OBSERVATIONS OF TWO OCCULTATIONS OF THE CRAB NEBULA BY THE MOON, AT 400 Mc/s

BY C. L. SEEGER AND G. WESTERHOUT

Lunar occultations of the Crab nebula (Tau A) were observed on 3 and 30 November 1955, using a 25-m mirror and 400 Mc/s receiver. It was found that the radio brightness is coextensive with the visible nebula. WOLTJER's data were used to calculate the corresponding optical occultations of the amorphous mass. The radio brightness distribution is smooth and flatter than the optical.

Introduction

A series of lunar occultations of the Crab nebula (M1, 05N2A, Tau A) occurred in 1955-1956 and those of November 3 and 30, 1955, were observed in Dwingeloo. These occasions, which will not recur at this latitude for a number of years, were judged of sufficient importance to interrupt the construction work on the drive of the 25-m telescope for two intervals of four days each and to install 400 Mc/s receiving equipment. Various test observations of point sources and extended regions made during these periods have been reported separately [1]).

The chief advantage of an occultation measurement is the high resolution obtainable. The resolution is limited only by the Fresnel diffraction pattern and by the precision of the observed occultation curve, i.e. the signal to noise ratio. At 400 Mc/s, the unit abscissa for the Fresnel pattern is

$$u = (\lambda/R)^{\frac{1}{2}} = 4.42 \times 10^{-5} \text{ radian} = 9''.1$$

where $R = 3.84 \times 10^{10}$ cm is the average distance of the moon.

Optically [2]), the Crab nebula has an east-west extension of about 6′ and it is known that the radio size is of the same order. Assuming a precision of one percent in the 400 Mc/s occultation curve, whether Fresnel diffraction will produce an observable effect depends on the steepness of the radio brightness distribution. Unless an appreciable part, say one quarter, of the total radio brightness lies in a strip of width $u/2$ or less, there may be no observable ripples on the recorded occultation curve. Furthermore, if the brightness distribution is relatively smooth and has a halfwidth on the order of 3′, the effect of Fresnel diffraction on its form and apparent position will be entirely negligible.

LINK [3]) and ELSMORE [4]) have stressed the importance of using such an occultation for finding an upper limit to the angular displacement that might be caused by refraction in an ionized lunar atmosphere. If present to a sufficient degree, such refraction would delay the intensity-time curve during ingress with respect to the curve predicted from simpler geometrical considerations alone, and advance the corresponding curve at egress. In the present case it was felt to be even more important to find the brightness distribution across the nebula. Earlier 3.7 m interferometer measurements by BALDWIN [5]) had shown that the radio diameter of the nebula was greater than the optical diameter. As this fact had received a rather prominent place in OORT's and WALRAVEN's [6]) explanation of the radiation from the Crab nebula, an independent check was desirable.

The result of a single ingress or egress curve is, of course, a "curved" strip distribution. Under more favorable circumstances than obtained during these occultations, where the centre of the moon passed almost exactly over the centre of the nebula, the disappearance and reappearance of the nebula would make possible a resolution of the brightness distribution in two coordinates.

Observations

The pertinent receiver parameters were

$\nu = 400$ Mc/s
$\Delta\nu = 9$ Mc/s
$t_0 = RC = 0^s.1$
Chart speed = 6 cm per minute

Tau A gave a net antenna temperature [7]) of about 123°K. Cable losses reduced this to approximately 75°K at the receiver input terminals. Thermal noise on the record was 1°K. The above time constant and paper speed were chosen to improve the discrimination against man-made interference. Time marks accurate to a fraction of a second were inserted on the record at frequent intervals during the observations. Interference, when audible, was noted on the records. Unfortunately, when working at such levels, it is quite possible for interference to produce a significant deflection and yet remain otherwise indistinguishable. One characteristic of such interference is of some slight help. It always produces a positive deflection.

The records were read every ten seconds, each

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[1]) C. L. SEEGER, G. WESTERHOUT and H. C. VAN DE HULST, *B.A.N.* **13**, 89 (No. 472), 1956.

[2]) L. WOLTJER, *B.A.N.* **13**, 302 (No. 478), 1957.

[3]) F. LINK, Radio Astronomy Symposium 1955, *I.A.U. Symposium No.* 4, Ch. 77, 1957.

