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SCIENCE

Radio Telescopes of Large Resolving Power

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I think that the event which, more than anything else, led me to the search for ways of making more powerful radio telescopes was the recognition, in 1952, that the intense source in the constellation of Cygnus was a distant galaxy—1000 million light years away. This discovery showed that some galaxies were capable of producing radio emission about a million times more intense than that from our own Galaxy or the Andromeda nebula, and the mechanisms responsible were quite unknown. It seemed quite likely that some of the weaker sources already detected with the small radio telescopes then available might be similar in character; if so, they would be at distances comparable with the limits of observation of the largest optical telescopes. It was therefore possible that more powerful radio telescopes might eventually provide the best way of distinguishing between different cosmological models. It was not until 1958 (*1*) that it could be shown with some certainty that most of the sources were indeed powerful extragalactic objects, but the possibilities were so exciting even in 1952 that my colleagues and I set about the task of designing instruments capable of extending the observations to weaker and weaker sources, and of exploring their internal structure.

The early observations were severely limited both by the poor angular resolution and by the limited sensitivity. It was usually impossible to obtain any information about the structure of a source, and adjacent sources could often not be properly separated, whilst attempts to relate the radio sources to optically visible objects were often prevented by the poor positional accuracy. The use of interferometers allowed better positions to be obtained, and sometimes made it possible to derive simple models for the source structure. Few of the sources were found to have an angular size greater than 2 or 3 minutes of arc.

The problem of making detailed maps of such sources arises simply from the fact that the wavelengths used are some million times greater than optical wavelengths—so that even to obtain a radio picture with the same resolution as that of the unaided human eye ($\sim 1'$ arc) we would need a telescope having a diameter of about 1 km operating at a wavelength of 50 cm. At the same time the instrument will be effective only if the surface accuracy is good enough to make a proper image, corresponding to errors of $\leqslant \lambda/20$ or a few centimeters; the engineering problems of building such an instrument are clearly enormous.

With the development, around 1960, of masers and parametric amplifiers capable of providing receiving systems of good sensitivity at wavelengths of a few centimeters, it became possible to build telescopes of diameter 10 to 100 m with sufficient sensitivity and with angular resolutions of $\sim 1'$ arc; even with such instruments the engineering problems of constructing a rigid enough surface are considerable, and it is likely to be difficult to build a conventional paraboloid capable of angular resolutions much better than $1'$ arc.

I would like now to describe an entirely different approach to the problem in which small aerial elements are moved to occupy successively the whole of a much larger aperture plane. The development and use of "aperture synthesis" systems has occupied much of our team in Cambridge over the past 20 years.

The principle of the method is extremely simple. In all methods used to obtain a large resolving power—that is, to distinguish the wave front from a particular direction and ignore those from adjacent directions—we arrange to combine the field measured over as large an area as possible of the wave front. In a paraboloid we do this by providing a suitably shaped reflecting surface, so that the fields incident on different parts of the sampled wave front are combined at the focus (Fig. 1a); the voltage produced in the receiving dipole represents the sum of these fields. We can achieve the same result if we use an array of dipoles connected together through equal lengths of cable (Fig. 1b).

Suppose now that only a small part of the wave front is sampled, but that different parts are sampled in turn (Fig. 1c); could we combine these signals to produce the same effect? Since, in general, we do not know the phase of the incident field at different times this would not normally be possible, but if we continue to measure *one* of the samples while we measure the others we can use the signal from this one as a phase reference to correct the values measured in other parts of the wave front. In this way, by using two small aerial elements, we can again add the fields over the wavefront—the area of which is now determined by the range of relative positions taken by the two aerial elements.

It might be thought that this method would be extremely slow, for if we are to sample an area of side D using elements of side d, it is necessary to observe with $2D^2/d^2$ different relative positions of the two aerial elements. In practice, however, the

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method is not significantly slower than the use of the large equivalent instrument. Although a large number of observations must be made, the results may be combined in a computer using additional phase differences, which correspond to many different wave directions (as in a phased array of dipoles), so that with the one set of observations an *area* of sky may be mapped which is limited only by the diffraction pattern of the small elements themselves. There are in fact some D^2/d^2 different directions which can be scanned in this way, and which would have had to be explored sequentially by a conventional instrument, so that the total observing time of the two methods is nearly the same.

It can also be seen that the sensitivity of the system is much better than would be associated with the small elements, for the signal from a particular point in the sky is contributing to that point on the map for the *whole* observing period; the resulting signal-to-noise is in fact equivalent to the use of an instrument having a collecting area $2d^2(2D^2/d^2)^{1/2} \sim 3Dd$, a figure which may be much greater than that of the elements themselves, and although it is not as great as if the full instrument of area D^2 had been built, it may exceed that of any instrument which *can* be built.

Unlike a paraboloid or array, in which both the sensitivity and resolving power are fixed as soon as the wavelength is decided, the value of d may be chosen so that the sensitivity, for any particular wavelength and type of observation, is matched to the resolution.

The method of aperture synthesis avoids the severe structural problems of building very large and accurate paraboloids or arrays, and allows both high resolving power and large effective collecting area to be obtained with a minimum of engineering structure and therefore cost. Provision must be made for the relative movement of the small elements, and their relative positions and electrical connecting paths must be known with an accuracy equal to the surface accuracy of the equivalent instrument ($< \lambda/20$). Automatic computing is needed to carry out the Fourier inversion involved in combining the observations to provide a map of the sky.

Historically, the forerunners of this type of instrument were realized in the early days when observations in both Australia and England with aerial elements having a range of separations were used to determine the distribution of radio brightness across the solar disk. In the earliest observations the sun was assumed to show spherical symmetry and no measurements of phase were necessary, so that a precise knowledge of the relative positions of the elements and of the electrical path lengths to the receiver was unnecessary. A similar technique was used to establish the profile of radio brightness across the plane of the Galaxy (*2*).

The first synthesis instrument capable of mapping an arbitrary distribution of sources was built at Cambridge in 1954 by John Blythe (*3*). It consisted of a long thin element covering, in effect, a whole row of Fig. 1c used in conjunction with a smaller element moved to 38 different positions along a perpendicular line (Fig. 2a) to synthesize a square instrument giving a resolution of 2°.2. This instrument provided the first detailed maps of the galactic emission at a long radio wavelength (7.9 m).

Larger instruments using this same configuration were built at Cambridge during the succeeding years, including an instrument of high sensitivity and 45′ arc resolution also at λ = 7.9 m (*4*) and a second operating at λ = 1.7 m with 25′ arc resolution, which was used by Paul Scott and others to locate nearly 5000 sources in the northern sky (*5, 6*).

