AN INVESTIGATION OF THE RADIO SOURCE 06N2A IN GEMINI

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Summary

A lunar occultation of the radio source 06N2A in Gemini was observed in the course of an investigation at a wavelength of 3·5 m, for which the " Mills Cross " aerial was employed. During the occultation the intensity of the source was reduced by over one-fifth, although less than one-tenth of the associated galactic nebulosity IC 443 was obscured. The radio source appears to resemble the nebula, and the relation between them is discussed with the aid of simple geometrical models of the source.

A comparison of the intensity of the source with previously published values shows that the emission at metre wavelengths is mainly non-thermal.

I. Introduction

During 1955 and early 1956 there occurred a series of lunar occultations of the radio source 06N2A in Gemini, and on October 8, 1955 the source culminated at Sydney during the maximum phase of one of these events. It was decided to carry out an investigation of the source, including observations of the occultation, using the 1500-ft " Mills Cross " which operates at a wavelength of 3·5 m.

It was pointed out by Link and Neužil (1954) that lunar occultations provide high resolution for studying the brightness distributions of radio sources. The method is particularly valuable when applied to sources such as 06N2A which, though of appreciable angular size, are too small to be investigated in detail at metre wavelengths by ordinary observations with existing radio telescopes.

The radio source 06N2A in Gemini has been identified with the galactic nebulosity IC 443 (Baldwin and Dewhirst 1954). A photograph of this object, taken in red light with the 48-in. Schmidt camera at Palomar as part of the National Geographic Society-Palomar Observatory Sky Survey, and kindly presented by Dr. R. Minkowski, shows that the nebula is roughly circular in shape and about 48 min of arc in diameter (Fig. 1). The optically bright regions show a filamentary structure : the brightest forms an arch at the sharply defined north-following boundary of the nebula, and other bright portions lie toward the south-preceding edge. The central regions of the nebula are partially obscured.

The first observation of a lunar occultation to be reported was that of Elsmore and Whitfield (1955), who observed an earlier occultation of 06N2A at wavelengths of 3·7 and 7·9 m.

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The results of the present investigation are described in Section II. Their. interpretation involves the aerial characteristics and the radiation from the galactic background and the Moon, and it is necessary to discuss these influences before comparing the optical and radio objects, as is done in subsequent sections.

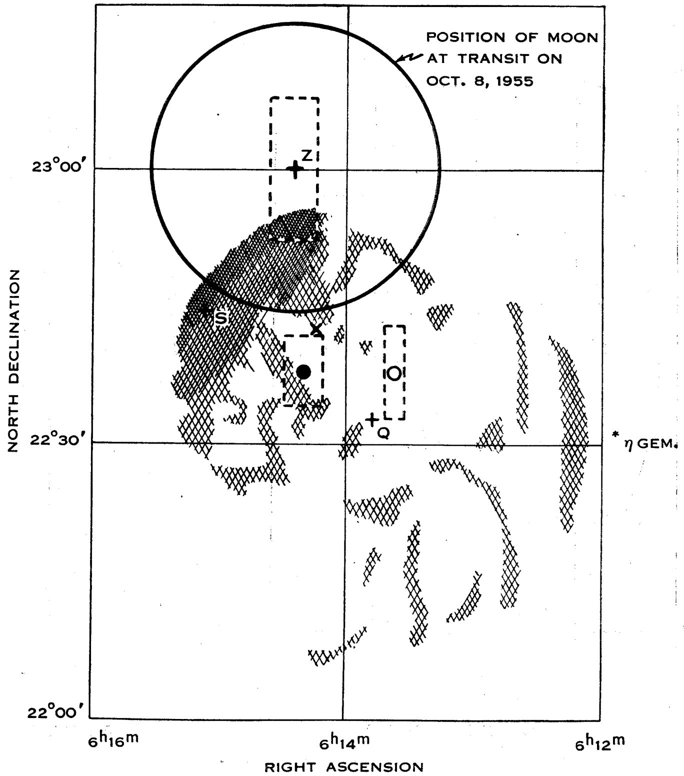

Fig. 1.—Diagram of the nebula IC 443 and the radio source 06N2A. The position of the centroid of the aerial response to the source is denoted by a solid circle; the peak by a cross (×); and the position obtained by Baldwin and Dewhirst by an open circle (1950·0 coordinates). The other positions shown are as follows: Z, centre of occulted radio brightness; Q, centre of IC 443, and of extended source Q in model of Section IV (b); S, centre of source S in model of Section IV (b); *, star η Geminorum. The areas enclosed by broken lines indicate the probable errors.

