Aust. J. Phys., 1994, **47**, 599–613

Compact Radio Sources, Quasars and Active Galactic Nuclei*

K. I. Kellermann

National Radio Astronomy Observatory†, 520 Edgemont Road, Charlottesville, VA 22903-2475, U.S.A.

Abstract

This paper reviews John G. Bolton's contributions to our understanding of compact radio sources associated with quasars and active galactic nuclei (AGNs), and his work leading to the discovery of quasars. Particular attention is given to the interpretation of the observed properties of quasars and AGNs within the framework of unified models which interpret the wide variety of observed properties as being the result of orientation rather than of any intrinsic differences.

1. Introduction

When I came to the California Institute of Technology in 1959 as a graduate student in physics, I was looking for a good research topic. Most of the professors I talked with asked me a lot of questions about my academic background. I don't think I impressed them too much because they all sent me away, telling me to 'think it over'. In any event, their research programs in particle physics, cosmic rays, low-temperature physics etc. didn't really excite me either. One professor sent me to see John Bolton, who was at Caltech at the time as a professor of radio astronomy.

John asked me two questions only. He didn't care whether I knew anything about physics and astronomy, or whether I could solve partial differential equations. First, he wanted to know what I knew about electronics. I admitted that I had never studied electronics; but, I told him, I was a radio ham, and I could use a soldering iron. He seemed pleased with that. His second question was how did I feel about heights? I thought he was referring to the fact that the Owens Valley Radio Observatory (OVRO) was located at an elevation of 4000 ft, so I confidently replied that heights didn't bother me. I was accepted. Of course, what he really wanted to know, as I discovered later, was whether I minded climbing on antennas high above the ground. Had I understood this at the time, my panic would have been only too obvious and that would have been the end, instead of the beginning, of my career in astronomy.

* Refereed paper based on a contribution to the John G. Bolton Memorial Symposium held at the Parkes Observatory, 9–10 December 1993.

† Operated by Associated Universities, Inc., under Cooperative Agreement with the National Science Foundation.

0004-9506/94/050599$05.00

John had never studied astronomy and didn't have much patience with formal course work. As far as I know he never taught a class while he was at Caltech. But he not only taught his students how to *do* radio astronomy, he taught us what research is all about. He learned his astronomy by reading the back issues of the *Monthly Notices of the Royal Astronomical Society* and the *Astrophysical Journal*—still a feasible task in the 1940s.

Just before I arrived at Caltech, John had convinced the Caltech administration to drop most of the required courses that physics students had taken for decades so that his students could get started on research rather than waste time sitting in classes. At least for the first few years, these so-called research programs consisted of surveying, stringing wires, digging holes, driving tractors (see also Ron Ekers' story in this issue p. 569), operating cranes, painting antennas, welding railroad track, and even planting trees. But he was always out there with us—surveying, digging, driving, painting, welding and wiring, harder, faster and better than anyone else. He taught by example and keeping up with him was hard work. But it was good fun, and we all learned that *real* research starts with building a better machine than the next guy.

2. The Spectra of Compact Radio Sources

John built the OVRO interferometer primarily to measure precise positions of extragalactic sources, and to determine their angular structure. To minimise the effect of confusion, which had plagued earlier interferometer systems, the OVRO interferometer was designed to work at decimetre wavelengths, considerably shorter than other radio telescopes at the time. My thesis research was to make observations of the flux density of sources at a number of wavelengths in order to study their radio spectra. My source list was selected primarily from a preprint of the Third Cambridge (3C) Catalogue (Edge *et al.* 1959) for northern sources and from the 85-MHz Mills Cross survey (Mills *et al.* 1958). Most of the sources I observed were much weaker at the shorter wavelengths, but a few had peculiar spectra.

Three of the peculiar sources, CTA 21, CTA 26 and CTA 102, were discovered by Dan Harris and Jim Roberts, using the first of the two 90-ft antennas which John Bolton was building for his interferometer. As described by Jim Roberts (see this issue p. 561), Harris and Roberts (1960) accidentally detected these three new sources during their 960-MHz study of sources selected from the 3C Catalogue. They listed these sources as NPC (not previously catalogued) and did not discuss why they were not included in the 159-MHz 3C Catalogue. Neither were these sources included in early releases of the more reliable 178-MHz revised 3C (3CR) Catalogue (Bennett 1963), which was being compiled at Cambridge from observations with the new 178-MHz telescope. It was not clear whether these sources were missing from the low-frequency catalogues because of observational error—due to confusion, for example—or whether they had unusual spectra and really were weaker at the longer wavelengths.

I re-observed all three sources in 1961 and 1962 with the Caltech interferometer at 20, 30 and 40 cm and found that the spectra of CTA 21 and CTA 102 were peaked near 30 cm. In 1962, while on a visit to Cambridge, England, I had the opportunity to examine the original records of the 178-MHz 3CR survey, and found that, although both sources were seen at 178 MHz, they were weak and were below the 3CR 9-Jy flux-density limit (Kellermann *et al.* 1962). Williams (1963) and Slysh (1963) both recognised that if the low-frequency turnovers in the spectra of CTA 21 and CTA 102 were the result of synchrotron self-absorption, the sources must be very small with an angular size of only about one hundredth of an arcsec, far smaller than any other known radio source. This was the first direct evidence for a new class of radio source which we now refer to as compact extragalactic radio sources. John recognised the importance of these sources and was looking for further examples when he began the survey of the southern sky with the new Parkes radio telescope. Marc Price and Doug Milne were assigned the survey zone south of declination −60° (Price and Milne 1965). Examining the survey data, John discovered a surprisingly strong source, 1934−63, which had a remarkably sharp low-frequency spectral cutoff (Bolton *et al.* 1963). Marc Price and I made careful observations of the radio spectrum of 1934−63 to compare with models of synchrotron self-absorption (Kellermann 1966). Shklovsky (1965) predicted that very small radio sources like 1934−63 should be time variable. This was dramatically confirmed by his student, G. Sholomitskii (1965) who discovered surprisingly rapid flux density variations in CTA 102. Although the importance of this discovery was not immediately appreciated, due in part to the speculation in the Soviet press that CTA 102 might be an extraterrestrial civilization, CTA 102 and 1934−63 became the prototypes for all future studies of self-absorbed compact radio sources and their time variability. Curiously, although it was John Bolton's discovery of 1934−63 that stimulated Shklovsky's analysis of the expected time variations from an expanding, optically thick synchrotron source, the flux density of 1934−63 has remained remarkably constant for the past three decades.