These instruments used a very cheap form of construction; for $\lambda > 1$ m an efficient reflecting surface may be provided by thin ($\sim$1 mm diameter) wires 5 to 10 cm apart. In the case of the λ = 1.7 m instrument, wires stretched across simple parabolic frames of welded steel tube provided a cylindrical paraboloid 450 m long and 20 m wide (Fig. 3) at a cost of about £2 per square meter.

With the need for still greater resolving power, we realized that physically larger systems operating at meter wavelengths would no longer prove successful, because of the limitation imposed by irregularities of electron density in the ionosphere. But at shorter wavelengths, where these are unimportant, it becomes difficult to make efficient reflectors by using stretched wires, both because of their deflection by the wind and because with the closer spacing needed there is difficulty with them twisting together. For operating wavelengths of <50 cm a much more rigid supporting structure must be used, and the engineering costs of building a long element become very great.

The obvious solution is to use the system illustrated in Fig. 1c, in which the engineering structure is confined to two small elements—where much higher costs per square meter are acceptable. The method for altering the relative positions of the two elements presents some practical problems; suppose that the elements are mounted on two railway tracks at right angles (Fig. 2b), so that for each position of A on the north-south track B is moved to every position along the east-west track. For values of $D/d \sim 50$ there are then 5000 different arrangements, and if B is moved each day the observations will take 5000 days; although a map will then be available for the whole strip of sky, the period is too long for a graduate student's thesis!

Alternatively B could be moved rap-

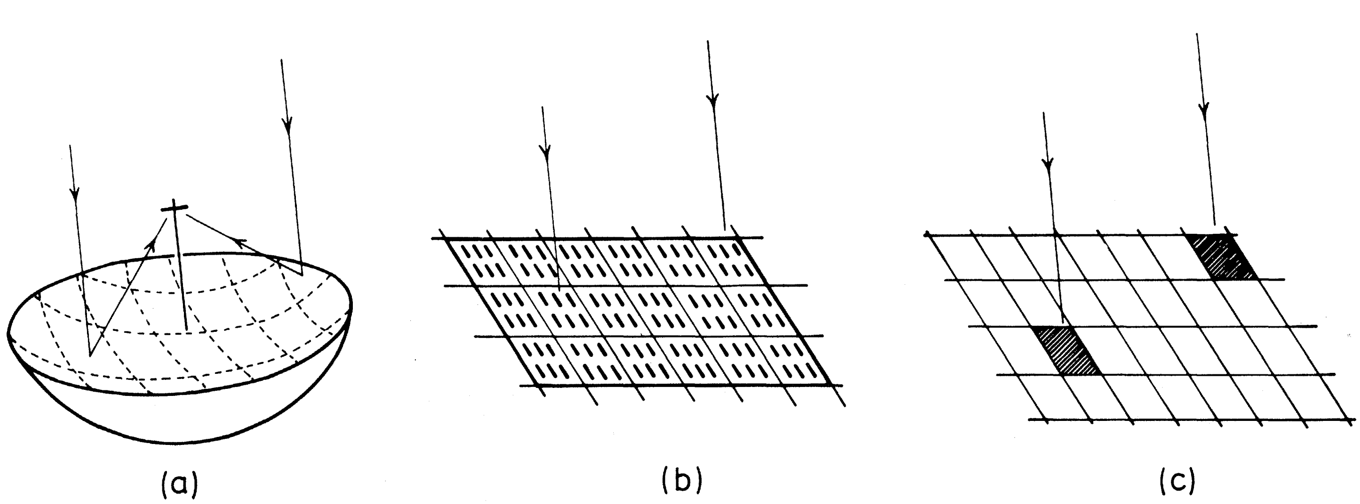


Fig. 1. The use of (a) a paraboloid, (b) an array of dipoles, or (c) the sequential sampling of the wavefront by small aerial elements to achieve a high resolving power by combining the signals from a large part of the incident wavefront.

idly—so that several positions could be fitted into the time during which the area of sky remains in the beam of the small elements. This will reduce the total time of the observations, at the expense of observing only parts of the strip of sky. We can clearly extend this period, and so allow more relative positions of *A* and *B* each day, if we arrange for the elements to track the chosen point in the sky for an extended period.

As soon as we do this, we realize that the rotation of the earth is itself providing us with a relative motion of *A* and *B* as seen from the source, without our having to move them on the surface of the earth at all. Suppose, for example, we have our two elements mounted near the North Pole and we use them to observe an area of sky centered on the Celestial Pole; in this case we do not even have to arrange for them to track. Over a 24-hour period one will have traced out a circular path about the other (Fig. 4a), and the signals recorded during this time can be combined to provide the same response as that of the equivalent ring aerial; by simply altering the separation along a line on say 50 successive days a complete aperture can then be synthesized. Ann Neville and I set up an experimental system in 1960–1961 to test the method and develop the computing; we used it to map a region 8° in diameter round the North Celestial Pole at a wavelength of 1.7 m (*7*). We connected up different 14-m sections of the long cylindrical paraboloid (Fig. 3) with some other small aerials to simulate the use of two 14-m diameter elements at different spacings. The effective diameter of the synthesized instrument was 1 km, and it provided an angular resolution of 4′.5 arc.

As well as showing that the method really worked, it provided some interesting astronomical results—in particular by allowing the detection of sources some eight times weaker than had been observed before; even though the area of sky covered was only some 50 square degrees the results were useful in our cosmological investigations.

In practice only 12-hour observations are needed because of the symmetry of the system, and observations need not be made *from* the North Pole or limited *to* the Celestial Pole, provided that the elements are situated on an east-west axis and each is able to track the required region of sky for 12 hours (Fig. 4b). At low declinations (δ) the synthesized instrument becomes elliptical with the north-south aperture reduced by sin δ. The engineering simplicity of moving the elements along a line and the consequent great saving in the area of land needed are, however, such great advantages that we eventually built three large instruments in Cambridge with equivalent instrumental diameters of 0.8, 1.6, and nearly 5 km.

These instruments are known as the Half-Mile, the One-Mile, and (because its construction coincided with the early negotiations for the entry of Britain into the European Community) the 5-km telescopes! The One-Mile telescope was the first to be built, and this started observations in 1964.

