THE DEVELOPMENT OF RADIO ASTRONOMY

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IT IS not often that we can witness the birth and development of a new science such as Radio Astronomy. Most sciences have had obscure beginnings and the world has been slow to realize their importance. Astronomy, for example, began with an interest in the stars and the motion of planets long before the beginning of recorded history but this interest could not develop into a science until after the invention of arabic numerals, which paved the way for the theories of planetary motion several hundred years later. The telescope gave a great impetus to research when in 1609 Galileo discovered the moons of Jupiter and Saturn's rings, but knowledge spread slowly in those days and it took more than 200 years to establish the basic facts of astronomy. We know that the sun is one star among 100 billion in the local galaxy and in the universe there are probably more than 100 billion other galaxies. With the additional techniques of photography and spectroscopy rapid advances are being made in all fields, so that we can study the atmosphere of the planets, the composition of the stars, and can investigate almost any problem we choose.

On the other hand, the science of radio astronomy has developed at a time when the world seems to be almost at the peak of its technical evolution. The radio sky was first glimpsed by Jansky in 1932. Within 15 years the significance of the new science was realized and then discovery followed discovery with bewildering speed. Radio stars were found, some of which are quite invisible to the astronomer, and others which are coincident with exploding stars and with galaxies in collision. Spiral arms have been mapped out in our local galaxy and radio signals have been detected from the neighboring galaxies in the universe. Nearer home, the sun, Jupiter, and even Venus have been found to be powerful radio emitters. The cause of these signals and the nature of the invisible stars are unknown and much research effort is being expended at the present time to solve these mysteries.

The Equipment Used by Radio Astronomers

Almost every observation so far has been made with the equipment shown schematically in Figure 1. Signals are picked up from space by the radio telescope to be magnified in the receiver and fed to a suitable display unit.

Radio telescopes fall into two categories, those with a single directional beam and those with multiple beams. A single beam is formed by the parabolic reflector, as shown in Figure 2, which acts like an autoheadlight in reverse. Waves from a radio star are focused by the paraboloid to form a spotlike image which has a diameter inversely proportional to the aperture of the telescope. Large apertures are expensive and one of the best images that has so far been obtained is ½ degree, given by the new 60-foot dish at Harvard. This emphasizes the main disadvantage of radio telescopes; the definition is extremely poor, not even as good as that of the human eye, but as we shall see later there are ways of overcoming this defect. At the focus of the paraboloid the image is allowed to fall on a dipole element which is formed from two metal

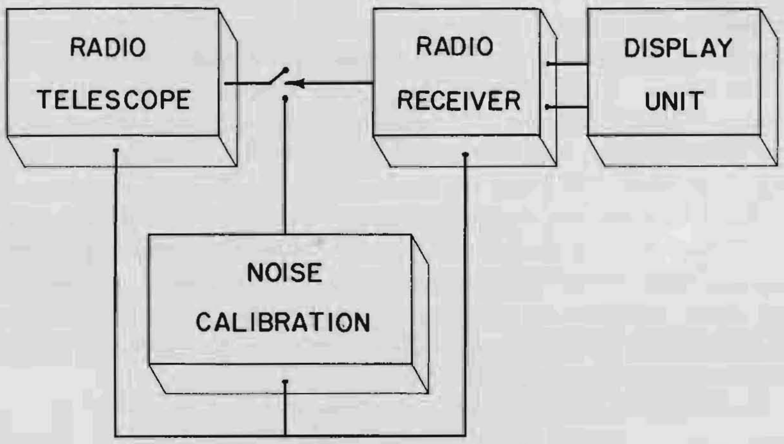

FIG. 1. The equipment used by radio astronomers.

rods similar to one side of an "H"-shaped TV antenna. Electric voltages and currents are induced in the dipole and are fed down a cable into the receiver.

A single beam may be produced in an endless number of ways which can become almost as complicated as the character of the designer. If dipoles are connected together to cover a flat area they are equivalent to a paraboloid telescope of the same area. The array of dipoles, however, will operate only over a narrow band of wavelengths and it is difficult to point the sensitive beam to various parts of the sky. A dipole may have 5 or more focusing rods placed in front of it to form a Yagi-type antenna which is frequently seen in use with short wavelength TV receivers. Electrical energy may also be picked up on a long metal helix. Both the Yagi and helix are equivalent to paraboloids with apertures of from 1 to 2 wavelengths.