3. Doppler Boosting and Unified Models

After I returned to the United States from Australia in 1965, Ivan Pauliny-Toth and I began a study of variable compact sources using the National Radio Astronomy Observatory's (NRAO) 140-ft radio telescope. A few sources, such as 3C 120, 3C 273 and 3C 279 (Pauliny-Toth and Kellermann 1966) showed surprisingly rapid variations in flux density, on time-scales as short as weeks. Simple light-travel-time arguments suggested that the limits to the linear size estimated from the time-scale of the variability implied unreasonably large energy requirements (Pauliny-Toth and Kellermann 1966) and that inverse Compton cooling would quickly quench the radio emission (Hoyle *et al.* 1966).

Coming from somewhat different directions, Shklovskii (1964), Rees (1966), Woltjer (1966), Ozernoy and Sazinov (1969), Ginzburg and Syrovatskii (1969), and van der Laan (1971) all realised that, if the radiating source expands or moves with velocity close to the speed of light, relativistic effects might explain the apparent discrepancy with simple synchrotron models. This is because, when the radiating source is moving with relativistic velocity, the radiation is beamed along the direction of motion with an apparent intensity given by

$$S(\theta)/S_{\rm i} = [1/\gamma_{\rm b}(1-\beta_{\rm b}\cos\theta)]^{n-\alpha} = \delta^{n-\alpha}\,, \qquad (1)$$

where θ is the angle between the direction of motion and line of sight, $S_{\rm i}$ is the flux density that would be observed if the source is at rest and the emission isotropic,

$\beta_{\rm b} = v_{\rm b}/c$ represents the bulk velocity of motion, $\gamma_{\rm b} = (1-\beta_{\rm b}{}^2)^{-1/2}$, α is the spectral index defined by $S \propto (\text{frequency})^\alpha$, and the quantity $\delta = 1/\gamma_{\rm b}(1-\beta_{\rm b}\cos\theta)$ is called the Doppler factor. For simple ballistic motion, $n = 3$. If, however, the motion is in the form of a continuous flow instead of discrete ejecta, then the effect of light-travel time contributes a factor of $1/\delta$, and so $n = 2$ instead of 3 (Lind and Blandford 1985).

If the source is oriented so that the Doppler boosting is close to the line of sight, the apparent luminosity is typically enhanced by a factor of the order of γ^3, so for $\gamma \sim 10$, $S(\theta)/S_{\rm i} \sim 10^3$. A popular theme in the current literature is to interpret the wide range of properties observed in compact radio sources and other AGNs simply as the result of the orientation of a population of intrinsically similar sources of anisotropic emission. Equation (1) makes specific predictions about the observed properties of the enhanced radiation from the beamed compact component compared with the non-beamed, or stationary, emission. These so-called *unified* models attempt to relate a class of Doppler-boosted relativistically beamed objects, which are oriented close to the line of sight, to a parent population of randomly oriented objects.

In one of the first unified models, Scheuer and Readhead (1979) suggested that radio-quiet quasars are the parent population of radio-loud quasars. However, radio observations (Strittmatter *et al.* 1980; Kellermann *et al.* 1989) of optically selected quasars showed that the number/flux-density relation is not consistent with the Scheuer/Readhead predictions, and that radio-loud quasars are largely extended radio sources which are not likely to be affected by relativistic beaming.

Later, using similar ideas, Orr and Browne (1982) considered the unification of a population of steep-spectrum extended quasars with a beamed parent population of flat-spectrum compact quasars. They suggested that all radio sources contain a relativistically beamed core as well as extended double lobes which are aligned along the direction of the beam. When the beam is oriented close to the line of sight, the flux density is enhanced by Doppler boosting and we see a core-dominated source, while those oriented in the plane of the sky appear to be lobe-dominated.

In a series of papers, Urry and collaborators discussed the unification of a parent population of low-luminosity galaxies with a beamed population of BL Lac objects (e.g. Urry and Padovani 1991; Urry *et al.* 1991). Antonucci and Miller (1985) considered Blazars (BL Lac objects and other optically violent variables and highly polarised quasars) to be the beamed population of the luminous radio galaxies and quasars.

Antonucci and Miller (1985) also introduced the idea of shadowing by dust to give anisotropy at optical wavelengths to unify Type I and II Seyfert galaxies. Encouraged by the qualitative success of these early unified models, but aware of their quantitative deficiencies, Barthel (1989) combined the Antonucci and Miller idea of an obscuring dust torus with relativistic boosting, to further distinguish between radio galaxies, flat- and steep-spectrum quasars, depending on the relative orientation of the beam, the torus and the line of sight. In Barthel's model, sources with the beam pointed close to the line of sight appear as compact flat-spectrum radio quasars, while those at intermediate angles, where the compact component is not enhanced by Doppler boosting, appear as steep-spectrum extended quasars. At large angles to the line of sight, the quasar component is shadowed by the dusty torus and the source is classified as a radio galaxy. Unlike the Doppler effect, which makes well-determined predictions [e.g. equation (1)], the uncertain thickness of the torus adds extra degrees of freedom to the model, and it is not surprising that it has removed some of the apparent discrepancies in the simple Doppler model.

