

Recent Discoveries in RADIO ASTRONOMY

The following article is based on an address presented at the Seventh Annual Meeting of the Corporate Associates of the American Institute of Physics, which was held at the Rockefeller Institute in New York City on October 1, 1964. Morton S. Roberts is on the staff of the National Radio Astronomy Observatory in Green Bank, West Virginia. The Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

By Morton S. Roberts

The application of radio techniques to astronomy has opened an immense new window on the universe. Till relatively recent times, the earth-based astronomer was restricted to an optical-wavelength region ranging over a factor of three. He now has available an additional part of the electromagnetic spectrum whose range in wavelength is more than a factor of one thousand.

Important discoveries in all branches of astronomy have been made at these radio wavelengths; I shall attempt to present a broad outline of some of the recent research in only two areas: our galaxy and extragalactic systems. This choice is not particularly restrictive since it embraces the observable universe. The findings described below represent the work of many astronomers throughout the world.

The study of the structure of and motions within our own galaxy, the Milky Way system, has been immensely advanced through the use of a radio spectral line. This line originates in a hyperfine transition in neutral atomic hydrogen. Since this radiation has a well-defined wavelength close to 21 cm, observed shifts in this wavelength can be related to a Doppler velocity and we can thus measure both the distribution and radial motion of this form of hydrogen. It is important to realize that the vast amount of dust in the plane of our galaxy limits our optical view in these directions to about 10 000 light years; this is just one-tenth of the diameter of our galactic system. The much longer 21-cm radiation is unhindered by this dust obscuration and we are able to view the entire extent of our galaxy.

The picture that has emerged from 21-cm studies of our galaxy shows an amazingly thin, flat disk of hydrogen over much of the region interior to the sun's position. This hydrogen is not uniformly distributed, but rather is con-

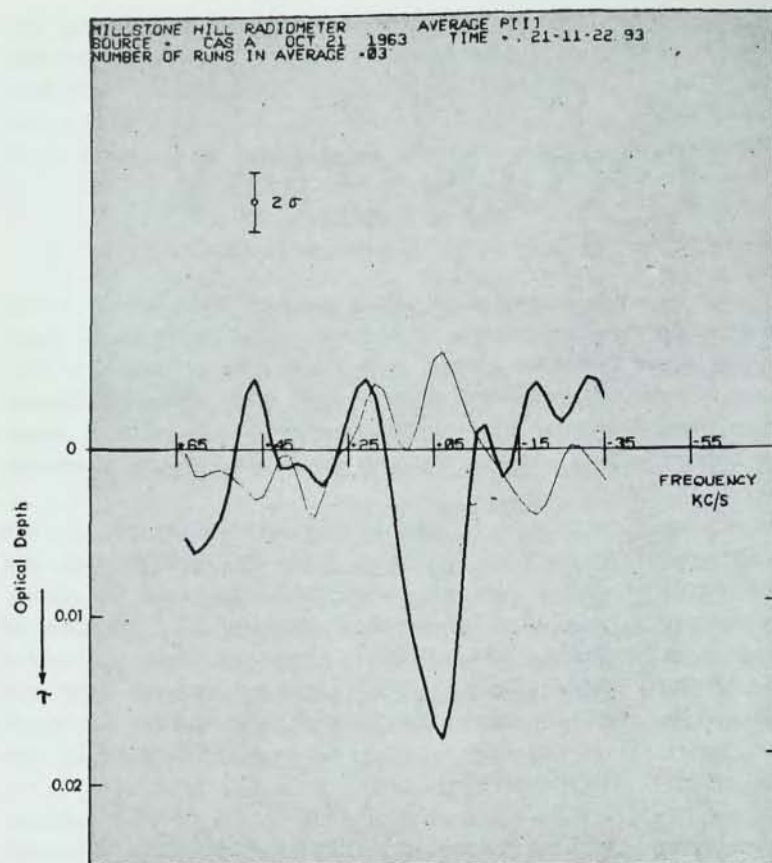
centrated in certain regions, giving rise to the concept of hydrogen arms in analogy with the stellar arms so prominently displayed in photographs of other spiral galaxies. The question of the spatial coincidence of the hydrogen and stellar arms is a matter of some controversy since the distance scales for both of these systems are based on differing assumptions and are derived by different techniques.