It is interesting that as early as 1954 we had discussed the possibility of building a high-resolution instrument on exactly these principles, and I have recently found two entries in an old notebook:

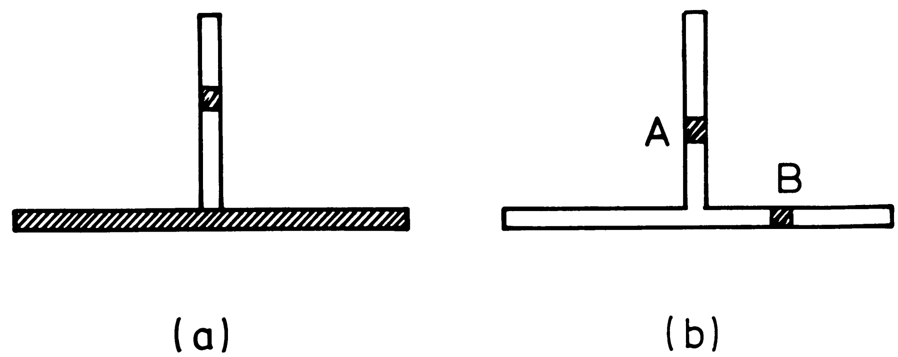


Fig. 2. (a) The arrangement used in the instrument built in 1954 by J. H. Blythe. (b) The equivalent instrument using two small elements.

Fig. 3. Photograph of the east-west arm of the λ = 1.7 m instrument built in 1957, with which nearly 5000 sources were located.

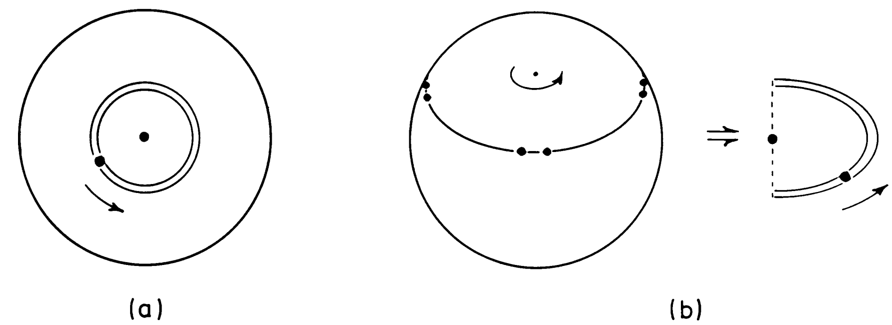


Fig. 4. (a) Two aerial elements mounted near the North Pole observing throughout the day are equivalent to one ring of a much larger instrument. (b) The elements may be used at other latitudes if arranged on an east-west line and used to track the chosen point for 12 hours.

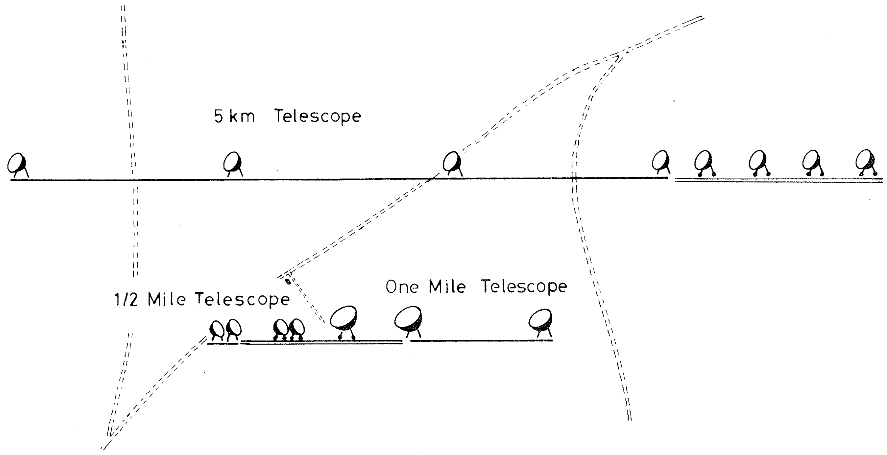


Fig. 5. Sketch map showing the arrangement of the One-Mile, Half-Mile, and 5-km telescopes.

"*8.6.1954 Possible research student and other projects*. . . . 3(f). North Polar Survey on 81.5 Mc/s. Effective gain area $\simeq 25^{ft} \times 1500 \simeq 37{,}500$ sq. ft. Effective resolving power area $\sim 10^6$ sq. ft."

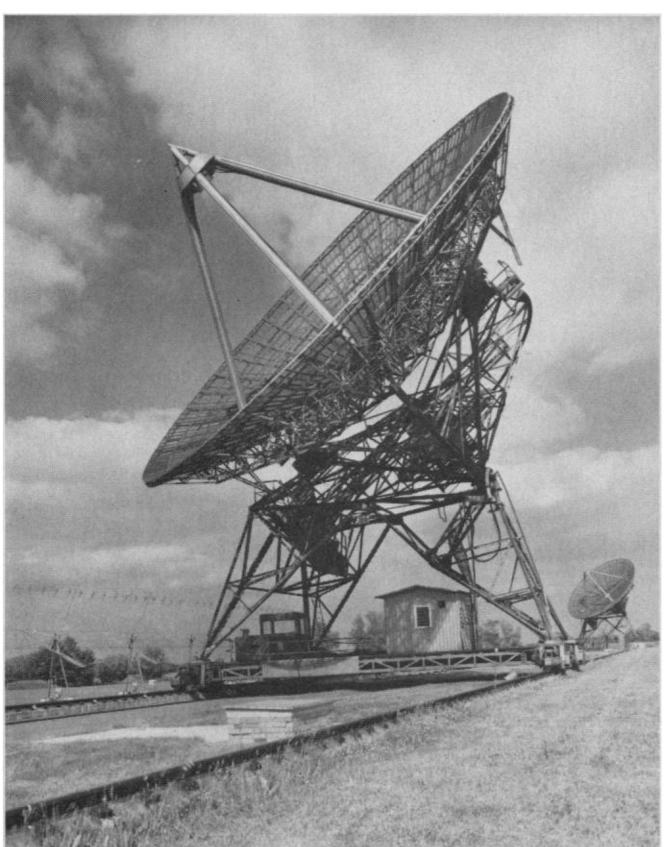
(The entry included a diagram of the proposed aerial element.)

"*29.6.1954* Do 3(f) in all directions where 180° rotation available. ? above about 20° might be possible by directing aerials in successively different directions—i.e. observation not on meridian."

A third entry on 22.7.1954 discusses the east-west rail track to be used for the latter program with two 30-foot aerials mounted on it, the arrangement of cabling needed to compensate for the different path lengths to the two aerials when observing off the meridian, and the selection of directions of observation "to give uniform cover of Fourier terms."

Why then, with its obvious simplicity and economy, did we not build this instrument in 1954? The answer is that at that time there were no computers with sufficient speed and storage capacity to do the Fourier inversion of the data. EDSAC I, which was the first stored-program computer, was built by Dr. M. V. Wilkes of the Cambridge University Mathematical Laboratory and came into operation in 1949. It was used for reducing John Blythe's observations and took some 15 hours of computing to do the 38-point transform for every 4 minutes of the 24-hour scan of the sky. It would not have been practicable to use it for the two-dimensional inversion needed for the earth-rotation synthesis. By 1958 the completion of the much faster EDSAC II and the development by Dr. David Wheeler of the Mathematical Laboratory of the fast Fourier transform (incidentally some 6 years before these methods came into general use) made possible the efficient reduction of the 7.9-m and 1.7-m surveys, and also enabled the trials of the 1.7-m earth-rotation synthesis to be made in 1961; even with EDSAC II, however, the reduction for the small area of sky covered in the latter survey took the whole night.

