This classic paper by Martin Ryle, B Elsmore and Ann Neville (*Nature*, 207, 1024, 1965) reports some of the early observations of radio galaxies with the One-Mile Telescope at Cambridge (the UK was yet to go metric) which "makes use of an advanced form of aerial synthesis to provide a resolution and sensitivity considerably greater than have been achieved hitherto". The principles of aperture synthesis were well documented earlier (e.g., Bracewell and Roberts, *Australian Journal of Physics*, 7, 615, 1954). Peter Scheuer had these principles laid out in his thesis in 1954, but remained in his thesis "because Martin Ryle took a severe line, that on engineering topics you shouldn't merely write theory, you should jolly well build the thing first" (Scheuer, in *The Early Years of Radio Astronomy*, ed W T Sullivan III, CUP, 1984). From the principles in 1954 to building a then modern full-scale telescope, the Cambridge One-Mile Telescope, which was described by Martin Ryle in a *Nature* paper in 1962, took about ten years. Images of two of the strongest radio sources, Cygnus A and Cassiopeia A at λ21.3 cm, obtained during the testing phase of the telescope, were published a little earlier by Ryle, Elsmore and Neville (*Nature*, 205, 1259, 1965).

The paper included here presents images of much weaker extragalactic radio sources at λ21 cm revealing clearly their extended structure, and part of a 'deep' survey at λ74 cm. These opened the door for examining the structure and properties of sources at different flux density levels as tests of different cosmological models, and also understand the physics of radio sources. In the early 1960s based on counts of radio sources, Ryle's group had ruled out the steady-state model of the Universe. It may not be out of place to mention that about a decade later, using the method of lunar occultation to determine the structure of weak radio sources with the Ooty Radio Telescope, Govind Swarup (*MNRAS*, 172, 501, 1975) and Vijay Kapahi (*MNRAS*, 172, 513, 1975) lent additional support to the big-bang or evolutionary model of the Universe.

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OBSERVATIONS OF RADIO GALAXIES WITH THE ONE-MILE TELESCOPE AT CAMBRIDGE

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ON July 6, Lord Bowden and other distinguished guests visited the Mullard Radio Astronomy Observatory, Cambridge, to inspect the new, large radio telescope[1] which has recently come into use. This instrument, which was constructed with the aid of a grant from the Science Research Council, makes use of an advanced form of aerial synthesis to provide a resolution and sensitivity considerably greater than have been achieved hitherto.

The telescope was designed primarily to further our understanding of the physical processes occurring in radio sources of different types, both galactic and extragalactic. In each case one of the chief requirements is a detailed knowledge of the structure for different wave-lengths and polarizations. Although the large baseline interferometers at Jodrell Bank[2] have set lower limits on the surface brightness occurring in many sources, they have not provided much information on their shape. More detailed interferometric observations, but with less-extensive base-lines, have been made at the California Institute of Technology[3] and the results have been interpreted in terms of various simple models of the brightness distribution; these models may not, however, be unique, and information has not been obtained for more complex sources.

From what is already known about the intrinsic radio luminosities of radio galaxies and quasars, it is clear that an investigation of the numbers of sources occurring in different ranges of flux density, and the examination of the spectra and other features of sources of different flux density, may allow powerful tests of different cosmological models. The present observations[4–6] have already imposed important restrictions on the possible models, and these restrictions should be increased if the observations can be extended to weaker sources; such an extension requires an instrument having both greater angular resolution and greater sensitivity.

The new telescope has been designed with these needs in mind. In the earlier large instruments at Cambridge, a long, thin aerial has been used in conjunction with a smaller movable one to carry out a one-dimensional synthesis. In the new telescope, the method is extended to two-dimensional synthesis using relatively small circular elements the spacing and orientation of which are varied to include all the relative positions present in the large equivalent aerial. Use is made of the rotation of the Earth to alter the projected position angle of an east–west axis on the sky; by using aerial elements capable of tracking a given point in the sky for 12 h all the information appropriate to an elliptical ring of a large equivalent instrument is obtained[1]. By repeating 12-h runs at each of a number of east–west separations, it is then possible to

