PHYSICS of NONTHERMAL RADIO SOURCES

A Conference on Physics of Nonthermal Radio Sources was held on December 3–4, 1962, at the NASA Goddard Institute for Space Studies in New York City. Organized by G. R. Burbidge (University of California, San Diego), L. Woltjer (Leiden), and A. G. W. Cameron (Goddard Institute), the purpose of the meeting was to review recent observational and theoretical results in this rapidly developing field. Radio-frequency radiation characterized by a nonthermal spectral energy distribution has been detected from Jupiter and from active regions on the Sun; however, the meeting was restricted to discussion of objects located outside the solar system, the so-called "discrete sources." Over one thousand of these localized regions of celestial radio emission have now been studied at two or more frequencies.

By *S. P. Maran*

THE fundamental observational problem in radio-astronomical investigations of discrete sources is the determination of the precise positions and spectra of these objects, as well as measurement of the brightness distributions of those sources large enough to be resolved by existing equipment. Recently, polarimeter measurements at a number of frequencies have provided data on the percentage of linear polarization and position angle of the electric vector for some of the more intense sources. This work, in turn, has made it possible to study the effects of Faraday rotation on the cosmic radio waves, leading to model-dependent estimates of the electron density and magnetic field strength in interstellar and intergalactic space.

The determination of precise positions for radio sources facilitates the use of powerful optical telescopes to discover the galaxy, ionized hydrogen cloud, gaseous remnant of a supernova explosion, or other object responsible for the radio emission. Not only have radio astronomers observed the remnants of the three galactic supernovae which were recorded long ago (their explosions were witnessed respectively in 1054, 1572, and 1604 A.D.), but, also, studies of a number of extended galactic sources have suggested that these too are the remains of ancient supernovae. According to R. Minkowski (University of California, Berkeley), the quality of recently obtained radio position data has made it possible to identify 57 intense radio sources with distant galaxies recorded photographically. On the other hand, the use of photographic positions has made possible the detection of weak radio emission from some thirty well-known bright galaxies. The number of optically identified radio sources is expected to increase considerably when more complete results become available for the southern hemisphere.

A. Moffet (California Institute of Technology) described the results of high-resolution interferometry carried out at the Owens Valley Radio Observatory. It is found that more of the resolvable extragalactic sources not characterized by simple brightness distributions can be classified as double sources, which possess two distinct emitting lobes, or as "core and halo" objects, which consist of a small, intense nucleus surrounded by a large region of low-surface brightness.

The optical properties of the galaxies identified with radio sources are often found to be peculiar. For example, long-exposure photographs taken by T. Matthews (California Institute of Technology) reveal that elliptical galaxies which are radio emitters have much greater volumes than other members of the same cluster of galaxies. Matthews' colleague, M. Schmidt, noted that at least three

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Fig. 1. The central region of Messier 87, a giant elliptical galaxy, is associated with the radio source Virgo A. The unusual "jet", shown here, emits linearly polarized optical radiation and has been resolved from the source as a whole by the 1420 Mc/sec interferometer at Meudon. (*Mount Wilson and Palomar Observatories Photo*)

fourths of the radio galaxies for which slit spectra have been obtained show line emission due to the λ3727 electric quadrupole transition of O II, and some show forbidden transitions of O III, Ne III, and Ne V, permitted transitions of the Balmer series, and other emission lines as well. Such spectra indicate the presence of a tenuous and highly ionized gas. E. M. Burbidge (University of California, San Diego) described the unusual appearance of these objects, some of which have extremely bright central nuclei. Others exhibit filamentary structure, and a few show "jets" like that of the giant elliptical galaxy, Messier 87 (Fig. 1).

Besides providing the chief clues to the mechanisms of energy generation, radio spectra place constraints on the formulation of theoretical models for sources and also on the scheme of radio-source evolution. R. Conway (Manchester) discussed the results of an international cooperative investigation of 160 nonthermal radio sources, utilizing measurements of flux density at nine frequencies in the range 38–3200 Mc/sec. If one plots the logarithm of the flux density [usually expressed in watts/meter^2 (cps)] versus the logarithm of the frequency, the resultant spectra are either linear, with flux density decreasing towards higher frequencies, or curved in the sense that the high-frequency spectrum falls below a straight-line extrapolation of the low-frequency data. Figure 2, taken from a

