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RADIO OBSERVATIONS OF M 31 AT 1400 MC

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Abstract

Radio continuum observations at 1400 Mc have been made of the disk radiation from M 31. A comparison of 1400 Mc scans along the major and minor axes of the optical object with similar observations at 408 Mc, by Large, Mathewson, and Haslam shows very good correspondence. A rough comparison of the brightness temperatures at the two frequencies indicates a spectral index of about -1.1, as compared with the value -0.5 found at longer wavelengths by Baldwin and Costain. An exploratory series of drift curves through the nucleus of M 31 at 3000 Mc gave negative results and set an upper limit of about three-hundredths of a degree on the maximum brightness temperature, tending to substantiate the very rapid decline of the emissivity with increasing frequency.

I. INTRODUCTION

The nearby, typical Sb spiral galaxy, M 31, should logically occupy an important position in the interpretation of observations of our own and other galaxies. This has been true in the case of optical observations and promises to be so for measurements of the neutral hydrogen 21 cm line. A similar benefit might be expected from studies of M 31 as a source of radio continuum radiation. However, a rather considerable observational effort has yielded, thus far, only a rough picture of the radio structure of the galaxy (Brown and Hazard 1951; Seeger, Westerhout, and Conway 1957; Large, Mathewson, and Haslam 1959; Brown and Hazard 1959; and Baldwin and Costain 1960). At low frequencies, where M 31 is a source of substantial strength, the angular resolution of the instruments used has not been very high and at centimeter wavelengths, where existing radio telescopes give good angular resolution, the emission from M 31 is so weak that it puts great demands on the sensitivity of conventional receivers. In general, the published radio measurements indicate that the source associated with M 31 consists of a "disk" component, coinciding with the main body of the optical object, and an extended "halo" component occupying roughly 50 square degrees surrounding the center of the galaxy and contributing a major share of the integrated flux. Both the disk component and the halo show an approximately elliptical outline with the major axes having about the same orientation as that of the optical object. In addition, the observations of Large, et al. (1959) at 408 Mc indicated the presence of fine structure in the halo component. However, in this regard there may be some indeterminancy in distinguishing possible fine structure from the effects of background discrete sources not associated with M 31.

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As has been pointed out by Baldwin and Costain (1960), there is a large divergence in published estimates of the spectral index of M 31, ranging from about -0.6 to -1.1. This large uncertainty undoubtedly arises from different interpretations of the extent of the radio source and of the effects of background radiation. In general, it is quite difficult to define the limits of integration in determining the flux of an extended source from measurements made with different angular resolutions. In the work of Baldwin and Costain an attempt is made to allow for this source of error. These authors find for M 31 a spectral index of -0.5 in the frequency range 38 to 408 Mc, and show that the variations in spectral index over the source are not large. This value for the spectral index of M 31 compares favorably with that found by Costain (1960) for the nonthermal component of the radiation from our own galaxy. The observations reported here were made in an attempt to extend to higher frequencies our knowledge of the brightness distribution of the M 31 source.

II. OBSERVATIONS

During July, August, and September, 1960, observations were made of M 31 at a frequency of 1400 Mc, with the 85-foot Tatel telescope. The receiver, a Ewen-Dae scanning hydrogen line radiometer, was used in the continuum as a load comparison radiometer, and was operated without image rejection at a local oscillator frequency of 1400 Mc and a 6 Mc bandwidth. The main lobe of the antenna has nearly perfect axial symmetry and a width between half-power points of 35.4 minutes of arc. The illumination of the paraboloid by the feed is strongly tapered, with the result that sidelobe response is extremely low. Nevertheless, because of the small intensity of the radiation from M 31, no observations were made during the daytime when there would have been the possibility of spurious response due to the sun. The receiver sensitivity was checked frequently by measuring the output of a standard noise tube, and the system response was calibrated by means of observations of the discrete source 16NOA. The adopted 1400 Mc flux density of 16NOA was 44.5×10^{-26} w $(m^2 \text{ cps})^{-1}$ and was derived from the accurate source to Cas A ratios of Heeschen (1961) and the flux density of Cas A, 2500 $\times 10^{-26}$ w $(m^2 \text{ cps})^{-1}$, measured by Findlay and Hvatum with the calibration horn of the National Radio Astronomy Observatory.

