The K$-z$ relationship, observations and theory.
Report of the Leiden TMR meeting, 31st January 1997

Present:

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1 Introduction

Huub Röttgering began the meeting by giving an overview of the K$-z$ relationship. A plot of K–magnitude against redshift was first created for the powerful 3CR radio galaxies in the early 1980's by Lilly and Longair, and showed a remarkably tight correlation (scatter $\lesssim 0.6$ magnitudes). This was originally interpreted as being due to passive evolution of the stellar populations of a single class of giant elliptical galaxies which formed in a reasonably simultaneous burst at high redshift.
Recent results have made the interpretation of this relationship more complicated. In particular, a recent study by Eales et al. of radio galaxies from the 6C sample (which are about a factor of 5 less radio powerful than the 3CR galaxies at any given redshift) has shown these to have K–magnitudes which are fainter than those of the 3CR galaxies by about 0.8 magnitudes at redshifts $z \gtrsim 1$, but similar at redshifts $z \lesssim 0.6$. Also, a study by McCarthy has shown that beyond a redshift $z \sim 2$ the dispersion in the K$-z$ diagram begins to increase rapidly.
Huub posed a number of questions which this meeting would hopefully address:

1. Are the K$-z$ relationships of different types of galaxy 'consistent' with each other?
2. Are the stellar population synthesis models accurate enough to allow observers to come to robust conclusions?
3. What increase in mass do we expect for these galaxies by merging over the epoch $1 > z > 0$.
4. Why do only the very massive galaxies seem to host the most powerful radio sources?

2 The K$-z$ relationship and its interpretation

2.1 The 3CR and 6C radio galaxies — *Philip Best*

There are two promising explanations of why the 3CR galaxies might be brighter than the 6C galaxies in absolute K–magnitude at redshift $z \gtrsim 1$: either (i) they are more massive galaxies and therefore contain a greater mass (luminosity) of stars, or (ii) their K–band emission contains a significant contribution of light associated with their powerful active nucleus.
The AGN can influence the K–band emission in three ways: line emission ([SIII] 9532) from photoionisation by AGN photons, reddened light directly from the AGN, and the K–band contribution of the relatively flat spectrum emission responsible for the alignment effect in powerful high redshift radio galaxies. These three processes were investigated for the 3CR galaxies, and the size of their effect estimated. The sum of the three effects contributes on average less than 0.3 magnitudes of the K–band emission. Therefore the higher absolute K–magnitudes of the 3CR galaxies must mean that they contain a greater mass of stars than the 6C galaxies. Radio galaxies at high redshifts

have jet powers close to the Eddington luminosity of their central black holes, and so if, as has been predicted by many authors, the mass of the central black holes are roughly in proportion with the mass of the galaxies, then the higher mass of the 3CR galaxies also explains why their radio luminosities are higher than those in the 6C sample.

When the infrared radial intensity profiles of all of the 3CR galaxies were summed to increase signal to noise, a clear excess of emission above the de Vaucouleurs profile was seen at radii $\gtrsim 35\,\mathrm{kpc}$, the same radius as that at which cD halos are seen to set in. This provides strong evidence that the 3CR galaxies lie in massive systems. Other evidence to support this theory includes the detection of X–ray emission associated with cooling flows about the high redshift radio galaxies, the detection of companions in narrow band [OII] imaging, spectroscopic studies of cluster galaxies around individual sources (eg 3C324), and the large stellar masses required for fitting the SEDs. In contrast, at low redshift the 3CR galaxies lie in isolated environments or small groups.

There is clearly a change of environment of the 3CR galaxies with redshift; the apparently simple 'passive evolution' track their K–magnitudes is not associated with simple evolution of a high redshift 3CR galaxy into a low redshift 3CR galaxy but instead is a 'cosmic conspiracy' that the brightest radio sources at all epochs are associated with galaxies of similar mass. For some reason, objects of higher mass than the 3CR galaxies do not produce powerful radio sources; this is perhaps because they live in relaxed clusters in which the gas and galaxies have virialised orbits and so provide little fuel for the AGN. The 'no evolution' track of the 6C galaxies is also unphysical, since the stellar populations of the galaxies must be evolving, and so this implies that some merging must be occurring to increase the mass of these objects over the epoch $1 > z > 0$.

2.2 Brightest cluster galaxies — *Alfonso Aragòn–Salamanca*

¿From the very red colours of elliptical galaxies, and the small scatter in their colour magnitude relationship, it is clear that ellipticalq galaxies must have formed at high redshift in a reasonably well–synchronised burst.