II. Observations

The instrument employed was the Mills Cross aerial at Fleurs, near St. Mary's, N.S.W., of which a detailed description is being prepared by Mills and others. The aerial is in the form of a cross whose arms are 1500 ft long, and has a pencil-beam response which is circular and of half-power width 49′ when pointed to the zenith, but which becomes elongated when the beam is swung to lower elevations owing to the foreshortening of the array. The principle of operation of the instrument has been described by Mills and Little (1953).

The aerial receives horizontally polarized radiation, and during a switching cycle of 1 min duration the beam is pointed successively in five adjacent directions in the meridian. Throughout the observations the spacing between these five positions was about 37 min of arc, which was roughly two-fifths of the beam-width in declination. On four days, including the day of the occultation, the central beam position was directed to Dec. +23° 05′ ; on two other days, to Dec. +21° 53′ ; and on one further day, to Dec. +24° 05′. The aerial beam

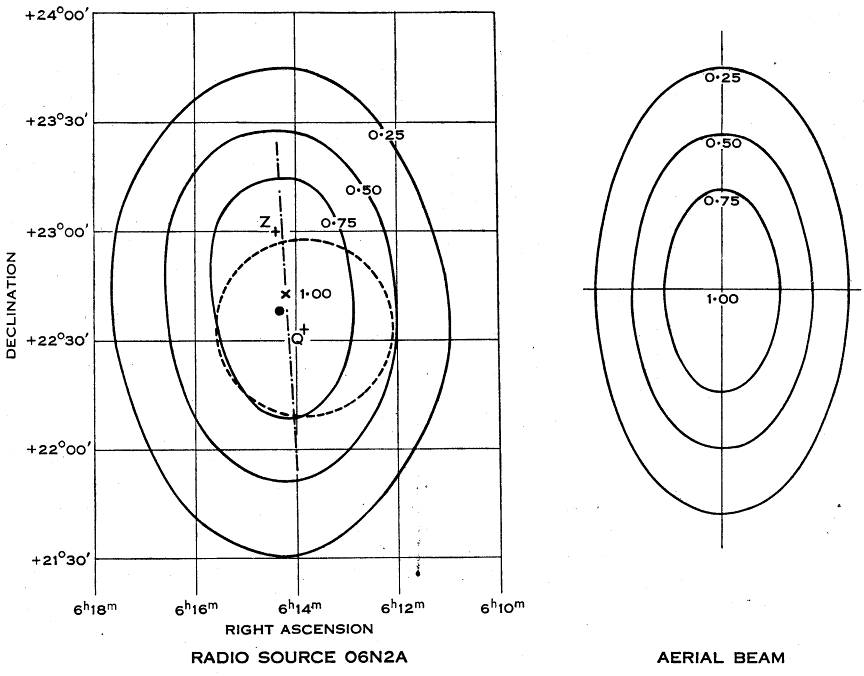

Fig. 2.—Contours of equivalent aerial temperature relative to the peak value for source 06N2A (1950·0 coordinates). As in Figure 1, the centroid of the aerial response is denoted by a solid circle and the peak by a cross (×). *Q* is the centre of IC 443 and *Z* the centre of occulted radio brightness. The equivalent aerial temperature at the peak is 4700 °K. The intensity contours of the aerial beam are also shown.

– – – – Approximate boundary of IC 443.

·–·–·– Major axis of observed aerial response.

cannot easily be swung in azimuth, and so it was not possible to follow the progress of the occultation. The intense radio source 05N2A in Taurus (M1, the Crab Nebula) passed through the aerial beam about three-quarters of an hour before 06N2A, and provided a check on the directional characteristics of the aerial.

