

Radio Galaxy Physics at Low Frequencies: Lobes, Jets and Environments

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Abstract. I discuss the key role of low-frequency observations in determining the physical properties of radio galaxies and radio-loud quasars, and their application in studies of the interaction between radio sources and their environments. Both observations with the current generation of radio telescopes and the prospects for future work are discussed.

1. Why Work at Low Frequency?

1.1. Introduction

Radio-loud active galaxies (including radio galaxies and radio-loud quasars) are characterized by twin, oppositely-directed jets which emanate from the core at relativistic speeds and contain, at a minimum, electrons (and/or positrons) and magnetic fields. The interaction of these jets with the interstellar/intergalactic medium on kpc-Mpc scales gives rise to the radio structures that we see on scales ranging from arcsec to (in the most extreme cases) tens of degrees. Given the focus of this meeting on radio astronomy with resolutions from a few arcseconds to a few arcminutes, the present review concentrates exclusively on these large-scale structures, the ‘lobes’ and ‘plumes’ generated by the jets.

Entire review articles could be (and have been) devoted to the morphological classification of radio-galaxy structures and its implications for the underlying physics (see e.g. Laing 1993). Here it is simply necessary to remind the reader of the best-known morphological distinction, that of Fanaroff & Riley (1974). They classified resolved sources seen at low resolution as being class I if they were centre-brightened and class II if they were edge-brightened, and noted that there was a reasonably sharp division in radio luminosity between the two, at a luminosity of approximately $5 \times 10^{24} \text{ W Hz}^{-1} \text{ sr}^{-1}$ at 178 MHz (using a modern cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$), with the class II (hereafter FRII) sources being more luminous. The crucial difference between the classes appears to be that in the FRI sources the jets take on a broad, bright, high-opening-angle appearance within a few kpc of the core, accounting for the centre-brightened appearance of FRIs on low-resolution images, while in FRIIs the jets seem to transport energy efficiently to the ends of the lobes (typically on 100-kpc scales) where they terminate in shocks which are thought to give rise to the observed radio hotspots and thus to the low-resolution edge-brightening of these sources. The strong relationship between Fanaroff-Riley class and luminosity (which should correlate reasonably well with the intrinsic kinetic power of the jet), and the somewhat less obvious relationship with host galaxy magnitude (e.g. Ledlow & Owen 1996) can be explained in terms of a model in which FRI jets are decelerated to trans-sonic speeds by entrainment of external material, while FRII jets are powerful enough

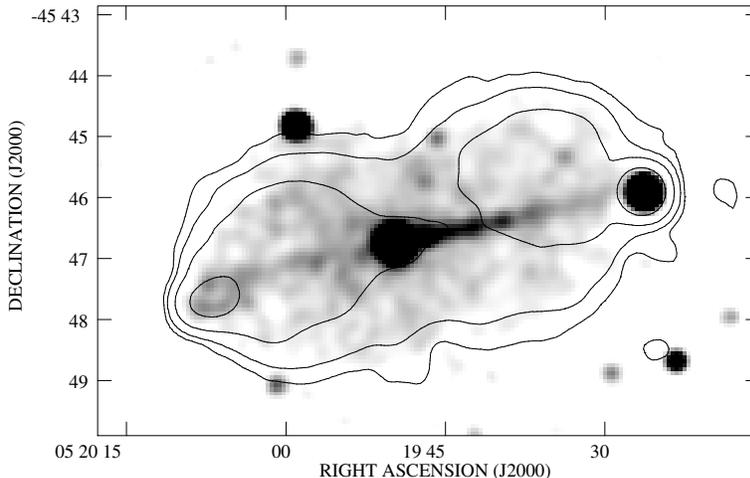


Figure 1. Synchrotron and inverse-Compton emission from the radio galaxy Pictor A. Greyscale shows X-ray emission as seen by *Chandra*, including X-ray emission from the AGN itself and some background sources, X-ray synchrotron emission from the jet(s?) and hotspots, and X-ray inverse-Compton scattering of the CMB from the lobes, all smoothed with a Gaussian of FWHM 16 arcsec. The *Chandra* data are those presented by Hardcastle & Croston (2005). Contours are from a VLA 330-MHz image with 30-arcsec resolution from Perley, Röser & Meisenheimer (1997), kindly provided by Rick Perley.

to escape the densest regions of the galaxy without much deceleration (e.g. Bicknell 1995). In what follows I will use ‘FRI’ and ‘FRII’ as shorthand for low- and high-luminosity sources respectively without worrying about the detailed classification of individual objects.