Nevertheless, inconsistencies still exist. For example, Schilizzi and de Bruyn (1983) pointed out that if account is taken of projection effects, then the extended components of superluminal sources would be among the largest known radio sources; this, of course, is statistically highly unlikely. Also, Singal (1993*a*, 1993*b*) has argued that the relative number density and size of quasars and radio galaxies vary with redshift, in apparent contradiction to the simple unified model which supposes that quasars and radio galaxies differ only in their orientation with respect to the line of sight, which should be independent of redshift. Singal also argues that, contrary to the prediction of unified models, the apparent angular size of quasars is comparable to that of powerful radio galaxies, and that the fraction of sources identified with quasars and radio galaxies is a function of flux density. Moreover, there appear to be real intrinsic differences in the polarisation properties of BL Lac objects and quasars (Kollgaard *et al.* 1992) which are inconsistent with interpreting quasars as the parent populations of beamed BL Lacs.

Another problem is associated with the apparent asymmetry of the observed jets. Nearly all of the compact parsec-scale jets are one-sided, and in almost every case the compact jet lies on the same side as the extended jet, which extends as much as several hundred kpc away from the core. If the one-sidedness of the compact jet is due to differential Doppler boosting of an intrinsically two-sided jet, the extended jets must also be relativistic. This interpretation is supported by polarisation observations of the extended radio lobes, which indicate that the extended jets are always on the near side of the source (Laing 1988).

4. Superluminal Motion

Another consequence of relativistic boosting is apparent faster-than-light velocity. Because the radiating source is almost catching up with its own radiation, when the motion is close to the line of sight, the apparent time-scale is compressed and the apparent transverse velocity $v_{\rm obs}$ is greater than the true velocity v. The apparent transverse motion is given by the well-known expression

$$\beta_{\rm obs} = (\beta_{\rm p} \sin\theta)/(1-\beta_{\rm p}\cos\theta)\,, \tag{2}$$

where θ is the angle between the direction of motion and the line of sight, and the subscript p refers to the moving pattern velocity. When $\beta_{\rm obs}$ is greater than unity, the apparent transverse velocity is said to be superluminal. The maximum value of $\beta_{\rm obs} \sim \gamma_{\rm p}$, and occurs when $\sin\theta \sim 1/\gamma_{\rm p}$. At any angle θ, the maximum observed velocity is $\beta_{\rm max} = \sin\theta/(1-\cos\theta)$. Typically, $\beta_{\rm obs}$ is $\sim$7, so $\gamma_{\rm p}$ is $\sim$7, $\beta_{\rm p} \sim 0{\cdot}99$, and $\theta \sim 8^\circ$.

Observations of the structure of compact radio sources made over the past two decades indicate that superluminal motion is very common, thus providing dramatic evidence for the importance of relativistic effects in compact radio sources (Zensus and Pearson 1987). Curiously, as early as 1963, Shklovskii (1964) suggested that the well-known optical jet in M 87 might appear to be one-sided as a result of differential Doppler boosting of an intrinsically two-sided jet [equation (1)]. VLBI observations of the radio counterpart indicate that the radio jet in M 87 (Reid *et al.* 1989) is subluminal, but more detailed observations with greater dynamic range and sensitivity are needed to see whether the jet-to-counterjet ratio is consistent with the observed motions and differential Doppler boosting.

For an isotropic distribution of pitch angles, the probability that a source will be favourably oriented within a narrow cone of width $\sim 1/\gamma$ is small, and so only a small fraction, of the order of $1/\gamma^2$, will be found to be superluminal. However, due to Doppler boosting along the line of sight, in a flux-limited sample, angles close to the line of sight will be preferentially selected and an excess of superluminal sources is expected over that in an isotropic sample.

Equations (1) and (2) make specific predictions about the expected relationship between Doppler boosting and apparent transverse velocity for a flux-limited isotropic distribution. A problem with all relativistic ballistic-type models is that the core and moving jet components observed by VLBI appear to have comparable luminosities, whereas Doppler boosting of the moving jet should cause it to appear more luminous by two or three orders of magnitude. Blandford and Königl (1979) made the ingenious suggestion that the core is actually the stationary throat of a relativistic nozzle and so its luminosity is also Doppler boosted. Later, Lind and Blandford (1985) generalised the breakdown between the velocity of the beam v_{b} used in equation (1), which determines the amount of Doppler boosting, and the velocity of the changing pattern v_{p} used in equation (2), which determines the apparent transverse velocity.

Cohen (1989) has shown that for $\alpha \sim 0$, and $2 < n < 3$, angles close to the critical angle, $\theta \sim 1/\gamma$, dominate so that β_{obs} is expected to be close to the maximum value γ. However, as shown in Fig. 1, the observed distribution of apparent transverse velocity in a sample of 37 well-observed compact radio sources is considerably more uniform than predicted, and does not show the expected concentration of velocities close to the maximum value.

Cohen (1989) discusses the effect of a spread in the intrinsic value of γ, as well as a difference in the velocity associated with the flow of relativistic particles, γ_{b}, and the pattern velocity associated with the changing structure of the source, γ_{p}. Additional complications arise if the motion is spread out over a cone of

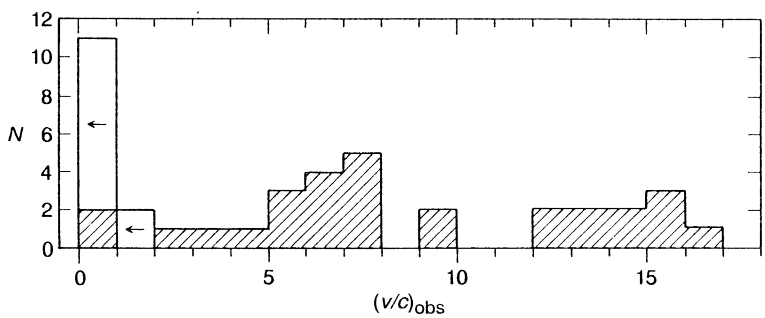

Fig. 1. Distribution of observed apparent transverse velocity for 37 compact radio sources.

angles rather than in a narrow beam, or if the relativistic motion consists of a smooth flow ($n=2$) rather than a ballistic motion ($n=3$).

