PROFILE OF A KEY PROGRAMME

A Study of the Most Distant Radio Galaxies

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Background

Galaxies associated with powerful radio sources are amongst the most frequently used cosmological probes, because their enormous radio luminosities enable them to be easily pinpointed out to large distances. During the last thirty years, several groups, notably Hyron Spinrad and his collaborators at Berkeley, have carried out remarkably successful studies using the 3C sample to locate galaxies at high redshifts. These galaxies have been used as standard candles to study both the geometry of the universe and the evolution of stellar populations in galaxies.

Until about two years ago, most of this work was concentrated on objects from the 3C Catalogue, i.e. the strongest known radio sources in the northern sky. Optical identification of this sample is now virtually complete. To extend searches for high-redshift galaxies to a larger number of fainter (and perhaps) more distant radio sources than those in 3C, it is desirable to develop techniques for separating the most promising high-redshift candidates from the tens of thousands of catalogued weaker radio sources. We have developed a method of preselecting these few high-z "needles" from the huge "haystack" of all radio sources. This search method is the basis of our ESO Key Programme.

The technique is based on groundwork laid with the Westerbork radio telescope during the mid-seventies (Tielens, Miley and Willis 1979; Blumenthal and Miley 1979). We use the fact that ultra-steep spectrum radio sources are systematically more luminous than sources having more normal radio spectra. Back in 1960, Dave Heeschen pointed out that a weak correlation existed between the radio spectra and luminosities or redshifts of radio sources. It was found that this correlation was more striking when the fractional identification of radio sources on the sky survey was plotted as a function of radio spectral index (Fig. 1). Reasonable statistics for the steepest spectrum objects (left hand side of the plot) were obtained by measuring radio structures and positions for about fifty 4C sources, selected to be the steepest spectrum ten percentile from the 4C catalogue. Almost all of these extreme objects corresponded to blank fields on the Palomar Sky Survey, in marked contrast to the 40% identification fraction found for sources with "normal" steep radio spectra. It seemed likely that the bulk of the ultra-steep spectrum radio sources were associated with galaxies beyond the plate limits of the Survey at distances which were inaccessible with optical techniques then available.

Two years ago, study of this sample was resumed, stimulated by the revolution in detector technology that had occurred over the preceding decade. It was clear that the leaps in sensitivity in the optical (CCDs), radio (VLA) and infrared (new arrays) regions of the spectrum warranted further work on the ultrasteep spectrum 4C radio sources. The renewed attack commenced while the PI was seconded by the European Space Agency to the Space Telescope Science Institute in Baltimore and therefore was carried out primarily with U.S. telescopes. The project consisted of optical infrared and radio imaging as well as optical spectroscopy; it forms the basis of Ken Chambers' Ph.D. thesis. So far, the most important results are:

(a) Demonstration of the ultra-steep spectrum selection criterion as the most efficient method so far developed for pinpointing galaxies at high redshift. The spectroscopic survey has shown that about half the sample have emission lines and are definitely at redshifts larger than about 0.6. Eight objects in the sample are confirmed identifications with optically extended objects having more than one emission line at $z > 2$, with two galaxies at $z \sim 3.8$ (see Chambers et al. 1988a, 1989 and figures). For comparison, the largest galaxy redshift known one year ago was $z = 1.8$ for 3C 326.1 (McCarthy et al. 1987a).

(b) Establishment of the existence of a population of galaxies at epochs corresponding to $z > 3$, i.e. when the universe was less than 10% of its present age. This opens up an exciting opportunity for studying the properties of the early universe. For the first time we can measure the spatial distribution of brightness and velocity for gas in objects out to at least a redshift of 4, providing unique information about young and forming galaxies. In addition, statistics of the space density of these objects and its redshift dependence is capable of providing considerable leverage on the geometry and evolution of the universe.

(c) Discovery that powerful high-redshift radio galaxies have optical and infrared extensions which are almost exclusively aligned along the axes of their associated radio sources (Chambers et al. 1987). The optical/radio alignment effect was seen independently in a sample of high-redshift 3C radio galaxies by McCarthy et al. 1987b. In exhibiting this alignment effect, powerful high-redshift radio galaxies are unexpectedly different from radio galaxies at low redshifts. This has considerable implications for work which uses powerful radio galaxies as "standard candles" to probe the geometry of the universe.