All observations were obtained in the form of scans in the region of M 31. The receiver output was recorded on a Sanborn strip-chart recorder and, in addition, was integrated over ten-second intervals while scanning. The integrated output is automatically digitized, printed, and punched on teletype tape. Using a one-second time constant, the peak-to-peak noise deflection on the strip-chart recording was of the order of 2 °K brightness temperature so that the maximum signal from the M 31 source, roughly 0.3 °K antenna temperature, was quite invisible on any given scan recording. Therefore, the detection and measurement of the radiation from M 31 was made possible only by averaging a large number of scans. This was done with a Bendix G-15 computer which accepts the data punched on the teletype tape. Internal estimates of error were made, based on the mutual consistency of the observations at any given scanning position.

III. DISCUSSION

The first series of measurements consisted of declination scans covering a 6° x 6° region centered on M 31. These observations clearly showed a source of maximum brightness temperature 0.3 °K (above the halo component), coinciding well with the main body of the optical galaxy. In addition, the discrete source at $\alpha = 00^h\ 31^m\ 45^s$, $\delta = +39°\ 12'$ (1950), found by Large, et al. (1959) at 408 Mc, was plainly evident and, in fact, seemed substantially stronger, relative to the disk component of M 31, than in the 408 Mc material. This source shows fairly good position correspondence with a faint group of distant galaxies and is probably not associated with M 31. If we assume that this source has a relatively normal spectral index of -0.7 to -0.9, then the spectral index of the disk component between 408 and 1400 Mc would appear to be substantially greater than the value -0.5 found by Baldwin and Costain (1960) at lower frequencies. This effect remains even when corrections are made for the slightly different beamwidths. If we adopt 14 °K as the maximum brightness temperature of M 31 (above the halo component) at 408 Mc, then with a spectral index of -0.5 we would expect the maximum brightness temperature at 1400 Mc to be about 0.7 °K. This is substantially greater than the observed value of approximately 0.3 °K; the observed maximum brightness temperature indicates a spectral index in the neighborhood of -1.0.

The quality of the material obtained in a preliminary survey of M 31 was too poor to warrant a more refined interpretation than that given above. It was therefore decided to restrict the scope of the observational program to the specific problem of determining the brightness distribution of M 31 along the major and minor axes for the purpose of making a direct comparison with the 408 Mc brightness distribution determined by Large, et al. (1959). The observations were obtained by stopping the telescope motion in hour angle and scanning in declination at such a rate that the telescope beam described a path along the major or minor axis of the galaxy. The result of averaging 88 such major axis scans is shown in the upper part of Figure 1; the average of 87 minor axis scans is shown in the upper part of Figure 2. The ordinate in each figure is antenna temperature. The estimated probable error of all observations is about 0.02 °K in brightness temperature. Each of the points plotted in Figures 1 and 2 is actually an integral over a small portion of the brightness distribution. The center of all scans was at $\alpha = 00^h\ 40^m$, $\delta = +41°\ 00'$ (1950), and the position angle of the major axis was assumed to be 38°.

The source indicated at the south end of the major axis distribution is the discrete source referred to above and is probably not associated with M 31. This source and the weak feature at the northern end of the scan make the base-line determination somewhat difficult. However, the single, broad, central maximum is well defined and seems to correspond fairly well in extent with the brightest parts of the optical galaxy. It seems reasonable to designate this feature as the "disk" component of the M 31 source. The brightness distribution along the minor axis (Figure 2) shows a rather complicated baseline and a central feature which seems to be marginally resolved into three components: a relatively strong and narrow central source, corresponding well with the position of the galaxy, flanked by two weaker sources at about one and a half degrees from the center of the galaxy. The central component probably corresponds with the disk component of M 31, and the two companion features are most likely the beginnings of the "spurs" found in the 408 Mc survey. The small inequality of the maximum antenna temperatures for the major and minor axis distributions is compatible with the error estimates and may be due, in part, to the complicated structure of the overlying halo component of the M 31 source.