There are two key emission processes that allow us to investigate the physics of large-scale radio structures (Figure 1). The better-known of these is of course synchrotron emission, which implies the presence of relativistic electrons and magnetic fields. An electron with Lorentz factor γ in a field of strength B emits at and around a characteristic frequency given by

$$\nu = \frac{3}{4\pi} \gamma^2 \frac{eB}{m_e}$$

(Longair 1994) where e is the charge on the electron (SI units are used here and throughout). For magnetic fields of the order 1–10 nT (plausible in lobes from equipartition arguments), it follows that electrons with γ of a few times 10^3 dominate the synchrotron radiation that we see at GHz frequencies. Synchrotron emission is seen at all wavebands from low-frequency radio through to X-ray.

The second important mechanism is inverse-Compton scattering of a background photon population. In general the most important photon background, because it has the highest energy density, is the cosmic microwave background (CMB). However, in some circumstances, other photon fields, such as the synchrotron photon population (SSC: e.g. Harris, Carilli, & Perley 1994), the optical/IR AGN emission (e.g. Brunetti, Setti, & Comastri 1997), or the extragalactic background light (e.g. Georganopoulos

et al., 2008) may be important. In inverse-Compton scattering the frequency gain of the scattered photon is of order γ^2 (e.g. Rybicki & Lightman 1979) and so for the $z = 0$ CMB, with $kT = 2.7$ K, $\gamma \sim 10^3$ electrons are required to scatter photons into the X-ray regime (~ 1 keV). Although inverse-Compton emission from the large-scale components of radio-loud AGN has mostly been studied in the X-ray (e.g. Kataoka & Stawarz 2005, Croston et al., 2005) it is of interest in the optical through to gamma-ray energy bands.

It is well known (see e.g. Longair 1994 for a derivation) that a power-law distribution of electrons gives rise to a power-law synchrotron spectrum: this comes about essentially because the synchrotron emission from a single electron is a smooth but relatively sharply peaked function of observing frequency. If $N(E) \propto E^{-p}$, then $S(\nu) \propto \nu^{-\alpha}$, where $\alpha = (p - 1)/2$. Clearly if radio galaxy electron energy spectra had power-law forms, we might think that there would be relatively little point in working at low frequencies, since we would get the same information at higher frequencies where the data analysis is easier. As I will show in the following sections, however, low-frequency data has several important roles.

1.2. Inverse-Compton

Observations of inverse-Compton emission from components of radio-loud AGN in principle allow us to determine the magnetic field strength in those components — the energy loss rate in synchrotron emission depends on the energy density in the magnetic field, the loss rate in inverse-Compton depends on the energy density in photons, both scale in the same way with the number density of electrons, and so if we can observe both processes and know the photon energy density we can essentially derive the magnetic field strength from the ratio of synchrotron and inverse-Compton fluxes (e.g. Harris & Grindlay 1979). Once we have the magnetic field strength, we can also derive the electron number density, the total internal energy density, the internal pressure and many other important dynamical quantities (e.g. Hardcastle et al., 2002). In practice, however, both the synchrotron and inverse-Compton spectra extend over many decades of frequency and we observe only a narrow part of the spectrum. Determining the spectral emissivity from both synchrotron and inverse-Compton processes thus involves integrating over the electron energy distribution to calculate a flux density at a particular frequency/energy (e.g. Hardcastle, Birkinshaw, & Worrall 1998). However, as stated above, the inverse-Compton scattering of CMB photons (the most important channel for the inverse-Compton emissivity of the large-scale lobes of radio galaxies) into the well-studied X-ray band is done by electrons with $\gamma = 10^3$, which radiate in synchrotron at frequencies of tens of MHz in typical sub-nT lobe magnetic fields. Inference of the magnetic field strength in lobes therefore requires us to extrapolate the electron energy spectrum from the electrons that we can see (typically with $\gamma \sim 10^4$) to the electrons that we cannot. Radio observations at the lowest available frequencies are crucial to allow this extrapolation to be made with any confidence, and so we very often compare 1-keV X-ray emission to, say, 330-MHz radio data (Hardcastle & Croston 2005; Goodger et al., 2008).