During the early stages in the design of the One-Mile telescope in 1961, I discussed with Maurice Wilkes the considerably greater problems of reducing the data from this instrument, but by then the replacement of EDSAC II was planned and the new TITAN computer, which came into operation in 1963, was easily capable of dealing with the output of the One-Mile telescope. The development of aperture synthesis has therefore been very closely linked to the development of more and more powerful computers, and it is interesting to speculate how our work in Cambridge would have proceeded if, for ex-



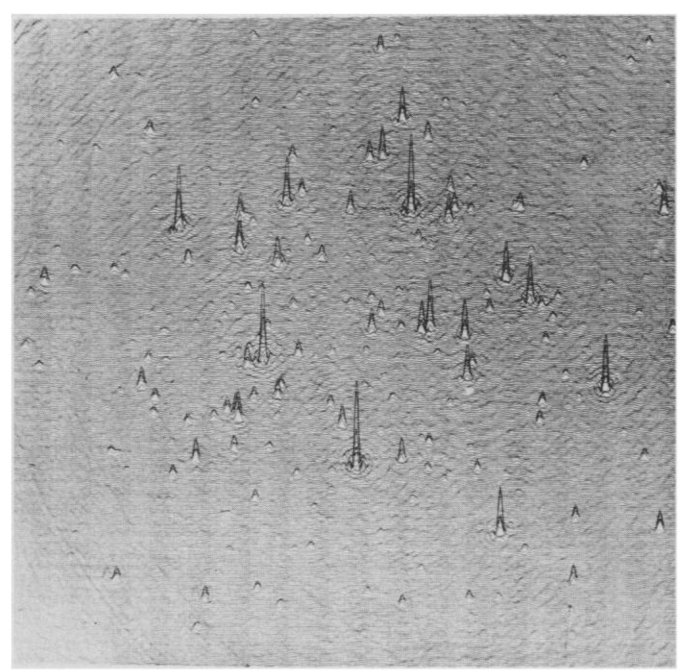


Fig. 6 (left). The One-Mile telescope, showing the west, rail-mounted dish in the foreground, with the two fixed dishes behind. Fig. 7 (right). Map obtained with the One-Mile telescope showing sources about 100 times fainter than had been observed before.

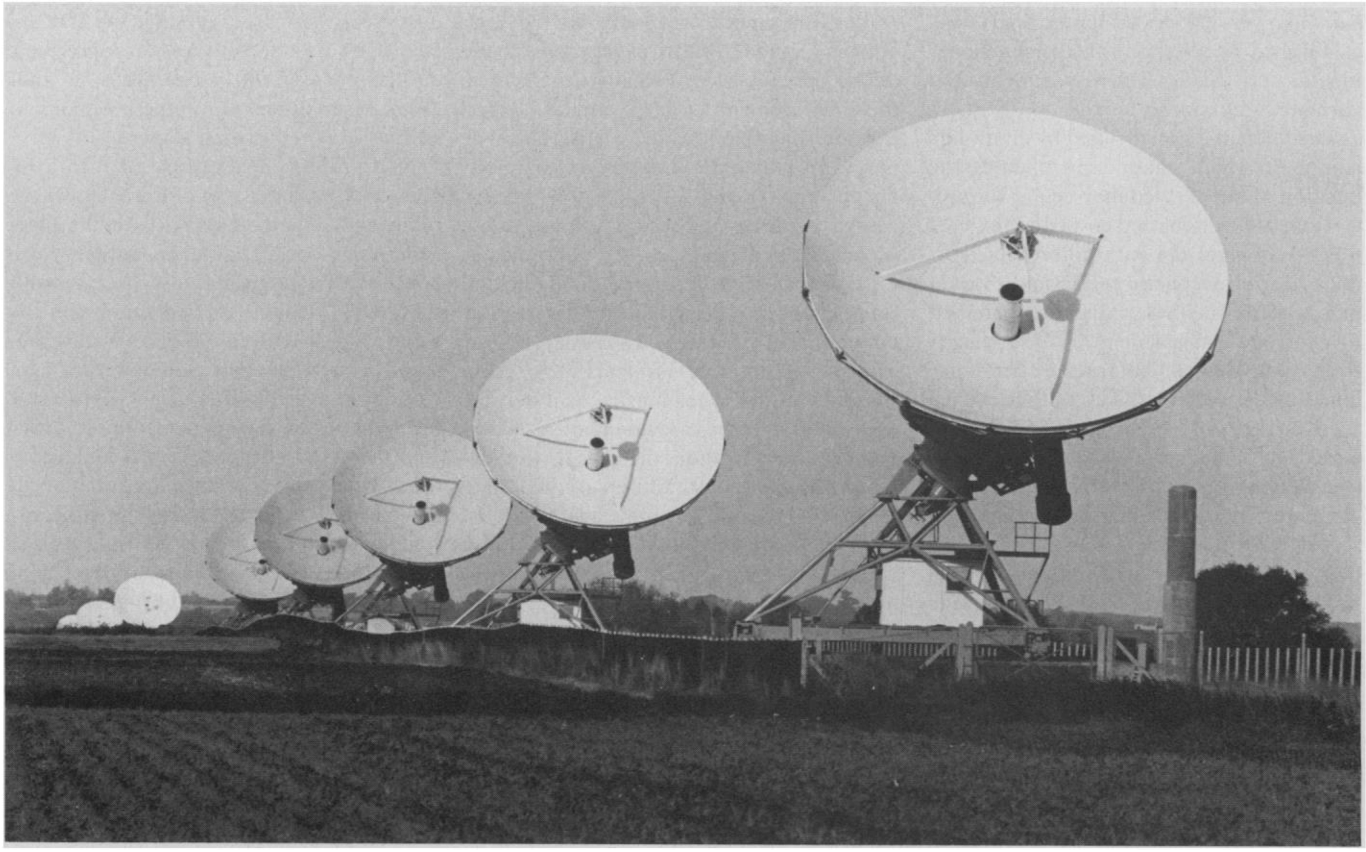


Fig. 8. The 5-km telescope, with the movable dishes in the foreground.

ample, computer development had been 5 years behind its actual course.

The two programs in my 1954 notebook subsequently formed the basis of two Ph.D. theses in 1964 and 1965.

Now I return to the design of the large instruments whose layout is shown in Fig. 5. The One-Mile telescope consists of three 18-m dishes, two fixed at 0.8-km spacing, the third mounted on a 0.8-km rail track (Fig. 6); this arrangement was cheaper than building the longer rail track and it also provided two spacings at a time. It was designed for two main programs: (i) the detection of much fainter and therefore more distant sources (see Fig. 7) in order to explore the early history of the Universe, and so try and distinguish between different cosmological models, and (ii) to make radio maps of individual sources in an attempt to understand the physical mechanisms within them; most of the sources studied have been powerful extragalactic objects, but the remnants of supernova explosions are perhaps physically as important.

The problem of the physics of radio galaxies and quasars and the cosmological problem are strangely linked; we appear to be living in an evolving Universe, so that very distant sources which, due to the signal travel time, we observe as they were when the Universe was younger, may be systematically different from a sample of nearby sources. But the intrinsically most powerful sources are so rare that there *are* no nearby ones, whilst the weak sources cannot be detected at great distances. If we are to understand *how* the Universe is evolving, we may first have to solve the physical problem of the individual source—so that we can infer the differences in its evolution at earlier cosmological epochs.

The Half-Mile telescope was built later by John Shakeshaft and John Baldwin. It was actually built very cheaply because, as can be seen from Fig. 5, it made use of the same rail track, and we were able to get the four 9-m dishes at scrap-metal prices from a discontinued radio link service, and only the mounts had to be built. It has been used mainly with a radio spectrometer covering the 21-cm wavelength band of neutral hydrogen to map the distribution of density and velocity of the hydrogen in a number of nearby galaxies, and forms part of a program concerning the formation and evolution of galaxies.

The 5-km telescope (Fig. 8) was completed in 1971, and because it represents a rather more advanced design I will describe it in more detail. It was designed solely for the purpose of mapping individual sources, and besides its larger overall size, the individual dishes are more accurate to allow operation at wavelengths as short as 2 cm. As a result the angular resolution is $\sim 1''$ arc, a figure comparable with the resolution attained by large optical telescopes on good mountain sites. It is at present being used on a wavelength of 6 cm, where the resolution is $2''$ arc.

In order to improve the speed of observation, four fixed and four movable elements mounted on a rail track are used, as shown in Fig. 5; this arrangement provides 16 spacings simultaneously, and a single 12-hour observation produces a $2''$ arc main response with circular grating responses separated by $42''$ arc. Sources of smaller extent than $42''$ arc can therefore be mapped with a single 12-hour observation; more extensive fields of view require further observations with intermediate positions of the movable elements to suppress the grating responses.

For operation at these short wavelengths, the positioning of the elements and the electrical cable connections must be stable and measured with an accuracy better than 1 mm. Conventional surveying methods allowed each element to be located to $\pm$ 10 mm, and the final alignment had to be based entirely on radio observations; the distance between the two outer fixed elements (on which the scale of declination is based) was found in this way to be 3430828.7 ± 0.25 mm, and no changes outside this error have been found over a 2-year period. The combination of azimuth and longitude, on which the measurement of right ascension depends, was established by observing the bright fundamental star Algol, which is a weak and variable radio source.

The telescope is controlled by an on-line computer which continually updates the position of the selected map center for precession, aberration, and so forth, and uses this to compute the path differences (corrected for atmospheric refraction) to each pair of elements; these values are then used to control electrical delays in the signals from each element before they are combined in the receivers. The outputs of the receivers are sampled by the computer and stored on a magnetic disk, so that at the completion of the observation they may be combined to form a map of the area observed. The map is then drawn on a curve-plotter controlled by the computer.

This instrument has been used in a wide range of astronomical programs from the study of ionized hydrogen clouds in our Galaxy to the study of distant quasars. Following the accurate calibration survey it became evident that as an astrometric instrument—to establish a coordinate system across the sky—it has a measuring accuracy comparable with that of the best optical methods, whilst overcoming some of the difficulties in optical work such as the measurement of large angles. Bruce Elsmore is involved in a collaborative program with optical observers to relate the positions of quasars (some of which are compact sources at both optical and radio wavelengths) as measured by radio means to those derived from the fundamental stars, in order to determine any large-scale nonuniformities which may exist in the present astrometric systems. He also showed how this type of instrument may be used for the direct measurement of astronomical time—without the need for collaborative observations at different longitudes to correct for polar motion—again with an accuracy comparable with that of optical methods ($\sim$5 msec in a 12-hour observation).

Another program is concerned with a study of the birth of stars. When a cloud of gas condenses to form a star, the dust which it contains provides such an effective screen that newly formed stars, with their surrounding regions of ionized hydrogen, can never be seen optically; only after this dust cloud has dispersed does the star appear. The dust introduces no appreciable absorption at radio wavelengths, so that radio observations allow these regions to be studied at the earliest stages.

NGC 7538 is an example of such a region, and the upper part of Fig. 9 shows the radio emission as mapped with the One-Mile telescope. The large diffuse component corresponds almost exactly with the optical nebulosity, and represents the cloud of gas ionized by one or more O-stars formed about a million years ago, with the dust sufficiently dispersed to allow the light to be seen. The compact lower component corresponds to gas ionized by much younger stars, which are still embedded in dust too dense for any optical emission to escape, and it is invisible on the photograph. When this southern component was mapped with the higher resolution of the 5-km telescope, the lower map was obtained, showing that there is an ionized cloud some 10″ arc in diameter, probably produced by the radiation from a star of spectral type O8, and an even more compact cloud to the south of this, produced by a still younger star, only a few thousand years old. The dust surrounding these two compact regions is heated by the young stars they contain, and both have been detected by their infrared emission (*8*).

But the most extensive program has been the mapping of extragalactic sources—the radio galaxies and quasars—which, during a brief fraction of their lives, produce some 10^{60} ergs of energy, equivalent to the total annihilation of the matter in about a million suns, by a mechanism which is not understood.

Figure 10 shows the new radio map of the source in the constellation of Cygnus—the first powerful radio galaxy to be recognized. The distribution of polarized emission from the north component is shown in Fig. 11, giving information on the magnetic field. Maps of a number of other sources made with the 5-km telescope are shown in Fig. 12.

In most cases the radio emission originates mainly in two huge regions disposed far outside the associated galaxy—although weak emission may also be detectable from a very compact central source coincident with the nucleus of the galaxy. In some cases much more extensive components or a bridge linking the components occur.