For purposes of comparison, Figures 1 and 2 show the major and minor axis brightness distributions at 408 Mc published by Large, et al. (1959). The half-power beam

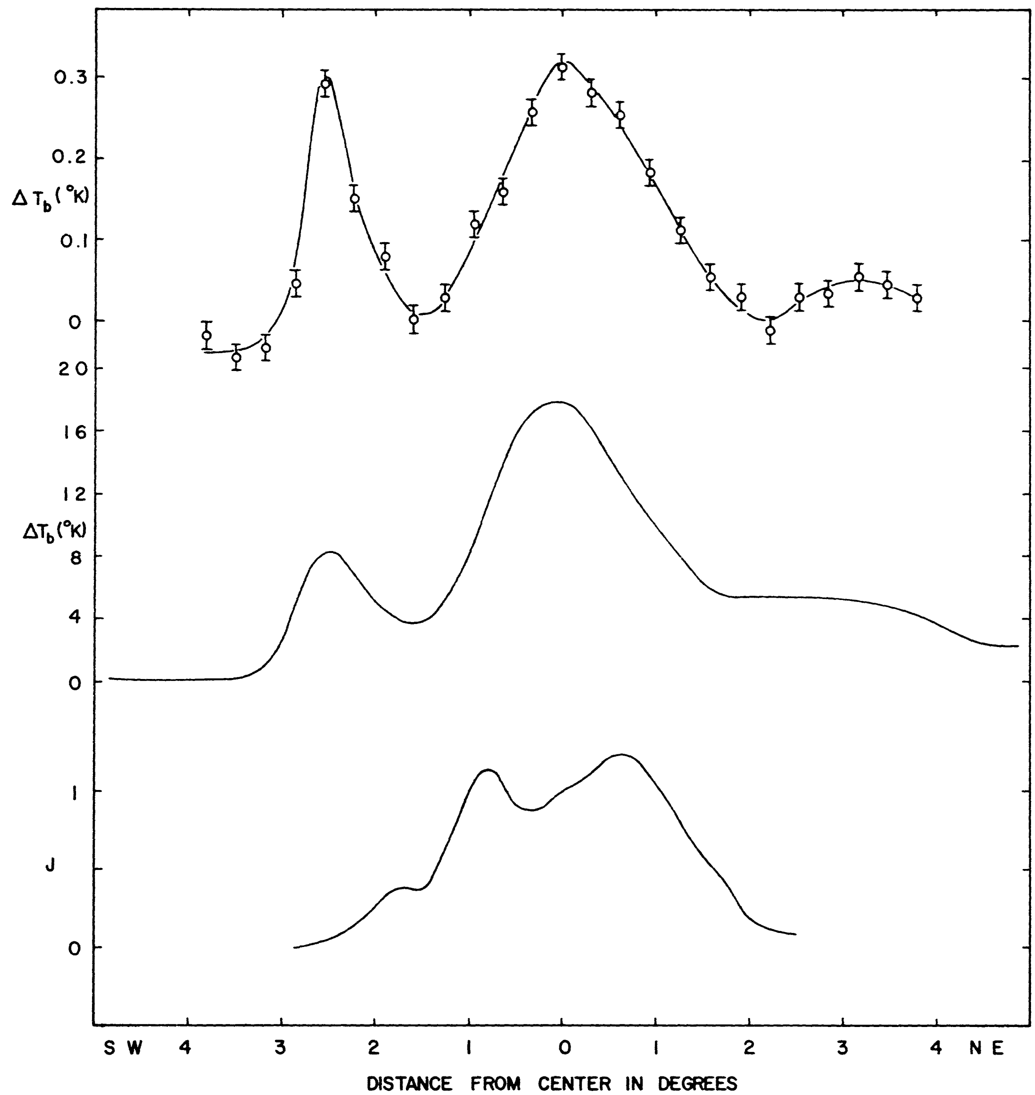

Fig. 1.—— Brightness distribution along the major axis of M 31 at 1400 Mc (upper curve), 408 Mc (middle curve, Large, et al. 1959), and in 21 cm H I line radiation (lower curve, van de Hulst and Raimond 1957). The ordinate in the first two curves is brightness temperature and that in the third curve is brightness in arbitrary units. The probable error of the observations plotted is indicated by the vertical extent of the associated straight lines.