In response to the problems encountered with reconciling the simple unified models with observations, and in particular with the observed distribution of superluminal velocities, Ekers and Liang (1990) suggested a non-Doppler model so that the apparent velocity distribution depends only on the corresponding solid angle. But this predicts a concentration of orientations near the plane of the sky, corresponding to values of β close to one, or two if the motion is intrinsically two-sided. This also is not consistent with the observed distribution shown in Fig. 1. To save their model, Ekers and Liang have appealed to Barthel's torus to discriminate against observing motion which lies in the plane of the sky with apparent velocities between c and $2c$.

5. Doppler Effects on Opaque Sources

In essentially all discussion of Doppler boosting and unified models, it has become customary to assume a spectral index $\alpha \sim 0$, a value which is generally assumed to be representative of the spectral index for compact radio sources. But, in an opaque synchrotron source we have $\alpha \sim 2 \cdot 5$, not zero, so $n-\alpha \sim 0$. Equation (2) shows that, in this case, the Doppler boosting is small and there is little bias toward observing superluminal sources with $\beta_{\rm obs} \sim \gamma$ in a randomly oriented sample. Indeed, if $\alpha = 2\cdot 5$ and $n < 2\cdot 5$, the receding (redshifted) component may appear brighter than the approaching (blueshifted) component as the K-correction term becomes more important than the relativistic boosting.

In general, the observed spectrum for a relativistically moving self-absorbed source will be a function of speed and the angle between the motion and the line of sight. For a homogeneous source, the self-absorption cutoff frequency is

$$\nu \sim 0\cdot 1 B_{\rm G}^{1/5}(S_{\rm Jy}/\theta_{\rm mas}^2)^{2/5}[(1+z)/\delta]^{1/5}\ {\rm GHz}\,. \tag{3}$$

Typically, VLBI observations refer to components with an apparent surface brightness $(S/\theta^2) \sim 1$ Jy/mas^2, so self-absorption is expected to become important below several gigahertz and depends only weakly on the magnetic field strength.

The spectrum of a homogeneous synchrotron source with a spectral index $\alpha = -0\cdot 8$ may be written as (Kellermann 1966):

$$S \sim \nu^{2\cdot 5}(1-{\rm e}^{-\nu/\nu_0})^{-3\cdot 3}\,. \tag{4}$$

Fig. 2 shows the spectrum of a self-absorbed synchrotron source, and how the spectrum is modified by Doppler boosting.

In a few sources, such as 1934–63 (Bolton *et al.* 1963; Kellermann 1966), 0237–23 (Arp *et al.* 1967), 2134+00 (Shimmins *et al.* 1968), and CTD 93 (Kellermann and Pauliny-Toth 1969), the observed spectrum is indeed characteristic of a self-absorbed synchrotron source. John Bolton was among the first to recognise the peculiar nature of these sources which are now frequently referred to as *Gigahertz Peaked Spectrum Sources*. VLBI observations do not show superluminal motions in these sources. This suggests that the motion in the peaked spectrum sources may lie near the plane of the sky, so the spectrum is not modified by differential Doppler boosting of the different components, and differential light-travel times are negligible.

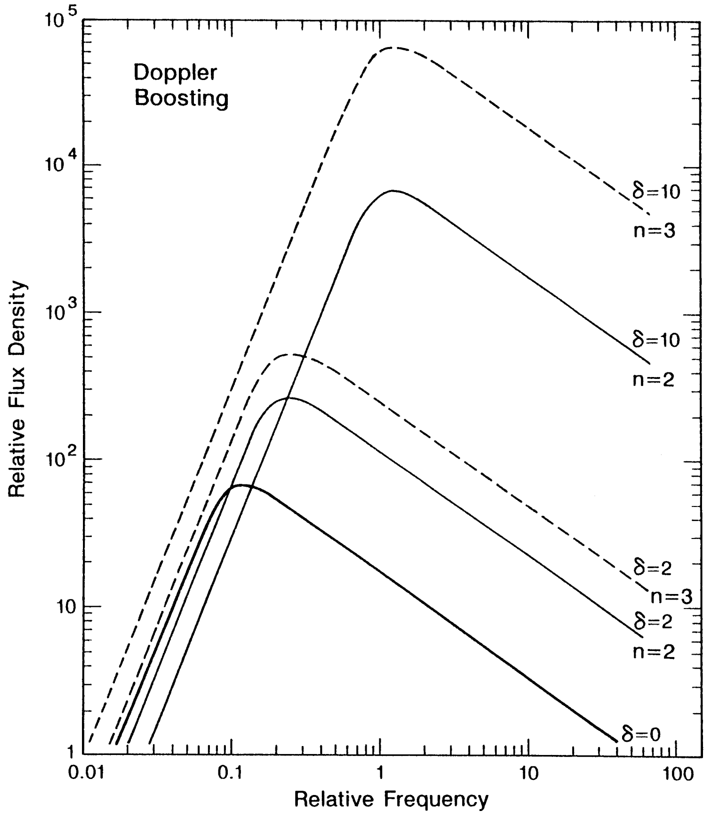

Fig. 2. Effect of motion on the observed spectrum of a homogeneous synchrotron source with a spectral index $\alpha = -0{\cdot}75$. The heavy solid curve represents the spectrum of a source at rest. The thin solid curves show the spectrum for $n = 2$ for Doppler factors of 2 and 10. The dashed curves show the spectrum for $n = 3$ for Doppler factors of 2 and 10.

In general, however, the observed radio spectra of compact quasars and AGNs do not show this simple characteristic shape, but more often show multiple maxima and minima, which approximate a spectral index, $\alpha \sim 0$, and the spectrum is said to be flat. For many years, it has been recognised that the so-called flat spectrum is probably due to the superposition of multiple self-absorbed sources which become opaque at different frequencies (e.g. Ozernoy and Sazinov 1969; Kellermann and Pauliny-Toth 1969; Cotton *et al.* 1980). In principle, the spectra of the individual components can be determined by VLBI observations made at different wavelengths, but this is difficult since VLBI observations are mostly made with fixed physical baselines (of the order of an Earth radius), so the resolution varies with wavelength. To the extent that it has been possible to untangle spectra of individual components of compact radio sources, they do indeed appear to have different cutoff frequencies which combine to give an apparent *flat spectrum*, as illustrated in Fig. 3.