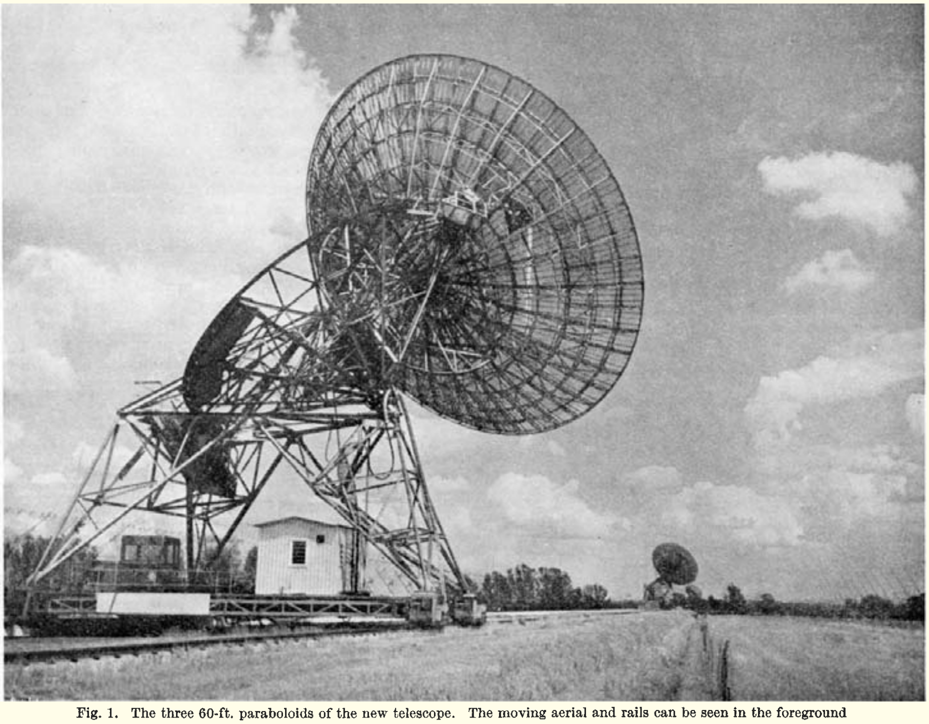

Fig. 1. The three 60-ft. paraboloids of the new telescope. The moving aerial and rails can be seen in the foreground

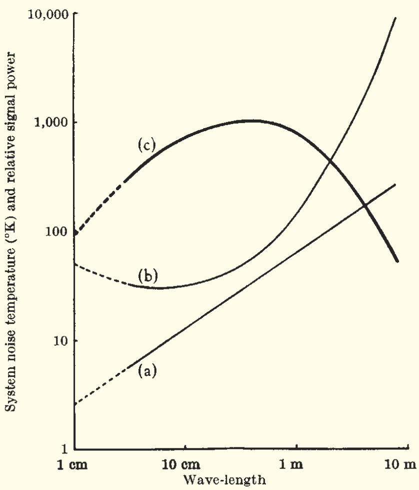

Fig. 2. Curves showing as a function of wave-length: (*a*) the variation in flux density of a typical radio galaxy; (*b*) the total system noise of a typical installation using low-noise amplifiers; and (*c*) the ratio of (*a*) and (*b*)

build up an equivalent elliptical aerial the major and minor axes of which are D and D sin δ, where D is the maximum separation of the aerial elements and δ is the declination of the area of sky under observation. A maximum separation (D) of about 1 mile (1,550 m) can be used in the new telescope.

Owing to the high cost of the stable rail foundations, two fixed paraboloids are used in conjunction with a movable one on 0·5 mile of rail track; this arrangement permits two different separations to be recorded simultaneously and halves the observing time. The use of an even shorter rail track and a larger number of fixed elements would have reduced the observing time still further but would have resulted in an increased cost.

The three elements may be seen in Fig. 1. Each is an equatorially mounted paraboloid 60 ft. in diameter. The instrument is being used to observe simultaneously at two wave-lengths, 74 and 21·3 cm, at which the final beam-widths are 80 and 23 sec arc respectively.

It is interesting to compare the signal-to-noise ratio achieved with this system, with those of more conventional instruments of the same resolution when used to observe a given area of sky in a given total time. If d is the diameter of each of the aerial elements and D is the maximum separation, it can be shown[7] that the signal to noise in the final map is equivalent to that of an instrument with a collecting area of approximately $3d \times D$, or 10^6 sq. ft. In addition, the ability to use wave-lengths considerably greater than those which would have to be used in a feasible paraboloid to obtain the same resolution confers a further improvement in the relative sensitivity. In Fig. 2 curves are shown of the relative flux density of a typical radio source at different wave-lengths together with typical values of the overall system noise (receiver noise and radiation from the ground and sky). It can be seen that the ratio of these two curves shows a well-defined maximum in the neighbourhood of 50 cm. If, for example, a resolution of 23 sec arc were to be achieved by the use of a 200-ft. paraboloid operating on a wave-length of 8 mm, the relative sensitivity would fall below that of the new instrument operating at $\lambda = 21$ cm by a factor of about 300.