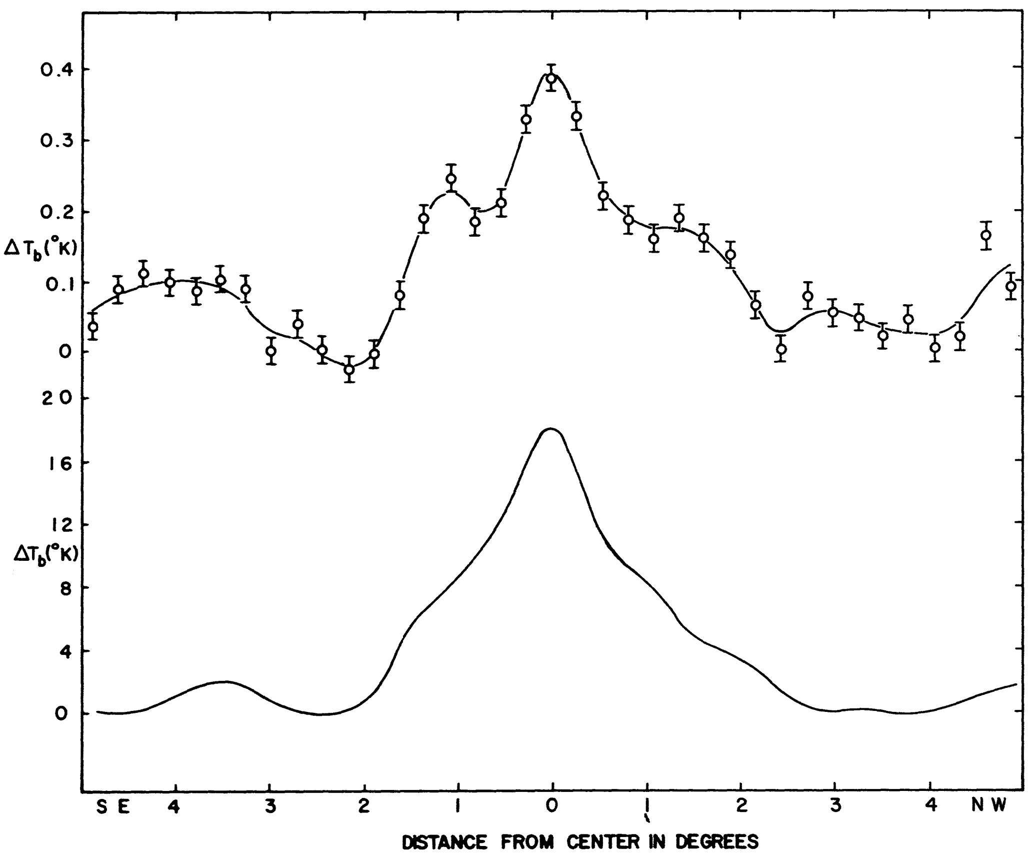

Fig. 2.— Brightness distribution along the minor axis of M 31 at 1400 Mc (upper curve) and 408 Mc (lower curve, Large, et al. 1959). The intensity units and the significance of the plotted points are the same as in Figure 1.

width for these observations was of the order of 40 x 56 minutes of arc, somewhat larger than for the present 1400 Mc observations. There is very good correspondence between most features shown in both surveys, and it is possible that some of these features, other than the obvious disk component, represent fine structure within the halo component of the M 31 source.

It is also of interest to compare the 1400 Mc brightness distribution with the distribution of emission in the 21 cm line of neutral hydrogen. The lowest curve in Figure 1 gives the distribution of the H I emission, integrated over velocity, as given by van de Hulst, Raimond, and van Woerden (1957). The angular resolution of the telescope used in making the 21 cm line study of M 31 was the same as that used in making the 1400 Mc continuum measurements. Except for the curious central minimum in the H I emission distribution, there is considerable similarity between the distributions.