[4]) B. ELSMORE, Radio Astronomy Symposium 1955, *I.A.U. Symposium No.* 4, Ch. 78, 1957.

[5]) J. E. BALDWIN, *Observatory* **74**, 120, 1954.

[6]) J. H. OORT and Th. WALRAVEN, *B.A.N.* **13**, 285 (No. 462), 1956.

[7]) C. L. SEEGER, G. WESTERHOUT and H. C. VAN DE HULST, *B.A.N.* **13**, 89 (No. 472), 1956.

reading being an average over plus and minus five seconds about the tabulated times. Interference lasting much less than ten seconds was minimized by the method of reading [1]. Interference lasting ten seconds or longer will appear in the data presented here and it is left to the judgement of the user of these data to smooth under peaks appearing on the individual curves which are not correlated with events on the other curves.

Since the sensitivity of 3 November differed from that of 30 November, the data of this day were adjusted in scale to fit the data of the 30th. Because of the circumstances, this adjustment must remain a matter of personal judgement.

The antenna had a half-power beamwidth of 2°. Setting in elevation and azimuth were accomplished by hand according to a calculated schedule which maintained a pointing error of less than $0^\circ.1$. The adequacy of the positioning schedule was checked during practice runs the day before each occultation.

The ingress of 3 November occurred with the source setting in the altitude range 3—2°. The observations were marred by scintillation and various forms of man-made static. There was also a steady baseline drift due to increasing air and ground radiation entering the antenna beam. Peaks and dips due to the slow scintillation [2] were as much as five percent of the Tau A signal during the period just prior to the occultation. Because of the monitoring for interference and the method of reading the record, the small-scale variations shown in Figure 1 are believed to be chiefly due to scintillation.

On 30 November, ingress occurred at an altitude of about 14° and egress at about 21°. From the point of view of interference, conditions appeared to be nearly ideal during ingress. During egress there was some small-scale interference and, also, a sudden change in the weather which impaired the performance of the part of the equipment mounted outdoors.

Table 1 gives the observational data and the results of a calculated eclipse, the details of which are set forth in the following sections. In this table, the first column gives the time of the observation or calculation. The units are mean solar minutes difference from the calculated time (t_0) when the moon's limb bisected the line joining the two central stars of the nebula. Then, for each event, there are four columns. Column 1 gives the intersection of the moon's limb with the line of constant declination passing midway between the two central stars of the nebula. The units are minutes of arc measured positively to the east from the mean right ascension of the two central stars. Column 2 gives the angle, measured clockwise from the east, of the moon's limb at this intersection. Column 3 gives the 400 Mc/s intensity of the radiation from the nebula in percent of the unobscured value. Column 4 gives the corresponding intensity of the calculated optical eclipse. The observed and calculated occultation curves are plotted in Figure 1.

Positional data

The 25-m telescope of the observatory at Dwingeloo is located at

Longitude $-\ 25^{m}35^{s}.247 = -\ 6^\circ 23' 48''.7$
Latitude $52^\circ 48' 46''.72$
Height above sea level 25 meters

Mr G. Pels determined the position of the central double star from a plate taken with the 12″ Leiden refractor. The mean coordinates for 1950.0 are

$\alpha = 5^{h}31^{m}31^{s}.46 \quad \delta = 21^\circ 58' 54''.8$
$\alpha = 5^{h}31^{m}31^{s}.64 \quad \delta = 21^\circ 58' 58''.9$

All occultation computations are made using the midpoint (M) of this double star as the coordinate centre. The mean place of point M is

$\alpha_M = 5^{h}31^{m}31^{s}.55 \quad \delta_M = 21^\circ 58' 56''.8$

The apparent place of point M was computed from the independent day numbers given in the *Nautical Almanac*.

$\alpha_M = 5^{h}31^{m}54^{s}.81 \quad \delta_M = 21^\circ 59' 11''.5$ (1955, Nov. 3.4)
$\alpha_M = 5^{h}31^{m}55^{s}.45 \quad \delta_M = 21^\circ 59' 11''.1$ (1955, Nov. 30.8)

The position of the centre of the moon was found by taking the hourly geocentric coordinates from the Nautical Almanac, interpolating half-hourly values, and correcting these for parallax with the formula given by Smart [3].