The position of the Moon at transit on the day of the occultation was computed from the data of Link and Neužil and information supplied by the staff of " The Nautical Almanac ". The relation of this position to the nebula IC 443 and the radio source is shown in Figure 1. Only about one-tenth of the area of IC 443 was covered by the Moon ; nevertheless, the radio intensity was reduced by about one-fifth. The centre *Z* of occulted radio brightness was found by comparing the record obtained during the occultation with those obtained on the control days; it lies further north than expected, but the uncertainty of the measurement allows of a more plausible position within the nebula. The dimensions of the occulted region were small compared to the aerial beam.

The principal results of the investigation at 3·5 m, with their estimated probable errors, are presented numerically in Table 1, and the observed contours of radio brightness of the source 06N2A in the absence of the Moon are shown in Figure 2.

TABLE 1

PRINCIPAL RESULTS AT 3·5 M

Property	06N2A Gemini	05N2A Taurus
Observed radio position (1950·0) Peak	$6^h\ 14^m{\cdot}2 \pm 0^m{\cdot}15$, $+22°\ 43' \pm 04'$	$5^h\ 31^m{\cdot}4 \pm 0^m{\cdot}1$, $+21°\ 59' \pm 03'$
Observed radio position (1950·0) Centroid	$6^h\ 14^m{\cdot}3 \pm 0^m{\cdot}15$, $+22°\ 38' \pm 04'$	$5^h\ 31^m{\cdot}5 \pm 0^m{\cdot}1$, $+21°\ 59' \pm 03'$
Position of optical centre (1950·0)	$6^h\ 13^m{\cdot}8$, $+22°\ 33'$	$5^h\ 31^m{\cdot}50$, $+21°\ 59'{\cdot}3$
Half-power width of aerial response to source (east-west × north-south)	$66' \times 99'$	$49' \times 86'$
Computed half-power width of aerial beam	$49' \times 83'$	$49' \times 82'$
Diameters of optical object	$48' \times 48'$	$\ll$beamwidth
Flux density (W m^{-2} $(c/s)^{-1}$)	$(66 \pm 15) \times 10^{-25}$	$(230 \pm 35) \times 10^{-25}$
Brightness temperature of equivalent disk, 48′ in diameter (°K)	14500	—
Proportion of radio intensity occulted by Moon	$0{\cdot}22 \pm 0{\cdot}05$	—
Flux density of occulted portion (W m^{-2} $(c/s)^{-1}$)	$(15 \pm 4) \times 10^{-25}$	—
Centre of occulted portion (1950·0)	$6^h\ 14^m{\cdot}4 \pm 0^m{\cdot}2$, $+23°\ 00' \pm 08'$	—
Topocentric position of Moon's centre at transit (1950·0)	$6^h\ 14^m{\cdot}4$, $+23°\ 01'$	—

The probable errors quoted are principally due to uncertainty in the performance and absolute calibration of the aerial, and the scatter of the daily observations do not contribute greatly to these errors. For instance, all the measured positions of the peak of 06N2A lie within a range of $0^m{\cdot}3$ in Right Ascension; and the total scatter of the daily values of flux density of this source was but 10 per cent. of the mean value. Ratios of flux density are thus more reliable than their absolute values.

The correction which was applied for refraction amounted to 3′ in declination, to which the troposphere and ionosphere contributed 2′ and 1′ respectively. Refraction in Right Ascension due to the ionospheric wedge effect was neglected, for the greatest deviation observed at 3·7 m by Smith (1952) is of order $0^{\mathrm{m}}\cdot 05$. The angular size of the diffraction pattern around the lunar disk is of order 1′; this is too small to influence significantly the reduction of intensity observed during the occultation. Solar interference was absent as the sources culminated before dawn, but ionospheric irregularities caused severe scintillations on one of the control days.

Observations of the source at a wavelength of 50 cm were made by G. Trent of the Radiophysics Laboratory, using a transit aerial at Potts Hill, Sydney. No reduction of intensity on the day of the occultation was observed, but the sensitivity of the system was such that a decrease of 20 per cent. would barely be detectable.

The occultation of 06N2A on January 25, 1956 was also visible at Sydney.* Unfortunately, a violent thunderstorm coincided with the event, and rendered useless the observations made by A. W. L. Carter of the Radiophysics Laboratory and the author.

For comparison, a summary of previous observations of 06N2A are given in Table 2.

TABLE 2

SUMMARY OF PREVIOUS OBSERVATIONS OF 06N2A

Reference	Wave-length (m)	Fre-quency (Mc/s)	R.A.	Dec. (north)	Flux Density (10^{-25} W m^{-2} (c/s)$^{-1}$)
Haddock, Mayer, and Sloanaker (1954) ..	0·094	3200	$6^{\mathrm{h}}\ 14^{\mathrm{m}}$	22° 30′	5·5
Hagen, Lilley, and McClain (1955) ..	0·21	1420	$6^{\mathrm{h}}\ 13^{\mathrm{m}}$	22° 40′	16
Piddington and Trent (personal communication)	0·50	600	$6^{\mathrm{h}}\ 13^{\mathrm{m}}$	23°	22
Ko and Kraus (1955)	1·24	242	$6^{\mathrm{h}}\ 15^{\mathrm{m}}\pm 1^{\mathrm{m}}$	$23°\pm 1°$	16
Rishbeth (see Table 1)	3·5	85·5	$6^{\mathrm{h}}\ 14^{\mathrm{m}}\cdot 3\pm 0^{\mathrm{m}}\cdot 15$	$22°\ 38'\pm 4'$	66
Baldwin and Dewhirst (1954) ..	3·7	81·5	$6^{\mathrm{h}}\ 13^{\mathrm{m}}\ 37^{\mathrm{s}}\pm 4^{\mathrm{s}}$	$22°\ 38'\pm 5'$	42
Baldwin and Dewhirst (1954) ..	7·9	38			65

III. FACTORS INFLUENCING THE OBSERVATIONS

Before the observed brightness distribution of the source is discussed in detail, it is necessary to examine certain factors which affect the observations. The performance of the aerial is of prime importance, because of the similarity of angular size between the aerial beam and the source. The results are also influenced by the galactic background in the neighbourhood of the source, and by the brightness temperature of the Moon itself.

* The quantity H (Greenwich Hour Angle of the source at the instant of its conjunction with the Moon) is given incorrectly by Link and Neužil for this occultation and two others of 06N2A in 1956.

(a) *The Performance of the Aerial*

The source 06N2A transits at a zenith angle of 57°, 12° beyond the normal operating range of the aerial. Under these conditions no detailed analysis of the behaviour of the aerial has been made, but it is known that the sensitivity is somewhat reduced and the beam elongated in declination.* Taurus-A (05N2A) may be considered as a point source when viewed by the aerial, and the observed beamwidth at half-power in declination is 86′, in fair agreement with the calculated value of 82′ (see Table 1). The east-west beamwidth agrees with the theoretical width of 49′, which should not vary with zenith angle. The adopted beamwidths at the declination of 06N2A are 49 and 87′.

The position of the centroid of the aerial response to 05N2A lies at the centre of the nebula M1, and so the collimation error of the aerial must be small notwithstanding the large zenith angle. For this reason the position quoted in Table 1 for the centroid of 06N2A is considered reliable, even though the position given by Baldwin and Dewhirst differs from it by $0^{m}\cdot 7$ in Right Ascension. There is, however, a displacement of $1\frac{1}{2}\pm\frac{1}{2}$ min of arc in azimuth between the peak and centroid of the response to 05N2A. As the latter is effectively a point source, this displacement indicates that the aerial beam is asymmetrical; possibly as the result of ground reflections which might become serious at such large zenith angles. Consequently, the displacement in Right Ascension between the peak and centroid of the Gemini source may not be real.

(b) *The Effect of the Galactic Background*

The source 06N2A is situated in a region of strong emission near the galactic anticentre. The records of the source have been analysed in detail over the range from $6^{h}\,00^{m}$ to $6^{h}\,30^{m}$ in Right Ascension, and the regions surrounding 06N2A give an almost uniform response, from which the deflection due to the discrete source is easily separated. Thus the galactic structure in the neighbourhood of the source is unlikely to affect the accuracy of the results. Confusion with another discrete source could significantly affect the observations if such a source exceeded about 5×10^{-25} W m^{-2} (c/s)$^{-1}$ in intensity and lay within an area of roughly 4 square degrees centred on the position of 06N2A. Results of earlier surveys enable the chance of this occurrence to be estimated as 1 : 60. Such confusion might possibly cause the discrepancy between the position obtained and that of Baldwin and Dewhirst, as their observations with an interferometer possessing a wide primary beam are more prone to confusion with another nearby source than the author's observations with a pencil-beam aerial.

(c) *The Effect on the Occultation of the Apparent Brightness Temperature of the Moon*

The Moon may be considered as a uniform disk, of which the apparent brightness temperature is negative. This arises from the obscuration of the galactic background, whose brightness temperature was found to be about

* The Mills Cross has recently been recalibrated by A. G. Little of the Radiophysics Laboratory. His measurement of the flux density of 05N2A is quoted in Table 1, and the other flux densities are based upon it.

1500 °K. This disk temperature is made less negative by two terms: firstly, that due to the reflection of galactic radiation by the Moon; and, secondly, the temperature of the lunar surface, which, according to the $1 \cdot 25$ cm observations of Piddington and Minnett (1949), is 270 °K at the Moon's last quarter. This lunar radiation is thermal, and so the effective brightness temperature at $3 \cdot 5$ m is likely to be similar. The magnitude of the former effect can be estimated as follows. The Moon is assumed to be a diffuse reflector of directivity 5 relative to an isotropic radiator and of reflection coefficient $0 \cdot 15$ (Kerr and Shain 1951). Then the effective brightness temperature of the reflected radiation is roughly $0 \cdot 15$ of the average brightness temperature of an area of sky opposite the Moon and covering one-fifth of the celestial sphere.

No complete survey of this region is available at a wavelength of $3 \cdot 5$ m, but the required temperature is estimated to be 1500 °K at $3 \cdot 0$ m using the contours of Bolton and Westfold (1950). At $3 \cdot 5$ m the value is likely to be higher by a factor of about $1 \cdot 5$. Reflected solar radiation is unlikely to contribute greatly to this as no solar activity was present on the day of the occultation. Thus the estimated brightness temperature of reflected radiation from the Moon is $0 \cdot 15 \times 1 \cdot 5 \times 1500$ °K or 340 °K, giving a final value of 900 °K for the negative apparent disk temperature of the Moon, corresponding to a negative flux density not exceeding $1 \cdot 5 \times 10^{-25}$ W m^{-2} (c/s)$^{-1}$. The presence of an extraneous discrete source within the occulted area would not greatly affect the result unless its intensity exceeded 2×10^{-25} W m^{-2} (c/s)$^{-1}$; considerations similar to those employed in Section III (*b*) give the chance of this circumstance as about 1 : 250. It is thus almost certain that the total flux density of occulted background is small compared to the reduction of 15×10^{-25} W m^{-2} (c/s)$^{-1}$ observed, and the balance is attributed to the obscuration of the discrete source 06N2A.

IV. Discussion

(*a*) *Contours of Equivalent Aerial Temperature*

A contour diagram of equivalent aerial temperature of the source 06N2A is shown in Figure 2. The portions outside the quarter-power contour are indefinite and have been omitted from the determination of the position of the centroid, though they have been included in the value obtained for the flux density.

The asymmetry of the aerial beam, discussed in Section III (*a*), may be sufficient to account for the observed skewness of the east-west section of the aerial diagram (Fig. 3). The shape of the aerial beam in the north-south direction is not accurately known, but the close spacing of the contours on the northern side shows that the source has a northern boundary sharp compared to the aerial beam.

