power points and D is the distance of the Moon from Earth. At 430 Mc/s this corresponds to 0·09″ at 125 kc/s and to 0·26″ at 1 Mc/s. The 430-Mc/s record, smoothed with a gaussian beam 2 sec of time wide in order to show its main features, is shown in Fig. 1. The angle between the limb of the Moon and the line joining the two source components was only 15° so that the two components are not clearly separated, but their presence is shown by the beating in the fringe pattern. The extensive diffraction pattern shows the presence of fine-scale structure in the source of less than 1″.

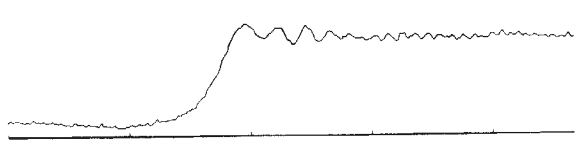

Fig. 1. Facsimile of observed occultation curve at 430 Mc/s using 1-Mc/s bandwidth and smoothed with a time constant of 1 sec. Horizontal scale: universal time, 1 div. represents 1 min

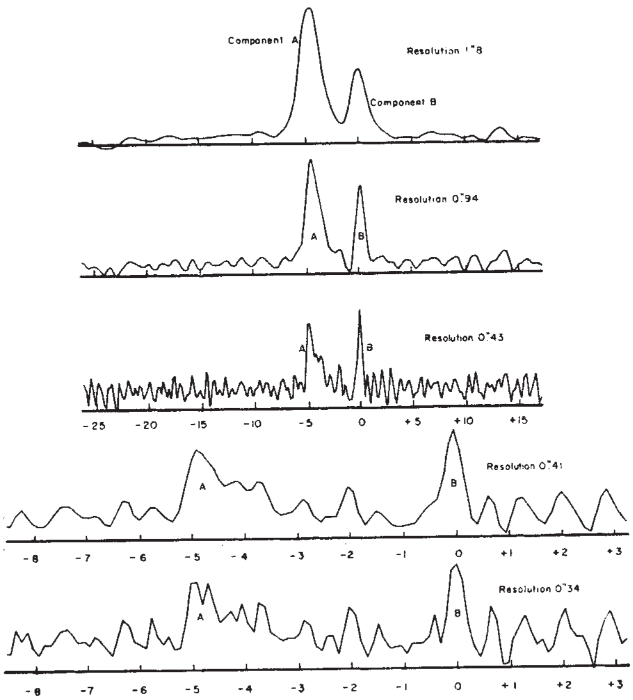

Fig. 2. Derived distributions across 3C273 using different resolutions and obtained using the 1-Mc/s bandwidth observations. The effective resolution is indicated on each curve. All records are normalized so that an unresolved source would have constant height at all resolutions. Horizontal scale: distance from component *B*, along position angle 299°, in seconds of arc

The record was analysed using a procedure based on Scheuer's convolution method for recovering the true strip brightness distribution, as seen by a beam of some assumed size, from the observed occultation curve. It differs mainly from the procedures outlined by Von Hoerner[9] and by Scheuer[4] in that account is taken of the curvature of the limb of the Moon, for, as shown elsewhere, this is an important consideration when aiming at a resolution of 0·1″ where the diffraction pattern and the restoring curve extend to a distance of 3′ from the limb of the Moon. In calculating the time scale of the diffraction pattern the source position given by Hazard, Mackey and Shimmins[1] was adopted and initially the Moon was assumed to be truly circular. However, a preliminary analysis showed that the use of the scaling factor derived in this way produced a marked asymmetry associated with a pronounced overshoot in the restored distribution of component *B*. As discussed elsewhere, this is a clear sign of an error in the restoring function (as well as evidence that the source is of small angular size) and, as the position of the source is known to the order of 1″, must be due to the relevant section of the limb of the Moon deviating from a true circle by about 2°. The scaling factor was therefore adjusted experimentally until all signs of the overshoot had disappeared and the narrowest distribution for *B* obtained, a procedure analogous to focusing. This procedure is justified as there is no mechanism which could produce a narrower distribution than the true distribution.