The positions of the moon from the ephemeris were corrected to obtain the true positions of the moon. The correction term [4], obtained from star occultations, was a predicted value for 1954, and amounted to a shift in longitude of $\Delta\lambda = -\ 3''.0$. Therefore, the ephemeris was entered 5^{s} earlier than the times given. No correction was applied for the difference in refraction between the moon and the Crab nebula, which resulted in a time delay of less than $0^{s}.5$ [5]. The intersection of the moon's limb with the declination circle through point M, and the position angle of the limb at that intersection, were calculated from the positions of the moon's centre and the moon's radius, corrected for Dwingeloo. These data were then transformed into rectangular coordinates on the

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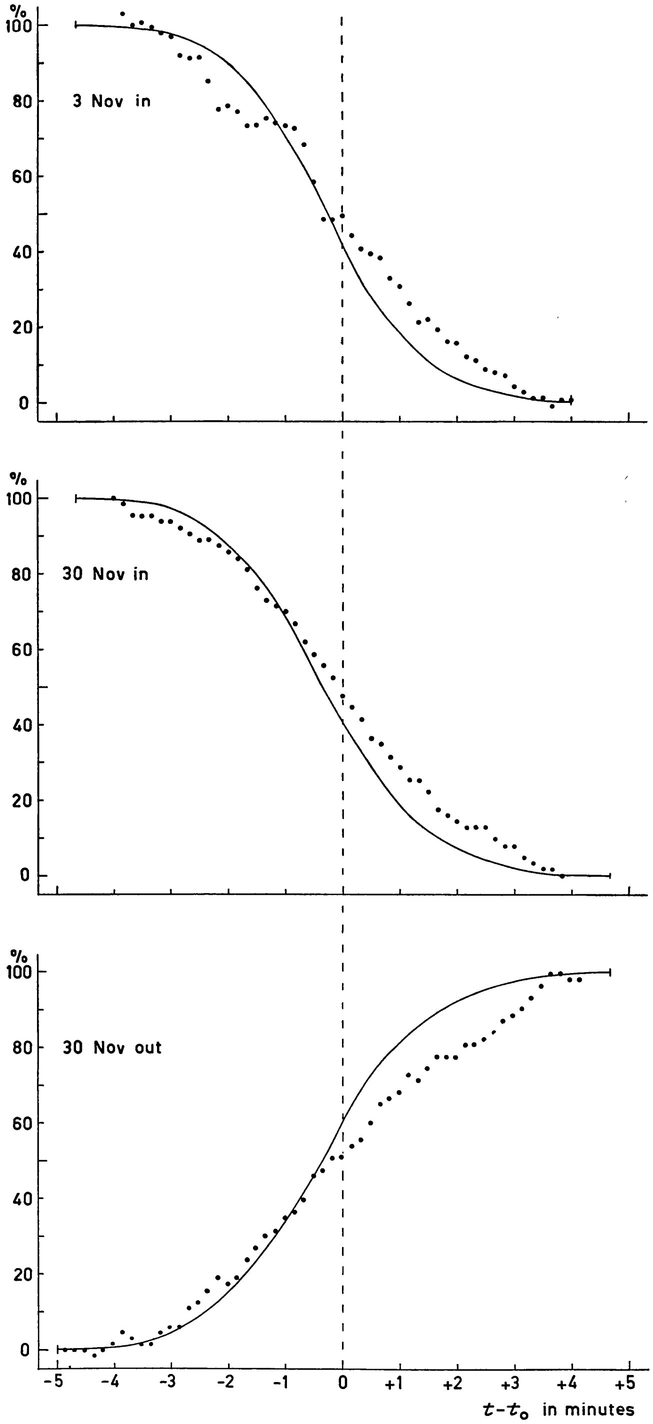
TABLE 1

