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An Old Fogey's History of Radio Jets

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Abstract: This paper describes a personal view of the discovery of radio jets in celestial radio sources. The existence of narrow, collimated optical features in distant objects has been known about since the early 20th century; however, the advent of radio astronomy in the 1940s and 1950s revealed the existence of a large number of discrete radio sources. The realization that many of these objects were not primarily stellar or local to our own galaxy, but rather extragalactic, followed the determination of accurate radio positions, enabling identifications with optical objects. High-resolution radio interferometers found that they were often compact, and with a double lobed structure, implying outflow from a central object. Shortly afterwards, accurate techniques for the measurement of polarization were developed. However it was not until the advent of synthesis instruments in the 1970s that radio images of the sources were produced, and the existence of radio jets firmly established and their polarization characteristics found.

Keywords: extragalactic radio sources; radio jets; polarization; radio interferometers

1. Introduction

This conference, on the Polarization of Astrophysical Jets, concentrates on the latest results from observations at many wavelengths, and from theoretical calculations and simulations. It seems appropriate, therefore, to describe some of the historical background to the discovery of jets in the 20th century. Some of this story coincides with the professional career of the author, who knew many of the protagonists, and who is inevitably somewhat biased towards the development of radio astronomy at the University of Manchester. Other histories have been written, including the extensive review of the development of radio astronomy by Woody Sullivan [1] and the history of the radio work at the California Institute of Technology by Marshall Cohen [2]. Much of the early history of radio astronomy is also covered in the classic book by I. S. Shklovsky [3]. This paper mainly discusses the events leading up to the discovery of radio jets in extragalactic sources.

2. The Early Discoveries

M87 (NGC4486, Virgo A) has featured prominently in this conference due to its pronounced optical and radio jet. The optical jet was first discovered in 1918 by Heber Curtis using the Lick Observatory 36-inch Crossley Reflector [4] where he noted that " . . . A curious straight ray lies in a gap in the nebulosity in PA 20 degrees, apparently connected with the nucleus with a thin line of matter." The ray is brightest at the inner end, which is 11 "from the nucleus." Early observations around 1947 by the Sydney group found the radio position [5], and the identification with M87 was established, along with that of Centaurus A, though their extragalactic nature was uncertain at the time. However, it soon became clear that they must be extragalactic.

Radio astronomy rapidly developed in the few years after the war, primarily in Manchester, Cambridge and Sydney. The initial reason for the Manchester group for building radio telescopes out at Jodrell Bank was to try to detect cosmic rays using radar techniques. Instead, reflections from the trail of ionization left behind by meteors were found, and for several years, the main interest of the group was in meteor research. However celestial radio sources were also investigated, and students were encouraged to devise new ways of studying them. Figure 1 shows a photograph of the group taken in 1951 to celebrate Bernard Lovell being made the world's first professor of radio astronomy.

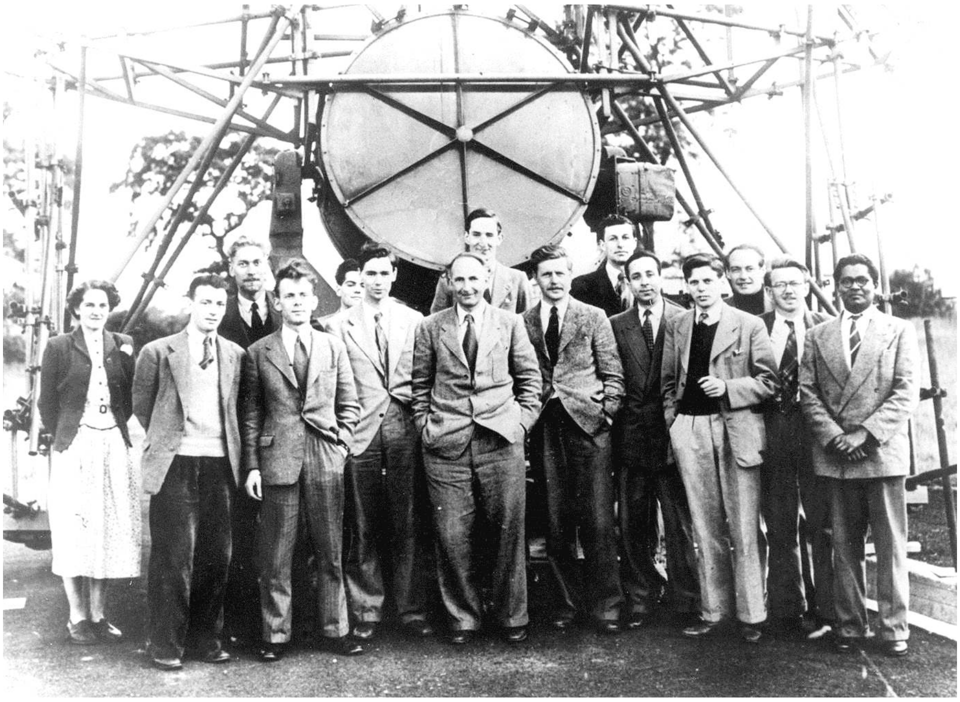

Figure 1. Photograph of the Manchester group in 1951 in front of a WW2 searchlight mirror mount used to hold a meteor radar antenna. From left to right their names are Mary Almond, Cyril Hazard, Roger Jennison, Stanley Greenhow, Gerald Hawkins, John Davies, Bernard Lovell, Gordon Little, John Clegg, Alan Maxwell, Ismail W.B. Hazzaa, Tom Kaiser, Sandy Murray, Tim Close and Mrinal Das Gupta. D. Greening and Robert Hanbury Brown are missing.