Having obtained the true scaling function, the observed occultation curves were restored with a series of restoring functions each using a different assumed beam width. The restored curves for a 1-Mc/s bandwidth are shown in Fig. 2. These curves represent the true brightness distribution convolved (*a*) with the assumed beam and (*b*) with a gaussian of half-power width 0·26″ due to the bandwidth. The effective beam width in each case is indicated on each curve; at the maximum resolution used it is set almost entirely by the receiver bandwidth. The curves are normalized so that an unresolved source would have a constant height at all resolutions.

Some interesting features are immediately obvious from these curves. As the height of component *B* is constant for all resolutions within the limits of experimental error and as there is no significant broadening at the highest resolution it must have an angular size $\leqslant 0\cdot 3''$. On the other hand, the curves for component *A* show an appreciable diminution in height going from a resolution of 3·6″–1·8″, showing that it contains structure wider than 2″ of arc. As the resolution is decreased below 1″ the nature of this structure becomes clear. There is a weak extended source just visible in the noise and at least 5 sec of arc in extent on which sits a narrower source in which the majority of the emission originates; the extension from *A* to *B* noted earlier is probably part of this extended source. A comparison of the areas under the curves at different resolutions indicates that the extended region contains 40 per cent of the total flux from *A* while the central region contains the remaining 60 per cent. At the highest resolution, structure begins to appear in the central region itself which may be considered to consist of two separate components. One component has a half-width of 1·5″ and overall extent of about 2″ with a remarkably flat top and contains 40 per cent of the total flux of *A*; the second component contains 20 per cent of the total flux, is asymmetrically placed with respect to the extended central component and has a half-width less than or equal to 0·3″. The exact configuration of these two sources is somewhat uncertain as the shape of the restored curve depends on the scaling factor adopted for the restoring function and this is not necessarily the same for *A* as for *B*. However, there is no doubt that the asymmetry of *A* is real and that the small angular size component is situated on the side of the extended source more remote from *B*. Apart from a suggestion of a weak discrete source between *A* and *B* there is no evidence of any other source in the region.

In order to increase the resolution we now consider the observations made with a bandwidth of 125 kc/s which sets a limit to the resolution of about 0·1″. These restored curves are shown in Fig. 3. At a resolution of 0·35″ the restored curve is similar to that obtained for the same resolution using a bandwidth of 1 Mc/s, but with a poorer signal/noise ratio. As the resolution is increased still further component *A* disappears into the noise while *B* is still clearly visible. Because of the low signal/noise ratio of the narrow component of *A* and the possibility that the scaling factor is not the same as for *B* there is no evidence that it has been resolved. Its angular size is therefore $\leqslant 0\cdot 3''$. The signal/noise ratio also limits the resolution for *B*. The half-width of this source at a resolution of 0·22″ appears to be slightly increased to 0·29″, but on the other hand there is no significant change to its height. The broadening is therefore not significant and we conclude that its half-width is $\leqslant 0\cdot 15''$. A comparison of the total fluxes observed at different resolutions

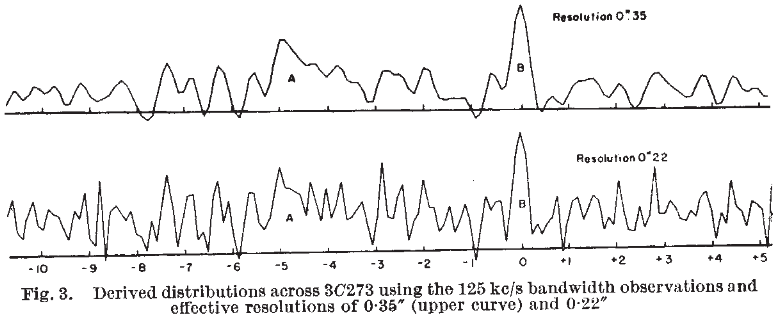

Fig. 3. Derived distributions across 3C273 using the 125 kc/s bandwidth observations and effective resolutions of 0·35″ (upper curve) and 0·22″

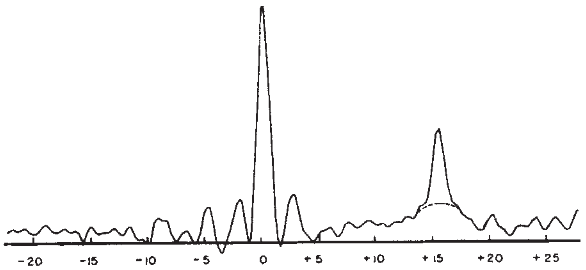

Fig. 4. 1,420 Mc/s distribution across 3C273 at position angle 103° using a resolution of 0·6″. The broken line represents the possible separation of *A* into a narrow central source situated on a more extended region of emission

shows that within the limits of experimental error all the flux from *B* arises in this small angular size component.