It is possible to increase the quality of the image by means of the interferometer. Two separate antennas are spaced at either end of a long baseline and the signals are mixed together in the receiver. A radio star perpendicular to the baseline produces signals that are in phase at each antenna. As the earth rotates and the radio star makes an angle with the baseline the signals will differ in phase and tend to cancel out. In this way a radio star produces periodic variations as it rises, passes due South and sets. Now the effective aperture of the telescope is equal to the length of the baseline, so that a narrow beam can be produced with reasonable economy. Unfortunately, not one but many narrow beams are produced, so that the results become difficult to interpret. Despite this limitation, however, the interferometer has done much valuable work in determining the angular diameter and exact positions of radio stars.

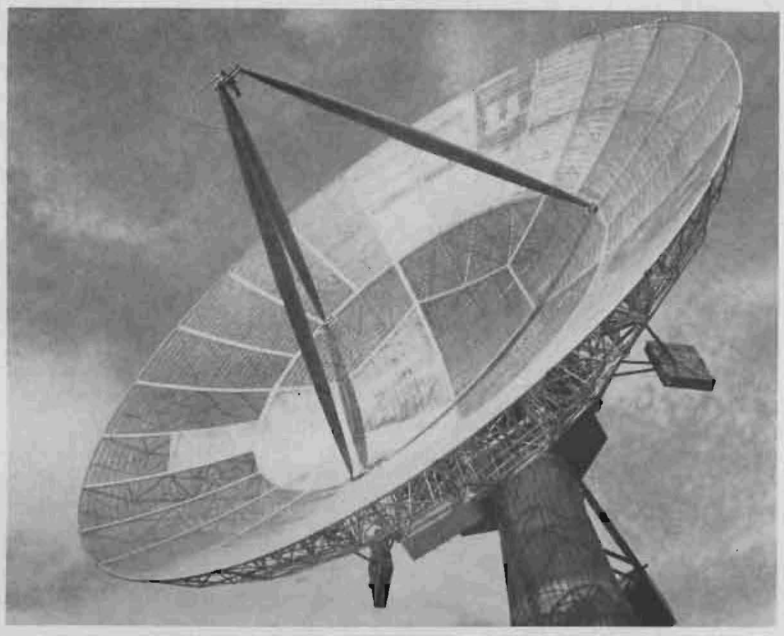

FIG. 2. The 60-foot George R. Agassiz Radio Telescope. Photo by Robert E. Cox with kind permission of Sky and Telescope.

The receiver is similar in many respects to those used in TV, except that the voltage gain is high ($\sim$10 million) so that the radio noise due to thermal motion of electrons at the input of the receiver is readily detected. In radio astronomy great care has to be taken to maintain a constant gain in the receiver because a fluctuation, say in the temperature of the filaments in the tubes, would produce a variation of noise at the output which would mask the faint signals being detected from space. A standard source of energy is put in the place of the telescope to calibrate the receiver as shown in Figure 1. This is usually a diode vacuum tube since the noise power is accurately known in terms of the current flowing through the tube. To minimize the effect of variations in the thermal noise of the receiver the calibration is sometimes carried out automatically at a rate of 25 times per second. In this way a 25-cycle note is produced at the output and the amplitude of the note is independent of receiver noise, being proportional to the difference between the cosmic signal and the standard source. There will always be slight ripples in the output however, even with an ideal system, because we are comparing two noise signals which are varying in a random manner about a certain mean level. These ripples can be greatly reduced by integrating the signals over long periods of time.

One of the most impressive ways of displaying the noise from the cosmos is to use a loud-speaker system. The sun and local galaxy can be heard as a gentle hiss; the galactic noise remains steady but the storms

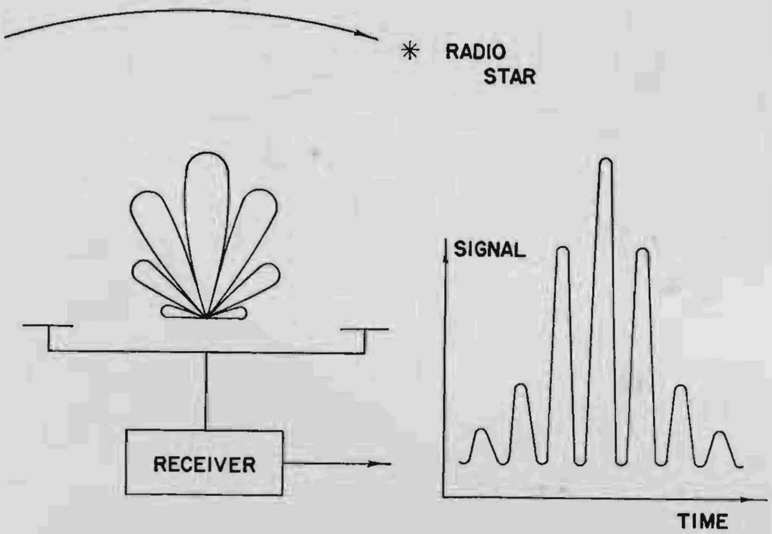

Fig. 3. A radio interferometer and the signal it produces when a radio star passes through the antenna pattern.

on the sun swell and fade many times during the course of an hour. Jupiter is the performer that really dominates the air. When heard over a high fidelity system, its roars and rumbles almost convince one that the Romans were right in their ideas about the Gods. For quantitative work, however, it is essential to obtain a permanent record in a form amenable to analysis. If the signal is fed to a milliammeter with a pen attached to the arm, a mark will be made which is proportional to the intensity of the signal. If the mark is made on a roll of paper driven at a constant speed then a precise intensity-time graph is produced. Radio stars can be observed by sweeping the telescope slowly across the sky, for when the star is in the center of the beam the pen gives a maximum deflection. One of the most convenient scanning arrangements is to clamp the telescope and utilize the rotation of the earth. This has been the preferred method with an interferometer because the baseline is long and the instrument is mechanically unwieldy. The sensitive beams are therefore allowed to drift across a star as the earth rotates and the pen record varies rhythmically as shown in Figure 3. A star of small diameter produces well-defined maxima and minima, but a large source forms an indistinct pattern. The depth of the minima give a measure

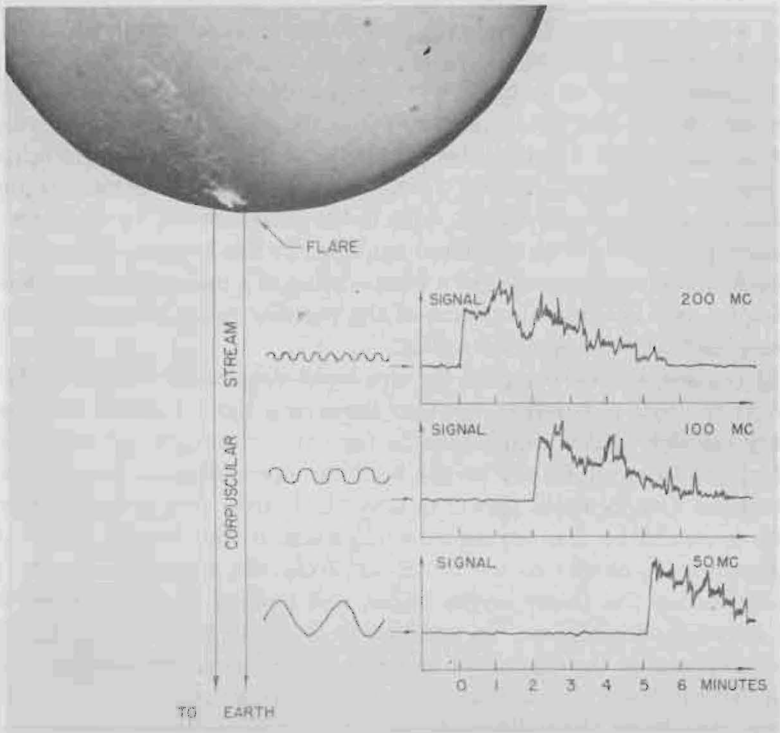

FIG. 4. Radio signals produced by a corpuscular stream as it travels through the atmosphere of the sun. Photograph taken at the Astrophysical Observatory, Kodaikanal, India.

of the diameter of the radio object. In specialized work, following the rapid movements of gas jets across the sun for example, the interferometer beam has been made to scan at a fast rate but the method presents practical difficulties and is not often used. The scanning is performed electrically by introducing a variable phase lag in the cable from one of the antennas.

Signals from the Sun

There are remarkable differences in the appearance of the sun at different radio wavelengths. Optically we see down through the solar atmosphere to the incandescent layer of gas called the photosphere. This layer is at an average temperature of 6200°C., but occasionally large areas become cooled to about 5000°C. and a dark sunspot appears. Sunspot regions are greatly disturbed and have been likened to storms. Ciné films show that part of the interior of the sun is disgorged to rain down incessantly as streams of white hot gas. The whole area is pierced by an intense magnetic field which probably has its origin in whirlpool motions below the photosphere. Sometimes a bright flare of light appears near a spot, as shown in Figure 4, and this is thought to mark the ejection of a stream of charged particles which impinge on the atmosphere of the earth a day or so later, causing beautiful displays of the Aurora Borealis. Above the photosphere we find the chromosphere, which is a red-coloured layer about 10,000 km thick, visible during a total eclipse of the sun. During an eclipse a white halo is also seen extending outwards for about a solar radius. This is the solar corona, an envelope of ionized gas shining with scattered sunlight. It has recently been shown that the outer edge corona is at a temperature of a million degrees; this is a helpful clue in explaining some of the peculiar radio effects that have been observed at long wavelengths.

At centimetric wavelengths the sun looks very much the same as it does in the optical band, except that the steady light is now able to pass freely through heavy cloud, rain or fog. At wavelengths of 20 cm the sun ceases to be uniformly bright but develops a ringlike halo. Viewed with radio eyes it would appear as a brilliant circle with a dusky center. This is caused by the temperature inversion in the corona where the temperature increases as we move out from the sun. Looking at the center we see the cooler layers below, and looking at the limb we see the hotter layers edge-on. In addition to the limb brightening, starlike points appear on the disc of the sun and contribute to the general radiation. It has been shown that these points occur near the visual sunspots, so at 20 cm the radio astronomer has a completely reversed image, a dark sun with bright sunspots.

There were further surprises in store for the radio astronomer when he looked at the sun at wavelengths of about 1 meter. A steady signal was observed corresponding to a temperature of a million degrees. To find the exact location of the noise source on the sun an attempt was made to observe an eclipse. Providence has so arranged the distances of the earth, moon, and sun that the circular shape of the moon exactly covers the photosphere. Without this fortunate coincidence our knowledge of the sun would for a long while have been quite sparse. As the moon gradually covered the solar disc it was hoped that the radio signal would disappear at a certain stage of the eclipse and thus reveal the radio source. The observations showed little variation in the signal and even at totality the radio sun was still shining. It was obvious that the radio sun was much larger than the optical, and the radiation was coming from the high corona.

Three types of major radio disturbances are recognized as emanating from the sun. They are noise storms, outbursts, and bursts. A noise storm originates in a cloud in the corona, vertically above a sunspot. The cloud is invisible optically, but on radio wavelengths it shows temperatures of billions of degrees. The enhancement of radio emission may continue for several days, and during periods of sunspot activity noise storms occur once every five days on the average. If the sun were to behave in the visible spectrum as it does at radio wavelengths the world would have been burnt to a cinder long ago. One of the most spectacular phenomena is the noise outburst which occurs after a solar flare. The flare is usually accompanied by an upward surge of hot gas which leaves the chromosphere with a velocity of about 100 km per second and then falls back again into the sun. An intense radio source, associated with the surge, moves outwards with a velocity of the order of 2000 km per second. This movement has been followed in a number of surges with the rapid scanning interferometer and there is evidence that the radio source does not fall back again but leaves the sun completely as a corpuscular stream of electrons and positive ions. As the stream forces its way through the ionized layers in the corona it is able to emit radiation of increasing wavelength. Three receivers would therefore detect the noise one after the other as shown in the records of Figure 4. After a time lapse of about 24 hours the corpuscular stream reaches the earth and excites the atmosphere to make it glow with the beautiful colors and forms of the aurora. A portion of the sun has been presented with majestic pomp to the earth.

Radio Stars

For many years the astronomer, with modest pride, has felt that he could count with certainty the number of bright stars in the sky. There are many, however, that he would have overlooked because they are invisible optically. Provisionally, these objects are called radio stars but it is certain that most of them are quite different from the stars of optical astronomy. The brightest radio star is in the constellation of Cassiopeia. It corresponds in position with one of the faintest nebulae that can be detected with the 200-inch telescope on Mt. Palomar. The nebula was found only after repeated searching near the radio position and it would probably have remained undetected if the radio data had not been available. So far the nature of the object is a mystery. Spectroscopic evidence shows that it is an irregular cloud of gas with violent internal motions and high excitations. The object is known to be within our local galaxy but opinion is divided as to whether the gas is dispersing or condensing, possibly to form a new star.

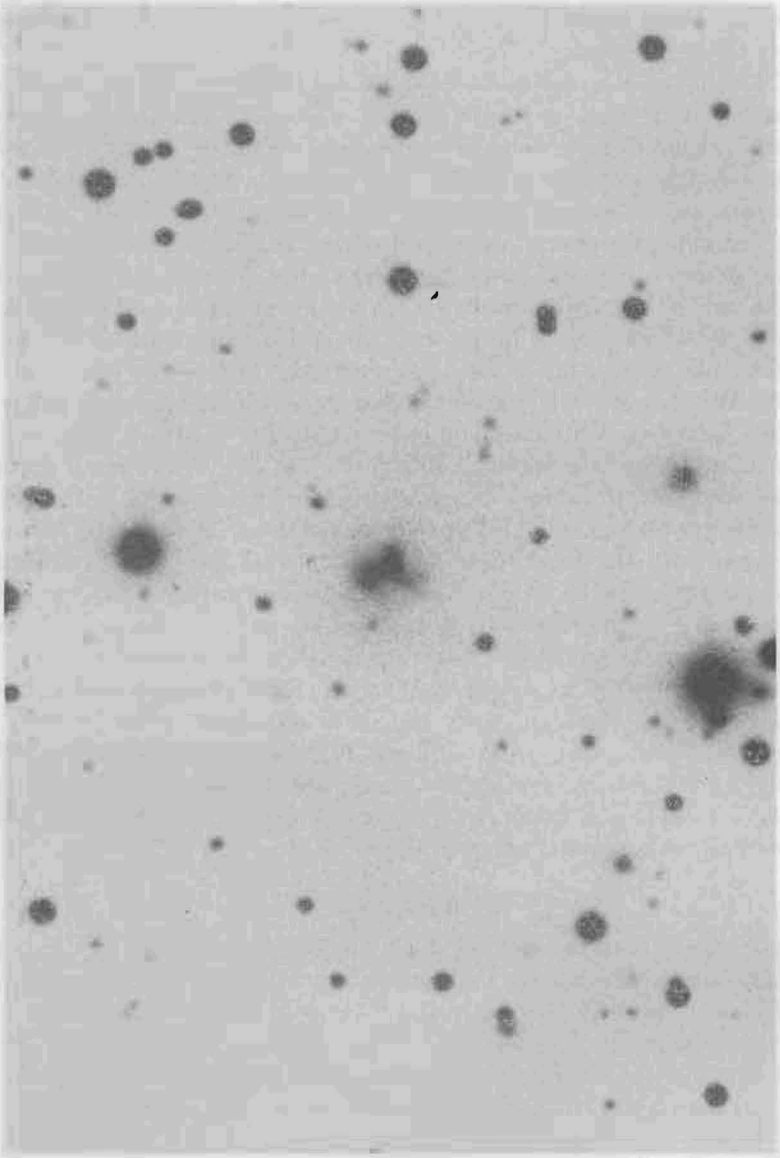

FIG. 5. Galaxies in collision. Photo by permission of Mt. Wilson and Palomar Observatories.

Cygnus A is the second brightest radio star. It corresponds to an object at a distance of 2×10^{21} km, a distance so great that its light and radio waves take 200 million years to reach us. Homo sapiens was certainly not in existence when the radio waves we receive now started on their journey. It is fortunate that the object was not at any greater distance for it would then have been beyond the limits of the visible universe as seen with the Palomar telescope. By careful photography the telescope shows that a remarkable catastrophe is taking place out there. Two galaxies, two huge systems of stars and gas, are involved in a collision. Figure 5 shows the galaxies in contact, but it is difficult to imagine that the spots and surrounding halo actually represent a cloud of stars some 3×10^{17} km across. Collisions of this kind are extremely rare and we would probably have to see well beyond our present range before we found another face-to-face, contact like that in Cygnus A. The consequences of galactic collisions have already been studied. Remarkably enough, the stars in the system are hardly affected at all; interstellar distances are so great that the star systems can pass through each other with only minor perturbations. The gas between the stars, however, meets with great violence. Part of the kinetic energy of the collision is emitted as radio waves; indeed, the process is extremely efficient, about 5% of the energy being converted in this way. It seems that collision and violent motion in gas clouds are an essential requirement for the formation of a radio source. Cassiopeia A contains gaseous filaments in rapid motion, Cygnus A is formed by gas clouds in collision, and we shall see that other radio stars are associated with this condition. It has probably taken a million years or so for the galaxies to pass through each other. Bearing in mind the fact that light takes 200 million years for the journey, we realize that the actual collision process must have been completed long ago and there will now be left two remarkable galaxies in space cleared of dust and gas, while between them will be a hot gaseous nebula, far larger than any that we encounter in the local galaxy. But these objects will not be visible to astronomers until a million years has passed.

There is one radio star that was observed in 1054 A.D., 12 years before William the Conqueror landed in England. In this year a star in the constellation of Taurus, the Bull, exploded, leaving an object which we now call the Crab nebula. The sudden increase in brightness was seen by Chinese astronomers who faithfully noted the event in their records and stated that the new star was visible by day as well as by night. According to modern terminology this was a supernova. Research shows that about once every 500 years in our galaxy a star reaches an unstable point in its evolution, whereupon the whole star explodes like a giant atomic bomb. The disintegration is complete and all that remains is an expanding ball of gas. Astronomers have checked the rate of expansion spectroscopically and also by taking photographs spaced many years apart. On extrapolating back, they find that the ball was a single point in the year 1054, thus confirming the identification. When the Crab nebula is photographed in the red light of hydrogen, as in

Figure 6, we notice a filamentary structure and it is clear that the nebula is in a violent state of motion. The expansion of gas again acts as an efficient generator of radio waves, although the exact process is still obscure. Interferometer measurements show that the whole of the visible nebula is transmitting, and the radio image fits almost exactly over the

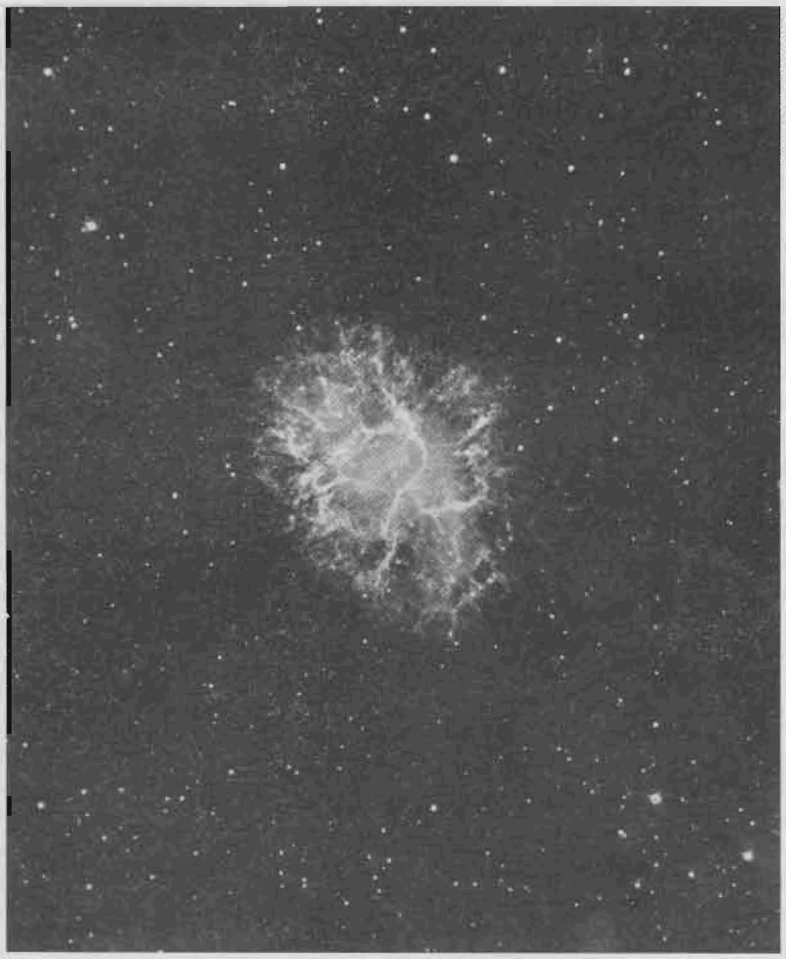

Fig. 6. The Crab Nebula photographed in hydrogen light. Photo by permission of Mt. Wilson and Palomar Observatories.

photographic image. Another supernova was observed by the famous astronomer Tycho Brahé in 1572 and this too has been identified as a radio star. The last supernova was recorded by Kepler in 1604, so that if the estimated mean rate of one supernova every 500 years or so is correct, there is a high probability that a supernova will occur in our time. This would present a unique opportunity for studying the entire process with all the superb equipment available to the modern scientist.

These three sources in Cassiopeia, Cygnus, and Taurus are among the few radio stars to have been positively identified. Recently a catalogue of over 1900 radio stars was made and the astronomical nature of most of them is still unknown. Much research will obviously be required before this mounting list of mysteries can be solved.

The Milky Way

The original observations of Jansky in 1932 were made on the Milky Way, our local galaxy. Radio interference was found which seemed to be coming from the galactic center. Surveys of the sky have since been made in great detail with wavelengths ranging from a few centimetres up to many metres. The radiation comes from a large elliptical area which is aligned with the general direction of the Milky Way. Optically there are dark obscuring clouds or lanes of dust, but these do not appear on the radio maps because the radio waves pass through them. Dark clouds obscure the center of the galaxy, which is probably the most interesting part, but this region is easily visible to the radio astronomer. So far very little research has been done on the galactic center and this remains an exciting field for the future.

It is not known yet whether the general galactic noise is the combined signal from millions of radio stars or whether it originates in the matter between the stars. In a few years time, when large radio telescopes are available, it may be possible to see if myriads of faint stars are producing the noise. Meanwhile much speculation goes on as to the exact origin of the signals.

There is one component in the radio spectrum, however, that is well understood. Radiation has been detected over a small waveband at 21 cm. This emission line is produced by the neutral hydrogen atom. If the spin of the proton and electron are aligned in the same direction there is a tendency for one of the spins to change. The probability of the change is very low so that a hydrogen atom waits several million years before changing. At this time it emits 9.4×10^{-25} joules at a frequency of 1420 mc. Although this seems an insignificant power output, the number of atoms in the direction of the antenna beam is usually sufficient to give a detectable signal. The signal strength gives a measure of the temperature and space density of the hydrogen, but what is more important, the exact frequency of the emission gives the velocity in the line of sight. As in the case of sound waves and light waves, the observed frequency of a source is higher when it is approaching and lower when it is receding so that the velocity of the source can be found. By measuring the velocity of the hydrogen with respect to the sun the astronomer is able to go one step further. The galaxy is rotating about its center and each star follows an orbit which is nearly circular. Stars on the edge of the galaxy travel more slowly than stars near the center. Hence a measure of velocity gives a measure of the distance of a hydrogen cloud from the galactic center and the position of hydrogen in space can be deduced.

Extensive surveys at 1420 mc have been made. It is found that the neutral hydrogen is concentrated within the spiral arms of our galaxy. By means of the hydrogen emission these arms may be traced out far beyond the optical limit which is set by interstellar absorption. For the first time we can picture the sun as it is set in one arm of a great spiral system as shown in Figure 7.

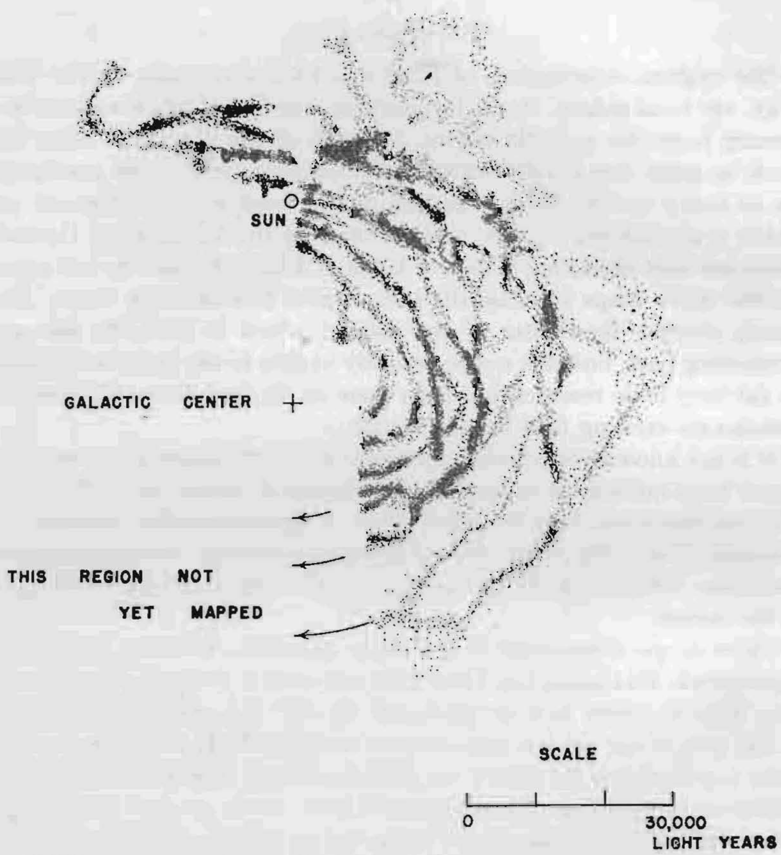

FIG. 7. Spiral structure of the local galaxy. Reproduced by kind permission of G. Westerhout and M. Schmidt, Leiden, Holland.

The hydrogen line has been detected in other galaxies besides our own. Recently emission was received from the great cluster of galaxies in Coma Berenices at a frequency of 1387 mc. Thus the radio signal is at a lower frequency, or reddened, by the velocity of recession of the cluster in the same way that the visible spectrum is shifted. Absorption by hydrogen has also been noted in the noise from the colliding galaxies in Cygnus. Again there is a shift of the radio line which corresponds to the red shift observed optically.

Jupiter

It is scarcely a year since the radio signals from Jupiter were discovered. Many tape recordings have already been made which illustrate the effects that this planet can produce. There are components of the hissing sound which are usually associated with the random motion of thermal electrons. It is unlikely that the noise is really thermal in origin because it is difficult to visualize how high temperatures could be produced on Jupiter. The atmosphere is composed of methane and ammonia and contains clouds at a temperature of −140°C, while the planet itself is presumed to be formed of solid ices, again at a low temperature. Other noises that have been recognized are grinding sounds and rumbles. When analyzed in detail these sounds are apparently composed of a series of two or three pulses following one another in rapid succession.