1.3. Low-Energy Cutoff

The assumption of a power-law spectrum for the synchrotron-radiating electrons clearly breaks down if the synchrotron frequencies of the minimum or maximum electron Lorentz factors lie in the observable waveband. For an observable low-energy cutoff

we require $\gamma_{\min} \gg 1$. Below frequencies corresponding to this energy we will see a transition to the inverted ($S(\nu) \propto \nu^{1/3}$) spectrum of the low-frequency tail of the single-electron spectrum — the details of this transition will depend on whether there is a true cutoff or simply a deviation from a power law. Our best hope of seeing this is at low frequencies and in regions where the magnetic field is relatively high, in particular the hot spots of FR II radio sources. A spectral turnover at low frequencies has indeed been seen in a few sources (3CR405, Carilli et al., 1991, Lazio et al., 2006; 3CR123, Hardcastle, Birkinshaw, & Worrall 2001; PKS 1421–490, Godfrey et al., 2009), where typical values of γ_{\min} are found to be of the order 500–1000. Optical synchrotron self-Compton emission traces electrons of similar energies and has been used to constrain the low-energy cutoff (e.g. Hardcastle 2001, Brunetti 2002) but observations of low-frequency synchrotron emission are crucial in all cases to establish whether a low-energy cutoff is genuinely present.

It should be noted that there are alternative interpretations of the low-frequency turnover in hotspots (see e.g. Stawarz et al., 2007) and more observations are needed; in particular, it is difficult to separate the spectrum of the hotspots from that of the surrounding material, and so higher resolutions at lower frequencies will be crucial in establishing the nature of turnovers in the hotspots of more typical radio sources.

1.4. Spectral Ageing

By far the most common use of multi-frequency radio observations of radio-loud AGN is to carry out ‘spectral ageing’ analysis. At a basic level there is a clear physical motivation for this kind of work: since the loss rate of electrons to both synchrotron and inverse-Compton processes, dE/dt , goes as γ^2 , and hence E^2 , the characteristic loss timescale, $E/(dE/dt)$, goes as $1/E$ or $1/\gamma$: higher-energy electrons lose energy faster than lower-energy ones. An initially power-law electron energy spectrum will deviate from a power law at lower and lower energies as time goes on: therefore we expect to see steeper synchrotron spectra at higher frequencies. For the simple case of a single population of electrons with an initially power-law energy spectrum, we can solve the diffusion-loss equation for the electron population to obtain two well-known solutions which differ only in the assumptions made about pitch-angle scattering: the Kardashev-Pacholczyk solution (KP: Pacholczyk 1970) which assumes no pitch angle scattering, and the Jaffe-Perola solution (JP: Jaffe & Perola 1973) in which pitch-angle scattering is effective. It is then simple to calculate the expected synchrotron emission from the electron population and fit to observations. In this sort of work low-frequency observations are crucial since they constrain the energy index of the initial power law, if the frequency of the observations lies well below the frequency corresponding to the characteristic energy of the aged electron spectrum.

The motivation for using these spectral ageing results is that, at least in some objects, there seems to be some correlation between regions of the source that we expect to be older (regions of the lobes distant from the hotspot in the case of FR IIs: regions of the plumes or lobes distant from the jet in the case of FR Is) and estimates of spectral age; for example, the work of Alexander & Leahy (1987), showing a roughly linear correlation between age and distance along FR II lobes, has parallels in work presented at this meeting, and this agreement seems to persist to high frequencies (Hardcastle & Looney 2008). But there are many very serious problems with the naive application of spectral ageing calculations to physical conditions in radio sources. These can conve-

niently be divided into problems with the principles and problems with the application of the technique.

Principles. The basic assumptions of the models commonly used are that there is a single ‘injection index’ that is constant over time; that the electrons evolve in a magnetic field which is (a) known, (b) constant with time and (c) normally taken to be the same as the field that they are currently in; that there is no *in situ* reacceleration; and that the particle population suffers no losses other than radiative ones. Apart from the first of these, it is fair to say that every single assumption here is *known* either observationally or from first principles to be incorrect.

