LARGE SCALE EMISSION FROM RADIO GALAXIES

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Radio galaxies are known to exhibit a variety of scales in their structure. First we have the nuclear sources, which so far have not been completely resolved even on the scale of 1/10 milliarcsecond with VLBI observing methods (e.g. Preuss, 1981). Then we have the 'jets' (which at some stage break up into 'blobs') which are considered to transfer energy from the 'nuclear engine' to the outer heads. The latter appear to be the sites of transfer of the collimated jet energy into a diffuse emission region. Despite their usually low brightness these diffuse emission regions dominate the internal energy content in particles and fields, even for the collimated doubles. Note that only 1% of the total energy in Cyg A is in the hot spots (Perola, 1981).

The diffuse emission regions of the nearest radio galaxy, Cen A, subtend an angle of nearly 10° in the sky. There are a number of radio galaxies (e.g. 3C 236, NGC 6251, NGC 315) which subtend $\sim$ 1°. An unfilled aperture instrument with a pencil beam, like the Mills Cross at a lower radio frequency, or a single dish telescope at high frequencies are well suited to study the extended emission. Synthesis telescopes in a very compact array (e.g. the 150 MHz Cambridge array, 610 MHz Westerbork system or 1420 MHz D-configuration of the VLA) can also be used to study the diffuse emission. One limit on the largest size of the object that can be studied is given by the field of view of the individual synthesis array elements, since the combination of separate fields has turned out to be rather difficult in practice. Another precaution which must be taken, especially when frequency comparisons for the determination of the spectral index are made, is the inclusion of the missing spacing information. Synthesis maps made at two frequencies with the same array, without the restoration of all the missing spatial components, cannot be used for spectral index studies. For both the pencil beam instruments and synthesis arrays the dynamic range imposes a crucial limit for studies of extended emitting regions. Bearing all the instrumental problems in mind, which lead to considerable selection effects, we can turn to the discussion of the accumulated data on diffuse emission in radio galaxies.

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The steps in the accumulation of knowledge about radio galaxies are intimately connected with the increase of both angular resolution and sensitivity of radio telescopes. Cen A was the first object which could be studied (e.g. Sheridan, 1958) when the best angular resolution available was $\sim 1°$. The development of single dishes, like the Caltech 90-ft or Parkes 240-ft antennas, which operated at decimetre wavelengths giving resolutions of tens of arcminutes, resulted in the next step forward in the study of Cen A. The basic structure of a radio galaxy was then established: a nuclear source coincident with the EO galaxy NGC 5128, the guided emission from the nucleus, a suggestion of tumbling motion in the outer diffuse regions. In the work of Cooper et al. (1965) observations of Cen A made at numerous frequencies from 19.7 MHz up to 4.8 GHz were used to discuss the spectral characteristics. A polarisation study showed very high degrees of linear polarisation. Cen A is shown in Figure 1, observed at 408 MHz by Haslam et al. (1981) with the Parkes telescope. In this map we see the foreground galactic radiation and in particular the peculiar 'spur' which was noted by Bolton and Clark (1960). We now know that this is not a bridge connecting Centaurus A to our Galaxy but a rather peculiar coincidence.

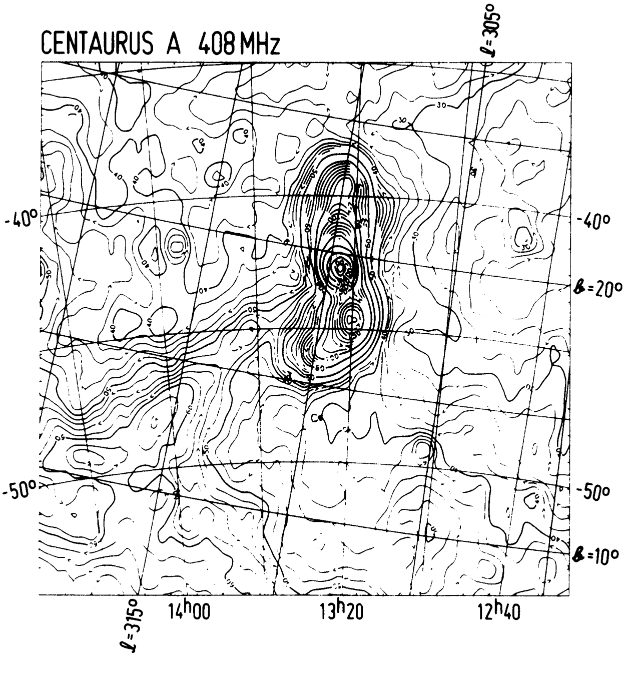

Figure 1:
A 408 MHz map of the Cen A region (from Haslam et al., 1981). (HPBW = 51')

The major advance of our knowledge was connected with the successful application of the synthesis technique to the mapping of radio galaxies. In a series of papers from Cambridge (e.g. Macdonald et al., 1968; Mackay, 1969) a large sample of extended sources from the 3C catalogue were mapped, revealing an astounding wealth of structural detail.