There is not yet an accepted mechanism for producing the aligned optical/infrared flux. Some powerful constraints are provided by 2.2 micron array observations of 3C368 which suggest that the emission is produced mainly by young stars formed by an interaction of the radio jet with the interstellar medium (Chambers et al. 1988b). However, it is difficult to understand how the necessary $10^9 M_\odot$ of stars could be formed in such a process.

The success of our search technique and the importance of distant radio galaxies in their own right and as probes of the early universe prompted us to propose a project under the ESO Key programme initiative. The direct objectives of this project are twofold. First we wish to extend the work described above to fainter radio sources and more distant galaxies, thereby increasing the number of identified ultra-high-redshift galaxies by about an order of magnitude. Secondly and more importantly, we shall study the detailed properties of the early-epoch radio galaxies that we detect.

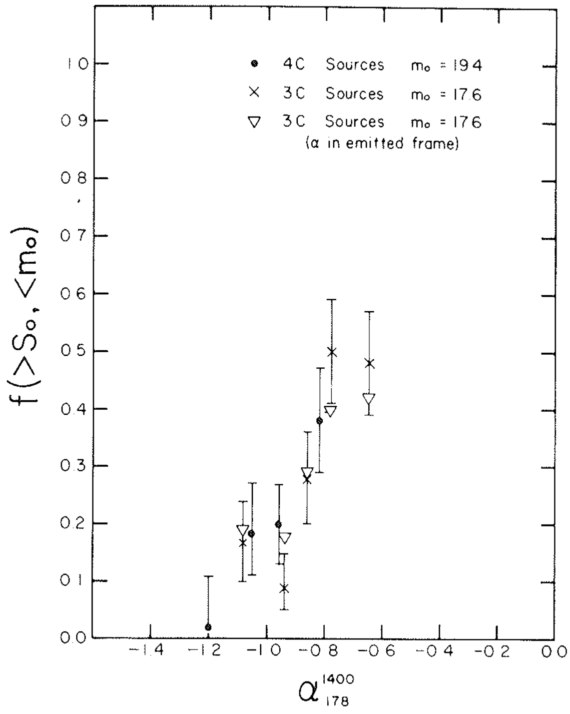

Figure 1: *The fraction of radio sources optically identified on the Palomar Sky Survey plotted against the observed metre-wave radio spectral index (from Blumenthal and Miley, 1979).*

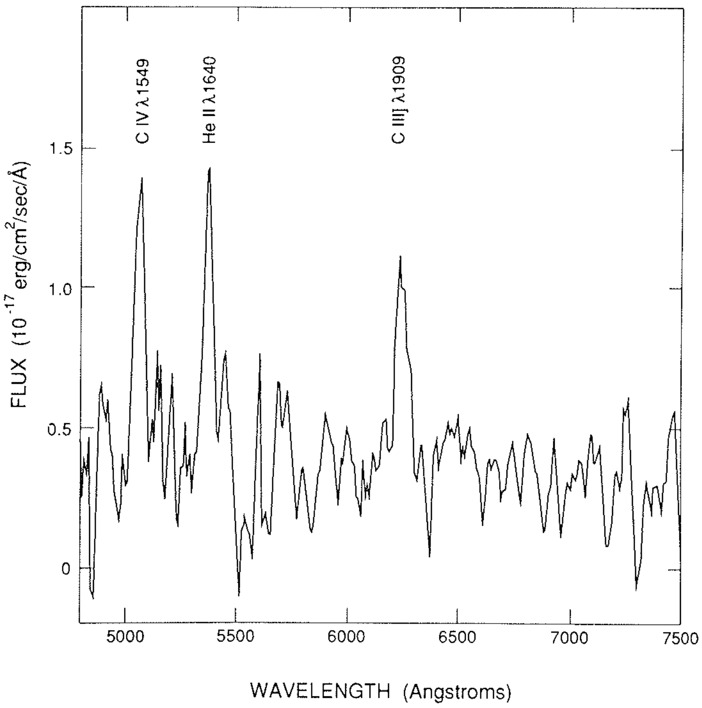

Figure 2: *The spectrum of the radio galaxy 4C 40.36 at a redshift of 2.3 (from Chambers, Miley and van Breugel 1988a).*

Finding More High-z Galaxies

The 4C sample covers less than a third of the sky and includes only the brightest radio sources. It is therefore desirable to apply our search technique to larger and fainter samples of radio sources. Both Lyman alpha emission and radio emission from 4C41.17 could easily be seen if it were at a redshift of 6, above which Lyman alpha would be shifted outside optically observable wavelengths.