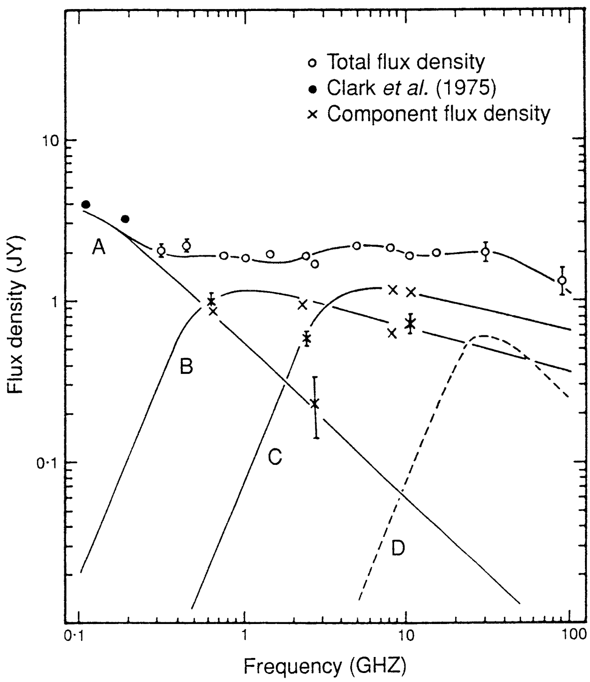

Fig. 3. Radio spectrum of the quasar 0735+178, showing the deconvolution into separate components, each with a different self-absorption cutoff frequency (taken from Cotton *et al.* 1980).

The multi-peaked sources generally show superluminal motion, as their real motion is close to the line of sight so that differential light-travel effects are important, and the differential Doppler boosting of the components gives the multi-peaked spectra. When John Bolton came to the United States in 1969 to give the first Jansky Lecture at the NRAO, I showed him many examples of what we were calling *flat spectra*—but which I suggested were due to multiple self-absorbed sources. John looked at the spectra and asked: 'Why do you suppose all the components peak at about the same flux density?' I never could decide whether he asked that question because he really didn't know and thought I might, or whether he was asking as the Professor asks the student to see if I had learned my lesson well. I didn't know the answer then, and still don't. Indeed, with the subsequent appreciation of the importance of Doppler boosting, this 'cosmic conspiracy' is even more difficult to understand (Cotton *et al.* 1980). The commonly adopted Blandford and Königl 'nozzle' model reduces the problems introduced by differential Doppler boosting, but requires that $\gamma_b \sim 0$, at least at the throat of the nozzle, thus introducing the extra degree of freedom allowed when $\gamma_p \neq \gamma_b$.

6. Taxonomy of Compact Radio Sources

John Bolton, together with his colleagues and students, was involved in the discovery and subsequent investigation of essentially all the currently recognised types of extragalactic radio sources. With Gordon Stanley, John isolated the first discrete radio source, Cygnus A (Bolton and Stanley 1948*a*, 1948*b*). Using a sea interferometer, originally built to observe the Sun at 100 MHz, they measured the source position and placed an upper limit to the angular diameter of 8 arcmin. John then went on to discover five other discrete sources with the sea interferometer (Bolton 1948). Joined by Gordon Stanley and Bruce Slee, they then made their painstaking measurements of the accurate positions of Virgo A and Centaurus A, using sea interferometers in Australia and in New Zealand (see Orchiston in this issue p. 541). This led to the first identification of discrete radio sources with the external galaxies M 87 and NGC 5128 respectively (Bolton *et al.* 1949). However, as discussed elsewhere (see Ekers on p. 569), Bolton *et al.* found it hard to accept the apparent large radio luminosity implied by an extragalactic identification and appear to have considered M 87 and NGC 5128 to be Galactic nebulae. Later interferometer observations made at much shorter wavelengths detected the compact radio nuclei of Virgo A (Palmer *et al.* 1967), Centaurus A (Wade *et al.* 1971), and Cygnus A (Hargrave and Ryle 1974), all of which have since been shown by VLBI observations to have dimensions of the order of 1 milliarcsec.

Measurements of radio structure in the early 1960s made with the Caltech interferometer by John's students and collaborators indicated that extragalactic radio sources generally have two well-separated regions of radio emission (Maltby and Moffet 1962). Accurate radio positions led to the identification of many sources with distant galaxies with a remarkably small dispersion in optical luminosity (e.g. Bolton 1960; Maltby *et al.* 1963). Especially exciting was John's identification of 3C 295 with a faint galaxy, which led to Minkowski's (1960) measurement of a redshift of 0·46 (Bolton 1990). This was by far the most distant known galaxy at the time.

Following the pioneering work of Shklovskii (1952) and Ginzburg (1951), it was widely accepted that the non-thermal radio emission observed from galaxies was due to the synchrotron mechanism. Burbidge (1959) pointed out the extreme energy requirements of extragalactic synchrotron sources. The Caltech observations that the radio lobes were well separated from the parent galaxy exacerbated the problem of the origin of the energy and how the energy was supplied to the radio-emitting regions. Minimum-energy arguments suggested that the largest radio sources, such as Cen A, contain the most energy (Burbidge 1959), although they are much less luminous than some much smaller sources such as Cyg A. But the largest sources are presumably the oldest. This puzzled John. If radio sources lose energy by expansion and radiation, the largest (oldest) sources should contain the least energy. He speculated whether in fact the size of radio galaxies was constant, or even collapsed with time (Bolton 1969).

However, the discovery of compact radio sources in the nuclei of many radio galaxies, in other elliptical galaxies, and even if the centre of our own Galaxy, contributed to the growing evidence for violent activity in the nuclei of galaxies (e.g. Burbidge *et al.* 1963; Ambartsumian 1965), and the existence of a massive central engine located at the galactic nucleus which supplied energy to the distant radio lobes.