The finer detail provided by the 5-km telescope has already enabled some important conclusions to be drawn; the energy is probably being produced more or less continuously over a period of 10^7 to 10^8 years in a very compact nucleus and not, as was originally thought, in some single explosive

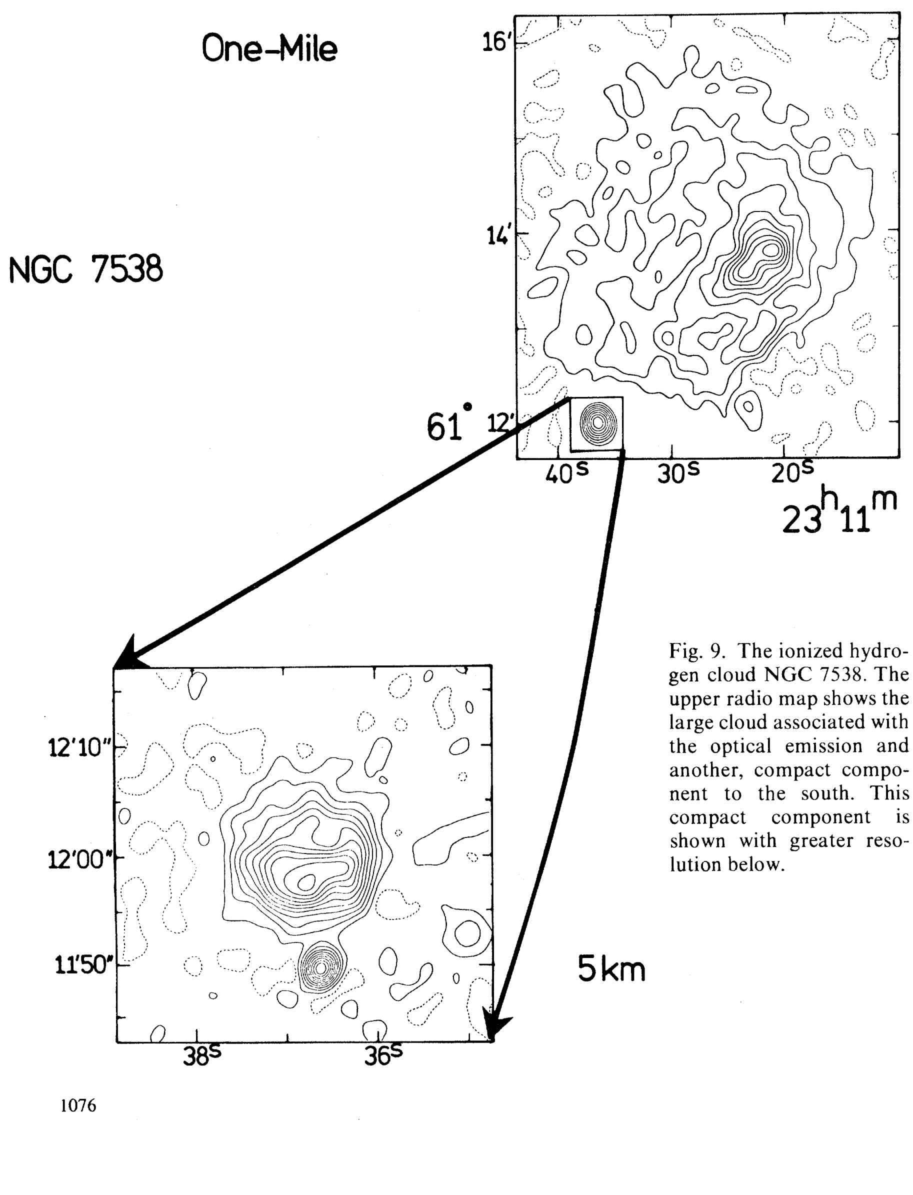


Fig. 9. The ionized hydrogen cloud NGC 7538. The upper radio map shows the large cloud associated with the optical emission and another, compact component to the south. This compact component is shown with greater resolution below.

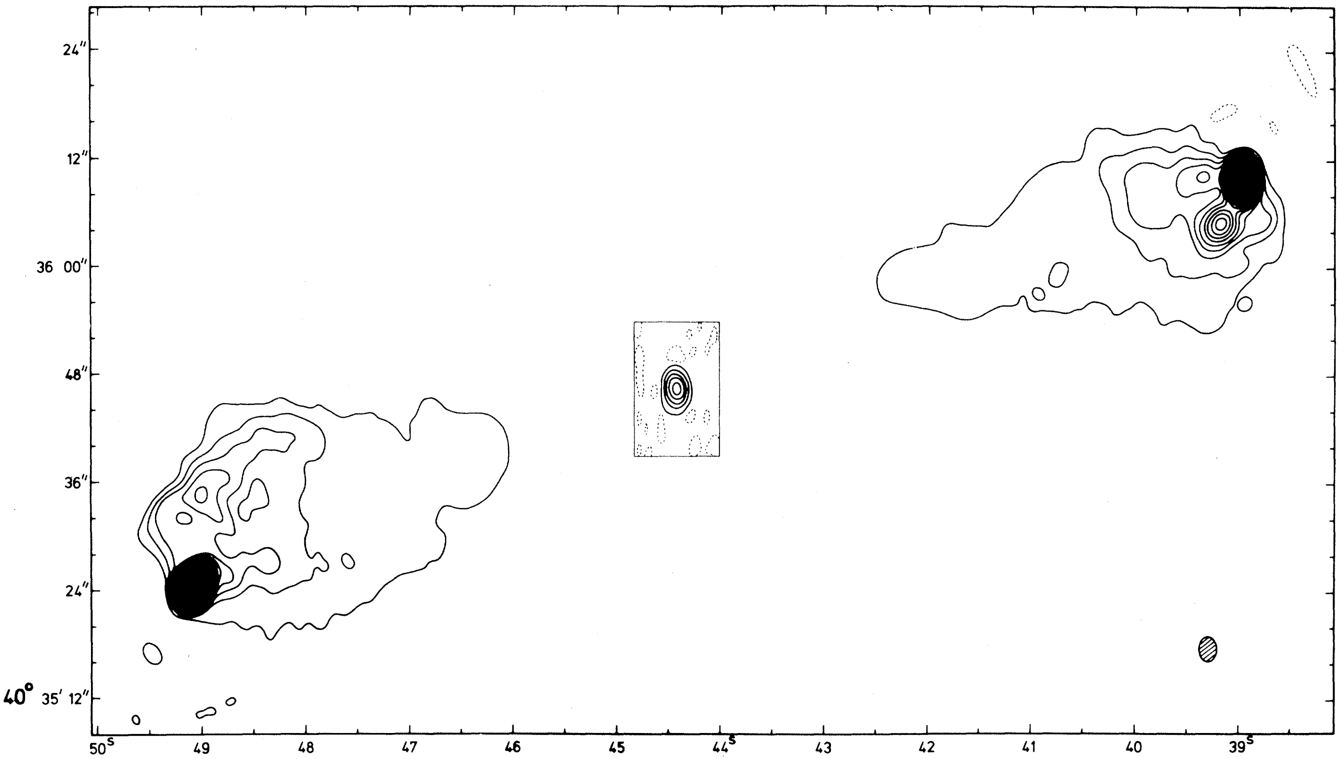


Fig. 10. The powerful radio galaxy in the constellation Cygnus mapped with the 5-km telescope. The compact outer components are exceedingly bright (31 and 41 contours). The central component, which corresponds to the nucleus of the optical galaxy, is very weak and is drawn with contours spaced at one-fifth of the interval.