An inspection of Figures 1 and 2 suggests that the intensity of the disc component of the M 31 source, relative to the other features shown, is abnormally weak at 1400 Mc compared to its intensity at 408 Mc. However, because the beam-widths differ somewhat, it is necessary to analyze the data in a more quantitative manner before drawing conclusions concerning the spectral index of the disk radiation. This can best be done, for the limited material available here, by correcting one of the two sets of data for the effects of the different angular resolutions. The technique that has been used in comparing the 1400 Mc results with the 408 survey consists of a partial sharpening of the 408 Mc brightness distribution to a resolution comparable with that of the 1400 Mc observations. The procedure for making these corrections is derived in the Appendix and has been applied to the two-dimensional 408 Mc brightness distribution of Large, et al. The resulting major axis brightness distribution, at a position angle of 38°, is given in the

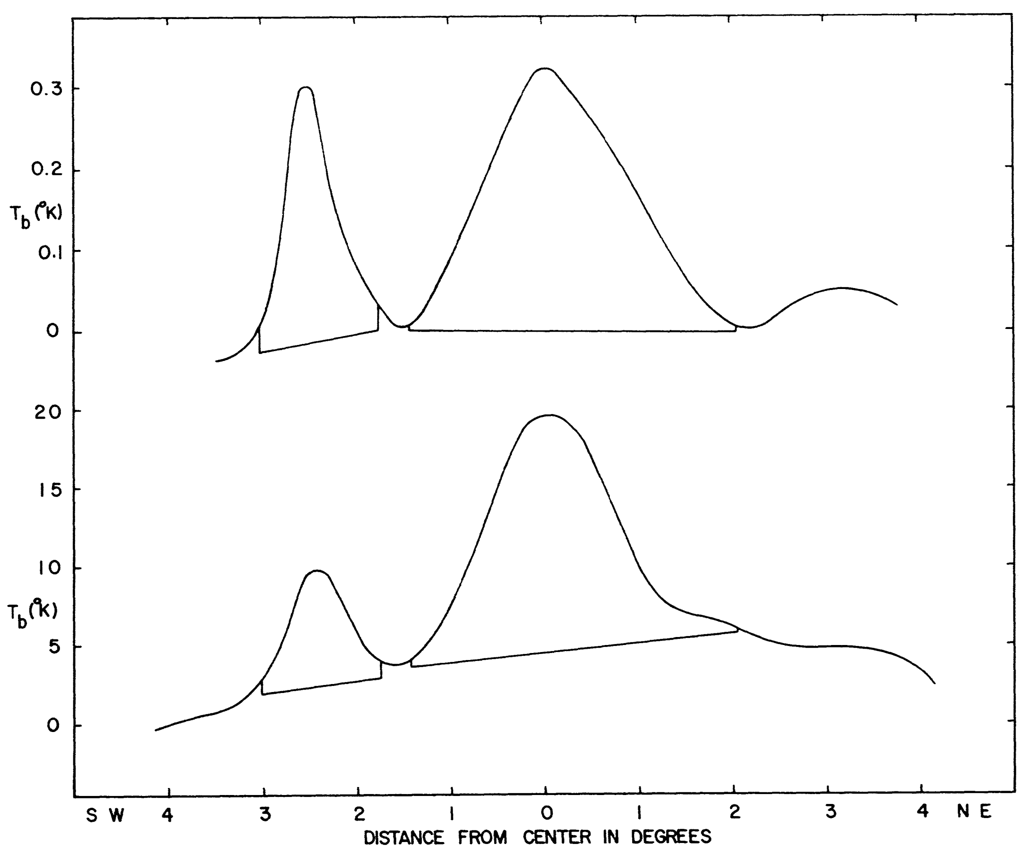

Fig. 3.—— Brightness distribution along the major axis of M 31 at 1400 Mc (upper curve) and the corresponding 408 Mc distribution after adjustment for the beamwidth correction described in the text. The ordinate for both distributions is brightness temperature.

lower part of Figure 3. It was found that the uncorrected distribution at this position angle differed somewhat from the major axis scans of Large, et al., perhaps because these authors have used a slightly different position angle for the major axis. The source of small angular size at the south-west end of the major axis does not show any enhancement as a result of the sharpening process; this is because the source is located a small distance away from the line representing the adopted major axis.