McGee and Bolton (1954) were the first to appreciate that the strong radio source Sagittarius A was probably associated with the nucleus of our own Milky

Way Galaxy. Subsequent high-resolution interferometer measurements (Balick and Brown 1974) detected the compact component now known as SgrA* which is believed to be the true nucleus of our Galaxy. Later VLBI measurements made over a wide range of wavelengths (e.g. Lo *et al.* 1985) showed that the measured angular size closely follows the λ^2 law expected from interstellar scattering. The true dimensions of SgrA* are less than 0·4 milliarcsec or only 3 AU (Backer *et al.* 1993).†

Sgr A* is the smallest and weakest known AGN with a 5-GHz luminosity of only 10^{16} W m^{-2} Hz^{-1}. The nuclei of some other spiral galaxies, such as M81 and NGC 4594, are stronger and have luminosities of about 10^{20} W m^{-2} Hz^{-1}. Seyfert and Markarian galaxies, as well as the nuclei of some giant ellipticals, including radio galaxies such as M 87 and NGC 5128, are stronger yet, with luminosities of about 10^{22} W m^{-2} Hz^{-1}. The strong radio galaxies such as Cyg A have luminosities of 10^{25-26} W m^{-2} Hz^{-1}, while the quasars range up to 10^{28} W m^{-2} Hz^{-1}. Although compact radio sources show a range in luminosity of order 10^{12}, from SgrA* to the most luminous quasars, they all have a remarkably similar luminosity per unit volume near 1 mW km^{-3}.

Quasars were discovered as a result of the combined efforts of radio and optical astronomers at Cambridge, Jodrell Bank, Caltech, the University of Sydney and Parkes. The first group of sources later recognised as quasars were originally discovered in the late 1950s as part of the Cambridge 3C survey (Edge *et al.* 1959). Some sources remained unresolved on the longest baselines of the Caltech interferometer, so had angular diameters less than 30 arcsec. Long-baseline radio-linked interferometer measurements by Henry Palmer and his team at Jodrell Bank showed that a few sources, including 3C 48, 3C 147, 3C 196 and 3C 286, appeared to have remarkably small components (Allen *et al.* 1962). 3C 48 was unresolved with a diameter less than 0·5 arcsec (Rowson 1963). Encouraged by the large redshift which had just been measured for 3C 295, John and his colleagues at Caltech and Mt Palomar naturally assumed that these other very small diameter sources were also distant radio galaxies. When 3C 48, 3C 196 and 3C 286 were identified with variable star-like objects, the interpretation shifted in favour of Galactic stars (e.g. Matthews and Sandage 1963).

Using an accurate position measured with the Caltech interferometer, John Bolton identified 3C 48 with a 16th-magnitude stellar object in the Palomar Sky survey. Following consultations with Ira Bowen, John also noticed that two of the lines in the 3C 48 spectrum could be identified with the 2798 Å line of Mg II and the 3426 Å line of [Ne V], with a redshift of 0·37, but this interpretation was apparently rejected on spectroscopic grounds (Bolton 1990).

In December 1960, John left Caltech with his family for Australia, to take charge of completing the 210-ft antenna at Parkes, NSW. The identification of 3C 48 was reported by Matthews, Bolton, Greenstein, Munch and Sandage as a late paper at the December meeting of the American Astronomical Society, but it was apparently described by Sandage, who presented the paper, as a Galactic star. Unfortunately, abstracts of late papers were not published at that time, and

† (Note added in proof). New VLBI observations made at 3·5 mm show that the intrinsic size is less than 0·13 mas or 1 AU (Rogers *et al.* 1994).

so the only written record of this work is a second-hand report which appeared in the March 1961 issue of *Sky & Telescope*. In view of its small radio and optical dimensions, the detection of both radio and optical variability, and its peculiar optical spectrum, 3C 48 was generally accepted as the first identified radio star (e.g. Greenstein 1963), or 'the remnant of a very old supernova' (Greenstein 1961; see also Greenstein in this issue p. 555).

A spectrum of 3C 48, taken shortly after John left for Australia in December 1963, also showed the 3727-Å line of [O II] with the same redshift as he had previously found for the [Ne V] and Mg II lines (Bolton, personal communication 1990), but the significance of this was not appreciated by others (Greenstein, unpublished 1963) until 5 February 1963, when Schmidt (1963) determined the redshift of 3C 273, and Greenstein re-examined the 3C 48 spectrum (Greenstein and Matthews 1963; Schmidt 1983). Indeed, as late as December 1962, Matthews and Sandage (1963) described 3C 48, 3C 196 and 3C 286 as Galactic stars. For 3C 48 they remarked: 'The lines could not be identified with any plausible combination of red-shifted emission lines.'

The lunar occultation measurements of Hazard *et al.* (1963), in which John played such an important role, gave the position for the separate components of 3C 273 accurate to 1 arcsec, which led directly to the determination of the redshift of 3C 273 (Schmidt 1963).

Thirty years later, one wonders why 3C 273 was not identified earlier, particularly when other sources were already known to be identified with star-like objects. At cm wavelengths, 3C 273 is the second or third (depending on epoch) brightest source in the 3CR catalogue away from the Galactic plane. Only Virgo A, and sometimes 3C 84, are stronger. However, no special attention was paid to 3C 273 in the early 1960s. The Jodrell Bank radio link interferometer was operating at a low frequency of 159 MHz, where most of the radio emission from 3C 273 is from the extended jet component, so that no fringes were observed from 3C 273 on the longest baselines. Thus, 3C 273 was not recognised as being particularly small or of any special interest until Moffet (1961), using the Caltech interferometer, showed it to be nearly unresolved. Position measurements at Caltech were made at 960 MHz, where the jet component is still relatively strong compared with the stellar core. This introduced a frequency-dependent shift in the centroid away from the stellar component due to the contribution of the jet, but this was not recognised until after the occultation measurements.