The flat hydrogen distribution shows a curious, rather symmetrical distortion at large distances from the galactic center; on one side this sheet flares up and on the other down. If our galaxy were viewed edge on by some distant observer, he would find that the hydrogen distribution appears as an integral sign on its side.

Although one side of this distortion points toward the Magellanic Clouds, the two galaxies nearest our Milky Way, ordinary tidal effects are not great enough to give rise to the observed "tide" and "countertide". A resonance phenomenon caused by tidal forces and relative motions (unknown) of this triple system has also been suggested. Another proposal explains the distortion as a hydrodynamic effect resulting from the flow of intergalactic gas past our galaxy.

In considering large-scale motions within the galaxy, the assumption of pure rotational motion is often made; 21-cm observations have shown that this is not the case. For example, there is a spiral feature located well in towards the center of our galaxy—the "3-kiloparsec arm"—which is moving out from the center at a velocity of about 50 km/sec. I shall refer later to a possible explanation for the origin of such an expanding arm.

There is little doubt that our galaxy contains a general magnetic field. This was first suggested from the observed optical polarization of star-



The discovery in the radio spectrum of interstellar OH as published by S. Weinreb, A. Barrett, M. Meeks, and J. Henry. The heavy line shows 8000 seconds of data taken with the antenna beam directed at the strong radio source Cassiopeia A; the OH line at 1667 Mc/sec appears in absorption. The light line shows 6000 seconds of data taken with the antenna beam slightly displaced from Cassiopeia A. The frequency scale, in kc/sec, is with respect to the local standard of rest for a line rest frequency of 1 667 357 kc/sec.

light, the magnetic field being invoked to explain the necessary alignment of the polarizing dust particles. Three separate examples of radio-derived evidence also require a galactic magnetic field for their explanation: (1) the general nonthermal and presumed synchrotron radiation from our galaxy, as well as the polarization of this radiation over large regions of the sky; (2) the dependence of the polarization of radio sources on galactic latitude—i.e., angular distance above or below the galactic plane—in the sense that objects at lower latitudes are less polarized (this is attributed to a net depolarization of the intrinsically polarized sources arising from random Faraday rotation caused by interstellar clouds and a magnetic field within the galactic plane); and finally (3) the Zeeman splitting of the 21-cm hydrogen line. This last effect is a direct measure of the magnetic field and actually gives the field strength. Unfortunately, this experiment is difficult and both positive and negative results for the same region have been reported by different observers.

Nevertheless, the combination of all these observations conclusively point to a galactic magnetic field. Thus the whole of interstellar space

must be regarded as a magnetoionic medium. A complete theory of galactic structure must be much more complicated than when viewed on a strictly gravitational basis, at least for the gaseous component.

An important discovery, made less than a year ago, was the detection of the OH radical in interstellar space by means of its microwave lines at about 18 cm. All four of the predicted lines have been observed; thus far only in absorption against strong continuum sources. Of special interest are the OH measurements made toward the galactic center. Here, three anomalies occur: (1) the abundance of OH may be as much as a thousand times greater than in the solar vicinity; (2) although all four of the predicted lines have been found, their observed relative strengths differ from the theoretically predicted values; and (3) the kinematic properties of the interstellar medium in the galactic center region, as displayed by the radial velocities of the OH clouds, although apparently ordered, are highly complex. The 3-kpc expanding arm with a velocity of -50 km/sec appears at OH frequencies, but other absorption features at both negative and positive



Shown above are several examples of galaxies in which neutral atomic hydrogen has thus far been detected. The two galaxies in the upper row are Sb spirals, those in the middle row are Sc spirals, and those in the bottom row are irregular-type galaxies. (All of the photographs are from the Mt. Wilson and Palomar Observatories except for the one at the lower left, which is from the Harvard College Observatory.)

velocities have also been found. A satisfactory model to explain these effects has not yet been developed.