It must be noted here that the next steps of increasing angular resolution by the increase of baselines and frequencies resulted in a loss of capability of mapping large and diffuse emission regions. The Molonglo Cross could add new information on extended sources (e.g. Cameron, 1971; Schilizzi and McAdam, 1975). An important finder survey was the study of a complete sample of intense radio sources using the NRAO 300-ft telescope by Bridle et al. (1972). The Westerbork synthesis telescope made its impact in this field, particularly due to a considerable increase in the dynamic range, which resulted in the detailed study of numerous large radio galaxies (e.g. Miley and van der Laan, 1973; Miley, 1973; Willis et al., 1974). At the low frequency end of the spectrum the 150 MHz array in Cambridge (e.g. Waggett et al., 1977) and the 160 MHz Culgoora telescope (Slee, 1977) added necessary information. High frequency maps of radio galaxies have been made in Effelsberg (Baker et al., 1975; Hachenberg et al., 1976). In the southern sky only the Fleurs synthesis telescope (e.g. Christiansen et al., 1977) is available for mapping with < 1' resolution. Finally the VLA (e.g. Perley et al., 1979; Burns and Christiansen, 1980) has come on line to produce the beautiful maps of both the diffuse regions and the inner structures of numerous radio galaxies. All these efforts during the last two decades have shown that observations of each single radio galaxy at various angular resolutions were necessary to arrive at today's understanding of the structure of radio galaxies, which we will outline in the following paragraphs.

First it was the classical double sources (as example see Figure 2) with their strong outer heads aligned with the core source that instigated the twin-jet picture of their origin. In these sources one suspects lossless beams of relativistic plasma ejected along a line on both sides of the core which at a certain distance (a few hundred kpc) are randomized in a bow shock front. Magnetic field amplification due to compression of the plasma combined with particle acceleration via turbulent processes then leads to the enhanced emission of the hot spots. The diffuse tails extending back towards the nucleus can be viewed as the embers of former activity. This picture is confirmed by observation, since the heads are invariably observed with a flatter spectrum,

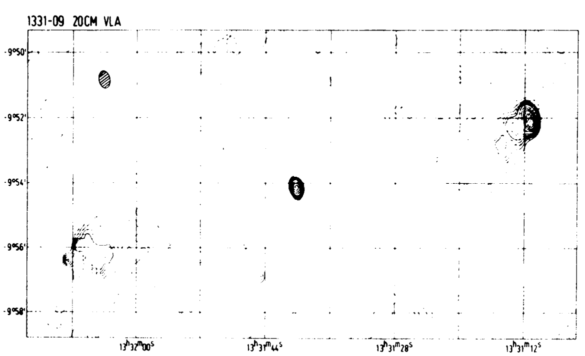

Figure 2:
A 1446 MHz VLA map of the large radio galaxy 1331-09. Contours are given at 4, 8, 12, 16, 20, 30, 50, 70, 90, 120 mJy/beam (HPBW = 22" x 13" in p.a. 13°). Polarisation bars show the E-vector and are proportional to polarised intensity. The overall extent is 1.7 Mpc (H_0 = 50 km s^{-1} Mpc^{-1}).
Courtesy of D.A. Graham.

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while there is a continuous spectral steepening along the extended ridges towards the nuclei (e.g. Högbom, 1979). Most of the polarisation observations give additional support to this view (Laing, 1981; Dreher, 1981). At the outer boundaries a net field orientation perpendicular to the ejection axes is often observed showing a high degree of disorder as well (i.e. low percentage polarisation), whereas in the diffuse inward extensions the fields are mostly found to be well ordered and aligned with the main emission ridge. Thus it seems as if an originally random field were compressed at the shock front and, in the fainter regions, continuously stretched by shear forces, caused by the flow of matter relative to a surrounding medium (Laing, 1980).

Apart from the classical doubles we have complex non-aligned sources, which do not exhibit hot spots, and which have lower radio luminosities. Brightness peaks occur near the cores, while streamers of emission often extend far beyond these maxima fading away continuously. High resolution observations with present synthesis telescopes nevertheless suggest a common origin of classical doubles and complex sources. In what follows we like to summarise the effects which are thought to determine the large scale appearance of radio galaxies (cf. Miley, 1980).

