PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC
88:594–595, October 1976

RECENT ADVANCES IN FAR-EXTRAGALACTIC RADIO ASTRONOMY*

H. VAN DER LAAN
Leiden Observatory, Leiden, The Netherlands

I. Identifications and Luminosity Functions

More than two decades ago Rudolph Minkowski warned against the hazards of selection when optical peculiarities are appealed to in shoring up positionally doubtful identifications of radio sources with galaxies. Such hazards now beset X-ray astronomy; in radio astronomy they belong to the past. A Leiden-Westerbork catalog of 1100 sources, six magnitudes deeper than 3C, with a characteristic positional accuracy of 1 to 2 arc seconds, is in press (Willis, Oosterbaan, and De Ruiter 1976). Combining these fields and deep plates from Hale Observatories and KPNO yields hundreds of identifications of great reliability using only positional criteria (De Ruiter, Willis, and Arp 1976).

The radio luminosity distribution of a flux-limited complete sample is notoriously broad. That the luminosity functions of quasars in the radio and optical spectral ranges nevertheless show some coupling has been recognized many times. The m_v distribution of a radio flux-limited sample is clearly dependent on that radio flux limit. For 3C sources, quasar identifications cut off before the Palomar Sky Survey plate limit is reached; for Westerbrk surveys the m_v values reach much fainter limits. To find apparently faint quasars deeper optical plate material alone does not help, deeper radio fields are also required, so that the ratio of radio to optical power does not shift to the high values where the luminosity-ratio function is very steep. There are now plenty of precise radio positions to find quasars to the limits of the best optical telescope systems.

Recent studies of the bivariate luminosity function by means of a galaxy sample that forms the intersection of radio flux- and optical flux-limited complete samples show that there may be a strong functional relation between the absolute optical luminosity of elliptical galaxies and their median radio power, of the form $\tilde{P}_{\text{radio}} \propto P^2_{\text{opt}}$ over a large range of optical power (Colla et al 1976). The coupling between median radio power of the nuclear sources in such galaxies and their absolute magnitude is even stronger. These relations, which require more statistical evidence over greater magnitude ranges, will, if confirmed, provide important clues for understanding radio galaxy genesis and development.

II. The Structure of Radio Galaxies

A. *Doubles, triples, and sundry.* The observational facts about radio galaxies and the current interpretive state of affairs are well summarized in recent reviews (Moffet 1976; Miley 1976; Rees 1976). The fundamental physics is deeply hidden in the explosive nuclear regions of giant ellipticals. We can study the phenomena that seem to be the far-flung consequences of that activity by means of radio telescopes such as the Westerbork Synthesis Radio Telescope (WSRT). Careful mapping of total intensity and linear polarization distributions can reveal the scales and geometry of circumgalactic magnetic fields and the mode of production and transport of cosmic ray fluxes. From this, some features of the centrally concentrated processes can be inferred.

Maps of intrinsically strong double sources with dynamic range and sensitivity sufficient to show features whose brightness is a small fraction ($\sim$ 1%) of the peaks, show that the explosive activity is repetitive. The repeated ejections take place along the same large-scale axis and many sources show remarkable geometric symmetry even when the fluxes of pair members are very different. The space density of giant ellipticals, their radio luminosity function, and the radio spectral data together imply repetitive particle production and particle losses by diffusion (van der Laan and Perola 1969), an inference verified in the case of radio trails, where the time sequence is given a neat spatial trace by the motion of the active galaxy in a cluster medium (Miley, Wellington, and van der Laan 1975).

Sensitive maps reveal that apparent doubles in fact often are centered on an active radio nucleus. The central source is then frequently straddled by several radio pairs along the one major radio axis. The central machine is intrinsically active, survives major explosions every few million years, and remembers its axis of ejection. Surely this is suggestive food for theoretical thought!

B. The giant radio galaxies 3C 236 and DA 240, discovered in the course of a Leiden-Westerbork program (Willis, Strom, and Wilson 1974) are now subject to detailed multifrequency polarization studies with the WSRT supplemented by data from the Effelsberg

*A summary of one of the invited papers presented at the Rudolph Minkowski Symposium, A.S.P. Summer Meeting, Berkeley, 18–22 May 1976.

100-m telescope. Preliminary results show that there is a remarkably large fractional polarization, even at long wavelengths, indicating very small values of intrinsic Faraday rotation. The implication is that the free electron densities in the diffuse radio lobes are very low, with the product $\langle n_e B_{||} \rangle$ as low as 10^{-8} cm^{-3} gauss. Within each radio lobe there is considerable brightness contrast, but there is no hint of synchrotron opacity, i.e., there are no ultracompact components there as are found in galactic nuclei. The magnetic field is generally wrapped about the ends of the bright concentrations. This is also true in other sources: elongated features have magnetic fields in the direction of greatest length and for nearly spherical features or the hemispherical ends of elongated structures the field is tangential. Preliminary distributions of spectral index do not establish the necessity of reacceleration. Generally the indications are that the particle fluxes are produced in the galactic nuclei, transported in highly collimated flow to the outer regions where they scatter. Near scattering surfaces there are brightness peaks and hydromagnetic features on a scale rather smaller than the overall size; outside these concentrations the brightness distributions are smooth, the magnetic field scale is large, and the spectrum may be steeper, indicative of radiative losses with age, enhanced by some adiabatic cooling. For the giant sources the magnetic fluxes involved are so large, yet so regular, that I tend to think of the diffuse components as preexisting circumgalactic fields inflated by an injected cosmic ray flux.

(C) *Radio tunnels.* If the relativistic particle transport occurs in highly collimated beams, it is intriguing to wonder whether there is any direct evidence of these channels. In several recent WSRT programs, maps have been made of sources at λ6 cm with a 6 arc second beam which had earlier been mapped at λ21 cm with a 22 arc second beam. In at least half a dozen cases the high-resolution map shows a surprising feature not suspected from the low-resolution map. Examples are 3C 310, BO844 + 31, 3C 449, 3C 129, and NGC 1265. For example, 3C 310 is a smooth relaxed source at 22 arc seconds which one might expect to be completely resolved at 6 arc seconds (Miley and van der Laan 1973). The high-resolution map shows, that embedded in the large diffuse source there is a narrow tube protruding from the central compact source in the directions of the diffuse halves of the source.

These tunnels appear to have widths less than one or two kpc but lengths greater than 30 kpc. They may be very common in radio galaxies and quasars but it requires just the right combination of dynamic range, linear resolution, and surface brightness sensitivity to detect them. Their contribution to the total flux is small, so that for beamwidths much greater than the tunnel widths they become undetectable. Their lengths range up to a few galactic diameters. These features may be the tunnels through which the cosmic ray fluxes are transported to the far-out regions. In the channel walls some fraction of these fluxes are entrained to light them up with synchrotron emission. More of these features are now being searched for and our hope is to establish their polarization structure as well. This requires another large sensitivity improvement of the WSRT at λ6 cm. No doubt these features, especially in more remote radio galaxies than the ones mentioned, where their angular size is at the one arc second scale, form one of the areas in which the VLA promises exciting advances.

I am indebted to many colleagues at Stockholm, Dwingeloo, and Leiden for sharing their results prior to publication, particularly Jan Högbom, Richard Strom, George Miley, Tony Willis, and Hans de Ruiter.

REFERENCES

Colla, G., Fanti, C., Fanti, R., Gioia, I., Lari, C., Lequex, J., Lucas, R., and Ulrich, M. H. 1976, *Astr. and Ap. Suppl.* (in press).

Laan, H. van der, and Perola, G. C. 1969, *Astr. and Ap.* 3, 468.

Miley, G. K. 1976, in *Proceedings NATO Summer School on the Physics of Nonthermal Radio Sources*, G. Setti, ed. (Dordrecht: D. Reidel Publishing Co.) (in press).

Miley, G. K., and Laan, H. van der 1973, *Astr. and Ap.* **28**, 359.

Miley, G. K., Wellington, K. J., and Laan, H. van der 1975, *Astr. and Ap.* 38, 381.

Moffet, A. T. 1976, in *Galaxies and the Universe*, A. Sandage, M. Sandage, and J. Kristian, eds. (Chicago: University of Chicago Press), p. 211.

Rees, M. in *Proceedings NATO Summer School in the Physics of Nonthermal Radio Sources*, G. Setti, ed. (Dordrecht: D. Reidel Publishing Co.) (in press).

Ruiter, H. de, Willis, A. G., and Arp, H. C. 1976, *Astr. and* Ap. Suppl. (in press).

Willis, A. G., Oosterbaan, C., and Ruiter, H. de 1976, *Astr. and Ap. Suppl.* **25**, 453.

Willis, A. G., Strom, R. G., and Wilson, A. S. 1974, *Nature* **250**, 625.