NRAO ONLINE 29   1957 FLINDERS. LECTURE

VISTAS in RADIO ASTRONOMY

Published in the Australian Academy of Science Yearbook p 65 1957

QUOTE:

INTRODUCTION

I am deeply conscious of the honour that has been conferred on me in being invited to deliver this, the first of the Matthew Flinders Lectures. I am also conscious of my own limitations in the face of this exacting task and in accepting the invitation I have taken it as a tribute not so much to myself as to the whole of the radio astronomy group in the Radiophysics Laboratory of which I have the good fortune to be the leader.

Matthew Flinders was one of Australia's most illustrious explorers. He came to Sydney in 1795 at a time when substantial parts of our coastline were quite unknown. When he left practically the whole coastline was charted. Flinders's contribution to this was not only substantial in quantity—he mapped the greater part of the southern coast and the Carpentaria region—but was outstanding in quality. His charts are only now being replaced in many areas. Flinders circumnavigated Australia for the first time and indeed the name Australia was given to our continent by him.

In order to accomplish what he did Flinders was clearly a great navigator. He also made important contributions to branches of science used in navigation: meteorology and magnetism. In 1806 in a paper to the Royal Society (from 1806) he showed that a change in barometric pressure tended to be associated with a change of wind and could be used to predict such a change. He also studied the variations of the compass on board ship. He was the first to experiment systematically on the cause of these variations and his research was so successful that he was able to devise a method for suppressing them. The “Flinders bar", a soft iron bar so placed as to counteract the effects of other soft iron on the ship, is standard equipment on ships today.

But Flinders is known best for his work in outlining parts of a new continent. In this lecture I propose to discuss the new science of radio astronomy. In Australia research in radio astronomy began after the second world war at a time when radio waves from the sun and the Milky Way had already been discovered. Since then we and our colleagues in other countries have explored many branches of this science and we are beginning to outline it as Flinders and contemporary explorers outlined Australia a century and a half ago.

Radio astronomy is simply astronomy using radio waves for the observations. The discovery that radio waves as well as light can be used for observing the heavenly bodies has given us a new tool for use in studying the universe. In many cases we observe, by radio, things which are invisible optically so that we obtain new clues to the nature of the universe. And I need scarcely remind you that, in the detective story which is science, clues add up non-linearly: two and two can add up *to* more than four.

Radio waves are used in astronomy in two ways: echoes of signals transmitted from the earth can be observed after reflection from astronomical bodies, or radio waves emitted naturally by these bodies can be studied. The latter is far more important because, owing to power limitations, the echo or radar method is restricted to relatively near objects. As yet the moon is the most distant object from which an echo has been received. I shall not discuss the echo method in this lecture.

The radio waves emitted by the sun and other astronomical bodies are the same kind of waves-electromagnetic waves-as light but the millionfold difference in wavelength carries with it radical differences in emission, in propagation, and in capabilities for reception.

Light originates in atomic processes. Radio waves also can originate in atoms and there is one very important spectral line, the 21 centimetre line of atomic hydrogen, in the radio part of the spectrum. But they can also originate in other processes which do not involve the properties of individual atoms. These processes can be described in terms of the radiation which the classical electromagnetic theory indicates as arising from accelerated charges, which are equivalent to changing electric currents. These charges may be individual electrons or groups of electrons. In these cases it is not necessary to invoke the quantum theory. The simplest process is the thermal emission from an ionized gas which can be considered as the sum total of effects due to electrons accelerated during collisions with ions or molecules ("free-free transitions" in the words of the quantum theory). Another important process is the emission from electrons moving in magnetic fields. The resulting spiral motion involves acceleration and hence radiation. This radiation is well known in the laboratory in synchrotrons and is frequently called "synchrotron radiation". Ionised matter may also show organised motions of groups of electrons or ions which constitute changing electric currents and may give rise to radiation. So-called "plasma oscillations" are an example of such group motions.

On the propagation side the wavelength difference leads to two main differences in behaviour. Firstly, radio waves can freely penetrate clouds of small particles, terrestrial clouds or the obscuring clouds of interstellar space, which so often prevent optical observations. This is because the particles are very small with respect to the radio wavelength and is an extension of a principle familiar in its application in infra-red photography. Secondly, ionised gas, which may be nearly transparent to light, is opaque to radio waves of sufficiently long wavelength. The terrestrial ionosphere is the best known example of this situation.

Now the outer atmospheres of stars are strongly ionised so that radio waves cannot reach us from the relatively dense inner regions responsible for most of the light. The radio waves emitted by the sun originate in the high solar atmosphere in regions which, optically, we have great difficulty in seeing at all. Stars presumably radiate similarly but all the radiation from beyond the solar system which has been identified originates in interstellar space, in the extremely diffuse matter which exists between the stars. So far we have identified thermal emission from relatively cold (100°K) neutral atomic hydrogen and from hot (10,000°K) ionised gas, and very intense emission, which must arise in non-thermal processes, from certain diffuse nebulae which are characterised by most violent internal motions. Radio waves may well be considered the characteristic radiation of interstellar matter.

In this connection, it is interesting to recall the words of Karl Jansky, the father of radio astronomy. Speaking of the radiation from the Milky Way which he had discovered he wrote that the source of this radiation must lie "in the stars themselves or in the interstellar matter distributed throughout the Milky Way". His second alternative now appears correct.

On the instrumental side, radio astronomy suffers from an outstanding disadvantage relative to optical astronomy: lack of angular resolution. This arises from the relatively great wavelength. Diffraction effects limit the angular resolution of a radio or optical telescope to an angle of the order of *lambda/D* radians where lambda is the wavelength and D the diameter of the object-glass of an optical telescope or the aerial of a radio telescope. This gives, for an optical instrument of 1 cm aperture, a limiting resolution of a fraction of a minute of arc; for a 10-metre diameter radio telescope operating at a wavelength of one metre, about 5 degrees. The major instrumental developments of radio astronomy have been aimed at overcoming this limitation.

I propose now to show you by a process of sampling something of the directions of development of radio astronomy. I shall discuss various unsolved problems of astronomy and in each case tell you of the new information which radio methods is yielding. In most cases this information is fragmentary; in one it is surprisingly detailed; however I do not present these cases as ones which are solved but as ones in which optical and radio methods are working together towards solutions. Because of this fragmented pattern I have entitled my lecture "Vistas in Radio Astronomy" following the examples of a recent book "Vistas in Astronomy" (Arthur Beer editor London 1955). I was abashed to find that the editor of this volume had found 192 vistas; besides these, the four I shall present look small fry indeed! My vistas include :

(1) The ejection of matter from the sun and the production of terrestrial aurorae and magnetic storms.
(2) The origins of cosmic rays.
(3) The shaping of spiral galaxies.
(4) The furthest limits of observation.

I have approached these subjects from the point of view of basic problems of astronomy concerning which radio astronomers are in the process of obtaining new information. Some of this radio information can immediately be used to elucidate questions which are already formulated. More usually, however, a new discovery simply presents a new puzzle which has to be solved before we can use it in attempting to explain the physical nature of things. "Radio stars" were such a discovery. At first their nature was a mystery but the intense ones are now considered to be nebulous bodies composed of extremely rarefied gas in most violent motion. Along with this evidence came the hypothesis suggesting them to be sources of cosmic rays so that their study may well help to unravel one of the great mysteries of physics, the origin of cosmic rays.

I now proceed to discuss my selected problems, taking them in order of distance from the earth.

EJECTION OF MATTER FROM THE SUN AND THE PRODUCTION OF TERRESTRIAL AURORAE AND MAGNETIC STORMS

An old standing but intriguing problem of geophysics is the cause of polar aurorae and magnetic storms. These phenomena are closely associated, they occur together, and moreover the strong tendency for association with disturbances on the sun shows them to be of solar origin. Without going into detail the evidence indicates that both phenomena are caused by the ejection from the sun of clouds of gas, mainly fully ionised hydrogen, *i.e.* an electrically neutral mixture of protons and electrons. Such ejections frequently occur at the time of solar flares. The gas is ejected with a velocity of the order of 1000 km/sec and takes about a day to reach the vicinity of the earth. When it does so it gives rise to great electric currents high above the earth, which are the immediate cause of the magnetic storm effects, and to a glow in the upper atmosphere, which is the aurora. This much is established, a major clue being the observed delay of about a day between the occurrence of great flares on the sun and the onset of terrestrial magnetic storms and aurorae. But neither the mechanism of ejection nor that of the production of aurorae and magnetic storms by the cloud on its arrival near the earth is understood. Nor are there reliable optical observations of the gas being ejected or on its way from the sun to the earth.

A glow like the aurora could be excited by the simple impact on the atmosphere of high velocity protons and electrons. But on quantitatively checking the hypothesis that it is caused by the direct impact of the cloud ejected from the sun a most interesting discrepancy is found. Protons and electrons having the velocity indicated by the time of travel from the sun to the earth (1000 km/sec) would not be able to penetrate the atmosphere to anything like the 100 km heights at which aurorae are commonly seen. It follows that there must be some more complex mechanism at work, perhaps using the energy of the bulk of the cloud to accelerate a relatively few particles to quite high energies.

It is quite evident that the subject is in urgent need of observational evidence, either of the solar ejection process, of the passage of the gas clouds through inter-planetary space, or of their arrival near the earth. Radio astronomy is giving such evidence of the first, the ejection process, in the case of those disturbances associated with solar flares. There is also a strong probability that it will be able to tell us something of conditions just outside the earth through the study of the kind of low frequency atmospherics known as ''whistlers", but the latter study has not yet proceeded far enough for me to describe it here. And. of course radio methods supply a high proportion of what is already known of the phenomena at the earth itself.

Returning to the radio evidence about the ejection process, it was observed early in the history of radio astronomy that big solar flares are often accompanied by large outbursts of radio emission. In one of the characteristic forms this emission tends to be concentrated in one or two frequency bands and the bands tend to drift with time as illustrated in the dynamic spectrum at the top in Fig. 1 [Figures are included at the end of the text]. Such a burst is called a Type II burst. When two frequency bands are observed they are in a two-to-one ratio and are clearly a fundamental and second harmonic emitted by a non-linear oscillating system. The fundamental frequency is believed to be set by the electron density at the place of origin. Since the high solar atmosphere where these bursts originate is fully ionised the frequency is an indication of the actual gas density. Now in the case illustrated in Fig. I, which is typical, both bands drift towards lower frequencies, corresponding to a decrease in density at the place of origin. The simplest interpretation is that the burst is due to a disturbance moving upwards in the solar atmosphere. Quantitatively, the variation of gas density with height is known, and the derived upwards velocity is from 500 to 1000 km/s, agreeing reasonably with that of the ejected clouds which cause aurorae etc. There is also complementary evidence from directional studies that disturbances towards the limb of the sun move outwards on the disk ·with similar velocities. The disturbances giving rise to such bursts therefore occur at the same time as the clouds causing aurorae are ejected, and move with similar velocities. Hence there is good reason for believing that these bursts are caused by the passage up through the solar atmosphere of the ejected gas clouds responsible for magnetic storms and aurorae, and, as a corollary, that radio waves can be used to observe the genesis of these phenomena. Systematic studies of radio burst spectra and position on the sun are now in progress which we hope may lead to major developments in understanding of solar physics and solar-terrestrial relations.

ORIGINS OF COSMIC RAYS

One of the most tantalising and elusive questions of modern physics is that of the origin of cosmic rays. Observations show that a shower of charged particles: electrons, mesons, protons etc.-the bric-a-brac of atomic physics-is incident on the surface of the earth from above. It has been found that this is caused by the incidence on the top of the atmosphere of a primary shower composed of high energy protons and other atomic nuclei. These particles range in energy from 10^9 electron volts to the fantastically high energy of 10^{17} or 10^{18} electron volts and they appear to arrive isotropically from all directions. Since the particles are charged they are deviated from straight lines by magnetic fields and this is apparent in the case of the earth's field. In addition it is now believed that there are appreciable magnetic fields in interplanetary and interstellar space which cause the particles to follow very complex paths. This will obscure any tendency of the particles to arrive from the direction of principal sources of cosmic rays.

The two main clues to the origin are the composition of the particles and occasional observed increases in intensity at the time of certain solar flares. The particles appear to consist of protons and the nuclei of other atoms in the approximate proportions found in the matter of the sun and stars and in the interstellar gas. Such a composition suggests an origin in some rare mechanical or electrical accelerating process, operating perhaps in the outer atmospheres of stars, or perhaps in interstellar space, and accelerating those nuclei which happen to be favourably situated. The second clue is the observation of occasional increases of cosmic ray intensity following big solar flares. Five large increases have been observed since 1942. The increases range from about 10% to some forty times, depending on the locality of the observations and the component of the cosmic rays observed. The increase in the low energy components is particularly marked. The onset of the increase is abrupt and there is a marked delay, ranging from about 10 to 100 minutes between the onset of the flare and the cosmic ray increase. Such observations leave little doubt that at times the sun can give rise to cosmic rays, but it is generally thought that at normal times the great majority arrive from outside the solar system. Thus there may be two or more mechanisms of origin: one characteristic of the sun and similar stars, the others are not so restricted.

In the face of such lack of observational evidence, theories of origin must be largely speculative. The most plausible of those current was originated by Fermi. He started from the idea that there are in interstellar space numerous discrete clouds of gas drifting about with more or less random velocities. If a particle were to suffer a series of elastic collisions with such clouds it could gain energy. This is an extreme extension of the idea of equipartition of energy in a gas. It is well known that molecules of different masses in a mixture of gases tend to attain equal kinetic energies. The gain of energy by the lighter bodies at elastic collisions is exemplified by a head-on collision between a relatively heavy billiard ball and a light pingpong ball moving with equal speed. The lighter ball bounces off with a speed approaching three times its original so that it shows a very considerable net gain in kinetic energy. Fermi's idea is that whole clouds or parts of clouds, with their astronomically great masses and correspondingly great energies, may be considered as equivalent to giant molecules in the sense that the colliding atomic particle tends on the average to gain energy at the expense of the kinetic energy of the cloud. Now this mechanism of collision between clouds and particles would not work in normal circumstances since the collision would not be elastic. A proton entering a cloud would simply dissipate its energy in collisions with molecules in the cloud, as do cosmic rays in the earth's atmosphere. If the cloud were tenuous enough and the particle energetic enough it might pass through without appreciable loss of energy but neither would it be deviated and so it could gain no energy. Fermi's suggestion was that a magnetic field in the cloud could give the required deviation without loss of energy and so simulate an elastic collision. Quantitative considerations suggest that the mechanism is feasible.

Radio astronomy has given us a further clue, but one which required optical confirmation before it had any weight. Cosmic radio waves are remarkable for the high intensities observed, intensities which correspond to black-body temperatures of up to tens or hundreds of millions of degrees Kelvin. Such unexpectedly high intensities are reminiscent of the unexpectedly high energies of cosmic rays and it was suggested by Alfven and Herlofson that the emission from "radio stars" might be due to emission from very high energy electrons spiralling round lines of magnetic force in specially disturbed regions of interstellar space. This is the mechanism, mentioned earlier as responsible for the emission of light from the particles in a synchrotron as they are accelerated in circling round in the magnetic field, which is commonly called "synchrotron radiation". At this stage the suggestion was pure speculation. But Shklovskii extended the hypothesis and brought it right down to earth. One of the best known of the "radio stars" is the Crab Nebula, the expanding remnant of a supernova which was observed to explode in the year 1054. Now the light emission from this nebula has presented serious anomalies. Shklovskii suggested that not only the radio emission but also an important part of the light is emitted by the synchrotron process. It is a characteristic feature of synchrotron emission that it must be plane polarised with the electric vector in the plane perpendicular to the magnetic field. This follows since the acceleration of the electrons which give rise to the emission is in this plane. This prediction of plane polarisation is susceptible to test and has been beautifully verified in the optical case. *A* picture by Oort and Walraven of the Crab Nebula with indications of the direction and degree of polarisation superposed is shown in Fig. 2. In the radio case no such polarisation has been observed but there are certain difficulties, instrumental and propagational, which remove any significance from the negative result. The light from at least one other radio star, the peculiar galaxy NGC 4486, has also been found to be plane polarised. It is now reasonably certain that in the Crab Nebula, and presumably in many other similar bodies, the synchrotron emission process is operative. This implies the presence of high energy electrons and magnetic fields and it is immediately obvious that the processes which accelerate electrons are likely also to accelerate protons and the other positive nuclei which comprise cosmic rays. This suggestion is in accord with theoretical considerations and it is very probable that the Crab Nebula and similar bodies in the galaxy are substantial sources of cosmic rays. This discovery does not provide direct evidence on the mechanism of generation of cosmic rays, but conditions in the Crab Nebula, *viz.* exceedingly high turbulence and extensive magnetic fields, are in line with the Fermi hypothesis. **It also suggests that the main sources of galactic radio waves may also be the main sources of cosmic rays.** (our emphasis)

In our galaxy the main part of the radio emission originates fairly uniformly throughout a more or less spherical region extending beyond the sun. There is also a concentration in a thin disk centred on the galactic plane, and in this disk there are numerous localised concentrations such as the Crab Nebula. As viewed from the earth these sources yield a distribution of radio brightness over the sky, showing a ridge following the Milky Way, with a major peak in the direction of the centre of the galaxy.

These ideas should provide cosmic ray workers with a further stimulus to try to beat the obstacles provided by cosmic magnetic fields and to try to obtain information on the directions of the principal sources of the cosmic rays incident on the earth.

We now return to the other optical clue: the emission of cosmic rays by the sun at the time of occasional big flares. It also has an associated radio clue. Among the types of bursts of solar radio waves recognised through observations of dynamic spectra is one known as Type III, which has the features illustrated in the middle and bottom spectra of Fig.1. These show a frequency drift similar to the Type II burst shown on top but the rate of drift is much more rapid. Groups of these bursts similar to that shown in the middle spectrum frequently occur at the time of solar flares though they are not restricted to these times. If these bursts can be explained along lines similar to those used in explaining Type II bursts then they must be due to disturbances moving upwards in the solar atmosphere with velocities in the range 2×10^4 to 2×10^5 km/sec.

No solar phenomenon is known having such a velocity but if it exists it is unlikely to be detectable optically. But the cosmic ray increases, occurring at times after the associated flares of from 10 to 100 minutes, imply a mean velocity between the sun and earth of from 2×10^4 to 2×10^5 km/sec, the same range as that inferred for Type III bursts. This velocity does not fit the speed of the actual cosmic ray particles incident on the atmosphere, which is about 0.9 or more of the velocity of light. This difficulty is precisely analogous to that encountered in relating Type II bursts to auroral particles, and similarly may be interpreted in terms of the ejection from the sun of clouds of particles which later, by a secondary process, give rise to the actual cosmic rays.

The hypothesis linking Type III bursts with solar cosmic rays is quite speculative and there are, of course, alternative explanations for the delay between the flare and the onset of the cosmic rays. The cosmic rays may not be emitted from the sun until after some condition has had time to develop, or the cosmic rays may be emitted without delay but may not proceed to the earth directly but may reach it after travelling a long and devious path along which they may be guided by interplanetary magnetic fields. The observational evidence is very sketchy-for example we have yet to obtain radio burst spectra at the time of one of the flares accompanied by a cosmic ray increase. Such evidence should soon be forthcoming. Two new radio spectrographs will shortly be operating in the United States, which with our own, makes a total of three: and we are adding facilities to our own for locating the apparent position of the burst on the solar disk. When such systematic observations become available we may hope to form a reasoned judgment.

Radio astronomy has thus given us two leads on the origin of cosmic rays. In the cosmic case it has given us a strong suggestion that we should look for sources of cosmic rays in bodies like the Crab Nebula which are intense sources of cosmic radio waves, and, by inference, we should follow up the idea of generation in turbulent interstellar matter which is permeated by magnetic fields. In the solar case it has given us a hint that the origin may be bound up with the emission of Type III bursts but has not provided us with a substantial clue as to the physics of emission of cosmic rays by the sun.

The Structure of Spiral Galaxies

Observation shows us that the matter in the universe is not distributed uniformly but tends to be accumulated into aggregates of increasing extent and complexity: into stars, into groups or clusters of stars, into galaxies and into clusters of galaxies. Of these, galaxies are the most extensive of which we have systematic knowledge and one of the great problems of astronomy is an understanding of their structure. The broad picture derived from optical astronomy is of an irregular array of galaxies extending through space to the limits of observation. Each contains a vast number of stars: from about 10^9 to 10^{11} or 10^{12}, and occupies a vast space: diameters range from tens to hundreds of thousands of light years. The distance between neighbouring galaxies may be a million light years and we have practically no knowledge of the matter, if any, which lies between. The galaxies themselves show diverse forms, some are irregular, some are circular or elliptical (see Fig. 3) and others, the spiral galaxies, show the well known but diverse forms of spiral structure (see Figs. 4 and 5). Now the spiral galaxies have a consistent feature. Each appears to include a remarkable collection of interstellar gas and dust and very bright stars concentrated in a surprisingly thin disk lying in the plane of rotation. The dust layer is very obvious in Fig. 5. Gas and dust and the characteristic bright stars are absent from elliptical galaxies.

When we consider the physical processes involved in the structure of galaxies a physicist will normally accept the idea of the concentration of matter into vast agglomerates as a natural consequence of gravitation. If the matter was formed in agglomerates in the beginning, gravitation would tend to hold them together; if it was more uniformly dispersed, gravitation might well cause the condensations. Similarly the generally spherical shape, with a tendency to flattening when rotating, is an expected effect. It should be remembered that the stars are so far apart that they practically never collide so that one which is attracted towards the centre of a galaxy will normally pass right through and go out a nearly equal distance on the other side. Thus the form of elliptical galaxies appears consistent with the equilibrium of stars under gravity. But the spirals present two puzzles. Why the remarkably thin disk in the equatorial plane? And why the spiral arms? It is probable that the concentration of interstellar matter in a thin disk is explicable when we take into account the effect of collisions of interstellar gas clouds in damping out excursions above and below the disk; and it is thought that the characteristic bright stars are recently formed from interstellar matter, so these also should be expected to be in or near the disk. But the spiral arms are a mystery. One of the complications is that parts of the galaxy at different distances from the centre rotate with different angular velocities so that an existing pattern would be smeared out in a relatively short time. Spiral structure must be self-regenerating. Theories exist but astronomers have no confidence in them. The best known, due to Lindblad, predicts for example that the spiral should be rotating with the arms leading. Observations indicate that this is probably wrong. It is clear that forces in addition to gravity have to be taken into account. Perhaps these are mainly the viscous forces involved in collisions between clouds of gas, perhaps there may be electromagnetic forces as well. In this connection it is worth noting some of the really exotic structures seen in galaxies (see Fig. 6). What is the explanation of these curious isthmuses between galaxies? The problem of galactic structure is one where more observational evidence is vitally needed and it is one in which radio astronomy is making an outstanding contribution to astronomy in giving us a picture of the hydrogen distribution in our own galaxy.

Galactic Structure from the 21 cm Spectral Line of Atomic Hydrogen

In radio astronomy only one spectral line, the 21 cm line of atomic hydrogen, has been observed. But of all possible lines from all possible types of matter we could scarcely conceive a more useful one. The line is observed in emission, or absorption, from interstellar hydrogen. Now the matter in the universe is mainly hydrogen and though much of it is condensed into stars, a fraction of equal order exists as a gas in interstellar space. The main constituent of this gas, neutral atomic hydrogen at a temperature of about 100 K, is completely invisible optically. The hydrogen only becomes visible when it is excited and ionised, usually by the ultra-violet light of some nearby bright star. So with the discovery of the line a major constituent of the universe became "visible" for the first time. Moreover in our galaxy this radiation has the ability to penetrate the absorbing clouds of particles which so restrict our optical view in the vicinity of the galactic plane (cf. Fig. 5).

The history of the application of this line in astronomy provides a magnificent tribute to the imagination, ability and perseverance of one small group of astronomers working with Professor Jan Oort in Leiden. The possibility of detection of the line was suggested by van de Hulst, then one of his students, in 1945. Equipment for its observation was constructed and the line observed in 1951 by Muller and Oort. However they were beaten to the actual discovery by some weeks by Ewen and Purcell of Harvard and the account of discovery was published simultaneously in Nature by the above groups and by the Australians Christiansen and Hindman who had been informed by Purcell of the Harvard work and asked to check it. They were able to confirm the discovery in the remarkably short time of about six weeks. The next step was the application of observations to delineate the spiral structure in our galaxy by the method outlined below. Owing to the immediate availability of appropriate equipment, Christiansen and Hindman were able to make the first scrappy observations of spiral structure but the Dutch workers proceeded steadily and have produced a detailed picture of the part of the Milky Way visible from Holland. The corresponding southern information is being derived here [Australia] and the results I shall show combine the two series of observations.

The current incomplete picture of spiral structure in the vicinity of the galactic plane is indicated in Fig. 7. The central part of the figure is a plan view in the galactic plane. The dotted areas denote concentrations of neutral hydrogen as derived by the Sydney workers, the hatched areas those derived in Leiden. The black areas are regions of ionised hydrogen and the bright stars characteristic of spiral arms in external galaxies and have been derived optically. The optical information is limited to the region near the sun by the obscuration caused by clouds; the radio information is relatively more crude but extends to very distant parts of our galaxy. The radio picture leaves no doubt as to the general type of spiral structure present though it is to be expected that it will be modified in detail with more precise observations and more refined interpretation. The 21 cm information is derived as follows.

In a direction such as that of the line ABC the 21 cm line profile has the form shown at the top of Fig. 7. The natural width of the line is vanishingly small and the observed widening is believed entirely due to Doppler shifts. Further, the intensity of a part of the profile is not greatly influenced by temperature but depends mainly on the amount of hydrogen with the appropriate line-of-sight velocity in the direction concerned. Hence a peak such as that at B1 in the profile is indicative of a concentration of hydrogen with that velocity. The main part of the velocity is due to rotational motion of the galaxy as a whole, objects at varying distances from the centre of the galaxy rotating with different velocities as do the planets round the sun. The actual motion is known approximately from optical data so that the distance of the concentration of hydrogen responsible for the peak at B1 can be deduced. The profile in the direction ABC shows peaks at A 1, B1 and C1 corresponding to hydrogen concentrations at A, B and C respectively. Observations in other directions show similar peaks corresponding to hydrogen concentrations at appropriate distances and the whole picture of Fig. 7 has been synthesised from such observations.

The observations have been extended to three· dimensions but the results are more difficult to display. At the bottom of Fig. 7 a section normal to the galactic plane is shown. Note that the vertical scale is exaggerated. The section shows concentrations where it cuts the spiral arms and gives an approximate idea of the structure of the galactic disk.

An interesting new aspect of this work concerns the shape of this disk. The hydrogen is concentrated in a layer which is only about 700 light years thick and which is very flat. But, as shown in the section, the layer is bent upwards at one edge and down at the other. The place where it is bent down is the edge nearest to the Clouds of Magellan, the nearest external galaxies, which lie in the direction towards which it is bent. This distortion appears to be a tidal effect exerted by the Clouds of Magellan on our galaxy. But it is greater than would be expected from gravitational attraction and a theory is not yet developed. Perhaps it, too, may require the introduction of large-scale forces other than gravitation.

To radio astronomy then belongs the credit of establishing beyond doubt that our galaxy is a spiral. [our emphasis] It has given us the general form of the spiral structure and has established with surprising precision the general shape of the disk of atomic hydrogen which lies near the equatorial plane. These are major contributions to the study of the reasons why galaxies are shaped as they are.

The Furthest Limits of Observation

There is no doubt in my mind that the greatest achievement of astronomy through the ages has been the revelation of how vast is the universe and how small is our world in comparison. I should like to remind you of the truly astonishing recession through the years of the astronomical horizon : of the elucidation during the middle ages of the nature and size of the solar system, which placed the earth as a small unit in a system thousands of millions of miles in extent ; of the first measurements about 1838 of the distances to several of the fixed stars, which extended the astronomical horizon to distances which were so great they had to be measured in light years; of the gradual realisation of the extent of the system of stars in the Milky Way; and then finally the enormous jump which came around the 1920's when the spiral nebulae were firmly identified as independent system of stars like our own galaxy, and were seen to extend to limits of observation then extending to a thousand million light years. This fantastic step was largely due to the 100-inch Mt. Wilson telescope which can see tens of millions of galaxies. The more recent 200-inch Palomar telescope can see about 10^8 galaxies out to a limit of about 2 x 10^9 light years. And in this vast range there is as yet no clear evidence of the systems of galaxies coming to an end or even changing. [our emphasis**]**

Can the universe of galaxies then go on for ever? We have every-day evidence precluding a simple infinite universe. When we look at the night sky the space between the stars looks black. In an infinite static Euclidean universe in which the galaxies extended to infinity any straight line would ultimately intersect a star and the whole sky should blaze like the disk of the sun. This model is therefore too simple. But relativity and modern cosmology have presented us with not one, but a number of very different world models, or universe models, as alternatives, and cosmology urgently requires more observational data to help weed out the false ones. Nevertheless the simple observation of the blackness of the sky remains as one of three really significant observations in all cosmology.

The second basic observation about the distant parts of the universe is the so-called "red-shift". Distant galaxies show a displacement of spectral lines towards the red which appears to be proportional to their distance from us. This displacement has the characteristics of a Doppler shift and is generally interpreted as indicating that distant galaxies are receding from us with velocities which are proportional to distance. Incidentally the observation of the red-shift suggests an explanation of why the spaces between the stars are black. If the red-shift law may be extrapolated to greater distances-a hypothesis be it noted-the light from the more distant ones would be displaced out of the visible range.

At the present time we have two basic concepts of the origin and nature of the universe, and numerous variants of each. Both concepts consider the red-shift as indicative of expansion. The first concept which is due largely to Lemaitre is that, at a very remote time in the past, the whole of the matter in the universe was assembled in a relatively small volume. An inconceivably vast explosion took place, throwing matter outwards in all directions. The fastest moving objects continued to move fastest and are now the furthest away. Assuming the velocities to have remained constant, the matter must have been in a small volume about 10^{10} years ago. This would have been the date of the explosion and the birth of the universe as we know it.

The other concept, which has been developed largely by the recent school of astrophysicists at Cambridge, including Hoyle, Bondi and Gold, is known as the "continuous creation of matter" hypothesis. It is supposed that the universe has no beginning nor end, nor has it spatial limits. On a large scale it is unchanging in space or time. Expansion is accepted as an observational fact and the difficulty of the expected decrease in mean density due to it is met by postulating that new matter is created from nothing at such a rate as to exactly counterbalance the expansion effect. This rate turns out to be so low that the chance of observing such creation appears negligible.

Now we can try to decide between such theories on the grounds that one appears more reasonable or that one fits the observations better. But we should be clear in our minds which criterion we are using; the first is really philosophical, the second strictly scientific. The present position is that we do not have adequate observational evidence to apply the observational test. If we wish to make a tentative decision we must do it on the grounds of personal choice.

The main chance of deciding scientifically between these theories depends on obtaining observational evidence on the nature of the universe at very great distances: The "explosion" theory predicts that if we look far enough afield we may come to a region where it differs from that around us : an "edge" of some sort to the system of galaxies. The continuous creation theory postulates no change as one of its axioms. Both are complicated by relativistic effects. At present the great optical telescopes are employed on studies which may show such effects but nothing certain has yet emerged. This negative result, out to distances of at least 10^9 light years, is the third basic observation of cosmology. Radio studies of "discrete sources" have been reported which appeared to show an "edge of the universe" effect but we now consider the observations to be at fault. We shall now discuss this evidence.

Radio Observations of Extremely Distant Galaxies

The first hint of the existence of discrete radio sources, or "radio stars", was obtained by Hey, Parsons and Phillips, who in 1946 found irregular fluctuations in the radio waves from an area in the constellation of Cygnus. These were shown by Bolton and Stanley in 1948 to be due to the existence of a small intense radio source, and this source was identified by Baade and Minkowski in 1952 as two colliding galaxies at a distance now known to be about 200 million light years. Our present interest in this source is not so much in its nature, though colliding galaxies are quite sufficiently interesting, but in its fantastically high radio emission. It emits as much radio energy as light. In consequence we could observe it if it were much further away than the most distant optically observable galaxies. Other similar colliding galaxies then should provide a tool for the exploration of the extremely remote parts of the universe. But we suffer from a serious limitation. Without optical identification we cannot yet tell whether a faint radio source is faint because it is distant, though a powerful emitter, or because it is a poor emitter though not very distant. This limitation could be removed if we could measure the red-shift of the radio source and use this as a distance criterion. But this is difficult; so far it has been possible to measure the red-shift for only two extragalactic bodies; the Cygnus source and a cluster of galaxies in the constellation of Coma.

Failing such definite measures of distance it is possible to resort to statistics. If the radio sources in the universe are uniformly distributed and deviations from a static Euclidean universe can be neglected, the numbers of observable sources should increase with decreasing intensity according to a -3/2 power law, *i.e.* $N_s = kS^{-3/2}$, where N_s is the number of sources of intensity S or greater. This follows since an increase in the distance to the furthest observable sources by a factor "a" increases the volume of observable space, and consequently N, by a^3 but decreases S by $1/a^2$. Now there have been two extensive surveys of radio sources: the Cambridge 81.5 Mc/s one and the 85 Mc/s, incomplete, Sydney one. The Cambridge one, the first completed, indicated a significant departure from the -3/2 power law which was interpreted by Ryle and Scheuer as due to a real change in the density or average strength of radio sources at extreme distances. This would have been a result of first class cosmological importance. It would have invalidated an axiom of the continuous creation theory. But the results obtained by Mills and Slee in Sydney are in gross disagreement with the Cambridge ones. (See Fig. 8 for a comparison of a sample area.) This is not the place to discuss the detailed reasons for this discrepancy. One at least of the surveys is grossly wrong and I believe that the Cambridge one is invalid owing to serious confusion effects arising from lack of angular resolution. The Sydney statistics show no departures from the -3 /2 power law greater than instrumental uncertainties. Consequently the current position is that there appears to be no reliable radio evidence showing an "edge of the universe" effect.

In the field of cosmology, then, radio astronomy is in a tantalising position. There is every reason to suppose that some galaxies which are far beyond the current optical limits are visible to radio telescopes. But so far we have been unable to make use of this potential source of information because of lack of detail in radio observations. This position has been aggravated by the disagreement between Cambridge and Sydney observations after the raising of high hopes by the Cambridge work. But there is every reason to suppose that improved radio telescopes and more critical analysis will take the effective radio horizon out to distances where the recession velocity approaches the velocity of light and decisive results on "world models" can be obtained.

Conclusion

Let us now glance back at these vistas in an attempt to see something of the outline of radio astronomy. We have seen, in the magnetic storm case, a possible way of studying the ejection of tenuous clouds of gas from the sun into interplanetary space; in the cosmic ray case, optical and radio observations dovetailing with theory in the study of conditions in interstellar space where cosmic rays may arise; in the galactic structure case, a whole new world of interstellar hydrogen made visible for the first time, but requiring the data of optical astronomy for its interpretation; and in the very distant galaxies case, the probability of extending the astronomical horizon well beyond the optical limits.

The picture which is emerging shows firstly a tendency in radio astronomy towards the study of interstellar matter. There is little doubt that this field will remain a major interest, but it is not the only one. It shows, secondly, and this is even more important, that the questions to which radio astronomy is contributing are quite fundamental questions in astronomy. **Radio and optical astronomy are not distinct disciplines but are complementary parts of a single science: astronomy. The outstanding difference between the two is in their ages; radio astronomy is the youngest child of the oldest of the sciences. It is at an age at which its rate of growth is likely to be spectacular**.(our emphasis)

REFERENCES

A general account of radio astronomy up to about 1953 is given in the book "Radio Astronomy" (Oxford 1955) by the author and R. N. Bracewell. A popular account of radio astronomy is available in the recent book, "The Changing Universe" (New York, Random House, 1956) by John Pfeiffer.

Fig 1

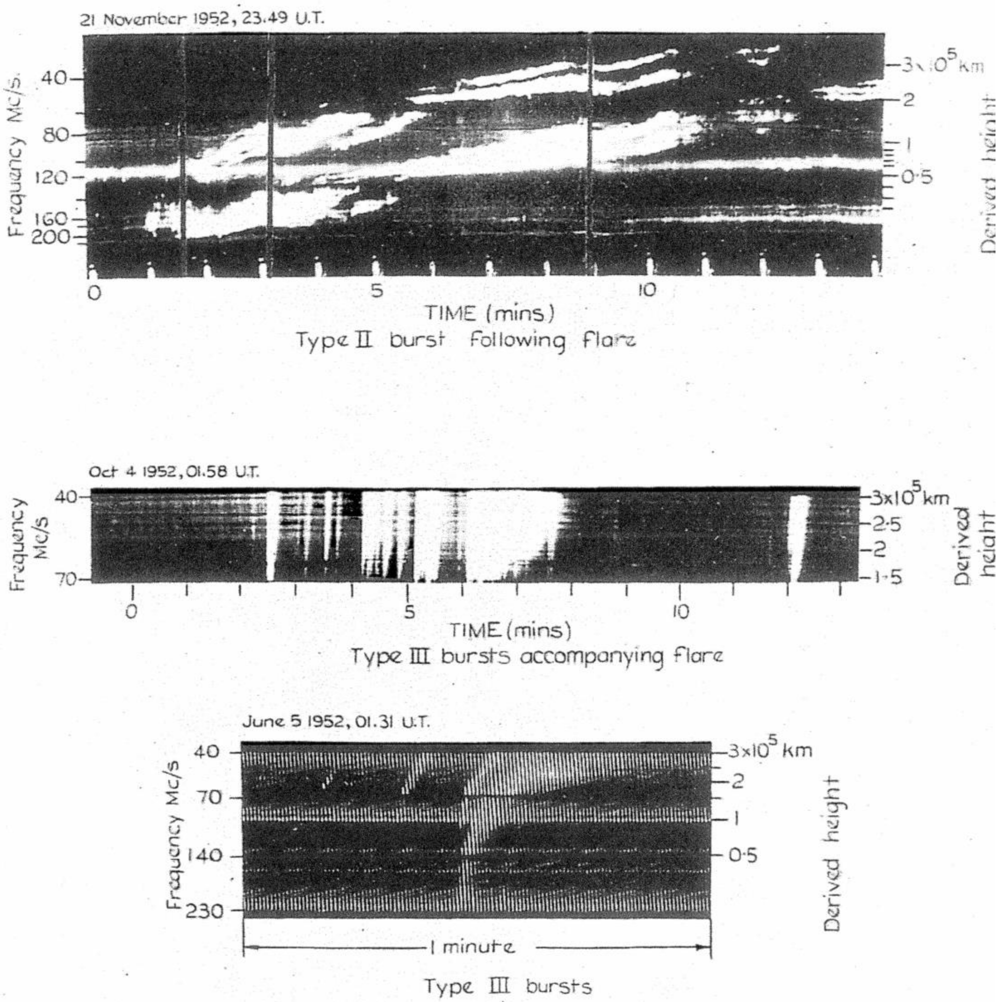

FIG. 1: *Time varying spectra of Type II and Type III solar bursts.*(1)

A vertical section of each is an instantaneous spectrum at the time indicated; white indicates high intensity.

The Type II spectrum (*above*) shows fundamental and second harmonic frequency bands, both displaying the typical slow frequency drift.

The middle spectrum shows a cluster of Type III bursts and the bottom one several on an expanded time scale. The fast frequency drift and existence of a second harmonic in one case can be best seen in the latter.

Fig. 2

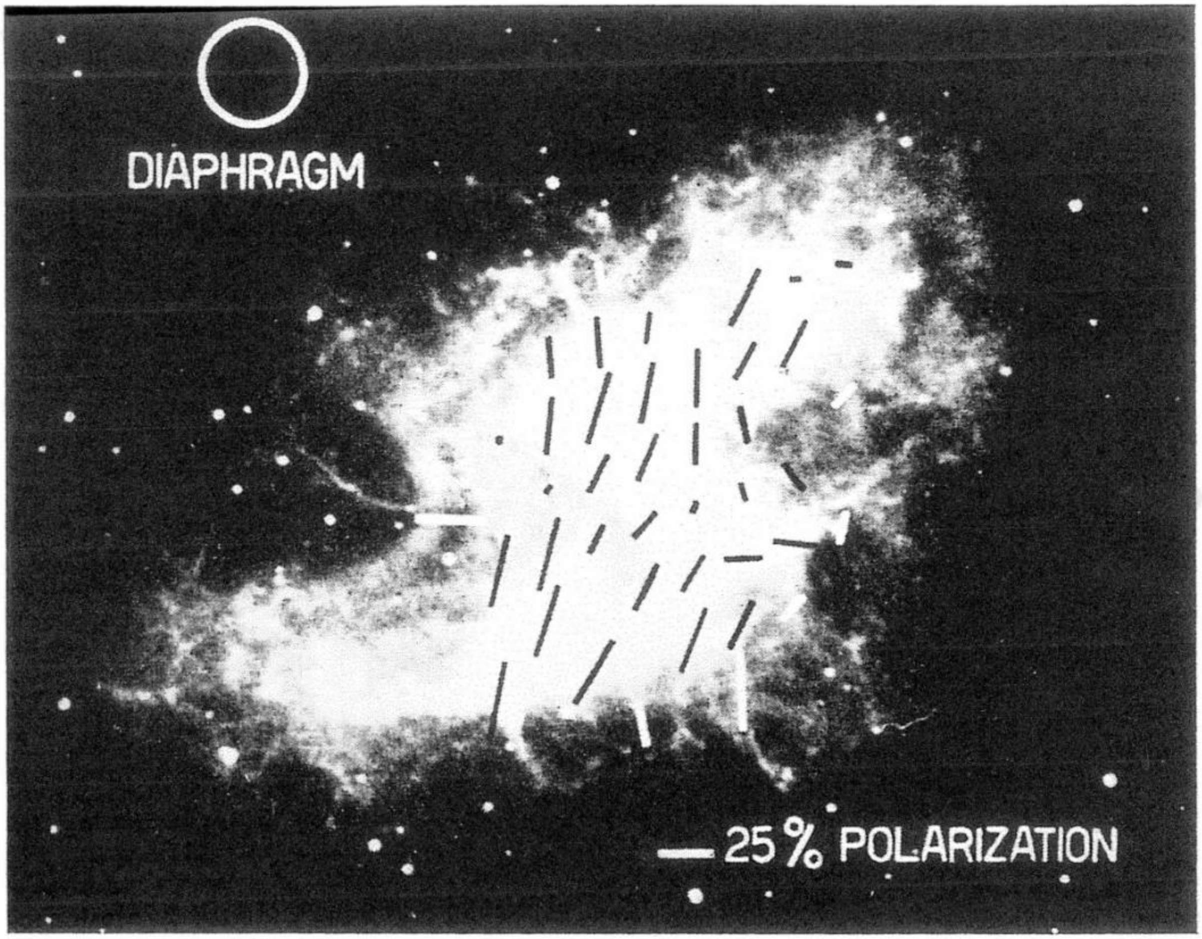

FIG. 2: *Optical polarization in the Crab Nebula.*(2)

The length and direction of the short lines, white or black according to ease of seeing, indicate the percentage polarization and direction of the electric vector, respectively.

Fig. 3

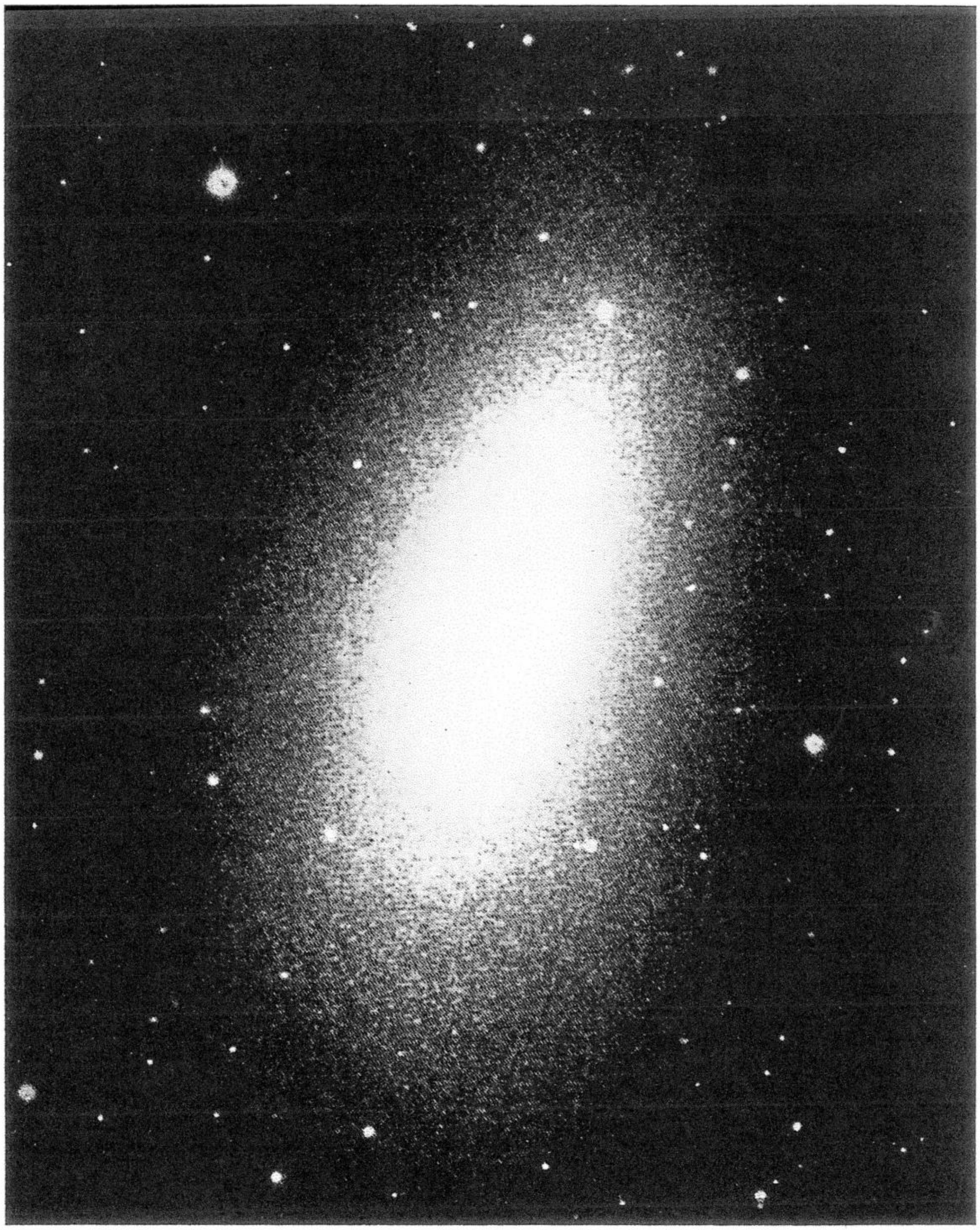

FIG. 3: *A sample Elliptical Galaxy*, NGC 205 (Type E5).

These galaxies range from circular to elliptical and appear devoid of gas and dust and of certain bright stars characteristic of the arms of spiral galaxies.

(Mt. Wilson and Palomar Observatories, 200-inch.)

Fig 4

FIG. 4: *One of the forms of spiral galaxies seen face-on,* M51 (*Type Sc*).
(Mt. Wilson and Palomar Observatories, 200-inch.)

Fig 5

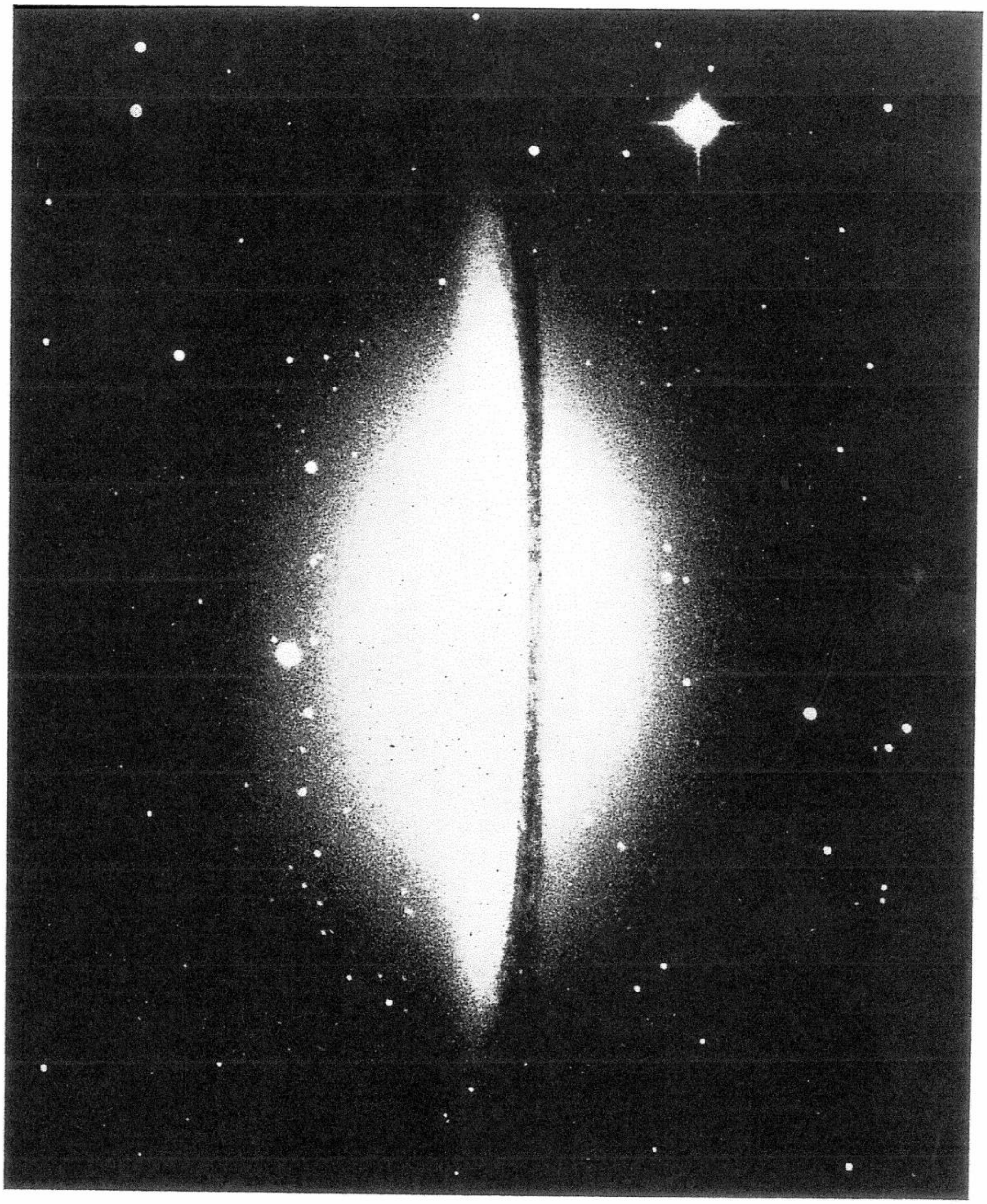

FIG. 5: *A spiral galaxy seen edge-on,* M104 (*Type Sab*).
The dark central band is due to obscuring clouds concentrated in a thin disk.
(Mt. Wilson and Palomar Observatories, 200-inch.)

Fig 6

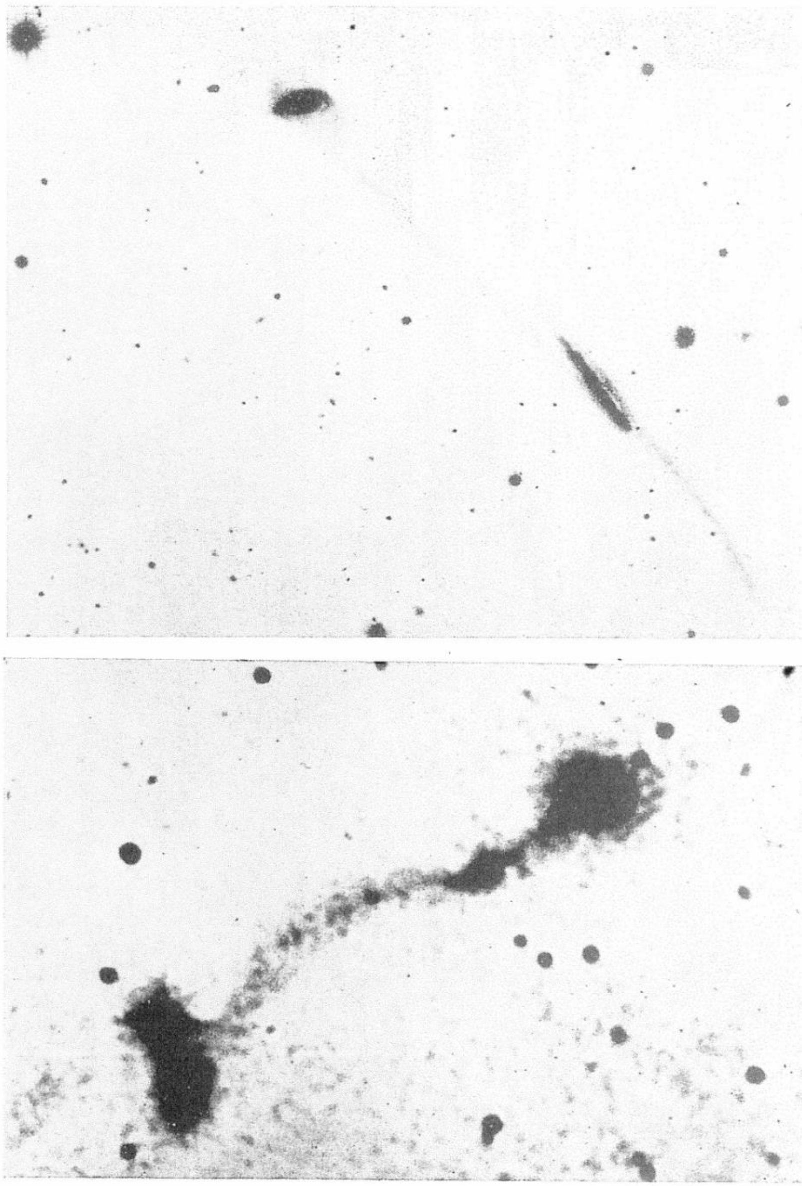

FIG. 6: *Isthmuses of luminous matter, presumably stars, connecting galaxies.*

In the lower picture the contrast has been enhanced, and the detail destroyed, by repeated re-photographing using high contrast photographic paper. (Negative prints)

(E. Zwicky: *Top*: Physikalische Blatter, Heft 9, 1953.
Bottom: Publ. Ast. Soc. Pac. *64*, 244, 1952.)

Fig 7

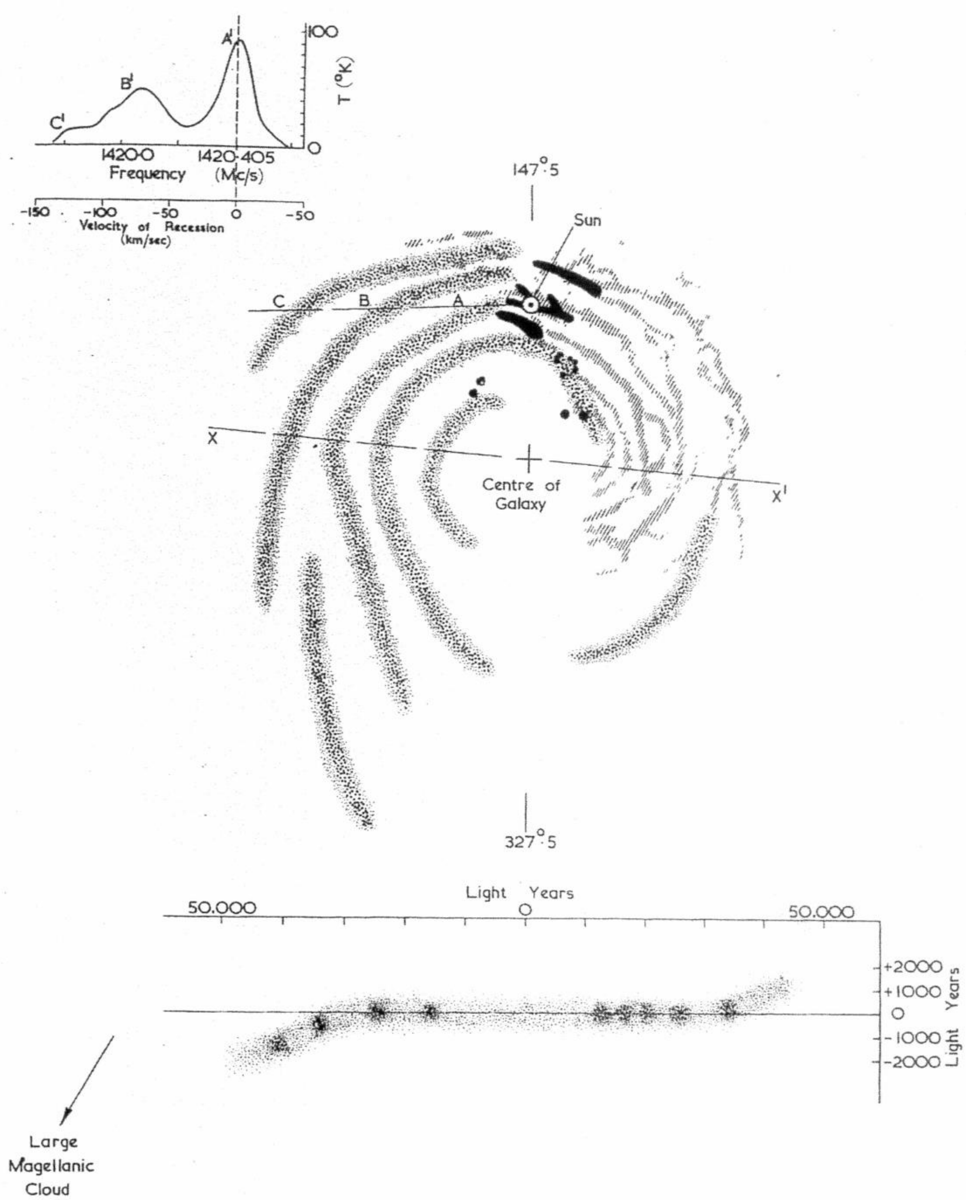

FIG. 7: *A composite picture of spiral structure in our galaxy.*

The central figure is a plan view in the galactic plane. The dotted areas represent concentrations of neutral hydrogen based on Sydney 21-cm observations; the hatched areas similar regions based on Leiden ones. The black areas denote optically derived regions of ionized hydrogen and associated bright stars.

The typical line profile above is that observed in the direction ABC (intensity expressed as brightness temperature). The section below shows the distribution of neutral hydrogen, derived from radio observations, in the plane through XX' normal to the galactic plane. This plane passes through the Large Magellanic Cloud. The vertical scale is expanded.

Fig 8

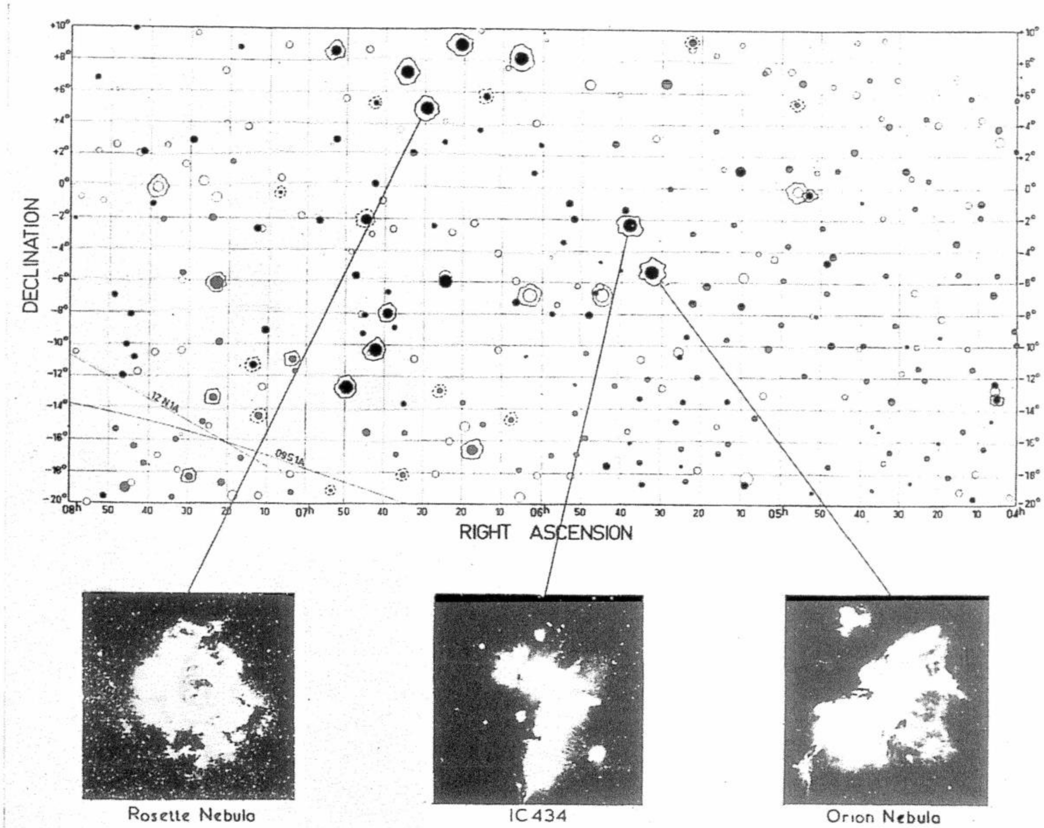

FIG. 8: *A comparison of the Cambridge (open circles, 81.5 Mc/s) and Sydney (full circles, 85 Mc/s) surveys of discrete radio sources in a sample area in the sky.*(9)

Sizes of circles indicate intensities; wavy lines round them, extension in angular size. Pictures of prominent nebulae identified in the Sydney survey are shown below.