Infrared studies of brightest cluster galaxies out to redshifts $z \sim 1$ show little evidence for luminosity evolution; the galaxies lie close to, or even slightly fainter than, the track expected for a non-evolving population on the K$-z$ relationship. This is clearly unphysical since the stellar populations themselves must be evolving, and therefore be younger and brighter at higher redshifts. The V$-$K colour of the brightest cluster galaxies is about 0.5 magnitudes bluer at redshift $z \sim 0.5$ than at zero redshift, which is in accordance with passive evolution of the stellar populations.

The interpretation of these data must be that the central galaxies accumulate matter through mergers and accretion over the epoch $1 > z > 0$, such that at redshift zero they are less massive, and therefore appear fainter than the passive evolution prediction. This growth can be parameterised by considering the offset of the brightest cluster galaxies from the K$-z$ relationship expected for passive evolving stellar populations. This offset can be parameterised according to $L(z) \propto (1+z)^{\gamma}$. For a Universe with $\Omega = 1$, the measured growth has a γ value of -2.2 ± 0.3 if the stellar population formed at redshift $z = 2$, and $\gamma = -1.7 \pm 0.3$ for $z_{\mathrm{f}} = 5$. This corresponds to growth of a factor 3.2 to 4.6 between redshift 1 and 0. These values can be compared with that predicted from the semi–analytic models developed by the Durham group: their theoretical value is $\gamma \approx -2.4$, consistent with the data. The models also predict a similar (although slightly higher) scatter in the K$-z$ relationship to the 0.3 magnitudes measured from the data.

2.3 Giant radio galaxies — *Garret Cotter*

A sample of 20 giant radio sources from the 7C sample has been selected according to the criteria $90'' < \theta_{LAS} < 180''$ and $400\,\mathrm{mJy} < S < 1\,\mathrm{Jy}$. Selected in this way, you can be fairly confident that the sample will be complete.

Spectra have been taken of the galaxies to determine their redshifts, which lie out to $z \sim 1$, and

show that the emission lines of giant radio galaxies are significantly less powerful than those of the 3CR and 6C galaxies. This indicates that their central active nuclei are not exceptionally strong. Radio spectral ageing techniques show that the hotspot advance velocities of these sources are of order 0.1 to $0.2c$, and so the ages of these sources are not significantly older than those of the 3CR sources. The combination of rapid hotspot advance speeds and only moderate power central engines means that these radio sources must lie in relatively diffuse environments, and so their environments differ from those of the 3CR and brightest cluster galaxies presented so far.
Those galaxies in the sample for which both redshifts and K–band data are currently available lie close to the 6C galaxies on the K$-z$ relationship; they are clearly fainter than 3CR and brightest cluster galaxies at redshifts $z \sim 1$.

2.4 GPS radio galaxies — *Ignas Snellen*

Gigahertz–peaked spectrum (GPS) radio sources are typically 10 to 100 pc in size, and their radio spectrum shows a peak at a frequency of about a gigahertz. At lower frequencies the radio emission falls due to synchrotron self–absorption: without this many of these sources would be sufficiently luminous as to be included in the 3CR sample. There are two current hypotheses as to the small size of GPS sources; either they are young radio sources which will grow into ordinary FR I and FR II radio sources, or they are small because they are confined by a dense surrounding medium.
The R$-z$ diagram of these sources shows a very tight correlation, with a scatter of 0.28 magnitudes. Their R$-$K colours lie on the track that would be expected for a passively evolving elliptical galaxy which formed at high redshift. They don't show the blueward scatter from this track that is seen in the 3CR galaxies due to the alignment effect, but that is not unexpected since their radio jets are very small and if these are young sources then their AGN will have only a small region of influence. The absolute K magnitudes of these galaxies do not, however, show any sign of evolution of the galaxies. Repeating the same evolution analysis as Alfonso did for the brightest cluster galaxies, a value of $\gamma = -1.2 \pm 0.4$ is attained, indicating that these galaxies decrease in luminosity (mass) by 0.8 magnitudes, with respect to passive evolution, between redshift zero and one.
Some low redshift GPS sources are seen to lie in clusters, with extended halos surrounding the galaxies and many companions. Also, care needs to be taken to ensure that there is no K–band contamination from reddened quasar light: the spectrum of the source 1954+61 from the WENSS catalogue is flat at wavelengths below about 7000Å, but about that wavelength it rises very steeply due to nuclear emission coming through.