The large mass difference between H and OH (1:17) allows a separation of the thermal and turbulent velocity components in a given direction—the observational difference lying in the line widths of the H and OH absorption features.

Turning to other galaxies, I want first to speak of the hydrogen-line studies of some of the nearer of these systems, and then of the continuum measures of normal and the so-called radio galaxies, as well as the quasistellar sources.

Relatively high angular resolution, hydrogen-line studies of galaxies yield data on the following: (1) the distribution of hydrogen, (2) its motions within the galaxy, (3) the total neutral atomic hydrogen content, and (4) the systemic velocity of the galaxy. From the hydrogen velocity field and rotation curve we may also obtain the total mass distribution and, of course, the total mass of the galaxy. All of these parameters are derived within the framework of certain simplifying assumptions.

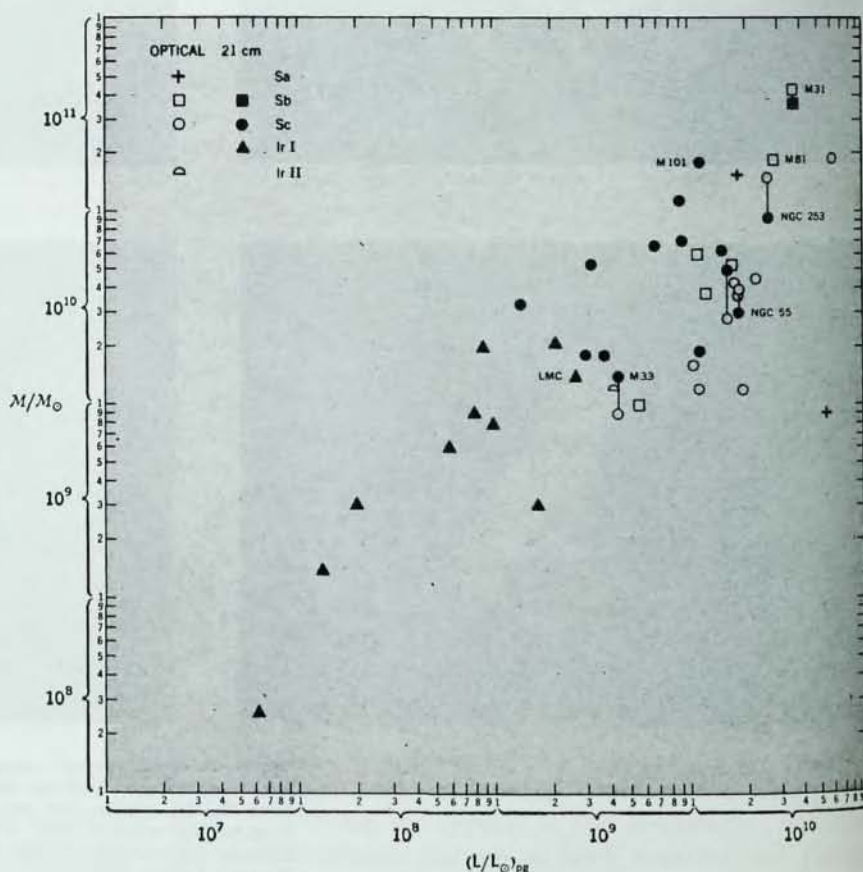
An added dividend of such studies follows from a comparison of systemic velocities measured at 21 cm and at optical wavelengths. Over a total range of -400 to $+1600$ km/sec, both measures

agree to within the errors of their determination. Thus the form of the Doppler expression (the inverse dependence on the laboratory wavelength) holds over a wavelength range of half a million. The highest-velocity galaxy thus far detected at 21 cm has a radial velocity of about $+1600$ km/sec; using a Hubble constant of $100 \text{ km sec}^{-1} \text{ Mpc}^{-1}$, this velocity corresponds to a distance of approximately fifty million light years.