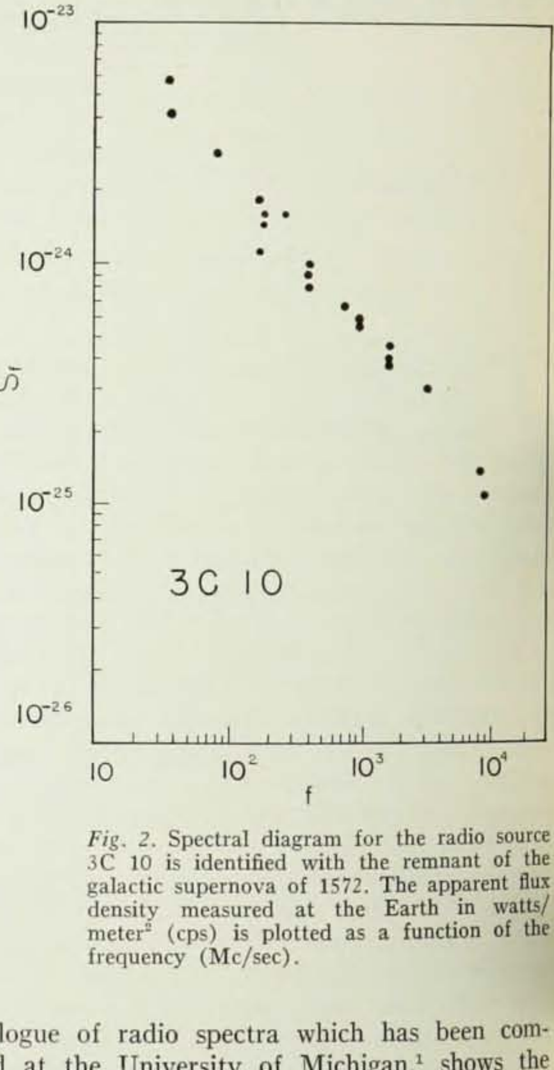

Fig. 2. Spectral diagram for the radio source 3C 10 is identified with the remnant of the galactic supernova of 1572. The apparent flux density measured at the Earth in watts/meter^2 (cps) is plotted as a function of the frequency (Mc/sec).

catalogue of radio spectra which has been compiled at the University of Michigan,[1] shows the frequency distribution of the radio emission from one of the best known galactic sources, 3C 10, which is believed to be the remnant of Tycho's supernova of 1572. Most other sources have not yet been observed at frequencies above 3200 Mc/sec. However, considerable progress is expected with the use of large antennas having accurately figured parabolic surfaces, such as the 85-foot radio telescopes located at the National Radio Astronomy Observatory and at Michigan (Fig. 3).

On the assumption that synchrotron emission from relativistic electrons is the primary contributor to the radiation of nonthermal sources, the spectral differences discussed by Conway can be regarded as reflecting variations in the electron energy distributions of the sources. Woltjer proposed a model radio source in which the magnetic field is a permanent property of the associated galaxy. He considers that particles produced by some catastrophic process in the central region of the galaxy explode outwards, filling and "lighting up" the volume occupied by the magnetic field. The objects with curved spectra are regarded as older sources which have lost their most energetic electrons. However, in the alternative theory presented by H. van der Laan (Cambridge), the curved spectrum sources are smaller and younger than the sources with straight spectra into which they evolve. The latter are produced when the expanding cloud of particles compresses the intergalactic magnetic field, giving rise to a shell-shaped emitting region in which the radiating electrons are secondary particles produced by collisions between high-energy protons and the ambient gas.

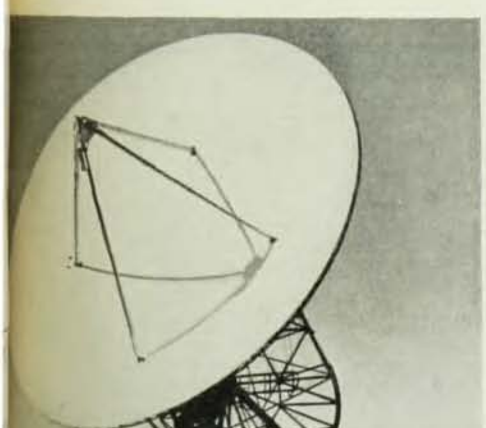

Fig. 3. Eighty-five-foot radio telescope at the University of Michigan is equipped with radiometers operating at 800, 8000, and 16 000 Mc/sec. This parabolic reflector has been used to measure the brightness temperatures of Mercury and Saturn and is now engaged in a survey of extragalactic radio sources. (*University of Michigan Radio Astronomy Observatory Photo*)

As the colliding-galaxies hypothesis has been generally discarded, the major unsolved problem of radio astronomy is still the nature of the mechanism which supplies enough relativistic particles to emit the 10^{44} ergs per second which are observed from the more intense nonthermal sources. A. G. W. Cameron advocated a method of collective formation of massive stars which evolve to the supernova stage nearly simultaneously, and G. R. Burbidge reviewed a half-dozen other suggestions which have been made by various workers, including I. Shklovsky, F. Hoyle, and Burbidge, himself. The superiority of any one of these theories has not yet been demonstrated, and much further work is under way. A basic problem is that even when the luminosity of a synchrotron source is known, it is not possible to determine separately the total particle energy and magnetic field strength. Rather, the figures usually quoted for these quantities are those which follow from the minimum total energy in particles and field which can explain the observations.

Considerable attention was devoted at the conference to the strange set of objects generally referred to as "radio stars". In the early stages of radio astronomy, this term was applied to all of the discrete sources, none of which had then been identified with external galaxies. The present usage of "radio star", however, refers only to certain objects of extremely small angular diameter (i.e., $< 1''$). Recent spectroscopic investigations[2] reveal the presence of enormous red shifts, which suggest that these "stars" are in fact distant galaxies receding at significant fractions of the velocity of light. If this interpretation is correct, their optical magnitudes lead to the conclusion that they are the brightest known objects in the universe.

In his concluding remarks at the conference, H. C. van de Hulst (Leiden) pointed out that in order to comprehend the presentations at a modern symposium on radio sources, one must be conversant not only with the practical techniques of radio astronomy, but also with nuclear physics, aerodynamics, hydromagnetics, and even optical spectroscopy. There still exists the need to integrate many apparently distinct technical specialties in order to evolve a scientific discipline capable of more fully accounting for the surprising properties of the radio galaxies.

References

1. W. E. Howard and S. P. Maran, in preparation.
2. See, for example: J. S. Greenstein and T. A. Matthews, Nature **197**, 1041 (1963).