By an ingenious method it has been found possible to locate the area which is generating the noise. The transmission is spasmodic, some days it is present, other days it is absent, but by observing over long periods of time the noise has been found to vary in synchronism with the rotation of the planet. This defines a north-south line, or line of Jovian longitude on which the source lies. The planet's speed of rotation, as given by observations of clouds in the atmosphere, varies between the equator and the poles. The equator rotates once in 9 hours 50 minutes 26 seconds, and the corresponding figure at the pole is 9 hours 55 minutes 24 seconds. By timing the variation of the signals the latitude of the source can be obtained. This is, of course, not a very exact determination, and the method is further complicated by the presence of more than one transmitting area. Despite these difficulties the main noise area has already been located. It is close to the famous red spot which has been observed in Jupiter's atmosphere since 1664. Surprisingly little is known about the spot from the optical observations. One hypothesis suggests that it is an island of solid ammonia or methane floating in the dense atmosphere, while at the other extreme it is considered to be the product of an active volcano. Perhaps the radio observations will help us to determine the true nature of this disturbance.

Radio observations have given indications that Jupiter may be surrounded by an ionosphere. The red spot region does not produce signals at every position as it rotates. There appears to be an attenuation of the noise as the spot approaches the East or West limb and this has been explained by reflection effects in the ionosphere. The double and triple pulses forming the rumble are also explained in terms of the ionosphere. A signal from some disturbance in the atmosphere is received by direct transmission to produce the first pulse, while the second pulse is the echo produced by the surface of Jupiter. The third component is reflected from the ionosphere back to the surface before reaching the receiver on the earth.

Radar Astronomy

We are not limited to passive reception of signals. Great advances were made during the Second World War in the detection of aircraft by means of radio echoes. In the same way a high power transmitter can be made to send out a series of pulses which will be reflected off celestial objects.

Meteors are the nearest bodies of interest in astronomy, for although they spend many years circulating between the planets, they spend the last second of their life in the atmosphere of the earth about 60 miles up. The meteor particle collides with the atmosphere at such a high velocity that it completely evaporates, producing heat, light, and ionization. By studying the echoes from the column of ionization it is possible to measure the velocity of the meteor with fair precision. With three or more radar stations one can determine the direction of motion of the meteor. Velocity and direction together define its orbit, or life history, and we can then trace back its path among the planets. Radar observations have shown that meteors are members of the solar system and do not come from the space between the stars. We now believe that meteor fragments are shed by a comet as the icy nucleus of the comet evaporates in the heat from the sun.

Farther out from the earth we come to the moon, and radio echoes have been obtained from the moon by many experimenters. At a distance of 200,000 miles, radar astronomers have to wait for a period of about 2 seconds before the echo returns. The echo is subjected to many effects on its journey to and from the moon and from the way it has changed we can learn many interesting things about the atmosphere of the earth and the surface of the moon. The radio wave forming the echo is formed, of course, from oscillatory electric and magnetic fields which are at right angles to each other. When the electric field is parallel to the receiving dipole a maximum signal is produced. In this way the direction of the field can be determined. It is found that the field is rotated many times as the echo pulse travels to the moon and back. Most of the rotation occurs in the ionosphere of the earth, as it is proportional to the electron density of the transmitting medium and the strength of the magnetic field of the earth. This rotation gives us information about the ionosphere at great heights above the earth's surface.

As the radio pulse is reflected from the surface of the moon the mountain ranges and craters cause interference so that the echo power fluctuates. This effect is not unlike the glitter that is seen when light falls on a rough, shiny object. There are other things that cause the signal to fluctuate more rapidly than the interference from a rough surface, but the origin of these rapid variations is at present unknown.

Radar astronomy will probably never become as spectacular as radio astronomy. With pulse techniques we certainly are making our first venture out into space, and the radio pulse can certainly visit and explore the moon even if mankind at present is limited to the earth. But we will require tremendously powerful transmitters if we are to bounce an echo off our neighboring planets such as Venus and Mars. To reach the nearest star is impossible: even if we did have sufficient transmitter power we would have to wait eight whole years for the echo to return. The output of the natural transmitters of the cosmos is far greater than any we can make on the earth. Cygnus A for example, on the edge of the visible universe, puts out a power which is more than a billion billion times greater than our man-made signals. Such considerations help us to realize our insignificant position as earth-bound mortals, and impress upon us the grandeur of the natural universe.