When I saw John in 1989, we discussed the history of 3C 273. He suggested two other reasons why 3C 273 was not identified earlier. It was the practice at Caltech to refer all amplitude and phase measurements to 3C 274 (Virgo A), which is less than 2 minutes of right ascension away from 3C 273. Since the most precise position measurements were made within a few degrees of transit, 3C 273 and 3C 274 could not be observed on the same day. Also, John reminded me that, initially, the Caltech interferometer operated with only an east–west baseline. Declinations were measured by counting fringes to determine the fringe rate, which is a measure of the declination of the source. But 3C 273 is located close to the equator where the observed fringe rate is insensitive to the declination, and so accurate declination for 3C 273 was not obtained at Caltech until well after the declinations of the other stellar sources were available from observations with the east–west interferometer (Read 1963).

An earlier Caltech interferometer position for 3C 273 was apparently in error by more than 1 arcmin and was tentatively misidentified with a galaxy (Schmidt 1983; and personal communication 1993). The correct position, which led ultimately to Schmidt's determination of the redshift, was derived from the 1962 lunar occultation measurements at Parkes as part of a program led by Cyril Hazard, who was then working at the University of Sydney. Earlier, Hazard had pioneered the occultation technique at Jodrell Bank, and the series of 1962 occultations of 3C 273 at Parkes resulted in what was then unprecedented angular resolution and position accuracy.

Although the first 3C 273 occultation, observed at Parkes in April 1962, gave inconclusive results for the position, it clearly showed the presence of a small component. By the time of the second occultation in August, Bolton and John Shimmins had obtained a reasonably good position from observations made with the Parkes antenna, and apparently John had made a tentative identification (Bolton 1990; and personal communication 1989), even before seeing the occultation results. A 200-inch plate obtained by Rudolph Minkowski showed the jet as well as the stellar component. The Parkes radio position lay between the stellar component and the end of the jet. John took extraordinary measures to ensure the success of the August occultation measurements, which were able to resolve the ambiguity (Hazard 1985; Bolton 1990; Robertson 1992). Bolton and Minkowski apparently identified the two main radio components of 3C 273 with the 13th-magnitude stellar object and faint jet (Hazard 1985). John communicated these exciting results to his colleagues at Caltech, which allowed Maarten Schmidt to measure the redshift of 3C 273 that untangled the 3C 48 puzzle and led to the recognition of the new class of extragalactic objects in the universe—now known as quasars (Schmidt 1983).

Acknowledgment

I thank Maarten Schmidt and Dave Jauncey for helpful discussions of the events surrounding the identification of 3C 273 with a quasar.

References

Allen, L. R., Anderson, B., Conway, R. G., Palmer, H. P., Reddish, V. C., and Rowson, B. (1962). *Mon. Not. R. Astron. Soc.* **124**, 477.
Ambartsumian, V. (1965). *In* 'The Structure and Evolution of Galaxies', Proc. 13th Solvay Conf. on Physics, p. 1 (Interscience: New York).
Antonucci, R. R. J., and Miller, J. S. (1985). *Astrophys. J.* **297**, 621.
Arp, H. C., Bolton, J. G., and Kinman, T. D. (1967). *Astrophys. J.* **147**, 840.
Backer, D. C., Zensus, J. A., Kellermann, K. I., Reid, M., Moran, J. M., and Lo, K. Y. (1993). *Nature* **262**, 1414.
Balick, B., and Brown, R. L. (1974). *Astrophys. J.* **194**, 265.
Barthel, P. (1989). *Astrophys. J.* **336**, 606.
Bennett, A. S. (1963). *Mem. R. Astron. Soc.* **68**, 163.
Blandford, R., and Königl, A. (1979). *Astrophys. J.* **232**, 34.
Bolton, J. G. (1948). *Nature* **162**, 141.
Bolton, J. G. (1960). Publn Owens Valley Radio Obs., No. 5, California Institute of Technology.
Bolton, J. G. (1969). *In* 'Quasars and High Energy Astronomy' (Eds K. N. Douglas *et al.*), p. 5 (Gordon and Breach: New York).
Bolton, J. G. (1990). *Proc. Astron. Soc. Aust.* **8**, 381.
Bolton, J. G., and Stanley, J. G. (1948*a*). *Nature* **161**, 312.
Bolton, J. G., and Stanley, J. G. (1948*b*). *Aust. J. Scient. Res.* A **1**, 58.