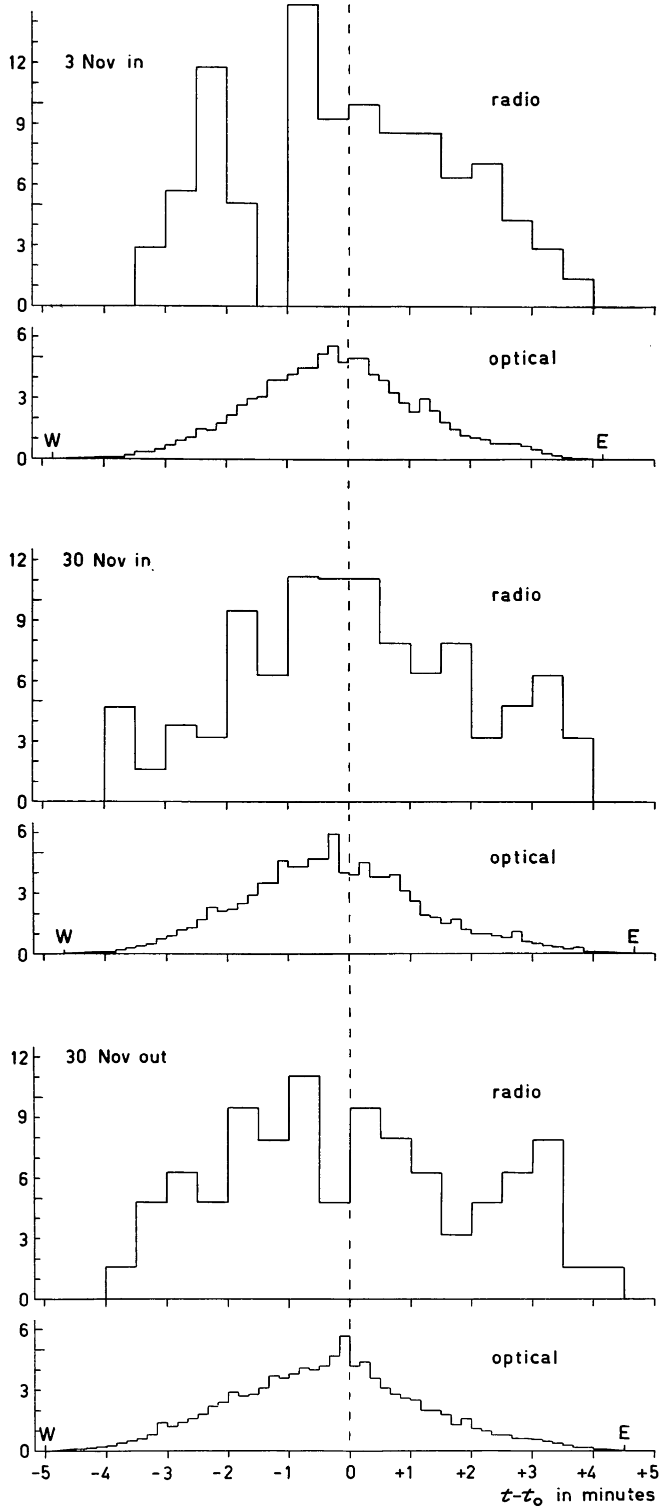
$t - t_0$ (UT)	IN Nov. 3				IN Nov. 30				OUT Nov. 30			
	moon's limb		percentage		moon's limb		percentage		moon's limb		percentage	
	X	φ	Radio	Optical	X	φ	Radio	Optical	X	φ	Radio	Optical
$-5^{m}\ 00^{s}$					− 3′.28	93°.09	100		− 3′.11	87°.00		.00
50				100.00	3.17		↓		3.00		0.0	.01
40				99.96	3.06		↓	100.00	2.90		0.0	.03
30				99.94	2.95		↓	99.96	2.79		0.0	.10
20				99.92	2.84		↓	99.94	2.69		− 1.6	.18
10				99.88	2.73		↓	99.89	2.58		0.0	.33
− 4 00	− 2′.65	104°.03		99.81	2.62	92.97	100	99.81	2.48	86.89	+ 1.6	.53
50	2.54		102.9	99.70	2.51		98.4	99.70	2.37		4.8	.79
40	2.43		100.0	99.54	2.40		95.3	99.46	2.27		3.2	1.17
30	2.32		100.7	99.31	2.29		95.3	99.16	2.17		1.6	1.67
20	2.21		99.3	98.94	2.18		95.3	98.75	2.07		1.6	2.25
10	2.10		97.9	98.55	2.07		93.7	98.22	1.97		4.8	3.06
− 3 00	1.99	104.31	97.1	98.04	1.97	92.85	93.7	97.48	1.86	86.79	6.4	4.49
50	1.88		92.1	97.34	1.86		92.1	96.57	1.76		6.4	5.67
40	1.77		91.4	96.42	1.75		90.5	95.40	1.65		11.1	7.07
30	1.65		91.4	95.32	1.64		88.9	94.10	1.55		12.7	8.64
20	1.54		85.7	93.83	1.53		88.9	92.42	1.44		15.9	10.45
10	1.43		77.8	92.38	1.42		87.3	90.15	1.34		19.1	12.63
− 2 00	1.32	104.60	78.6	90.61	1.31	92.73	85.7	88.08	1.24	86.68	17.5	15.05
50	1.21		77.2	88.39	1.20		84.1	85.90	1.13		19.1	17.91
40	1.10		73.5	85.70	1.09		81.0	83.43	1.03		23.8	20.66
30	.99		73.5	82.71	.98		76.2	80.52	.93		27.0	23.48
20	.88		75.7	79.59	.87		73.0	76.98	.82		30.2	26.58
10	.77		74.3	75.71	.76		71.4	73.46	.72		31.5	30.31
− 1 00	.66	104.88	73.5	71.77	.65	92.61	69.9	68.83	.62	86.57	34.9	33.94
50	.55		72.9	67.52	.54		66.7	64.57	.51		36.5	37.79
40	.44		68.5	62.99	.43		61.9	60.29	.41		39.7	41.87
30	.33		58.6	58.50	.32		58.7	55.57	.31		46.0	45.90