event. The source of this energy may be associated with the gravitational collapse of large numbers of stars, in the manner which Tony Hewish describes in his lecture, or with material falling into a much more massive collapsed object at the nucleus of the galaxy. The mechanism for transmitting this energy to the compact heads of the main components (for example, see Fig. 10) is not understood, but may involve a narrow beam of low-frequency electromagnetic waves or relativistic particles (*9, 10*). The interaction of this beam with the surrounding intergalactic medium might then accelerate the electrons responsible for the radio emission from the compact heads, and their subsequent diffusion into the region behind the heads can probably explain the general shape of the extensive components.

While much remains unanswered, the present conclusions were only reached when detailed maps became available; the physical processes relating the nucleus, the compact heads, and the extensive tails or bridges can clearly only be investigated when the relationship between these structural components is known.

What can we expect in the future? In 1954, the first aperture synthesis telescope provided maps with a resolution of 2°.2; today we have maps with a resolution of 2″ arc. Can we foresee a continuing development with radio pictures having much *better* resolution than the optical ones? The technical problems of increasing the aperture or decreasing the operating wavelength are severe, but they do not appear to be as serious as the limitations imposed by the earth's atmosphere; in optical observations atmospheric turbulence on a scale of ~10 cm in the lower atmosphere introduces irregularities in the incident wave front which normally limits the resolution to ~1″ arc. At radio wavelengths the contribution of these small-scale irregularities is not important, but there are also irregularities of refractive index on a much larger scale in the troposphere. Two distinct types have been found in a series of observations with the One-Mile and 5-km telescopes; neither can be attributed to variations of air density, and both are

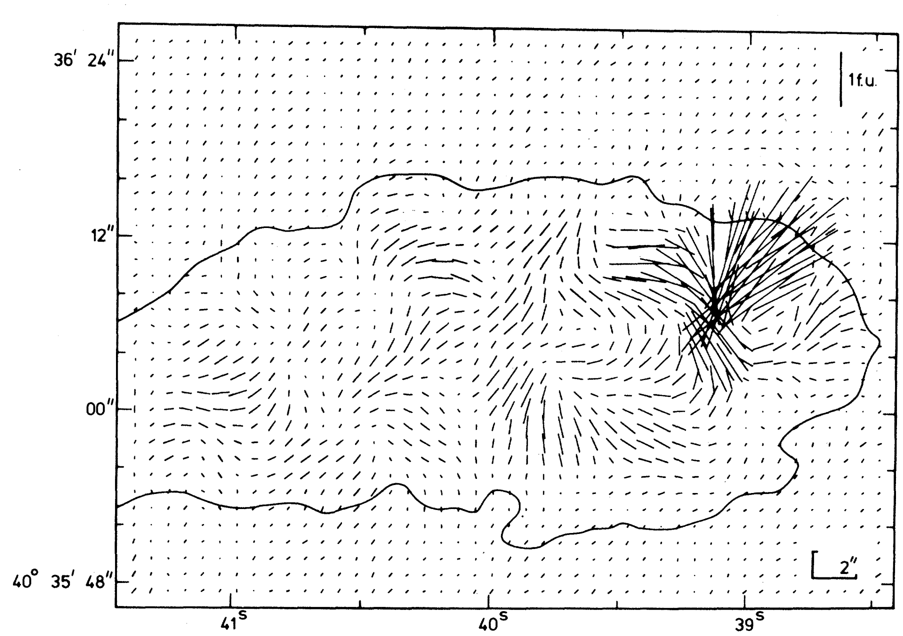


Fig. 11. Polarization of the emission from the north component of the Cygnus source, which shows the magnetic field to be turbulent on a scale of ~10^4 light years.

probably due to nonuniformity in the partial pressure of water vapor, which makes an important contribution to the refractive index at radio wavelengths. One class has a typical scale size of ~0.7 km and is attributed to turbulence in the troposphere due to solar heating of the ground in the same way that fair-weather cumulus clouds develop. These irregularities, however, are often detected in clear air conditions without the formation of cumulus clouds; they only occur during daytime and are more severe during summer months. The second class, which shows only slight diurnal or annual variation, has a much larger scale size, typically 10 to 20 km, and there may be still larger scales which have not yet been recognized. The origin of these disturbances is not known, and it is therefore not possible to predict how they might depend on geographical position.

Under very good conditions—representing about 1 percent of the total time—the atmospheric irregularities are extremely small and correspond to a distortion of the incident wave front by < 0.2 mm over 5 km; under these conditions, operation at a wavelength of 4 mm or less would be possible and should provide maps with a resolution better than 0″.2 arc. These excellent observing conditions have only been encountered during periods of widespread winter fog when the atmosphere is extremely stable, a result which illustrates the differing requirements in seeking good sites for optical and radio observatories!