Apart from the question of the engineering feasibility of constructing a paraboloid with sufficient accuracy to provide a resolution better than 1′ arc, it is therefore clear that if such an instrument were to provide maps having a comparable signal to noise, then the observing rate would have to be very much slower than that of the new telescope[8].

The aerials may be controlled individually but, normally, they are all operated from the Central Control Room shown in Fig. 3. This building also contains the receivers, digital converters and paper-tape punches on which the signals are recorded. When observations are made away from the meridian, large path differences to the different elements occur and it is necessary to introduce a path correction which varies continuously as the observations proceed. This correction and the control of the punches and telescope tracking motors are made automatically by means of a control tape previously prepared in the computer.

During the first seven months, the instrument has been engaged in three main observing programmes:

(1) Accurate Positions

In order to make full use of the resolution available at $\lambda = 21$ cm, the relative positions of the three instruments must be established with an accuracy better than $\sim 0{\cdot}5$ cm.

Attempts have been made to determine the necessary quantities (*a*) by observing small-diameter radio sources associated with stellar objects the positions of which have been accurately measured[9,10] and (*b*) by direct survey methods. The former method has been used by Adgie[11] and, as he points out, it suffers from the rather small number of sources for which the identity of optical and radio positions can be assumed; most of the sources also lie in a limited range of declination. For the second method we are indebted to the Ministry of Public Building and Works for the final survey of the instrument with an accuracy believed to be 1 in 10^6 and 0·5 sec arc.

A comparison of the two methods has revealed discrepancies greater than the uncertainty expected from either of the survey methods.

Although the cause of this discrepancy has not yet been discovered, it is possible to use the present results to determine the positions of sources having $S_{21} \geqslant 2{\cdot}5 \cdot 10^{-26}$ Wm^{-2} $(c/s)^{-1}$ with an accuracy of ± 3 sec arc in α and $\pm(2{\cdot}5 \operatorname{cosec} \delta)$ sec arc in declination.

Fig. 3. The control desk and part of the receiving system

Some 50 sources have been observed, about half being apparent point sources. The positions of a number have been examined on the prints of the 48″ Sky Survey and some possible new identifications have been noted. These include blue stellar objects close to the positions of the following sources: 3*C* 270·1, 3*C* 277·1, 3*C* 309·1 and 3*C* 454.

(2) Source Structure

When observing intense sources, the angular size of which is considerably less than the primary beam of the individual aerials, it is unnecessary to make observations with all separations of the aerial elements. Instead, a relatively small number of positions of the moving aerial along the full length of the rail track can be used to synthesize a grating instrument. This method was employed in the observation of the intense sources in Cygnus and Cassiopeia already reported[12]. Some of the sources investigated have been observed previously by Moffet and Maltby[3], who fitted simple source models to their observed amplitude-spacing curves. In several cases the distribution of radio brightness has been found to be more complex, while in others the sources have not previously been observed with sufficient resolution to show the detail now seen.

The results are presented automatically as contours on a curve plotter attached to the *Edsac II* computer.

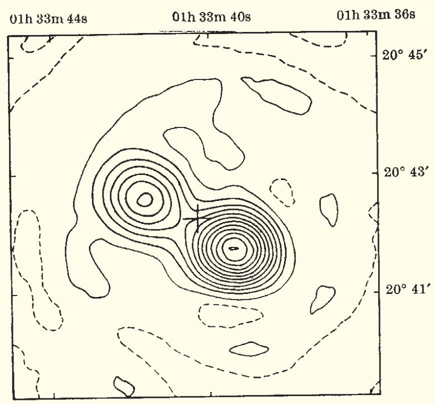

Fig. 4. 3*C* 47. The optical quasi-stellar object is marked by a cross

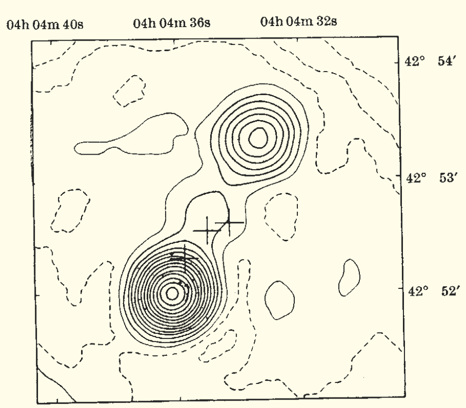

Fig. 5. 3*C* 103. The central of the three objects shown is probably a star with $m_{pg} = 16$. Two diffuse red objects ($m_{pg} = 18 - 19$) are also visible