20	.22		48.6	53.26	.21		55.6	50.89	.20		47.6	50.09
10	− .11		48.6	47.69	− .10		52.4	44.99	− .10		50.8	54.75
0 00	0.00	105.16	49.3	42.93	0.00	92.50	47.6	41.00	0.00	86.46	50.8	60.49
10	+ .11		44.3	37.90	+ .11		44.5	37.08	+ .10		54.0	64.68
20	.22		40.7	32.92	.22		41.3	32.58	.20		55.6	69.05
30	.33		39.3	28.69	.33		36.5	28.77	.31		60.3	72.61
40	.44		35.7	24.80	.43		34.9	25.01	.41		65.1	75.81
50	.55		32.9	21.47	.54		31.5	21.14	.51		66.7	78.63
+ 1 00	.66	105.44	30.7	18.71	.65	92.38	28.6	18.04	.62	86.35	68.3	81.25
10	.77		26.4	16.37	.76		25.4	15.68	.73		73.0	83.75
20	.88		21.4	13.37	.87		25.4	13.80	.83		71.4	85.72
30	.99		22.1	10.96	.98		22.2	12.00	.94		74.6	87.74
40	1.10		19.3	9.11	1.09		17.5	10.50	1.04		77.8	89.55
50	1.21		16.4	7.59	1.20		15.9	8.77	1.14		77.8	90.88
+ 2 00	1.32	105.72	15.7	6.41	1.31	92.26	14.3	7.47	1.24	86.24	77.8	92.53
10	1.43		12.1	5.33	1.42		12.7	6.44	1.35		81.0	93.65
20	1.54		11.4	4.31	1.53		12.7	5.47	1.45		81.0	94.65
30	1.65		8.6	3.50	1.64		12.7	4.61	1.55		82.6	95.43
40	1.77		7.8	2.68	1.75		9.5	3.84	1.66		84.1	96.22
50	1.88		7.1	1.90	1.86		7.9	2.71	1.76		87.3	96.87
+ 3 00	1.99	106.00	4.3	1.26	1.96	92.14	7.9	2.10	1.86	86.13	88.9	97.52
10	2.10		2.9	.75	2.07		4.8	1.60	1.97		90.5	98.13
20	2.21		1.4	.43	2.18		3.2	1.18	2.07		93.7	98.62
30	2.32		+ 1.4	.21	2.29		1.6	.83	2.17		96.8	99.00
40	2.43		− .7	.10	2.40		1.6	.58	2.28		100.0	99.33
50	2.54		+ .7	.03	2.50		0.0	.27	2.38		100.0	99.55
+ 4 00	+ 2.65	106.28	+ .7	.00	2.61	92.02	↓	.14	2.48	86.02	98.4	99.78
10					2.72		↓	.07	2.59		98.4	99.88
20					2.83		↓	.02	2.69		101.6	99.94
30					2.94		↓	.01	2.79		100.0	99.96
40					3.05		1.6	.00	2.90			100.00
50					3.16		1.6		3.00			
+ 5 00					+ 3.27	91.91	0.0		+ 3.10	85.91		

FIGURE 1



Lunar occultation curves of the Crab nebula on 3 and 30 Nov 1955. Dots are 400 Mc/s observations, solid lines the calculated optical occultations. t_0 is the calculated time of occultation of the mean position of the central double star.

FIGURE 2



The unsmoothed strip brightness distributions of the Crab nebula. Ordinates are in arbitrary units. If the same differencing interval had been used, the maximum of the optical distribution would have been about 1.5 times the radio maximum.

tangent plane through M and coordinates relative to M were found. Through interpolation, the occultation times of point M were found. These times were checked independently by computing them according to BESSEL's method [1]. These occultation times (t_0) and the corresponding radii of the moon were

3 Nov. 1955	ingress	$10^h02^m35^s.5$ U.T.	16′.47
30 Nov. 1955	ingress	$18^h05^m28^s.6$ U.T.	16′.78
30 Nov. 1955	egress	$18^h58^m11^s.5$ U.T.	16′.78

These times are accurate to one second and the positional data in Table 1 are good to one second of arc.

The optical occultation

To construct the optical occultation curves, the data of WOLTJER's [2] Table 2 were plotted on a scale of 10 cm per minute of arc. Then the outline of the moon's limb was drawn in for every ten seconds of time and the brightness summed for each ten-second strip. The strip brightness distributions obtained in this way are plotted in Figure 2. This figure also contains rough radio strip brightness distributions derived by differencing the data of Table 1 every thirty seconds. Because of the greater precision of the optical data, short vertical marks have been inserted in Figures 1 and 2 to indicate the limits of the nebula as defined by WOLTJER's measures. The data for the optical occultation curves and for Table 1 were found by cumulatively summing the previously tabulated brightness distributions.

The occultation curves in Figure 1 were plotted against time for convenience. A rough conversion factor of $0'.65/1^m$ can be used, but it must be noted that the aspect of the moon's limb was different for each curve, particularly for the 3rd of November when the tangent to the limb was more nearly in line with the long axis of the nebula.

Discussion

Bearing in mind that the data presented here are restricted to the 400 Mc/s east-west curved strip brightness distribution of the Crab nebula, Table 1 and the accompanying figures permit the following conclusions.

1) The radio source Tau A, at 400 Mc/s, has essentially the same maximum extent as, and is coincident with, the Crab nebula as defined by WOLTJER's [3] measures of the photographs taken by BAADE in the light of the green continuum.

2) The radio distribution is much flatter than the corresponding green light distribution.

3) The 400 Mc/s distribution is somewhat narrower than that found on 3.7 m by COSTAIN, ELSMORE and WHITFIELD [4].

4) The central stars are effectively half way between the east and west limits of the optical nebula. The half intensity points of the calculated occultation curves are consistently about 12″ west of these stars while the corresponding points on the 400 Mc/s curves for 30 November are about 3″ west.

5) The close agreement between the two half-intensity points, when the two curves for the 30th are compared using the calculations outlined in the previous sections, indicate the absence of any detectable refraction by an ionized lunar atmosphere. This was to be expected, on the basis of LINK's [5] calculations.

6) If the ingress and egress curves for the 30th are reflected upon each other it is apparent that the small difference in the scanning of the nebula by the east and west limbs of the moon changed the form of the observed occultation curves more than it changed the calculated optical curves.

7) Clearly, as mentioned by OORT and WALRAVEN [6], the ratio of the radio to the optical brightness distributions varies substantially across the nebula, being greatest in the outer regions.

Since discussion of these occultation data, as it may apply to theories of the conditions in the nebula, will be deferred until a later time, it remains only to acknowledge the assistance of many persons, members of the Netherlands Foundation for Radio Astronomy and of Werkspoor N.V., who contributed so much to the execution of these observations. The writers wish to express their special thanks to Mr G. PELS for checking the accuracy of the fundamental calculations involved in deriving the optical data. The radio source occultation prediction service of H.M. Nautical Almanac Office is gratefully acknowledged.

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