To find more $z > 2$ galaxies, we have selected several samples of radio sources known to have definite or suspected ultra-steep radio spectra from the Parkes, Molonglo and Texas surveys. These comprise a total of about 400 objects. The strategy that is being followed in our search for high-z galaxies is the following:

(i) radio observations with the VLA, and Molonglo Synthesis Telescope (MOST) to find which of the suspected sources definitely have ultra-steep spectra and to provide radio structural and positional information which can be used for their optical identifications. Most of these observations have already been carried out and the radio maps have been made.

(ii) an optical and infrared imaging survey of confirmed ultra-steep spectrum objects with the 2.2 m telescope.

(iii) spectroscopic search for emission lines from the high redshift candidates with EFOSC2 on the NTT.

The Nature of the Most Distant Galaxies

Once the high-redshift galaxies have been located, there are several crucial observations which need to be made in order to study the properties and interrelationships of the stars, ionized gas and relativistic plasma in these objects.

So far, the only case for which follow-up work has been analysed is 4C41.17 (Chambers, Miley and van Breugel, 1989). The results are fascinating (see figures). The source was identified with a faint extended optical object whose spectrum showed two emission lines corresponding to Lyman alpha and CIV 1549 at a redshift of 3.8. The extended optical continuum emission (~30 kpc for H_0 = 50 km/s/Mpc and q_0 = 0.5), together with the large equivalent width of the Lyman alpha indicate that 4C41.17 is a galaxy. At z = 3.8 it is the most distant galaxy known. It has a Lyman alpha halo which is extremely bright and extends for more than 20″ (corresponding to more than 100 kpc!). The gas is clumpy and has a turbulent velocity field with a gradient of about 2000 km/s.

Using the new InSb arrays at UKIRT, we have mapped 4C41.17 and several other high-redshift galaxies at 2.2 microns (for 4C41.17 this corresponds closely to optical V-band in its emitted frame). Infrared measurements will be crucial to studying stellar populations in these objects as well as searching for the presence of dust. Moreover, Lilly and Longair (1984) have demonstrated that the infrared "Hubble diagram" for distant radio galaxies has a relatively small dispersion compared with similar plots based on optical data.

Our ESO Key Programme is one part of a multispectral project to investigate the ultrasteep spectrum radio sources and their counterparts in other regions of the spectrum. The following sorts of observations are being proposed or carried out to investigate the nature of the $z > 2$ galaxies: broad and narrow band optical and infrared imaging, low and high resolution optical and infrared slit spectroscopy, optical and infrared polarimetry, deep radio intensity and polarization imaging, VLBI, HI radio spectroscopy and X-ray imaging. Most of these have already obtained observing time allocations.

Questions to be Investigated

The proposed project will be part of a comprehensive multispectral study into the nature of distant radio galaxies. Among the several important questions about evolution and activity in galaxies and about the early universe which we hope to investigate are the following:

1. What is the space density, radio luminosity and radio size functions of high-powered radio galaxies at $z > 2$ and how do these distributions vary with redshift?

2. What are the (optical and infrared) spectral energy distributions and how do they vary across the galaxies? How do the morphologies differ from those of low-redshift radio galaxies and normal giant ellipticals? What do they tell us about the populations (and ages) of the stellar components? This aspect will benefit considerably from the complementary theoretical input to the project by the Institut d'Astrophysique, Paris.

3. How are the morphologies of gas, stars and relativistic plasma related? Are they clumpy? If so, on what scale, and are the clumps related to galaxy formation?

4. What are the dynamical properties of the gas in the $z > 2$ galaxies and what constraints can be placed on the masses of the various components? How do they differ from the dynamical properties of low-redshift radio galaxies and normal giant ellipticals?

5. What is the mechanism for the optical/radio alignment effect? Is the presence of the alignment connected more with the high redshifts of the 4C sample or with their large radio luminosities?

6. How do the properties of intermediate-redshift radio galaxies differ from the properties of nonactive galaxies in the same clusters? Are additional galaxies detectable close to our $z > 2$ galaxies? Neighbours might be expected if our objects are located in forming clusters or in regions of the universe which are preferentially conducive to galaxy formation.

This Key Programme can be expected to produce a large body of data about the epoch at which galaxies are believed to be forming. Although we can speculate about questions, these results will contribute to answering; it is the serendipitous observations that often produce the most fundamental advances in astronomy. With this in mind, we embark on this programme on the lookout for the unexpected and in the hope that our observations will pose new problems which as yet cannot be envisaged.