The problem of the nature of the discrete sources ("radio stars") dominated discussion in the various groups. It was realized that the way forward was to get higher resolution by using interferometers, and the rather low radio frequencies used by today's standards (~100 MHz) required telescope separations of several 10's of km. If the objects were extragalactic, then they could have small angular sizes. Interferometry established that their brightness temperatures were also much higher than expected for stars and galactic nebulae, a fact that was, in itself, a mystery (see discussion by Jesse Greenstein in [6]), but which was resolved when it was realized that the radiation was non-thermal and polarized, and was due to synchrotron radiation from energetic electrons in a magnetic field.

3. The Angular Structure of Radio Sources

3.1. Double Lobed Radio Sources

The 1950s saw the development of long baseline interferometers. Radio-linked systems were needed to connect telescopes together for the long baselines required. The issues were how to connect with the bandwidth required to give adequate signal-to-noise ratios, and how to transfer local oscillator signals in order to maintain coherence. The first experiments used Very High Frequency (VHF) links for the signal, and overcame the coherence problem by using the intensity interferometer technique developed by Hanbury-Brown and Twiss. Jennison and Das Gupta [7], shown in Figure 1, built a portable dipole array and made fringe visibility measurements at 125 MHz on Cygnus A in 1951–1953, finding a double lobed structure with an angular size of 1.5 arc min. At this time, they were aware of the identification with a distant galaxy by Baade and Minowski [8]. The baselines ran from 0.3 to 12 km, and used a portable broadside array, as shown in Figure 2. More interferometers (now of the more conventional multiplying type) were built in the mid 1950s, using broadside antenna arrays and small dishes (see discussion by Richard Thompson in [6]), resulting in the realization that many sources had a double lobed structure, and some were compact (<12 arc s, [9]), see supplementary material.

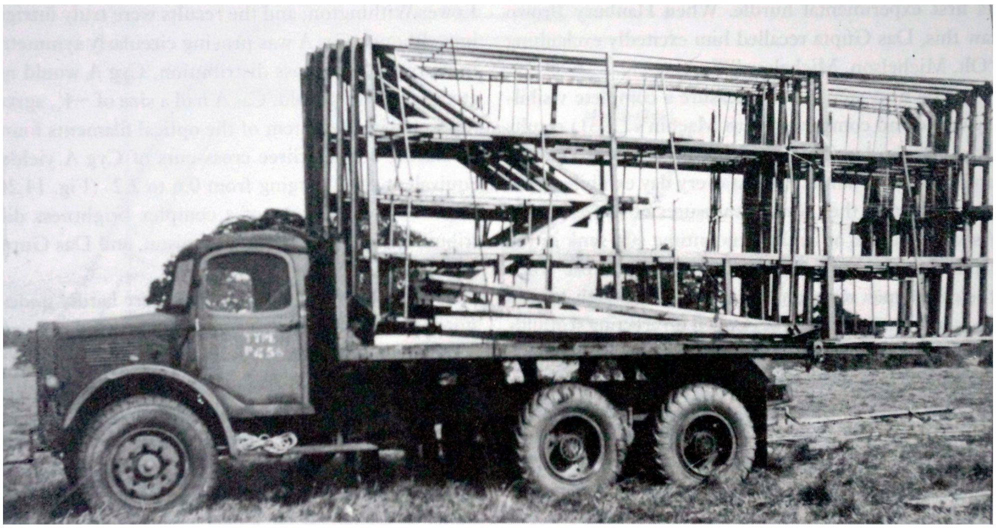

Figure 2. The portable broadside array used by Jennison and Das Gupta in 1951. The array, designed by Jennison, had a wooden frame supporting dipole antennas and was transported on an ex-war department army truck.

It became clear that more sensitivity was required to extend the work to weaker sources, and the only way to do this was by increasing the telescope collecting area. Bandwidths were still limited by the need for radio links, and receiver technology meant relatively high receiver temperatures. The advent of the 250-ft (76.2-m) MkI fully steerable telescope in 1957 enabled many more objects to be observed, and allowed the baselines to be extended to give higher resolution, using relatively small telescopes at the distant site. A tracking system also allowed a range of projected baselines to be covered, using variable delay line technology and allowance for geometric variations in fringe rate and delay. The major survey by Allen et al. [10] showed that there were sources that were less than ~1 arc s in size. These sources were both weak and small, and therefore were perhaps very distant. However, it was not until the accurate position for 3C273 was found by the lunar occultation technique at Parkes that a red-shifted quasar was identified [11]. The same issue of Nature in 1963 had 3 further papers, identifying 3C273 and 3C48 with optical objects, and finding their redshifts and discussing their energetics. Thus, almost the whole of modern extragalactic astronomy was founded in just 5 pages! Cyril Hazard [12] has recently reviewed the sequence of events leading to the discovery.