The hydrogen distribution within galaxies is not uniform with respect to the center—one side of the galaxy will often have much more neutral hydrogen than the other. An asymmetry also exists in the rotation curve (i.e., the rotational velocity as a function of the distance from the center); it cannot be reflected about the optical center of the system. Thus the assumption of an axially symmetric velocity field in spiral galaxies breaks down, at least for the interstellar material. Further, localized irregularities in the velocity field are found. It is clear that pure rotation does not exist in galaxies. Recent optical studies also support this conclusion.

The percentage of the total mass of a galaxy in the form of neutral atomic hydrogen is closely related to the structural type of the galaxy. Most

A mass-luminosity relation for galaxies. The ordinate gives the total mass of the galaxy, the abscissa is the absolute photographic luminosity (corrected for extinction in our galaxy and where possible for the inclination of the system to our line of sight). Mass determination from both optical and 21-cm measures are connected by a vertical line. Many of the 21-cm masses given here are based on statistically determined values of the radial location of the peak of the rotation curve. A selection effect favoring intrinsically bright galaxies is present in many of the optically determined masses.





A photograph (with the 200-inch telescope) of one of the most intense radio sources, Cygnus A. (Mt. Wilson and Palomar Observatories).

galaxies can be put into six basic structural classes: the ellipticals, four types of spirals differing in the size of their nuclear region and the structure and tightness of the coiled spiral arms, and finally the irregular galaxies. The irregular systems contain, on the average, about twenty percent hydrogen. The spirals closest in appearance to the irregulars, the Sc systems, contain about ten percent hydrogen, while the Sb spirals (including our own Milky Way) contain about one percent hydrogen. Thus far, no neutral atomic hydrogen has been detected in any of the other galactic types and it is safe to assume that this hydrogen-content—structural-type relation continues to values well below one percent. The over-all ratio of ionized to neutral atomic hydrogen is most likely small; in our galaxy it is less than 0.1 percent. At present, nothing is known about the molecular-hydrogen component of the interstellar medium.

Attempts have been made to interpret the hydrogen-content—structural-type relationship in terms of an age sequence for galaxies. However, the conclusions are strongly dependent on the assump-

tions employed in making such calculations. In fact, it can fairly easily be shown that these three different galaxy types, for which 21-cm measures are available, could all have existed for the same length of time, maintaining their present rate of star production with only small changes in their over-all interstellar-gas content.

That the hydrogen content is related to structural type is not too surprising, for the distribution of the interstellar material in different galaxy types is involved in the subjective classification scheme. The basic and thus far unanswered question is, why are there different galaxy types? Do they reflect variations in the initial conditions that existed when galaxies were formed, or do they indeed mirror evolutionary changes?

It should be noted that results such as these represent a combination of information gained at both optical and radio wavelengths. An outstanding example of such liaison is the optical identification and study of radio sources. Many such radio sources are extragalactic in nature and have given rise to exciting new concepts in astronomy and cosmology.

The radio galaxies have a radio output lying in the range of 10^{33} to 10^{38} watts; normal galaxies have an output of 10^{30} to 10^{32} watts; in the optical