The upper part of Figure 3 gives the 1400 Mc distribution of brightness temperature derived from the present observations, for comparison with the 408 Mc distribution. Although the angular extent of the disk component is fairly well defined for both distributions, it is somewhat more difficult to separate the disk component from the background radiation on an objective basis. In integrating these distributions for the disk radiation, limits of integration were set as shown in Figure 3; the vertical lines indicate the angular limits, and the horizontal lines indicate the background radiation limit. After integration, the resulting ratio of the 408 Mc response to the 1400 Mc response is 45.1, corresponding to a spectral index of -1.09. A similar determination of the spectral index for the discrete source south-west of M 31, using the integration limits indicated in Figure 3, yields a value of -0.64. Meaningful estimates of accuracy for each of these determinations are difficult to make. The uncertainty in each case may be as large as 0.2; however, since much of the error will be systematic in nature, the large difference in the spectral index for the two sources is probably significant. This difference lends support to the conclusion that the disk component of the M 31 source has a spectral index near -1.0 between 408 Mc and 1400 Mc, in contrast to the value of -0.5 found by Baldwin and Costain (1960) at lower frequencies. Because of the limited nature of the present observations, no reliable estimate of the total flux density of the disk component is possible.

In an attempt to check the foregoing conclusions, an extensive series of drift curves at 3000 Mc were made through the nucleus of M 31. At this frequency the beamwidth of the telescope is approximately 16 minutes of arc. These measurements yielded no indication of a source at the position of M 31, and it was possible to set an upper limit of about 0.03 °K on the maximum brightness temperature of the disk component. Taking into account the source size, this value is smaller than we would expect, by a factor of about two, if the source has a spectral index of -0.5, and thus seems to support the conclusion that the spectrum of the disk component of M 31 becomes steeper at higher frequencies.

IV. CONCLUSIONS

It should be emphasized that the conclusions reached here concerning the M 31 source refer only to the disk component, which probably represents a small fraction of the radiation from the source. The rather steep spectrum found, although at first surprising, is not unknown among "normal" galaxies (Heeschen 1960). However, the apparent increase of spectral index with increasing frequency is curious. The observations at 3000 Mc indicate that even at this high frequency there is no substantial thermal radiation from the disk of M 31. We do not at present have information on the effective electron density or mass of material in the H II regions of M 31, information which is necessary for a detailed estimate of the expected thermal radiation from the disk. However, excluding the effects of absorption, the upper limit set on the maximum brightness temperature at 3000 Mc is equivalent to about 1000 Orion nebulae at the distance of M 31. This corresponds to about 10^5 solar masses (Menon 1961). If the effective electron density for the ionized hydrogen of M 31 is less by a factor of 100 or 1000, than that for the Orion Nebula, then the total mass of ionized hydrogen in M 31 can be as high as 10^7 to 10^8 solar masses and still not have been detectable in the present 3000 Mc observations. In this connection it may be mentioned that a preliminary series of scans across M 33 at 3000 Mc showed this object to be a source of maximum brightness temperature of approximately 0.15 °K. It is clear that observations of somewhat higher angular resolution and considerably greater sensitivity will be of great value in advancing our knowledge of M 31 as a radio galaxy.

The author wishes to acknowledge the assistance of Mr. R. W. Hobbs who obtained some of the early observations reported here.

APPENDIX

If T_b is an observed brightness distribution and T_b' is that distribution which would have been observed using an instrument of slightly higher angular resolving power, then T_b and T_b' are related to the true distribution T by the convolutions

$$T_b = A * T \text{ and } T_b' = A' * T \ ,$$

where A is the actual apparatus function and A' is the apparatus function of slightly higher resolution. Taking Fourier transforms we find the spectrum of T_b' to be

$$\overline{T_b'} = \frac{\overline{A'}}{\overline{A}} \overline{T_b} \ .$$

For the present case let the apparatus functions be gaussian of the form

$$A(x,y) = \frac{1}{2\pi\sigma\tau} \exp \left\{ -\frac{1}{2} \left(\frac{x^2}{\sigma^2} + \frac{y^2}{\tau^2} \right) \right\} \tag{1}$$