In order to compare the results of the present investigation with those made earlier at 1,420 Mc/s using a comparable resolution, we show in Fig. 4 the restored 1,420-Mc/s distribution using an effective beam of 0·63″. This is close to the maximum possible resolution which is limited to 0·52″ by the bandwidth and time constant. The basic structure of component *A* is the same at the two frequencies. Thus there is a narrow component superimposed on a weaker, more extended source, and running towards *B* and more clearly visible at coarser resolutions a faint flat extension. Unlike the 430-Mc/s curves the narrow source is not asymmetrically placed with regard to the extended source which appears to extend away from *B* on the far side of *A*. The width of the narrow component is difficult to estimate because of the uncertainty in the base level. If we consider the extended source and central component as a single source then its half-width is 0·9″, indicating a source size of about 0·6″, while if we draw the zero as indicated by the broken line the central region is not significantly resolved and has a width $\leqslant 0·4''$. The structure seen around component *B* on the 1,420 Mc/s curve is not visible at 430 Mc/s and must be considered spurious and probably due to irregularities in the limb of the Moon, although the possibility remains that it is genuine but that the sources have a steeper spectral index than *B*. It is the presence of these sources which apparently led to the conclusion that *B* has a core-halo type of structure—a conclusion which is certainly not true at 430 Mc/s. However, the 1,420 Mc/s results still indicate that *B* is resolved, for the observed half-width is 0·92″, corresponding to an angular size of 0·7″. As the presence of the irregularities near *B* indicates that for this occultation the irregularities in the limb of the Moon may be a significant source of error it is possible that they are responsible for its apparent resolution although the narrow width observed for the central region of *A* is a strong suggestion that the resolution may be real. In this case, the structure at 1,420 Mc/s must be different from that at 430 Mc/s. This is, the source may be elongated or it may indeed have a core-halo structure but with the halo having a steeper spectral index than the core. Alternatively there may be two sources present with different spectral indices, only one being visible at 430 Mc/s and both visible at 1,420 Mc/s. A further possibility is that the two sources are oriented so that they passed simultaneously behind the Moon on June 7 but with an apparent separation of about 0·5″ on October 26, 1962. Whatever the explanation, it is now clear that component *B* has structure less than about 0·15″ of arc and there is no discrepancy between the occultation observations and alternative methods of estimating the source size.

It is now of interest to compare the optical and radio distributions. It seems reasonable to assume that component *B* is in fact coincident with the stellar object and that this object can be used as a reference point in making the comparison. Hughes and Van Hoerner have shown that the radio emission is essentially confined to a line joining *A* and *B*, a conclusion which was suggested by the early occultation observations. If we make this assumption then the position and extent of the various components of *A* can easily be deduced from the angles between the limb of the Moon and the axis of the source at the times of occultation.

The results of this analysis are summarized in Fig. 5. The narrow component at both frequencies lies very close to the end of the jet, 19·3″ and 20·1″ at 430 and 1,420 Mc/s compared with the optical value of 20·0″. The flat extended component at 430 Mc/s merges into the noise at a distance of about 8″ from *B* while the long flat extension at 1,420 Mc/s becomes visible at a distance of 10″, which is close to the start of the optical jet at 11″ from *B*. The sharp fall in the flux from the extended source visible at 430 Mc/s with a resolution of 0·4″ is 14″ from *B* which corresponds closely at 1,420 Mc/s to the edge of the extended source lying beneath the narrow component.

It seems clear that this extended source at 1,420 Mc/s is associated with the flat central component observed at 430 Mc/s, the main difference being that while at 1,420 Mc/s it reaches at least 6″ beyond the edge of the jet there is no evidence for any extension of the central component at 430 Mc/s. However, the 0·9″ resolution curve in Fig. 2 suggests that the extended region of *A* does reach beyond the edge of the jet which indicates that at least part of the extension at 1,420 Mc/s may be associated with the long flat extension rather than the central extended component. There is therefore a remarkable correlation between the optical and radio features; of particular interest is the constancy of the flux at 430 Mc/s over a large region of the visible jet and the strong suggestions that the narrow component arises in a shock-front at the leading edge of the jet. It may be noted that the change in the structure of the source with frequency will lead to an apparent change in position with frequency unless the resolution is adequate to reveal the detailed structure.