When the diagram is compared with the position of IC 443, the centroid is found to lie well toward the following side of the nebula, and slightly to the north of the optical centre. This indicates a concentration of radiation in the north-following quarter, in the neighbourhood of the brightest optical emission. Moreover, the observations during the occultation show that over one-fifth of the radiation originates in the small part of the bright north-following arch, occupying less than one-tenth of the total area of IC 443, that was covered by the Moon. This arch was not obscured during the occultation observed by Elsmore and Whitfield, and these authors postulated a concentration of radiation in its vicinity on the ground that the observed reduction in intensity of the

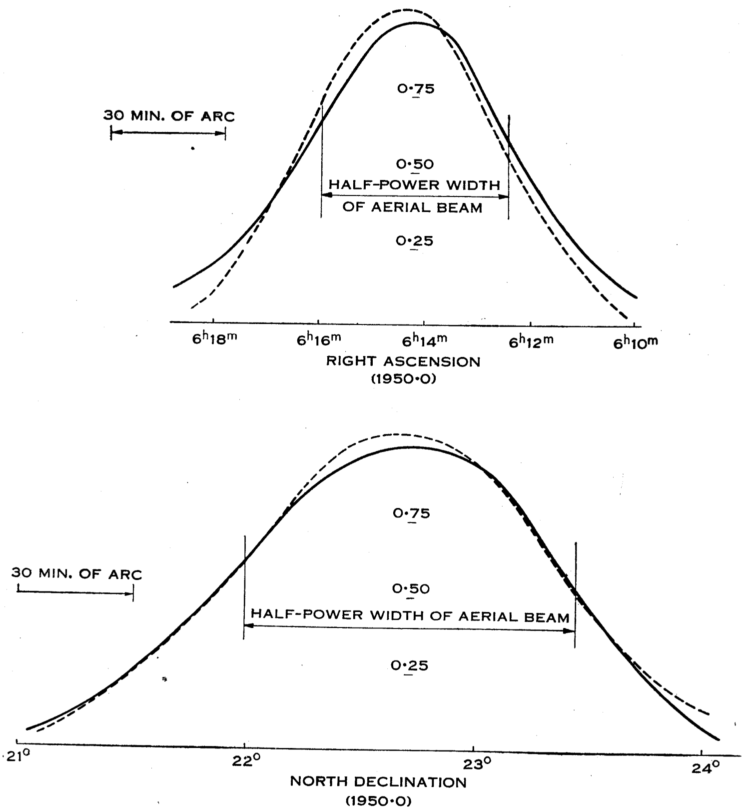

Fig. 3.—Sections through the peak of the contours of Figure 2 for source 06N2A, with those derived from the model of Section IV (*b*). (1950·0 coordinates.)

——— Observed section.

- - - - - Section derived from model of uniform disk Q and small source S.

source was less than that expected from the circularly symmetrical model of Baldwin and Dewhirst.

The major axis of the contour diagram is slightly inclined to the meridian: the peak of an east-west section through the northern extremity of the half-power contour is about $0^{m}\cdot 3$ later in Right Ascension than the peak of the corresponding section at the southern extremity.

The extent of the contours shows that the source 06N2A is similar in size to the nebula IC 443, whose diameter is 48 min of arc. Baldwin and Dewhirst quoted the half-power width of the source as 20 min of arc; their distribution was, however, derived from measurements of the amplitude but not the phase of the Fourier components of the east-west strip brightness, and they assumed that the source possesses circular symmetry. A source of half-power width 20 min of arc would give a much narrower response to the beam of the Mills Cross than that obtained by the author.

(*b*) *Elementary Models of the Source*

A simple model of the radio brightness distribution across the source has been considered. It combines an extended source Q possessing circular symmetry, centred at the geometrical centre of IC 443, with a source S which is sufficiently localized to resemble a point source when scanned by the aerial.

The position of S and the intensities of S and Q were chosen to give the measured value of total flux density and the observed position of the centroid. The extended source Q was represented by a uniformly emitting disk whose diameter, 48′, is roughly that of IC 443; and the optimum ratio of the intensities of S and Q was found to be 3 : 4.