The magnetic field strengths are *not* known, except in the few cases where inverse-Compton field strength estimates can be made (and even then we are making a spatially averaged, emission-weighted measurement). So far we have no inverse-Compton field strength estimates for FRI sources or (apart from uninteresting limits) for any cluster-centre object. Field strengths are certainly not constant integrated over the history of the electron, since the fields in hotspots are likely to be stronger than those in lobes (again borne out by inverse-Compton estimates) and since adiabatic expansion from hotspot or jet to lobe or plume will certainly change the field strength even in the absence of microphysical mechanisms to enforce near-equipartition fields. Thus, rather than considering a single field strength for losses, the quantity of interest is something more like the time integral of the magnetic field and photon energy densities, $\int (U_{\text{ph}} + B^2/2\mu_0) dt$ (and for the inner jets of FRIs and the large-scale structures of all classes of objects the inverse-Compton losses to various photon fields cannot be neglected). In lobes the field is probably spatially inhomogeneous on large scales (see the inverse-Compton mapping results of Hardcastle & Croston 2005) and on small scales (evidence for this comes from the strongly filamentary emission structure in high-resolution maps of radio galaxies). This has the consequence that the field strength that a particular radiating particle sees now, even if we have some reason to believe that we know what it is, may *not* be representative either of the effective field that it has experienced over its history or of the field strength seen by particles as a whole. The implications of this type of magnetic field structure for spectral ageing models have been explored by, e.g., Tribble (1993), Eilek et al., (1997) and Kaiser (2005), but have generally been ignored by observers. In fact, variations in magnetic field strength alone, in the presence of a pre-existing curved electron energy spectrum, have been shown to be capable of accounting for the apparent spectral ageing in Cygnus A without any spatial variation in the electron spectrum (e.g. Katz-Stone, Rudnick, & Anderson 1993) though the additional constraints provided by inverse-Compton field measurements are important here (Hardcastle & Croston 2005).

X-ray synchrotron emission provides evidence for very large-scale distributed particle acceleration in the jets of some FRI sources (e.g. Evans et al., 2005), and we certainly cannot rule it out in the lobes of FRIIs, particularly in diffuse ‘secondary hotspot’ structures (e.g. Hardcastle et al., 2007a). And finally, adiabatic expansion shifts the energies of all particles down and thus mimics ageing — this fact was recognised by Alexander & Leahy (1987) but has often been ignored since then. Even the idea of a constant injection index seems not to have much justification in the hotspots of FRIIs (but see Young et al., 2005 for the case of FRI jets). Given these numerous problems, even the proponents of spectral ageing analysis generally agree that there are large systematic uncertainties in the derived numbers; pessimists suggest that any agreement between spectral ages and dynamically derived ages is coincidental (e.g. Rudnick 2002).

Practice. In spectral ageing analyses presented at this meeting we have seen the choice of KP or JP spectra being made on the basis of which fitted the data better (though clearly, if either one of these is correct, the microphysical processes that determine which of the two it is are common to all sources); uniform, equipartition fields have been assumed without justification; injection indices have been assumed on a theoretical basis rather than measured; and ages have been estimated from spectra of physically large regions of an object (in extreme cases, from the *integrated* spectrum), although, even if every other assumption underlying the spectral ageing method were correct, it would still not be the case that the sum of many aged spectra would give any useful way of estimating a characteristic age. I say this not to criticise any participant — in fact I have done all of these things myself — but to emphasise that we have a duty to recognise the very severe limitations of what we are doing when we use these techniques, and to draw attention to the large systematic errors associated with any age measurement derived from them, which in extreme cases may lead us to obtain and quote in the literature completely meaningless numbers.

1.5. Doppler Boosting and Source Selection

Relativistic motions in components of radio-loud AGN (parsec-scale jet, kiloparsec-scale jet and possibly hotspots) in general give rise to bias in radio-selected samples: all other things being equal, a source oriented closer to the line of sight is more likely to be found above the flux limit. The effects of Doppler boosting are mitigated (though not completely removed) by selection at low frequencies, since the beamed components have flat spectra, while the unbeamed lobes or large-scale plumes/jets have steep spectra and so come to dominate the emission at low frequencies. Historically many important samples were selected at low frequencies simply because it was easier to survey large areas at these frequencies. However, bias is a problem at the GHz frequencies of, e.g., the NVSS or FIRST. Low-frequency followup will be an important component of the many sky surveys at other frequencies expected in coming years.

2. Environments and Low-Frequency Radio Emission

Other participants in the meeting discussed the role of low-frequency radio astronomy in the study of groups and clusters of galaxies. Here I will concentrate more on its value for studying the interactions of known radio sources with their environment.

Low-frequency studies have been key to many striking results on the large-scale structure of well-known radio sources like M87 (Owen, Eilek, & Kassim 2000) or Hydra A (Lane et al., 2004). We need to know what the large-scale structure *is* before we can start understanding what it tells us about environmental interactions. As a cautionary note, it is worth bearing in mind that low frequencies are *mainly* being used here to provide the short baselines needed to probe structure on large angular scales. Although the spectra of extended components of radio galaxies are steep, radio telescopes are more sensitive at high frequencies. It is not always the case that lower frequencies are better for studies of these sources — unless the required short baselines cannot be obtained in any other way.