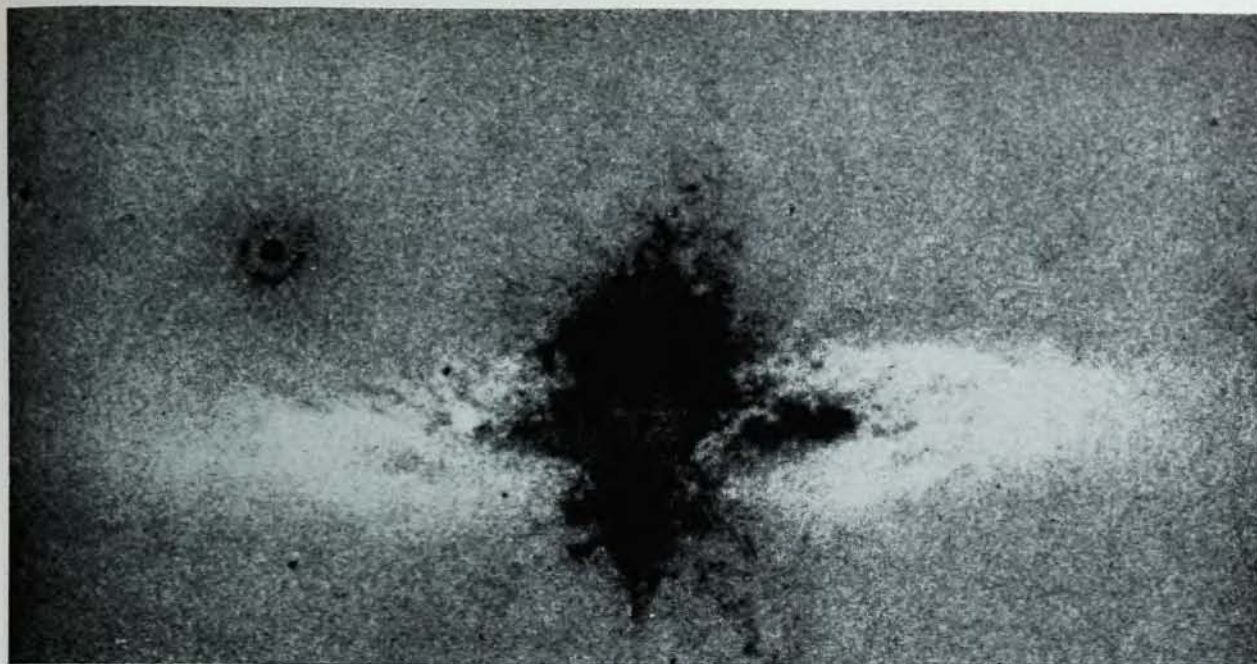
region, both the brighter normal and radio galaxies radiate about 10^{37} watts. An exception are the recently recognized quasistellar sources. Although their radio output lies in the range for radio galaxies, their optical power (which varies) is as much as one hundred times greater than that of galaxies. These various flux values can only be derived for those objects which have a distance estimate, and in this area of radio astronomy distances can only be obtained through optically measured redshifts. The largest value of z ($= \Delta\lambda/\lambda_0$) thus far measured for a radio galaxy is 0.46 for the radio galaxy 3C295. An even larger value, $z = 0.545$, has been obtained for the quasistellar source 3C147. A tentative value of $z = 0.850$ has been suggested for the quasar 3C286. This is based on only one spectral line at 5170 Å, which may be the redshifted line of MgII at 2800 Å.

It is possible that these quasars are actually the nuclear regions of galaxies and may therefore be just another aspect of, or stage in, the development of radio galaxies. The basic observational differences between quasars and radio galaxies are three: (1) Size. Quasars are very small, at least one order of magnitude and perhaps two to four orders of magnitude smaller than galaxies. (2) Optical luminosity. As noted above, the quasars

The M81 group in the constellation of Ursa Major. The "exploding galaxy" M82 is seen on the right. (Mt. Wilson and Palomar Observatories.)

are as much as 100 times brighter. (3) Ultraviolet excess. The spectral energy distribution is more intense in the ultraviolet for quasars.

Several points can be made for these possibly related objects. For many, the total energy in particles and magnetic field probably lies in the range of 10^{57} to 10^{61} ergs. The source of this energy is the basis for much of the interest in these objects. The first few radio galaxies that were optically identified (only ten years ago) were thought to be the result of collisions between two galaxies. This explanation for radio galaxies has fallen to the wayside. Merely the question of the energetics shows the difficulty in the collision hypothesis. Nuclear mechanisms are hard put to account for the necessary energy; the conversion of one solar mass of hydrogen to helium yields about 10^{52} ergs. A more effective energy source lies in gravitational collapse. The upper limit to the gravitational energy released in a collapse to the Schwarzschild limit is one order of magnitude greater, about 10^{53} ergs. The reasons for massive



A composite photograph of M82 obtained from a superposition of a yellow-sensitive positive with an H_{α} negative. The ejected material, strong in H_{α} , appears dark and perpendicular to the principal plane of the galaxy which in the composite appears much lighter. (Mt. Wilson and Palomar photograph by A. R. Sandage).

and rapid nuclear burning or for gravitational collapse of large amounts of matter are unknown.