A comparison has been made of the ratio of the fluxes of *A* and *B* from the 430 Mc/s records of August 20, 1962, and those of June 7, 1965. The comparison is somewhat complicated by the different angles of cut across the source in both cases and by the presence of some weak structure which may not lie along the line joining *A* and *B*. However, adopting all possible interpretations, it is clear that the ratio of *A* to *B* has not changed by more than 7 per cent and more likely by less than 2 per cent over the 3-year period. This suggests that unless both components are varying in the same way the flux of *B* has changed by less than 7 per cent which may be compared with the value of 51 per cent estimated by Dent at 8,000 Mc/s over approximately the same period.

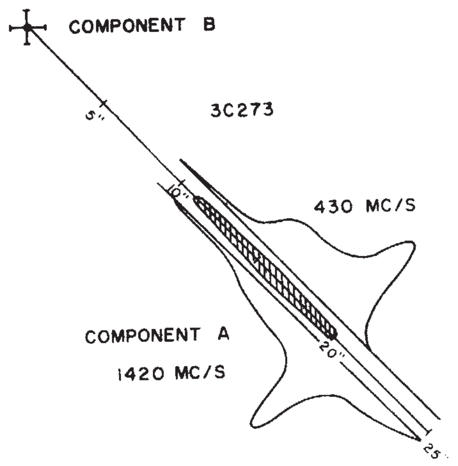

Fig. 5. Schematic representation of the optical, 430-Mc/s and 1,420-Mc/s distributions along the axis of 3C273. It has been assumed that component *B* is coincident at both frequencies with the stellar object. The shaded area represents the faint optical jet

We thank Prof. W. E. Gordon for his interest and encouragement throughout the course of the work.

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BRIGHTNESS TEMPERATURE OF SOLAR ACTIVE REGIONS DETERMINED FROM DRIFT CURVES OF THE SUN ACROSS A BROAD ANTENNA MAIN LOBE

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TWO methods are being used in investigating solar active regions of small diameter at radio frequencies; these are: scanning the Sun by high-resolution radio telescopes with fan beams or pencil beams and discussing solar eclipse curves providing high resolution in one dimension. Another method and its results are briefly discussed here, which can be described as the superposition of wide-beam transit curves.

From October 1960 to March 1964 continuous measurements of the total solar radio flux density were made with some interruptions at Tübingen at 3,750 mc/s. The main lobe of the 10 ft. horn fed reflector was about 110 min of arc wide. A number of solar transits were recorded from time to time in order to check the antenna characteristics. The integrated brightness temperature and flux density were derived from the antenna temperature of the continuous records, which is the maximum transit value[1,2]. The measurements were made to find the daily mean values of the quiet and slowly varying components and to record burst events. The slowly varying component is due to coronal condensations, which appear as small areas of enhanced temperature on the solar disk and disappear over periods of weeks or months. The apparent brightness temperature of the small active areas may be derived by superposing drift curves, provided the location and diameter of the enhanced areas on the solar disk are known. These data were available from optical maps and high-resolution radio observations. The results show that small active areas may be determined by the superposition method with small radio telescopes as used for daily measurements of mean values. The method may in particular be interesting at other frequencies than 9·1 cm and 21 cm at which solar radio maps are produced by high-resolution instruments. The 21-cm maps were edited from 1959 to October 1962 by Fleurs Observatory and the 9·1 cm radio maps are being edited by Stanford Observatory[3,4]. The essential idea of the superposition method is to regard the solar brightness distribution as a disk of uniform temperature superposed by Gauss-type sources of defined location and maximum temperature and width. A measured drift curve may be considered a result of the superposition of individual drifts of the main lobe across the quiet Sun described by a cylindric source model and a number of small areas of much higher temperature described by Gauss-type sources. The drift curve of an antenna main lobe described by a Gauss distribution $F_n = \exp\,(-\zeta^2/\alpha'^2 - \gamma^2/\beta'^2)$ across a cylindric source characterized by radius $R_\odot$ and uniform temperature T_c is given[1] by the relation:

$$T_{Ac} = T_c \left(1 - \beta_s\right) \frac{R_\odot^2}{'\beta'} \exp\left(- \frac{}{\alpha'^2} - \frac{\gamma^2}{\beta'^2}\right) \left\{1 - \frac{R_\odot^2}{2\alpha'^2} \left(\frac{1}{2} - \frac{\zeta^2}{\alpha'^2}\right) - \frac{R_\odot^2}{2\beta'^2}\left(\frac{1}{2} - \frac{\gamma^2}{\beta'^2}\right)\right\} \quad (1)$$

T_{Ac} is the main lobe contribution to antenna temperature caused by the source, and α', β' are the Gauss parameter of the main lobe, β_s is the stray factor of the antenna and ζ, γ are the distances of the source centre relative to the main lobe-centre in a rectangular co-ordinate system.

The term in parentheses is a correction if the source radius $R_\odot$ is not very small relative to α', β'.

The drift curve of a Gauss-type source across the main-lobe described by maximum temperature T_g and width parameters α, β is given by:

$$T_{Ag} = \left(1 - \beta_s\right) T_g \frac{\alpha\beta}{\alpha'\beta'} \exp\left(- \frac{\zeta^2}{\alpha'^2} - \frac{\gamma^2}{\beta'^2}\right) \quad (2)$$

In equation (2) it is assumed that $\alpha, \beta \ll \alpha', \beta'$, that is the widening of the transit curve due to finite source extension is neglected, since the half power width (HPW) would be $\mathrm{HPW} = \sqrt{\ln 2}\ \alpha\ \{1 + 1/2\ (\alpha/\alpha')^2\}$

The response of antenna temperature to a drift in ζ-direction through the centre of the solar disk and a number of small sources imposed located at (a_n, b_n) may now be written:

$$T_{A,tot} = T_{Ac}\left(\zeta, 0\right) + \sum_{n=1}^{n} T_{Ag}\left(\zeta - a_n, \gamma - b_n\right) \quad (3)$$

The summation of the stationary mean values of noise powers is correct if the contributions of the individual areas are incoherent. This is no doubt the case for any surface element of the solar disk emitting noise. Fig. 1 shows the location of the sources relative to the main lobe centre and the corresponding drift curves, where ζ and γ may be identified as hour angle and declination respectively. The resulting drift curve across the quiet Sun and one or more small hot areas is essentially the sum of exponential functions with different amplitudes K_n and different deviations a,b of the maximum with respect to the centre $\zeta = 0$ of the quiet Sun drift curve.

The maximum excentric deviation is $\zeta_{max} = R_\odot$, representing a source on the solar limb located at $\gamma = 0$. The resulting maximum of the superposed transit curve will be located between $\zeta = 0$ and $\zeta = R_\odot$. Since $\alpha', \beta' \sim 4\,R_\odot$ the amplitude at ζ_{max} will be practically the same as at $\zeta = 0$; at $\zeta = 1/2\ R_\odot$ we have $\exp\ (-1/69) = 0{\cdot}985$. So one may conclude that in any case the resulting maximum of $T_{A,tot}$ (ζ) will be situated close to $\zeta = 0$. The approximation $\zeta_{max} = 0$ simplifies the analysis considerably, the error being the smaller, the smaller the ratios ($R_\odot/\alpha'$; $R_\odot/\beta'$). If, for example, two or more hot areas are located on one half of the solar disk, the effect of unsymmetry will accumulate. But in general the sources will be distributed over the east and west half, so that the unsymmetry of $T_{A,tot}$ (ζ) will be partially cancelled. The best way, it is felt, of studying a special case of source distribution is to write equation (3) with all numerical values. The numerical values of the parameter of our telescope not related to the superposed sources are[1]:

$$T_\odot = 27 \times 10^3\ {}^\circ\mathrm{K},\ \beta_s = 0{\cdot}415,\ R_\odot = 32',\ \alpha' = 4{\cdot}14\ R_\odot,\ \beta' = 3{\cdot}85\ R_\odot$$

Inserting these values in equation (3) and setting $\zeta = 0$ we get the relation: