RADIO OBSERVATIONS
OF A LUNAR OCCULTATION OF THE CRAB NEBULA

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Summary

Observations were made at wave-lengths of 3.7 m and 7.9 m of the lunar occultation of the Crab Nebula on 1956 January 24. At 3.7 m, observations were made throughout the occultation, and the distribution of radio brightness across the nebula was derived. The position of the radio source agrees closely with that of the optical nebula but its size is somewhat larger.

At 7.9 m, severe man-made interference occurred during the emersion but observation of the immersion suggested that at this wave-length the source was considerably more extended. Recent optical evidence has suggested that the emission from the Crab Nebula is due to the acceleration of high energy electrons in weak magnetic fields; a variation of the spectral distribution of the radio emission from centre to limb may be associated with a radial variation in the energy spectrum of the high energy particles or of the magnetic field.

By comparing the time of obscuration at 3.7 m with the computed value, an estimate was made of the refraction occurring in the lunar atmosphere; an electron density at the Moon’s surface of $10^6$ cm$^{-3}$ was derived, a figure which corresponds to a surface density of the lunar atmosphere about $10^{-13}$ of that of the Earth’s.

1. Introduction.—During the period 1955–1956, two occultations of the Crab Nebula by the Moon were visible from Cambridge. Observations of these were made to determine in greater detail the distribution of radio brightness across the source, previously derived by interferometric methods (Baldwin, 1954; Mills, 1953), and to determine with more certainty the density of the lunar atmosphere deduced from the occultation of the radio source in Gemini (Elsmore and Whitfield, 1955).

The first occultation occurred low in the sky on 1955 November 30, and the observations were seriously affected by man-made interference. Only the second occultation, that of 1956 January 24, will be discussed.

2. Apparatus.—Observations were made at wave-lengths of 3.7 m and 7.9 m. At both wave-lengths, phase-switching receivers (Ryle, 1952) were used in conjunction with fixed aerial systems. The positions of the source, as seen from Cambridge at times of immersion and emersion, are indicated in Fig. 1.

(a) The 3.7 m wave-length aerial system.—The aerial system was designed to fulfil two conflicting requirements: first to discriminate between the radiation from the source and that from the general galactic structure, and secondly to allow continuous observation of the source for several minutes on either side of the calculated times of immersion and emersion. These conditions were satisfied by using two widely-spaced aerials on an axis which produced interference maxima running tangentially to the path of the source, as indicated in Fig. 1.
The two aerials were separated by a distance of 213 m on a horizontal axis of azimuth 120° East of North, giving an effective aperture of 37 wave-lengths. Each of the two aerials consisted of a broadside array of eight half-wave dipoles.

(b) The 7·9 m wave-length aerial system.—At 7·9 m wave-length, an existing aerial system was used which consisted of two groups of aerials mounted 56 wave-lengths apart on an East–West axis. One group contained 4, the other 16 Yagi aerials. The maxima of the reception pattern in the direction of the occultation were approximately horizontal and 2° apart. Two different phasing arrangements of the aerials in the larger group were necessary to observe both immersion and emersion.

Fig. 1.—The path of the source as seen from Cambridge on 1956 January 24. The axis of the 3·7 m aerial system has an azimuth of 120°E, and the position of the maxima and minima are indicated by −−−− and . . . . , respectively.

3. Observations: (a) 3·7 m wave-length.—The record of the occultation is shown in Fig. 2 together with a mean curve determined from records obtained on days before and after the occultation. Besides the deflection produced by the Crab Nebula, the records show minor contributions from other sources, the principal one being the nebulosity IC 443 in Gemini (maximum at 16\textsuperscript{h} 52\textsuperscript{m} 5 U.T.). The effect of these sources may be completely removed by subtracting the two curves from one another. The difference, at any time, represents the radiation from the area occulted by the Moon. In order to express this difference as a fraction of the total intensity, it is necessary to know the deflection that would have been produced, at this time, by the whole source. This was computed from a knowledge of the position of the source and the geometry of the receiving system. The occultation curves obtained at immersion and emersion are shown in Fig. 3(a).

The path of the Moon’s centre, as viewed from Cambridge, passed very near to the position of the centre of the Crab Nebula. Thus at immersion and emersion two nearly identical scans across the source were obtained. The two curves were superposed for comparison in Fig. 3(a); the time interval for the best fit was found to be 59·6 minutes. The calculated time interval between immersion and emersion was 59·2 minutes. The discrepancy of 0·4 minutes.
may be due to refraction in the lunar atmosphere and the significance of this result will be discussed in Section 4 (c).

(b) 7.9 m wave-length.—The observations at 7.9 m were very seriously affected by man-made interference. This limited the accuracy of the measurements at immersion to 15–20 per cent and made observation of the emersion impossible. The immersion curve is shown in Fig. 3 (b).

4. Interpretation: (a) Distribution of brightness.—During immersion, successive strips of the source are covered by the passage of the Moon from West to

![Fig. 2.—The record of the occultation of 1956 January 24, obtained at 3.7 m. The smooth curve is the mean of records obtained on days before and after the occultation. The dashed lines show the calculated times of immersion and emersion of the optical centre of the Crab Nebula.](image)

![Fig. 3.—Occultation curve of 1956 January 24 at (a) λ = 3.7 m and (b) λ = 7.9 m. Immersion and emersion are indicated by □ and ● respectively. The times are relative to the calculated time of immersion of the optical centre of the Crab Nebula (emersion displaced 59.6 minutes).](image)
East. Therefore the curve shown in Fig. 3 (a) represents the integral of the distribution of brightness projected on an East-West axis. This curve was differentiated to yield the distribution shown in Fig. 4. The shape of the outer limbs cannot be determined accurately, but the area beneath the curve for radial distances greater than 2.5 minutes of arc cannot be appreciably different from that shown.

The accuracy of the points in Fig. 3 (b) is not sufficient to give a reliable measure of the strip distribution of brightness at 7.9 m; it is, however, possible to find the approximate width of the source by determining the occultation curves for Gaussian models of brightness distribution. The curves for two such models, which correspond to probable error limits, are shown in Fig. 3 (b), and the corresponding brightness distributions in Fig. 4.

The most important feature brought out in Fig. 4 is the difference in apparent size of the radio source at the two wave-lengths. Whilst the radiation at 3.7 m is confined to a region just slightly larger than the visible nebula, a considerable portion of the radiation at 7.9 m comes from beyond this region. This result suggests that the object extends to considerably greater radial distances than is revealed in photographs. Occultation measurements at a wave-length of 75 cm in Holland* have shown that, at this wave-length, the source is smaller than at 3.7 m. Possible explanations for this progressive increase in size with increasing wave-length will be discussed in Section 5.

(b) Comparison with the optical Crab Nebula.—The visible radiation from the Crab Nebula comes from a nearly elliptical region approximately centred on a double star. The coordinates of the North-following component of this central double star are

R.A. 05h 31m 31s-5, Dec. 21° 58' 54" (1950).†

Using Bessel’s method, the times of immersion and emersion computed for this position were 16h 27m-7 and 17h 26m-9 U.T., respectively. These times were confirmed by interpolation of the Moon’s topocentric coordinates provided by Mr Sadler of the Nautical Almanac Office.

Since the position of the Moon at any time is known with great precision, an occultation provides a more accurate measure of the position of a radio star than is possible with conventional methods. In this case, where the source is extended, the time of immersion of the centre of gravity of the East-West strip distribution determines the effective right ascension. This time was 16h 28m-0 U.T. and corresponds to

R.A. 05h 31m 32s-2 (1950).‡

This coincides quite closely with the position of the centre of the optical nebula and with the most accurate position determined from interferometric observations by Baldwin (1954), R.A. 05h 31m 30s-5 ± 1s-5 (1950). A sketch of a photograph of the Crab Nebula, taken in red light (6300 A–6700 A), is included for comparison in Fig. 4.

Because the track of the Moon’s centre passed close to the position of the radio source, it was not possible to measure its declination accurately.

* We are indebted to Dr C. Seeger for sending us these results prior to publication.
† We are indebted to Dr D. W. Dewhurst of the Cambridge Observatory for making a special determination of this position.
‡ This result is based on the assumption that refraction occurs on the sunlit limb of the Moon only. If this is not the case, the position is R.A. 05h 31m 32s-7.
The high resolution of an observation of this kind makes it well suited to an investigation of fine structure in the brightness distribution. Unfortunately, the ultimate resolution, determined by Fresnel diffraction at the Moon's limb, was not realized in this case due to the smoothing of the original records. This was necessary because of interference which reduced the effective resolution to $\frac{1}{2} \cdot 3'$.

![Diagram showing the distribution of brightness across the Crab Nebula projected onto an East-West axis at $\lambda = 3.7$ m (full line) and $\lambda = 7.9$ m (dashed lines). The dotted line shows the position of the centre of gravity of the 3.7 m distribution (two solutions shown).

The observed intensity, averaged in this way, showed no variations from a smooth curve greater than about 4 per cent of the total intensity. This result suggests that there are no localized regions larger than $\frac{1}{2} \times \frac{1}{2} \cdot 3'$ having a surface brightness more than double the mean brightness near the centre of the source.

(c) The lunar atmosphere.—The difference between the calculated and observed time of obscuration of the source, $\sigma m = 4 \pm 0 m = 26$, may be attributed to refraction at the Moon's limb. If it is assumed that the refraction occurs only at the sunlit limb of the Moon, an angle of refraction of $13^\prime \pm 9^\prime$ is obtained. Although this value is hardly significant, it is very probable that the angle of refraction is less than $22^\prime$; this figure provides an upper limit for the electron density at the Moon's surface of $10^3$ to $10^4$ el. cm$^{-3}$. This derivation is discussed in a separate paper (Elsmore, in preparation), where it is shown that the density of the lunar atmosphere must be less than $10^{-18}$ of the density of the terrestrial atmosphere at sea-level.

5. Discussion.—Earlier observations at Cambridge by Adgie have provided information on the spectral variations of the total emission of several sources, including the Crab Nebula, over the range 3.7–7.9 m. These, together with the
present results, indicate that the emission from the central region of the nebula decreases with increasing wave-length, whilst in the outer regions the intensity increases rapidly with wave-length. The latter variation is in the same sense but appears considerably more marked than in the majority of radio sources. Such a variation might be due to: (a) re-absorption in the outer shell, (b) scattering by irregularities in the electron density in the outer regions; since scattering increases as the square of the wave-length, an appreciable broadening of the source might occur at longer wave-lengths, (c) a real variation of the emitted spectrum in different parts of the source.

Early models for the Crab Nebula (Greenstein and Minkowski 1953) proposed non-thermal sources embedded in ionized hydrogen, in order to account for the flat spectrum in the range 30–1200 Mc/s. The electron densities assumed were based on the supposition that the optical radiation was due to “free-free” transitions.

The work of Oort and Walraven (1956) has shown clearly that both the optical and radio emission may be explained in terms of the acceleration of fast electrons in weak magnetic fields, as originally proposed by Shklovsky (1953).

The electron density of any re-absorbing shell is now quite inadequate to explain the observed spectrum. If, on the other hand, the observed distributions were due to scattering, it would be necessary to postulate a scale for the irregular structure of a few km only.

It therefore seems more probable that the variation in the spectrum across the source is due to a real change in the emitted spectrum, such as might arise from radial variations in the magnetic field or in the energy spectrum of the fast electrons.

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