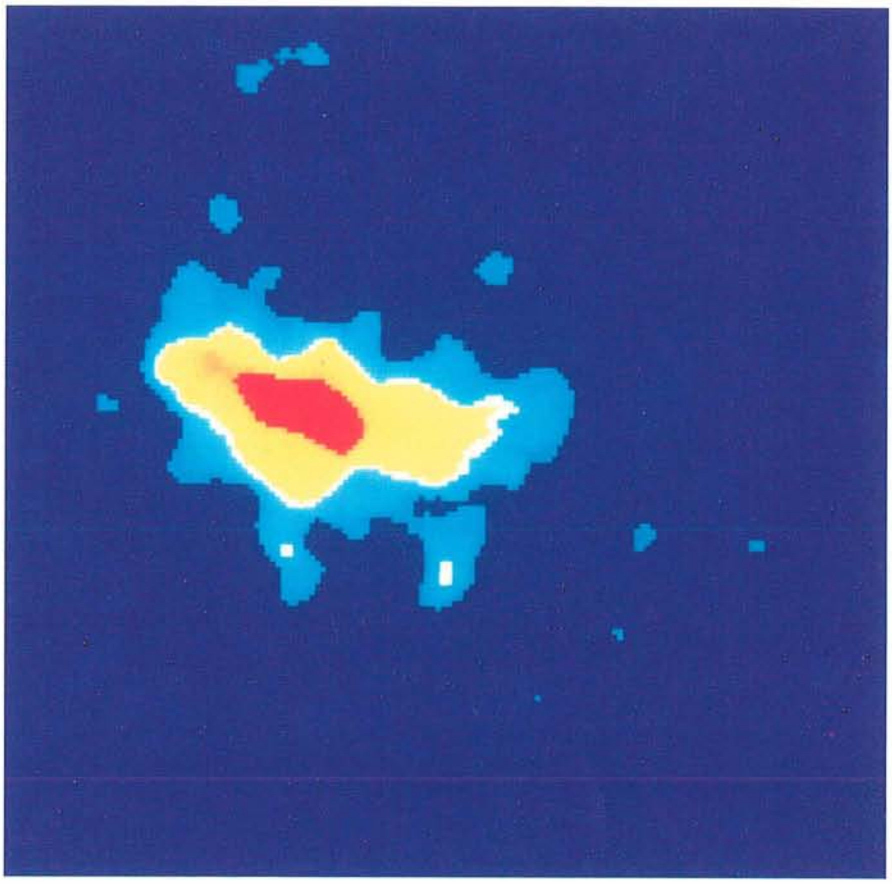

Figure 3: *Lyman alpha picture of 4C41.17 at a redshift of 3.8 (from Chambers, Miley and van Breugel 1989).*

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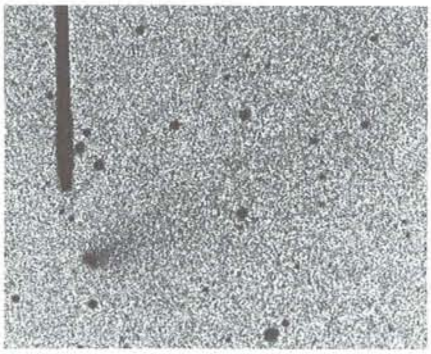
P/West-Hartley (1989k)

On May 11, 1989, Richard M. West at the ESO Headquarters found a new comet on a photographic plate obtained on March 14 by Guido Pizarro with the 1 m Schmidt at La Silla. This picture is a photographically enhanced reproduction from the 60 min blue-sensitive plate. The comet's head of magnitude 17.5 is seen as a short trail due to the motion during the exposure. The very faint, broad tail measures about 4 arcminutes. The dark, vertical line in the upper left part is an artificial edge mark on the plate.

Since only a single plate was available, it was not possible to determine the direction of motion with certainty. However, on May 28, Malcolm Hartley accidentally discovered a comet on a plate taken by S.M. Hughes with the U.K. Schmidt, about 15° West-South-West of the sky field shown on the photo. It was quickly realized that this object was identical with the comet seen earlier by West. A preliminary orbital computation by Brian Marsden of the IAU Central Bureau for Astronomical Telegrams indicates that it moves in an elliptical orbit with a period of about 7.5 years. It passed its perihelion in early



October 1988 at a heliocentric distance of about 318 million kilometres.