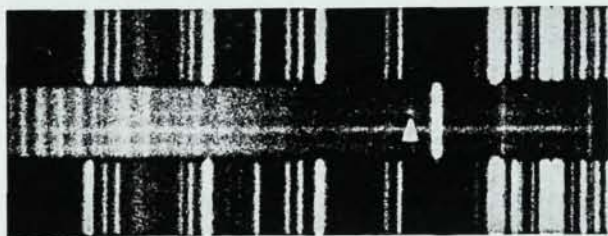
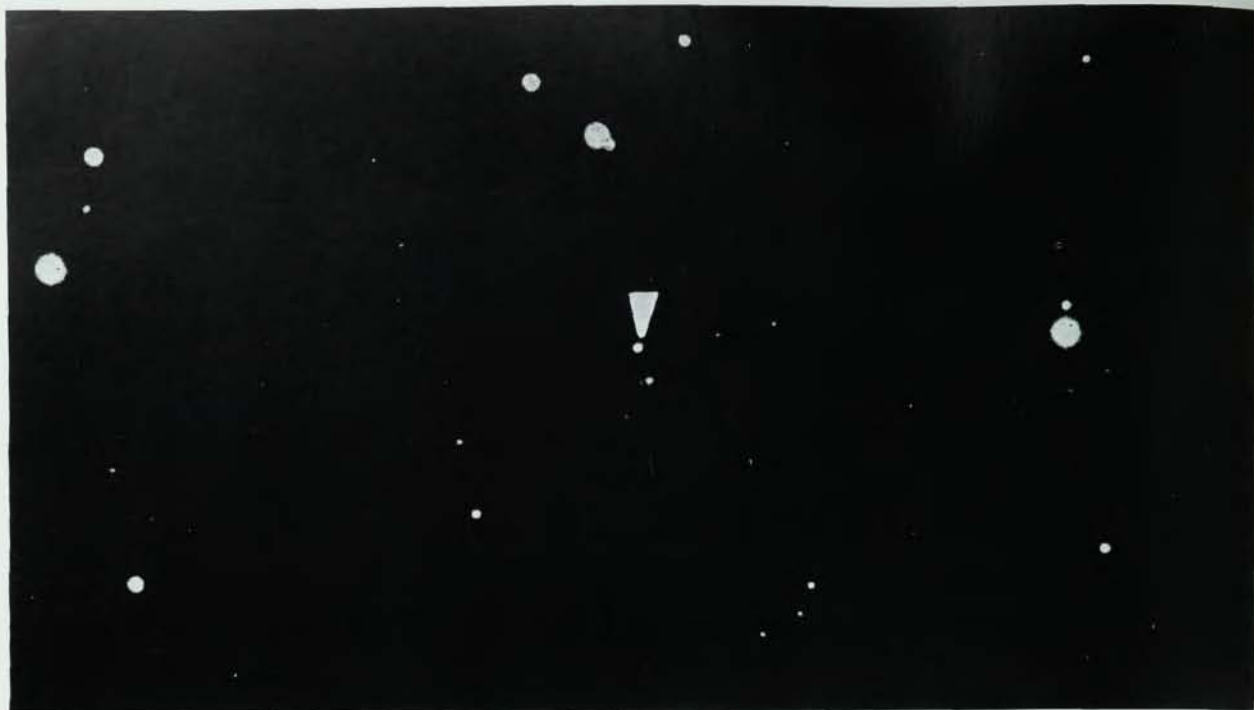
Whatever the source of the energy, there seems no way out of invoking a catastrophic occurrence involving a large mass, e.g., explosions in the nuclei of galaxies. Such explosions cannot be rare in the universe and may not even be unique in the lifetime of an individual galaxy. These conclusions follow from the time scale derived for such explosions and the observed number of radio galaxies. There are various lines of evidence pointing to a fairly short time scale for these events, of the order of 10^6 years for radio galaxies, and even shorter for the quasars; the time scale generally associated with galaxies is 10^{10} years. To account for the fraction of galaxies which are strong radio galaxies, estimated at one in 10^3 to 10^4 , we must assume that the necessary excitation conditions are frequent and perhaps even recurrent phenomena.