In the meantime the Caltech Interferometer [13] had also found that many sources had complex structures. All of these early observations used model fitting to measured visibility curves, but it wasn't until synthesis techniques were used that convincing images of radio sources were obtained.

3.2. Aperture Synthesis Imaging

The Cambridge group pioneered the use of aperture synthesis, firstly using interferometric arrays as survey instruments and later with the advent of the 1-mile telescope using dishes. An extensive study of 3C sources [14] with the 1 mile telescope confirmed the existence of double structures, though more complex structures were also found, as was also found by the Green Bank Interferometer [15]. A major breakthrough occurred in the early 1970s, when the Cambridge 5-km telescope was built.

Operating at 5 GHz, it had the sensitivity and resolution to map many sources, mostly from the 3C catalogue. The image by Hargrave and Ryle [16] of Cygnus A clearly showed that there seemed to be a central engine with an outflow that was interacting with the ISM in "hotspots" in the extended lobes of the source. The jet itself was not detected at that time, though theoretical work had shown that jets must be present. The first radio jet to be detected in a radio galaxy (3C219) was by Turland [17], which clearly showed an extended feature pointing towards an outer lobe. Earlier theoretical work showed that transport of energy from a central object to the outer lobes was necessary [18,19]; otherwise, energy losses were such that the lobes and hot-spots would fade, and so beam models became standard [20]. This is one of those rare occasions where radio astronomy was theoretically, rather than observationally, led. Perhaps the most convincing evidence for a radio jet in a very extended radio source, NGC6251, was found, again with the 5-km, in 1977 [21].

4. Polarization

This conference is about the polarization of jets, and so a brief history is appropriate. Polarization in extragalactic radio sources is often quite weak (a few %), so sensitive observations are required. Single dishes were used to measure the polarization of extended objects by rotating linearly polarized feeds, but the strong and variable Faraday rotation caused by the ionosphere caused problems at low frequencies, and so it became clear that the use of circularly polarized feeds gave more reliable results. It is interesting that early interferometric measurements only gave upper limits (see, e.g., [22]), though here depolarization at long wavelengths was partly responsible for their null result, and it later became clear that shorter wavelength observations were needed. Morris et al. [23] showed that linear polarization could be measured using circularly polarized antenna feeds, as also mentioned earlier by Cohen in 1958 [24]. The consensus grew that if one wanted to measure linear polarization, then circularly polarized antennas were best, and vice-versa for the measurement of circular polarization. The review by Gardner and Whiteoak in 1966 [25] showed that, though much was then known about the total polarization of discrete sources, polarization distribution measurements were needed. The work by Phil Kronberg and Robin Conway [26] (see supplementary material) pioneered the correction for non-ideal circularly polarized feeds by using 1st-order correction terms to allow for polarization leakage in interferometers. These later became known as D terms (probably because the Greek ε was not available on computer keyboards!) and they could be used for multi-telescope arrays in image synthesis.

Many sources had their polarization properties measured using combined data from a variety of single-baseline interferometers, until high-resolution synthesis instruments were developed and reliable polarization images could be produced. The first synthesis results were from the Westerbork array in 1973 [27], where outflow from the nucleus of 3C310 was found, followed by those from the Cambridge 5-km telescope in 1974 [28], at around the time that the existence of radio jets in many sources was established. VLA and MERLIN polarization measurements were made later, as these telescopes were developed, with polarized jets measured by the VLA in 1980 (e.g., 4C32.69, [29]) and MERLIN in 1985 (3C273, [30]). Since then, many high-resolution polarization images have been made, now extending from m-long wavelengths (e.g., using LOFAR) to mm wave, infra-red and optical, as elegantly discussed in this conference. It has also been found that, with accurate calibration, linearly polarized feeds can be used (e.g., with ATCA and ALMA), and indeed are preferable for the wide-band systems currently being developed for new telescopes such as the SKA. Mixed arrays with both linear and circular polarization can also be used as discussed in a recent VLBI paper [31].

5. Conclusions

This paper attempts to summarize some of the early work leading to the discovery of jets and the development of techniques for the measurement of their polarization. The talk (see supplementary material) included more photographs, often taken from copies of theses held in the University of Manchester, which for reasons of space and quality have not been included here. This history is inevitably incomplete, but perhaps adds a little to the much more comprehensive work by Woody Sullivan [1]. The efforts of the early pioneers were amazing, given the technical difficulties, not to mention the mud. Our current understanding of astrophysical jets has its foundation in their work.

Supplementary Materials: The talk and photographs are available online on the conference web site http://www3.mpifr-bonn.mpg.de/old_mpifr/jetpol/jetpol/Home.html.

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