This model, when smoothed by a Gaussian aerial beam, reproduced moderately well some of the features of the observed distribution (Fig. 3). It failed near the peak, where the response might be expected to be sensitive both to the structure of the source, which the model ignores, and to the aerial beam asymmetry; it also failed to give a sufficiently wide response in the east-west direction. This suggested that the radiation might be more intense towards the boundaries of the nebula, and so another simple model was tried in which the source Q was taken as a uniform ring around the boundary of IC 443, augmented as before by a small source S. This model gave a slightly broader response in the east-west direction and a more accurate value of equivalent aerial temperature at the peak, but was still unsatisfactory in shape. Some improvement to both models could be made by enhancing the radiation originating in the south-preceding quarter.

The models can qualitatively account for the inclination of the major axis of the contour diagram to the hour circle through the peak (Section IV (*a*)), but they are not consistent with the observed displacement in Right Ascension between the peak and the centroid. It would seem difficult to find a model which does reproduce this displacement and also the other features of the response, and which does not require emission from outside the boundary of IC 443. However, as suggested in Section III (*a*), the separation of the peak and centroid may be instrumental in origin.

If the results given by the models are meaningful, the source S would correspond to the bright arch on the north-following boundary of IC 443. The dimensions of this arch are much smaller than the aerial beamwidths, and the response to a source extending along it would not differ greatly from that of a point source. The amount of radiation cut off by the Moon is consistent with the identification of S with the bright arch. It seems possible that the bright filamentary structures in the south-preceding quarter may also emit strong radiation.

(c) *Nature of the Radio Emission from IC 443*

In Table 2 are quoted several previous measurements of the flux density of 06N2A. If the source were thermal and optically thin, its flux density would not vary with wavelength. It is difficult to measure accurately the flux density of an extended source and it is possible that thermal radiation is dominant at short wavelengths. At metre wavelengths, however, the flux density rises sharply with increasing wavelength, and so a strong non-thermal component is present.

The source seems to belong to the class of faint filamentary diffuse objects with strong non-thermal radio emission. These objects sometimes have sharp outer boundaries, and possess violently moving filaments in which it is presumed that radio waves are generated by non-thermal processes. This type of source seems distinct from sources such as the Orion Nebula (M42) and other galactic H II regions which are optically bright masses of ionized gas, in which the internal velocities are 10 or even 100 times less than the first kind. There is at present no evidence that the radio emission from such objects is other than thermal (Mills, Little, and Sheridan 1956).

V. Conclusions

An analysis of the data has indicated that at 3·5 m the source 06N2A must be similar in size to the nebula IC 443, and that there is an apparent resemblance between the optical and radio objects. It has established the presence of strong radio emission in the neighbourhood of the bright arch on the north-following edge, and suggested that the filaments in the south-preceding quarter may also be strong radio sources. It has suggested the occurrence of "limb-brightening" at a wavelength of 3·5 m, such as might be expected were the nebula an expanding shell of gas—perhaps the remnant of a nova or supernova outburst (Shklovskii 1954). The resemblance between the radio and optical objects may be less real than suggested, as the nebula IC 443 is heavily obscured in places, notably near the centre, and the true distribution of optical brightness may be very different from that observed.

It has been assumed throughout that the radio emission is confined within the visible extent of IC 443. This seems to be a reasonable requirement as the nebula has a well-defined boundary. Filamentary structures exist well outside the nebula on the north-following side, but they are of a type fairly common in the Galaxy and there seems to be no reason for supposing them to be associated with the radio emission from IC 443.

Although the measured flux densities of the source at shorter radio wavelengths may be compatible with the presence of an optically thin thermal source, there is no doubt that at longer wavelengths the flux density rises rapidly and the emission is mainly non-thermal. The source appears to resemble the filamentary non-thermal objects such as Cassiopeia-A rather than the hot ionized gas clouds such as the galactic H II regions.

VI. Acknowledgments

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