First we must remember the omnipresent projection effects (e.g. Reynolds, 1980). Then a number of kinematic effects may play a role. One of these effects is the *precession* of the ejection axis, which can be inferred from the rotational symmetry of the ridges extending from some of the hot spots in classical doubles (cf. Figure 2). The effect becomes more pronounced with increasing opening angle of the precession cone like in NGC 326 (Ekers et al., 1978) or 3C 315 (Högbom, 1979). The ridges of the radio emission are then thought to delineate the path traced out by the end of the jet in the past. There are also sources which show a *reflection symmetry* about an axis through the nucleus. Instead of precession one invokes here an encounter of the parent galaxy and a neighbouring galaxy, as Blandford and Icke (1978) illustrated for the case of 3C 31. Depending on the time scale of the encounter compared to that of the ejection of matter, there is again a continuous variety of morphologies with reflection symmetry, starting with HB 13 (Masson, 1979) or IC 708 (Vallée et al., 1981) in which probably a single encounter is observed. Other sources (e.g. 3C 449, Lupton and Gott, 1981; or 3C 40, Andernach, 1981) show evidence for the parent galaxy orbiting around a massive neighbour. While such a model gave reasonable fits to the first few bends of 3C 31 and 3C 449, the outer lobes usually deviate from the expected trajectories. This effect may be due to the most frequent factor shaping extragalactic radio sources — the *motion* of the parent galaxy *relative to an ambient medium*. Again there is a continuous sequence of deviation from collinearity of the two-sided ejecta that starts with the wide-angle tails and ends with the comet-like head-tail radio galaxies. The preferred occurrence of these sources in rich clusters of galaxies is in fact independent evidence for the existence of a hot dense intracluster medium (ICM). This medium is also believed to confine the extended and less dense blobs of relativistic plasma via its static thermal pressure and thus prevent

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these plasmons from diffusion at the relativistic sound speed of $c/\sqrt{3}$.

Less evident possibilities affecting cluster source morphology are either *buoyant* bubbles of plasma rising against the density gradient of a denser ambient medium or, vice versa, heavy bubbles falling in a gravitational field through a less dense medium. Some of the distortions in radio structure could also arise from a *large scale shear* in some intergalactic winds, for which we do not have as yet any other evidence.

Finally we must mention the *core-halo sources* which at first glance do not fit into the outlined scenario. The number of halo sources known today is much less than previously claimed (e.g. Sramek, 1970; Fomalont, 1971), since most of them have been reclassified. When seen at higher resolution, the halo-like extensions either resolve into classical doubles (3C 103, 3C 105, 3C 236) or wide-angle tails (3C 40) or head-tails (3C 264, 2247+11). We are essentially left with the two famous halo sources Per A (Gisler and Miley, 1979; Reich et al., 1980) and Vir A (Andernach et al., 1979; Kotanyi, 1980). Since the mapping of just these halos is largely limited by dynamic range problems due to their strong cores, we might argue that either too little structural detail is as yet seen, or that due to projection we simply see the emission of one of their extended lobes in front of the core. High resolution observations of Vir A and Per A show them to have the same twin-jet origin as the aligned double sources.

With this picture of morphological origin of the sources we still have to explain what makes the particles radiate over Mpc scales. From synchrotron theory we expect the spectrum to steepen with increasing distance from the sites of particle injection (either nuclei or hot spots). This is only in qualitative agreement with most of the two-frequency spectral index maps produced so far. In most cases the observed spectral steepening is less than expected from synchrotron aging calculations, i.e. the bare existence of high frequency emission far away from nuclei or hot spots implies that in situ particle acceleration must take place over large parts of the extended lobes.

Theory predicts a spectral break at a frequency that depends on magnetic field, particle age and rate of injection of fresh particles. Investigations of the spectral behaviour across the sources on the basis of maps at various frequencies have only recently localized source regions with such a spectral break (Winter et al., 1980; Andernach, 1981). In the complex sources these regions are the faint outer streamers, as e.g. in the case of the wide-angle tailed radio galaxy 3C 465 (Figure 3). The spectral distributions (Figure 3c) show a steepening of $\Delta\alpha \sim 1.3 \pm 0.6$ between 0.6 and 10 GHz to occur in the components A, F, G and H. From the equipartition field strength and the break frequency we may derive an age of the emitting particle ensemble. Again this age, together with the projected core distance, gives a lower limit to the mean transfer speed of particles in the plasmon. Here and in many other cases this speed is found to be highly super-Alfvénic, which implies that particle diffusion cannot be the mechanism of energy