That said, there clearly are cases where the spectra of components are steep enough that low-frequency observations — even when the shortest baselines are matched — win out over L-band and higher. The large-scale structure of tailed radio sources provides an example (see e.g. Eilek & Owen 2002; Sakelliou et al., 2008; Figure 2). Gen-

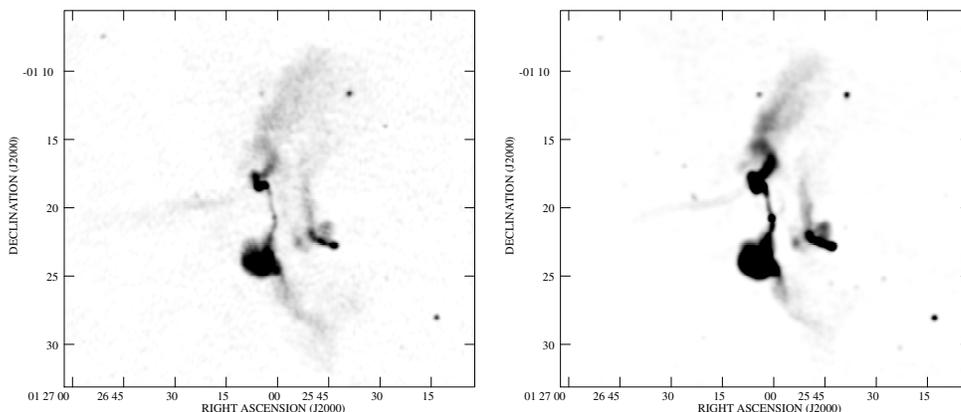


Figure 2. The radio galaxies 3CR040A and 3CR040B in the cluster Abell 0194 (Sakelliou, Hardcastle, & Jetha 2008). The two panels show VLA data at 330 MHz (left) and 1.5 GHz (right), in both cases with adequate sampling of the short baselines. Although the 1.5-GHz data have better image fidelity and noise properties, the 330-MHz data clearly give a better view of extended steep-spectrum structure in the plumes. The greylevels are chosen such that material with a spectral index $\alpha = 1$ should appear at the same greylevel on both maps.

erally it is the plumed/tailed FRIs, rather than the FRIIs, where low-frequency observations are crucial to find out what is going on at the boundaries of the source, since the boundaries of FRIIs are usually well-localized (except in the case of double-double sources). The dynamics of the large-scale structure of FRIs and their interaction with the external medium are much more poorly understood than in FRIIs, and the situation is exacerbated by the fact that we have yet to obtain an inverse-Compton measurement of the magnetic field strength in any FRI source. Typically we find (see e.g. Worrall & Birkinshaw 2000; Hardcastle et al., 2007b and references therein; see Dunn, Fabian & Taylor 2005 for a discussion of the situation in clusters) that the *minimum* pressures in the lobes or plumes lie considerably below the external thermal pressures derived from X-ray observations. Low-frequency radio data are crucial here to avoid serious bias in the estimates of internal pressure as a function of position introduced by the positional differences in radio spectral index. Recently, combining low-frequency radio and X-ray observations, we have shown that it is plausible that the ‘missing’ pressure in the radio galaxies may be provided by entrained, efficiently heated thermal material (Croston et al., 2008b). The nature of this missing pressure is one of the major unsolved problems in the astrophysics of low-power radio galaxies (numerically and energetically the dominant population in the universe) and a combination of low-frequency radio data and high-energy observations will be needed to make progress.

The discovery that comparatively low-luminosity radio-loud AGN like Cen A (Kraft et al., 2003) can drive strong shocks into the external medium has sparked interest in the episodic outbursts of FRI-luminosity radio sources; intermittent outbursts are likely to be much more efficient at heating and increasing the entropy of the rapidly cooling central hot gas. Several other low-power but young sources have been discovered (via X-ray observations) to be plausibly driving strong shocks into their kpc-scale environments, including NGC 3801 (Croston, Kraft, & Hardcastle 2007), NGC 6764 (Croston et al., 2008a) and B2 0838+32A (Jetha et al., 2008). The last-

mentioned of these sources is particularly interesting because, like Cen A, it has large-scale, steep-spectrum lobes that appear to be disconnected from the current outburst. Low-frequency observations in principle allow us to select such sources efficiently, with implications for the study of the duty cycle and fuelling mechanisms of radio-loud AGN.