Bolton, J. G., Gardner, F. F., and Mackey, M. B. (1963). *Nature* **199**, 682.
Bolton, J. G., Stanley, G. J., and Slee, O. B. (1949). *Nature* **164**, 101.
Burbidge, G. R. (1959). *In* 'Paris Symposium on Radio Astronomy' (Ed. R. N. Bracewell), p. 541 (Stanford University Press).
Burbidge, G. R., Burbidge, E. M., and Sandage, A. R. (1963). *Rev. Mod. Phys.* **35**, 947.
Cohen, M. (1989). *In* 'BL Lac Objects' (Eds L. Maraschi *et al.*), p. 13 (Springer: New York).
Cotton, W. D., Wittels, J. J., Shapiro, I. I., Marcaide, J., Owen, F. N., Spangler, S. R., Rius, A., Angulo, C., Clark, T. A., and Knight, C. A. (1980). *Astrophys. J.* **238**, L123.
Edge, D. O., Shakeshaft, J. R., McAdam, W. B., Baldwin, J. E., and Archer, S. (1959). *Mem. R. Astron. Soc.* **68**, 37.
Ekers, R. D., and Liang, H. (1990). *In* 'Parsec-scale Radio Jets' (Eds J. A. Zensus and T. A. Pearson), p. 333 (Cambridge University Press).
Ginzburg, V. L. (1951). *Dokl. Akad. Nauk. SSSR* **76**, 377.
Ginzburg, V. L., and Syrovatskii, S. I. (1969). *Ann. Rev. Astron. Astrophys.* **7**, 375.
Greenstein, J. L. (1961). Annual Report Director Mt Wilson and Palomar Obervatories, Carnegie Institution Washington, p. 80.
Greenstein, J. L. (1963). *Scient. Am.* **209**, 54.
Greenstein, J. L., and Matthews, T. A. (1963). *Nature* **197**, 1041.
Hargrave, P. J., and Ryle, M. (1974). *Mon. Not. R. Astron. Soc.* **166**, 305.
Harris, D. E., and Roberts, J. A. (1960). *Publn Astron. Soc. Pac.* **72**, 237.
Hazard, C. (1985). *In* 'Active Galactic Nuclei' (Ed. J. E. Dyson), p. 1 (University of Manchester Press).
Hazard, C., Mackey, M. B., and Shimmins, J. A. (1963). *Nature* **197**, 1037.
Hoyle, F., Burbidge, G., and Sargent, W. (1966). *Nature* **209**, 751.
Kellermann, K. I. (1966). *Aust. J. Phys.* **19**, 195.
Kellermann, K. I., and Pauliny-Toth, I. I. K. (1969). *Astrophys. J.* **155**, L71.
Kellermann, K. I., Long, R. J., Allen, L. R., and Moran, M. (1962). *Nature* **195**, 692.
Kellermann, K. I., Sramek, R., Schmidt, M., Schaffer, D. B., and Green, R. (1989). *Astron. J.* **98**, 1195.
Kollgaard, R. I., Wardle, J. F. C., Roberts, D. H., and Gabuzda, D. C. (1992). *Astron. J.* **104**, 1687.
Laing, R. A. (1988). *Nature* **331**, 149.
Lind, K. R., and Blandford, R. D. (1985). *Astrophys. J.* **295**, 358.
Lo, K. Y., Backer, D. C., Ekers, R. D., Kellermann, K. I., Reid, M., and Moran, J. M. (1985). *Nature* **315**, 124.
McGee, R. X., and Bolton, J. G. (1954). *Nature* **173**, 985.
Maltby, P., and Moffet, A. T. (1962). *Astrophys. J. Suppl. Ser.* **7**, 141.
Maltby, P., Matthews, T. A., and Moffett, A. T. (1963). *Astrophys. J.* **137**, 153.
Matthews, T. A., and Sandage, A. R. (1963). *Astrophys. J.* **138**, 30.
Mills, B. Y., Slee, O. B., and Hill, E. R. (1958). *Aust. J. Phys.* **11**, 360.
Minkowski, R. (1960). *Astrophys. J.* **132**, 908.
Moffett, A. (1961). Ph.D. thesis, California Institute of Technology.
Orr, M. J. L., and Browne, I. W. A. (1982). *Mon. Not. R. Astron. Soc.* **200**, 1067.
Ozernoy, L. M., and Sazinov, V. N. (1969). *Astrophys. Space Sci.* **3**, 395.
Palmer, H. P., Rowson, B., Anderson, B., Donaldson, W., Miley, G. K., Gent, H., Adgie, R. L., Slee, O. B., and Crowther, J. H. (1967). *Nature* **213**, 789.
Pauliny-Toth, I. I. K., and Kellermann, K. I. (1966). *Astrophys. J.* **146**, 634.
Price, M. R., and Milne, D. K. (1965). *Aust. J. Phys.* **18**, 329.
Read, R. B. (1963). *Astrophys. J.* **138**, 1.
Rees, M. (1966). *Nature* **211**, 468.
Reid, M. J., Biretta, J. A., Junor, W., Muxlow, T. W. B., and Spencer, R. E. (1989). *Astrophys. J.* **336**, 112.
Robertson, P. (1992). 'Beyond Southern Skies—Radio Astronomy and the Parkes Telescope', p. 230 (Cambridge University Press: Sydney).
Rogers, A. E. E., *et al.* (1994). *Astrophys. J. Lett.* (in press).
Rowson, B. (1963). *Mon. Not. R. Astron. Soc.* **125**, 177.
Scheuer, P. A. G., and Readhead, A. C. R. (1979). *Nature* **277**, 182.

Schilizzi, R., and de Bruyn, A. (1983). *Nature* **303**, 26.
Schmidt, M. (1963). *Nature* **197**, 1040.
Schmidt, M. (1983). *In* 'Serendipitous Discoveries in Radio Astronomy' (Eds K. I. Kellermann and B. Sheets), p. 171 (NRAO: Charlottesville).
Shimmins, A. J., Searle, L., Andrew, B. H., and Brandie, G. W. (1968). *Astrophys. Lett.* **1**, 167.
Shklovskii, I. S. (1952). *Astron. Zh.* **29**, 418.
Shklovskii, I. S. (1964). *Soviet Astron. AJ* **7**, 748.
Shklovsky, J. (1965). *Nature* **206**, 176.
Sholomitskii, G. (1965). *Astron. Zh.* **42**, 673 (*Soviet Astron. AJ* **9**, 516).
Singal, A. K. (1993*a*). *Mon. Not. R. Astron. Soc.* **262**, L27.
Singal, A. K. (1993*b*). *Mon. Not. R. Astron. Soc.* **263**, 139.
Slysh, V. I. (1963). *Nature* **199**, 682.
Strittmatter, P. A., Hill, P., Pauliny-Toth, I. I. K., Steppe, H., and Witzel, A. (1980). *Astron. Astrophys.* **88**, L12.
Urry, C. M., and Padovani, P. (1991). *Astrophys. J.* **371**, 60.
Urry, C. M., Padovani, P., and Stickel, M. (1991). *Astrophys. J.* **382**, 501.
van der Laan, H. (1971). *In* 'Les Noyaux of Galaxies' (Ed. D. O'Connell), p. 245 (Pontificia Academia Scientiarvm).
Wade, C. M., Hjellming, R. M., Kellermann, K. I., and Wardle, J. F. C. (1971). *Astrophys. J.* **170**, L11.
Williams, P. J. S. (1963). *Nature* **200**, 56.
Woltjer, L. (1966). *Astrophys. J.* **146**, 597.
Zensus, J. A., and Pearson, T. J. (Eds) (1987). 'Superluminal Radio Sources' (Cambridge University Press).

Manuscript received 17 February, accepted 28 July 1994