It has been suggested that our own galaxy has experienced such an explosion in its nuclear region in the not too distant past. The 3-kiloparsec expanding arm mentioned earlier may be the result of such an explosion created by the interaction

of part of the exploding gas with the interstellar matter in the plane of our galaxy. The explosive material will be less hindered in directions perpendicular to the plane of a galaxy. Such a situation is found in the relatively nearby galaxy, M82, which has great jets of material moving out of the nucleus in directions away from the principal plane. The observation data point to an explosion which occurred there in the last million years. The catastrophic events occurring in the nuclei of galaxies seem to offer an important key to our understanding these giant systems.

Radio sources now play a vital role in the basic cosmological question: what world model describes our universe? The history of radio-astronomical developments in this context is rather interesting and covers a relatively short time period. We start with the discovery of discrete radio sources which were inappropriately called "radio stars". As more and more were discovered, the question of their nature became more pressing. A few identifications with galactic objects were made, but whether most or even all were galactic was not known. The many sources at high galactic latitudes were difficult to explain. One suggestion would have these sources as magnetic knots in a galactic halo.

Eventually, improvement in the positional accuracy for radio sources showed that many of the brighter ones were extragalactic and it is now generally thought that most of these high-latitude sources are indeed extragalactic, with the fainter ones generally more distant. In fact, the most dis-



UPPER. A photograph (with the 200-inch telescope) of 3C295, a galaxy situated in the most distant cluster thus far discovered.

LOWER. The optical spectrum of this galaxy, obtained by Minkowski. The white marker points to an emission line at 5448 Å, the redshifted line of (O II), at 3727 Å. The intense emission line to the right, extending over the length of the slit is the night sky emission line of (O I) at 5577 Å.

tant galaxy thus far discovered was found through optical study of an accurately located radio source. This object, 3C295, is located in a cluster of galaxies. This method of using radio sources to draw attention to distant clusters is very promising and should result in a significant extension of the redshift-magnitude relation. (Clusters are necessary here for an absolute magnitude calibration of the galaxy).

With the acceptance of the extragalactic nature of these sources, the cosmological problem has been examined anew. One approach is through source counts. Thus, for a nonexpanding infinite

Euclidian universe of uniform density, the number N of sources above a given flux level should vary as the $-3/2$ power of the limiting flux S , i.e., a plot of $\log N$ vs $\log S$ should be linear with a slope of $-3/2$. All expanding homogeneous models require a slope flatter than $-3/2$.

Although, at first, observers differed on the actual value of the slope, three different independent surveys now agree; all get slopes close to -1.8 . A fourth, very preliminary, determination agrees within its errors with this value. Much remains in the analysis of these data; if the slope remains less than -1.5 the only explanation will be a higher density of radio sources at great distances or the occurrence of more radio galaxies (i.e., more explosions) further in the past. Either case differs from the steady-state universe; we would be living in an evolutionary universe.

The derivation of world-model parameters from such observational data, however, are much more difficult and are dependent on a knowledge of the frequency distribution of intrinsic brightnesses for radio sources as well as their evolutionary history.

In terms of the theme, "Trends in Physics", the trend in radio astronomy can be sensed from the fact that much of what I have just reported was completely unknown five years ago. Five years hence, an even more exciting outline of developments in radio astronomy could, I am sure, be presented.