3. The Future

LOFAR and the LWA (and to a lesser extent the new generation of facilities working at higher frequencies, such as e-MERLIN, the EVLA, and ALMA) will substantially change the way in which we study radio-loud AGN. The new generation of low-frequency radio telescopes will see a large fraction of the sky at any one time and the images they produce, particularly at the bright end, will be dominated by AGN emission; bright 3CR sources, which have been the staple of single-object radio galaxy work since the 1970s, will have to be imaged and modelled over a large area of the sky for any given pointing simply in order to achieve the instruments' target sensitivity and dynamic range. We may find, therefore, that much of the low-frequency data we need is generated as a by-product of the sky surveys that will be carried out as a matter of course with these instruments; the challenge then becomes to make sure that these data are available for scientific work and is not lost as part of the data reduction process. If we can deal with the technical and organizational challenges, though, the rewards will be immense. Here I mention a few areas in which we can expect to make progress.

3.1. Lower Frequencies

If it turns out to be technically possible to work at frequencies of tens of MHz, this pushes the electron energy we are probing down by a crucial factor of a few — in particular, it means that we will see directly via synchrotron radiation the electrons that are producing keV photons in inverse-Compton, and will no longer have to rely on extrapolation of the electron population. However, high resolution will be particularly important here — in the case of LOFAR, the long baselines of the international stations will be needed, and it remains to be seen whether this can actually be done in practice. On the timescales of these instruments, we also expect to get some imaging capability in higher-energy X-rays (via missions like *Simbol-X*) which will allow us to see the inverse-Compton emission from electrons radiating at hundreds of MHz, so there will continue to be an important synergy between low-frequency radio and X-ray work.

3.2. Dynamic Range and Image Fidelity

All of us who have worked on low-frequency imaging know that problems of dynamic range and image fidelity are much worse at lower frequencies than they are at L-band and above. Partly this may arise from the worse RFI environment, partly from other factors, but it represents a real limitation on our ability to work on the physics of bright radio sources at low frequencies. The good news is that this problem *must* be solved if the next-generation instruments are to deliver their goal of wide-field, high-sensitivity imaging, since, as mentioned above, all fields will contain bright radio-loud AGN. Work on bright sources with complex structure should benefit as a result.

3.3. Multifrequency/Polarization

So far AGN studies at low frequencies have made relatively little use of polarization, although the strong intrinsic polarization of the large-scale structures of the sources makes them ideal backgrounds for Faraday rotation/depolarization studies. For a source in a group or cluster environment, the Faraday-active medium is the hot, X-ray emitting phase of the IGM; clearly we already know something about this, but in principle polarization studies at low frequencies can probe much lower particle densities than the current generation of X-ray telescopes. The key will be the availability of broad-band, high-resolution polarization data at multiple bands below 1 GHz. Although the environmental magnetic field is a complicating factor, combination with X-ray data should give us an extraordinarily sensitive probe of radio source environment interactions.

3.4. Large Samples

It is finally worth noting that the state of the art in detailed imaging studies (as opposed to simple integrated flux measurements) of large samples of radio sources gives us samples of ~ 100 objects, which may have taken years to decades to compile and for which the vital complementary data at other wavelengths are patchy, inhomogenous or in some cases missing altogether. The new radio instruments combined with the many new optical/IR sky surveys becoming available over the next few years should put us in a position where meaningful *statistical* studies of radio AGN physics, with samples at least an order of magnitude larger, should be possible.

4. Summary

The aim of this review has been to provide a sketch of the potential, as well as some of the limitations, of low-frequency studies of radio-loud AGN. I have argued that low frequencies have a vital role to play in our understanding of the physics of these sources and are very useful — though not always required — in studies of the interactions of large-scale components of radio sources with their environments. If we can effectively exploit the large investment in next-generation low-frequency radio telescopes, the future is very bright for radio galaxy studies.

Acknowledgments. I am grateful to collaborators too numerous to list here but particularly including Judith Croston, Dharam Vir Lal, Chiranjib Konar, Nazirah Jetha and Irini Sakelliou for their contributions to work discussed in this review. I thank the organizers of the conference for inviting me and the Royal Society for generous financial support provided through the Research Fellowships scheme.

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