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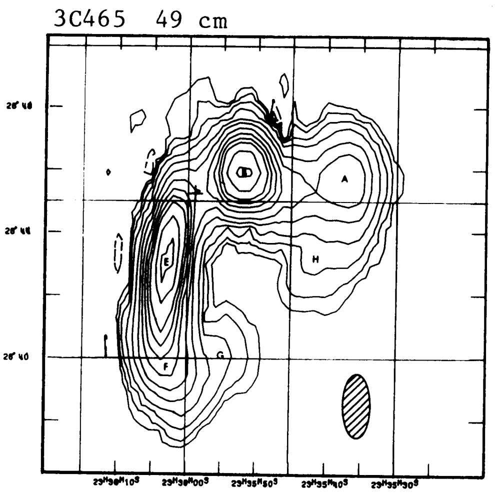
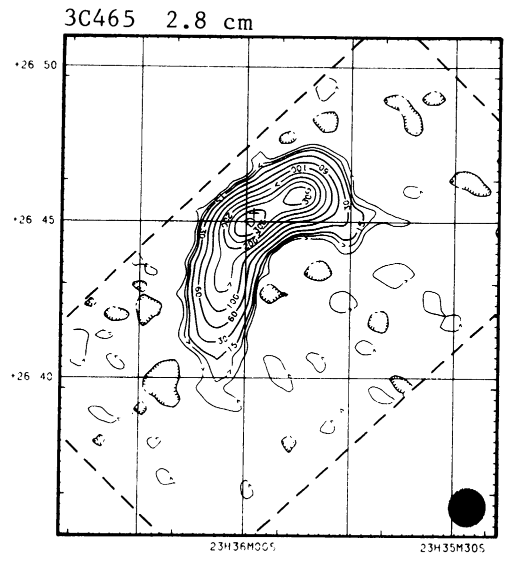
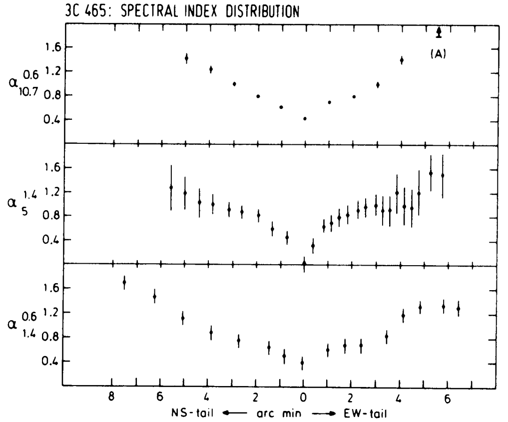


(a)



(b)



(c)

Figure 3: *(a)* 3C 465 as seen with the WSRT at 610 MHz (van Breugel, 1980); *(b)* 3C 465 as seen with the 100-m telescope at 10.7 GHz. Contours are at -5 (ticked), +5, 10, 15, 30 ... mJy per beam area (= hatched circle). The cross marks NGC 7720. *(c)* Spectral index distributions along the ridge line of the source defined in van Breugel (1980). The top figure results from a convolution of the 0.6 and 10.7 GHz data to 1!2 x 2' resolution, while the figures below are from van Breugel (1980) with a resolution of 23" x 51" and 0!9 x 2' (bottom).

transfer. The time scale derived from the spectral break must then be viewed as the time elapsed since injection of fresh particles has ceased in these components. If particle reacceleration is triggered by the plasmon's motion through the ambient medium, then the derived age may also be the time since ram pressure has stopped their motion. We see that even the existence of a spectral break in a source component does not imply the absence of particle injection throughout the source.

Finally we stress the need for in situ particle acceleration in the extended lobes of the so-called *relaxed doubles* like 3C 219 (Perley et al., 1980) or 3C 388 (Burns and Christianson, 1980). Here the older particles had time to diffuse out of the beams and hot spots to form extended envelopes around them, which do not seem to interact with the ICM. Recently Strom et al. (1981) have carried out a careful spectral index comparison across DA 240 using a 610 MHz Westerbork map and a 5 GHz Effelsberg map. They argue that neither departure from equipartition nor super-Alfvénic diffusion from the hot spots is likely to explain the lack of sufficient spectral steepening in the extended envelopes surrounding the hot spots. Stimulated by the fine scale structure observed in the lobes of the relaxed doubles 3C 310 and 3C 326 Smith and Norman (1980) have proposed a model in which shock waves are generated by supersonically moving knots accelerate particles. At higher resolution the extended lobes of DA 240 (Strom and Willis, 1981) also exhibit fine scale structure suggesting the plasmons to be in a turbulent state. Today we have more and more evidence for such fine structure from VLA maps of extended lobes (compare e.g. the maps of Cen A by Christiansen et al. (1977) and Schreier et al. (1981)). We may well ask whether in these lobes we start to resolve the shock waves proposed by the models. Thus with further multifrequency VLA observations of at least the brighter lobes of relaxed doubles there seems to be hope that the working mechanism for reacceleration can be tied down in the near future.

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