and

$$A'(x,y) = \frac{1}{2\pi m n \sigma\tau} \exp \left\{ -\frac{1}{2} \left(\frac{x^2}{m^2\sigma^2} + \frac{y^2}{n^2\tau^2} \right) \right\} \ , \tag{2}$$

where $m < 1$ and $n < 1$. Taking the Fourier transforms of equations (1) and (2) we find

$$\frac{\overline{A'}(u,v)}{\overline{A}(u,v)} = \exp \left\{ 2\pi^2 \left[(1-m^2)\,\sigma^2 u^2 + (1-n^2)\tau^2 v^2 \right] \right\} .$$

If the apparatus functions are not greatly different in dispersion, that is, if m and n are nearly unity, the approximation

$$\exp \left\{ \theta^2 \right\} = 1 + \sin^2 \theta + \text{-------}$$

will hold to a fairly high accuracy and we can write

$$\overline{T_b'}(u,v) \cong \left\{ 1 + \sin^2 \left[\pi (1-m^2)^{1/2} \alpha u \right] + \sin^2 \left[\pi (1-n^2)^{1/2} \beta v \right] \right\} \overline{T_b}$$

or, for low spatial frequencies,

$$\overline{T'_b} \approx \left[1 + (1-m^2)\sin^2 \pi\alpha u + (1-n^2)\sin^2\pi\beta v\right] \overline{T_b}, \tag{3}$$

where the "peculiar intervals" α and β are given by

$$\alpha = \sqrt{2}\,\sigma \text{ and } \beta = \sqrt{2}\,\tau.$$

Taking the Fourier transforms in equation (3) we get, in the notation of Bracewell (1960)

$$T'_b = \left[\frac{(4-m^2-n^2)}{2}\ {}^2\delta\ (x,y) - K'\right] * T_b, \tag{4}$$

where

$$K' = \frac{(1-m^2)}{4}\left[{}^2\delta\ (x-\alpha, y) + {}^2\delta\ (x-\alpha, y)\right] + \frac{(1-n^2)}{4}\left[{}^2\delta\ (x, y+\beta)\ {}^2\delta\,(x, y-\beta)\right]$$

and the δ's are two dimensional impulse functions.

In the present case this correction technique is being applied to the 408 Mc survey for which the beam shape was described as elliptical. However, at the position angle of the major axis of M 31, the beam width is essentially the same as in the perpendicular direction. Since the grid of values of T_b was chosen to be aligned with the major and minor axes, the correction procedure becomes symmetrical and equation (4) reduces to

$$T'_b = \left\{{}^2\delta\ (x,y) + (1-m^2)\left[{}^2\delta\ (x,y) - K'\right]\right\} * T_b,$$

where

$$K' = \frac{1}{4}\left[{}^2\delta\ (x+\alpha, y) + {}^2\delta\ (x-\alpha, y) + {}^2\delta\ (x, y+\alpha) + {}^2\delta\,(x, y-\alpha)\right].$$

As applied to the present problem $\alpha = 27'.7$ and $m = 0.767$.

REFERENCES

Baldwin, J. E. and Costain, C. H. 1960, M. N., 121, 413.

Bracewell, R. N. 1960, chapter in Menzel, D. H. (ed.), The Radio Noise Spectrum (Cambridge: Harvard University Press), p. 141.

Brown, R. Hanbury and Hazard, C. 1951, M. N., 111, 357.

------. 1959, ibid., 119, 297.

Costain, C. H. 1960, M. N., 120, 248.

Heeschen, D. S. 1961, Ap. J. 133, 322.

Large, M. I., Mathewson, D. S., and Haslam, C. G. T. 1959, Nature, 183, 1250.

Menon, T. K. 1961, Pub. N. R. A. O., 1, 1.

Seeger, C. L., Westerhout, G., and Conway, R. G. 1957, Ap. J., 126, 585.

van de Hulst, H. C., Raimond, E., and van Woerden 1957, B. A. N., 14, 1.