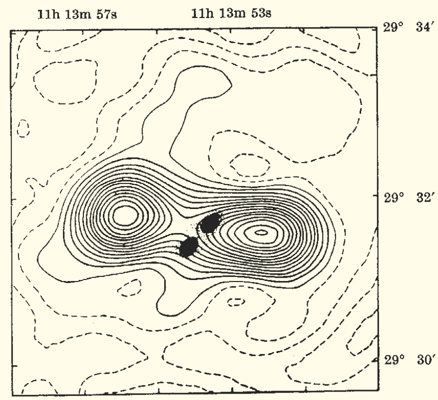

Fig. 6. 4*C* 29·41. The two 15·15^m galaxies in a common halo are shown

Observations have been made on both 74 and 21 cm; the maps obtained for some of the sources on a wave-length of 21 cm are shown in Figs. 4–7. In order to simplify the examination of the structure of the sources, the scales of all the maps are such that the beam appears circular; the scale of the maps is therefore the same in right ascension, but varies as sin δ in declination.

(*a*) 3*C* 47. This source was one of the original group of quasars[13]. The new observations (Fig. 4) show that it consists of two components having flux densities in the ratio 1·8 : 1. The components have an angular separation of 62 sec arc and are disposed nearly symmetrically either side of the optical object which lies about 8 sec arc north of the line joining them. The more intense component is just resolved with an angular extent of ~ 10 sec arc in R.A.; the weaker component cannot be resolved, but could be of the same angular size. The interferometric observations of Anderson *et al.*[14] and the absence of interplanetary scintillations[15] have shown that there is little structure as small as 2 sec arc.

The optical object has a red-shift $\Delta\lambda/\lambda = 0{\cdot}452$ (ref. 13), and the observed angular separation of the two components corresponds to a physical separation of 200–300 kpc depending on the cosmological model adopted. It is therefore physically one of the largest radio sources known, with a component separation some three times that of Cygnus *A*; its radio luminosity is nearly the same as that of Cygnus *A*.

This result is important in relation to theories of quasars and radio galaxies, since, even if the two components are supposed to be ejected at speeds close to that of light, and in a line perpendicular to the line of sight, the radio source must be at least 3×10^5 years old; a life in excess of 10^6 years seems more likely. The presence of intense ultraviolet emission from a stellar object associated with such an old source indicates either that there is a continuing source of energy for the ultra-violet source which does not give rise to intense radio emission, or that a second release of energy can occur in such objects.

The large physical dimensions of the two emitting regions (7–35 kpc) also require a total energy in the form of fast particles and magnetic field, which is comparable with that of Cygnus *A* ($\sim 10^{62}$ ergs). As discussed by Fowler[16], the relatively short life-time which has been associated with quasars only requires sources of energy of 10^{59}–10^{60} ergs; the association of a quasi-stellar optical object with a radio source having energy requirements some 100–1,000 times larger may place greater emphasis on those mechanisms of energy release in quasars which are capable of supplying this greater energy.

(*b*) 3*C* 103. This source (Fig. 5) consists of two components separated by 88 sec arc, each having an angular