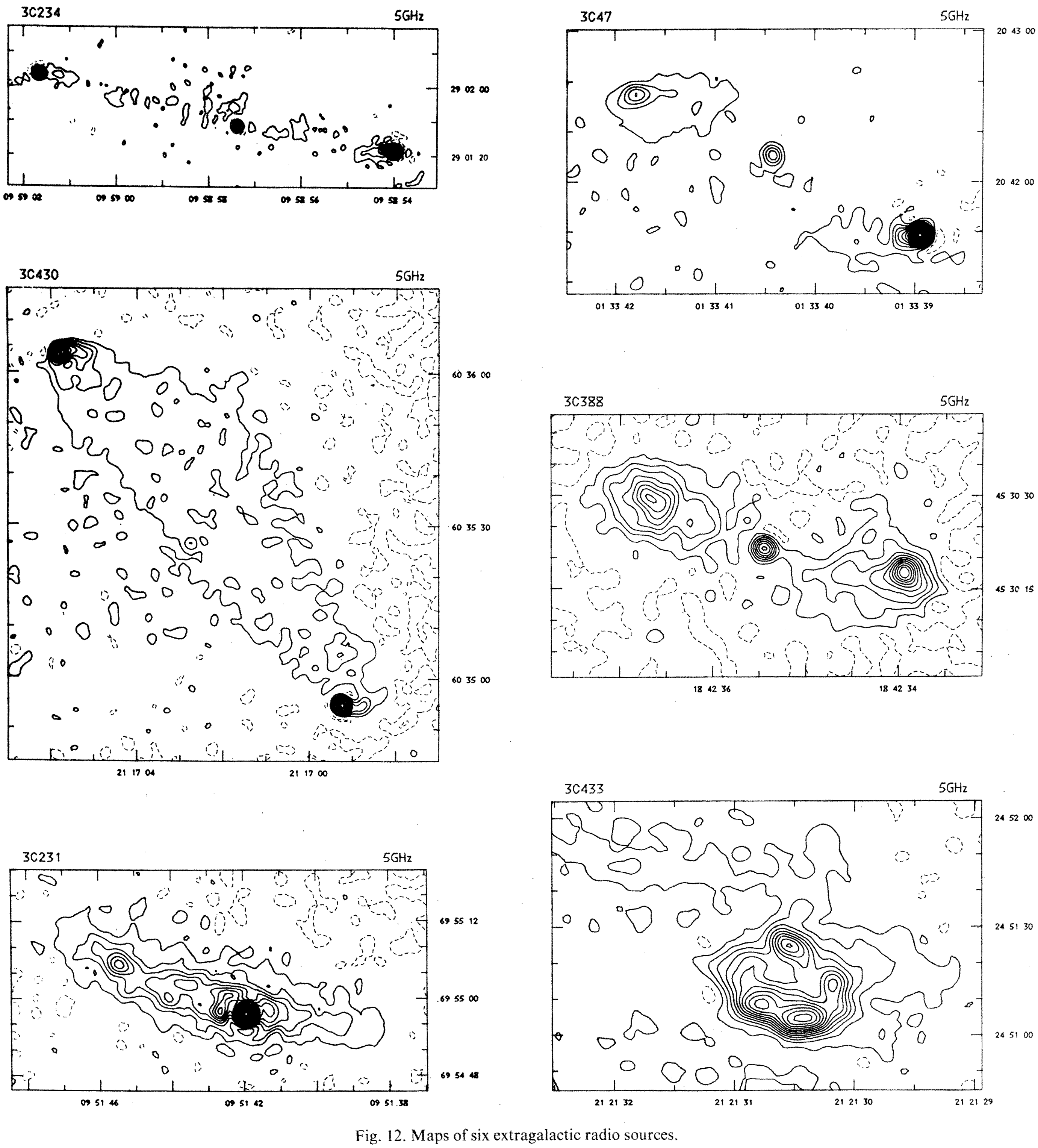


Fig. 12. Maps of six extragalactic radio sources.

For most of the time the atmospheric irregularities are considerably worse, and although there is insufficient information on scale sizes >20 km, the use of instruments much larger than this will introduce difficulties associated with the curvature of the atmosphere. One might guess that it should be possible to build instruments which would give a resolution better than 0″.5 arc for perhaps 50 percent of the winter months.

To reach a greater resolution new techniques capable of correcting for the atmospheric effects will be necessary. One simple, though expensive, solution would be to build a second dish alongside each element, so that observations of a reference point source close to the area to be mapped could be made simultaneously at every spacing. The observed phase errors for this reference source could then be used to provide a continuous correction for the signals from the area being mapped.

Such techniques can clearly be extended to the interferometers having baselines of many thousands of kilometers (very long baseline interferometers) which have been made possible by the development of atomic frequency standards. These instruments have shown the existence of very small components, ~0″.001 arc in some sources. A comparison source for eliminating both atmospheric and instrumental phase was first used at Jodrell Bank in the special case of sources of the OH maser line at $\lambda = 18$ cm, where different components within the primary beam can be distinguished by their frequency; if one is used as a phase reference the relative positions of the others can be found (*11*).

For continuum sources a reference outside the primary beam of the instrument must, in general, be used, and two elements at each location are needed. This technique has been used in the United States to reduce both instrumental and atmospheric phase variations in measurements of the gravitational deflection of radio waves by the sun (*12*); one pair of elements was used to observe a source close to the sun, while the other pair observed a reference source about 10° away.

The accuracy of the correction, and hence the shortest wavelength at which mapping could be achieved, would depend on the angular separation between the area to be mapped and a reference source sufficiently intense and of sufficiently small angular size. But even if adequate phase stability can be attained in this way, there is a serious practical difficulty in making maps with resolution ~0″.001 arc, due to the inevitable poor sampling of the aperture plane. Even with five or six stations distributed across one hemisphere of the world, and using every possible combination of the signals from them, with observing periods lasting several hours, the fraction of the aperture plane which can be filled is still very small, so that the field of view which can be mapped without ambiguity from secondary responses is unlikely to exceed ~0″.02 arc. Whilst there seems little hope of deriving complete maps of most sources with this resolution, there are certainly some central components where such a map could provide very important information.

But I think it may also be important for our understanding of the mechanisms operating in the main components of radio sources to obtain complete maps with intermediate resolution; for this work extensions of the present synthesis techniques, while retaining good filling of the aperture plane, are needed.

The last 25 years have seen a remarkable improvement in the performance of radio telescopes, which has in turn led to a much greater understanding of the strange sources of "high-energy astrophysics" and of the nature of the Universe as a whole.

I feel very fortunate to have started my research at a time which allowed me and my colleagues to play a part in these exciting developments.

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Pulsars and High Density Physics

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Discovery of Pulsars

The trail which ultimately led to the first pulsar began in 1948 when I joined Ryle's small research team and became interested in the general problem of the propagation of radiation through irregular transparent media. We are all familiar with the twinkling of visible stars, and my task was to understand why radio stars also twinkled. I was fortunate to have been taught by Ratcliffe, who first showed me the power of Fourier techniques in dealing with such diffraction phenomena. By a modest extension of existing theory I was able to show that our radio stars twinkled because of plasma clouds in the ionosphere at heights around 300 km, and I was also able to measure the speed of ionospheric winds in this region (*1*).

My fascination in using extraterrestrial radio sources for studying the intervening plasma next brought me to the solar corona. From observations of the angular scattering of radiation passing through the corona, using simple radio interferometers, I was eventually able to trace the solar atmosphere out to one-half the radius of the earth's orbit (*2*).

In my notebook for 1954 there is a comment that, if radio sources were of small enough angular size, they would illuminate the solar atmosphere with sufficient coherence to produce interference patterns at

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This article is the lecture which he delivered in Stockholm, Sweden, on 12 December 1974 when he received the Nobel Prize in Physics, a prize which he shared with Sir Martin Ryle. Minor corrections and additions have been made by the author. The article is published here with the permission of the Nobel Foundation and will also be included in the complete volume of *Les Prix Nobel en 1974*, as well as in the series Nobel Lectures (in English) published by the Elsevier Publishing Company, Amsterdam and New York. Professor Ryle's lecture appears on page 1071 of this issue.