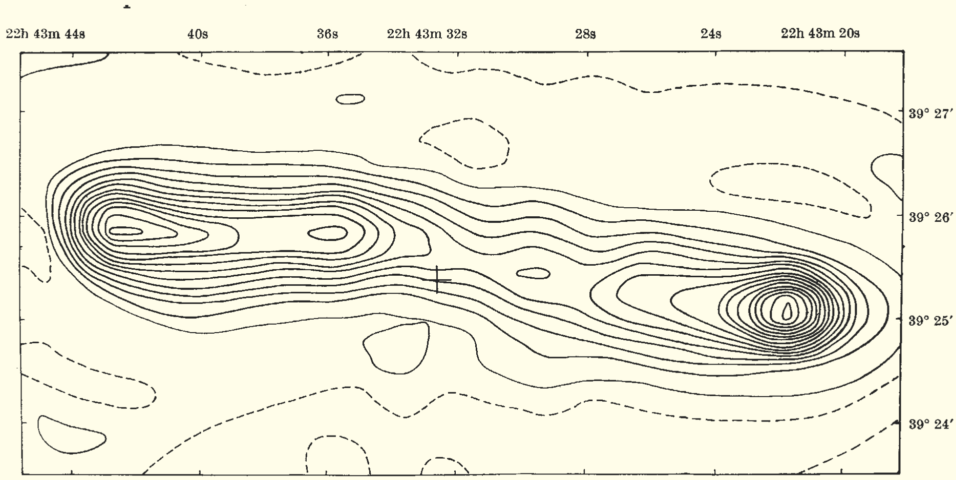

Fig. 7. 3*C* 452. The 16^m galaxy suggested as an identification (refs. 18, 19) is shown at $\alpha = 22$ h 43 m 32·6 s. This galaxy has a red-shift $\Delta\lambda/\lambda = 0{\cdot}082$, implying a separation between the outer peaks of 280 kpc

diameter < 10 sec arc; a faint bridge joins the two components. The south following component has a flux density some 1·9 times greater than the other. No associated optical object has previously been suggested, and the low galactic latitude ($b^{II} = 7°$) may involve considerable obscuration; some possible objects are marked in Fig. 5.

(*c*) 4*C* 29·41. This is a source from the 4*C* catalogue[17]. Its flux density at 21 cm is $1{\cdot}8 \times 10^{-26}$ Wm^{-2} (c/s)$^{-1}$ and it consists of an extended or double major component, separated from a second, unresolved component, by 50 sec arc (Fig. 6). Two 15^m elliptical galaxies in a common halo are probably associated with the radio source.

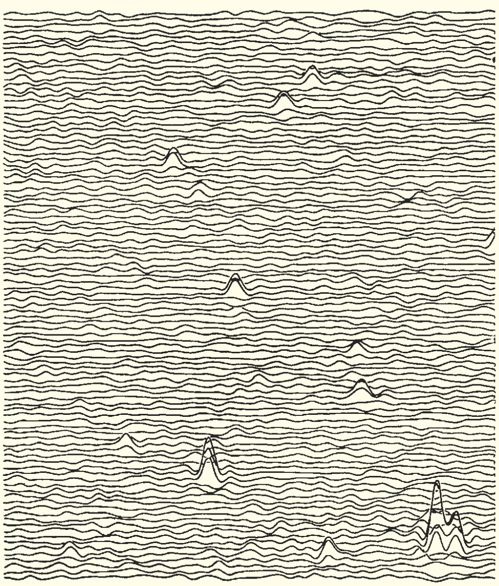

Fig. 8. Part of the first deep survey at $\lambda = 74$ cm obtained with the new instrument; the figure covers an area of about 1 sq. degree. The source near the centre has a flux density about 1/25th that of the weakest sources in the 4*C* catalogue (ref. 17)

(*d*) 3*C* 452. The contour map is shown in Fig. 7 and reveals a remarkable ridge of emission 4 min arc in length and 20 sec arc in width; it also shows an intense and elongated source at either end of the ridge, neither of which is completely resolved in declination.

The position of a galaxy which has been suggested by Dewhirst[18] and Matthews[19] as the identification is shown in Fig. 7.

(3) Deep Survey

A test survey has been made using the instrument to synthesize a full 1-mile aperture in order to provide a detailed map of an area of sky which is some 3° in diameter at 74 cm and 50 min arc diameter at 21 cm. The amplifiers used in these observations were only of moderately low noise-level (T_R = 450° at 74 cm and 400° at 21 cm), yet nevertheless extremely faint sources can be distinguished. Part of the 74-cm map (of area approximately 1 sq. degree) is shown in Fig. 8. The more intense component of the double source in the lower right-hand corner has a flux density $S_{74} = 0{\cdot}17 \times 10^{-26}$ Wm^{-2} (c/s)$^{-1}$ and the source near the centre of the map has $S_{74} = 0{\cdot}04 \times 10^{-26}$ Wm^{-2} (c/s)$^{-1}$.

We thank Dr. S. Kenderdine who was responsible for the reduction of the deep survey observations, Miss Judy Bailey for help in the programming, E. A. Parker for permission to use the results of his search for optical identifications before publication, and Prof. M. V. Wilkes for the use of the *Edsac II* and *Titan* computers.

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