3 Outliers from the K$-z$ relationship

3.1 1138$-$262 — *Laura Pentericci*

1138$-$262 is a radio galaxy with a redshift of $z = 2.2$, and a K–magnitude $K \sim 16.2$. This value is comparable to the 3CR and 6C galaxies at redshifts $z \sim 0.8$, and so this galaxy is exceptionally luminous. The K–band contains Hα line emission, but the contribution of this line is calculated to be $\lesssim 0.5$ magnitudes. The presence of any point source component can also be tightly constrained at $\lesssim 0.2$ magnitudes. Even accounting for the maximum values of these two effects, the galaxy still lies significantly brighter than the mean K$-z$ relationship, with its magnitude implying a mass of order $10^{12} M_\odot$.
A study of this galaxy has been made to investigate the cause of this high luminosity. An narrow–band Lyα image shows the galaxy to reside in a large Lyα halo, and indicates the presence of a companion galaxy. An X–ray detection of the object has been made, indicating the presence of a large quantity of hot intracluster medium around the galaxy (the X–rays are unlikely to be associated with the AGN, since X–ray and radio core luminosities are reasonably well correlated,

and the radio core of 1138 is only very weak). Deep radio images show that the radio emission is very clumpy, with large rotation measures (6000 $\mathrm{rad\,m^{-2}}$, cf. Cygnus A with $\sim$ 500 $\mathrm{rad\,m^{-2}}$) and large gradients in the rotation measure. All of these factors suggest that 1138 lies in a moderately rich cluster environment, consistent with the central galaxy being very massive.

3.2 WN 0617+50 — *Carlos de Breuck*

WN0617+50 is a radio source from a sample of ultra–ultra–steep–spectrum radio sources ($\alpha >$ 1.3), selected using the WENSS, TEXAS, NVSS and FIRST catalogues. The source 0617+50 has $S_{1.4\mathrm{GHz}} \sim 27\,\mathrm{mJy}$, $S_{325\mathrm{MHz}} \sim 200\,\mathrm{mJy}$, and $\alpha \sim 1.37$. The selection of ultra–steep spectrum sources is a successful way of picking out very high redshift galaxies.
The radio source has a size of 5 arcsec and, in a 25 minute K–band Keck image, there is no optical counterpart visible between the two radio lobes. Although conditions were not totally photometric, an estimate for the upper limit of the K–band flux is K $\gtrsim$ 22. On the K$-z$ diagram this would correspond either to a galaxy with a redshift greater than 10 or to an extremely faint galaxy.
The galaxy lies on the edge of the 90% confidence ellipse of an IRAS source with a 60μm flux of 614 mJy, although there are other objects with which this source could be associated.

4 Theoretical Expectations

4.1 Evolution of massive galaxies in clusters — *Simon White*

Semi–analytic models of galaxy evolution assume that the mass is dominated by the dark matter, and that the gas cools and collects within the dark matter halo, to form cold rotating disks. Star formation occurs quiescently in the disks or violently during disk mergers. In any single collapse the efficiency in converting gas into stars is low, and so there is much gas left for star formation in later mergers. Elliptical galaxies and bulges form during mergers, and can then grow new disks if more matter cools onto them. Stochastical methods are employed to determine when mergers occur, and feedback from star formation is taken into account.
Objects with a density greater than 200 times the mean density at any epoch are considered to be collapsed and virialised. Following these objects, the blue galaxies are generally found in filaments and the red galaxies in clusters, reproducing the observed the segregation of morphological types. The star formation in these objects can also be traced, and at $z \sim 3$ the abundance of galaxies forming stars at a few solar masses per year is similar to that measured by Steidel. The models also predict cosmic star formation histories comparable to those suggested by recent observation. The epoch by which 50% of the stars have formed is $z \sim 1$.
To investigate the evolution of the central cluster galaxy mass, two methods were employed. The first was to select clusters at low redshift in the simulation, and to investigate the evolution of the average masses of their largest pregenitors. The largest pregenitors are typically a factor of about 10 less massive by redshift 1, a factor 30 by redshift 2 and a factor 100 by redshift 4, as compared to the masses at zero redshift. The second method was to pick clusters at high redshift and compare the masses of their central galaxies with those at low redshift. The central cluster galaxies are less massive by about a factor 5 at redshift 1, 10 at redshift 2 and 25 at redshift 4. It is also possible to track the abundance of objects with masses in excess of $10^{11} M_{\odot}$ in the model. Compared with redshift zero there are only one thrid as many per comoving number density at redshift 1, a tenth as many at redshift 2 and a thousandth as many at redshift 3.
It is important to note that the final mass of a galaxy divided by its number of pregenitors is reasonably constant for different masses of galaxies. That is, that large galaxies don't undergo significantly more mergers than small galaxies; they are just composed of larger progenitors.

4.2 Population synthesis models — *Alessandro Bressan*

One major assumption that appears to go in to understanding the K$-z$ relationship is that the galaxies are formed in a single short lived burst of star formation at high redshift. Of a sample of 124 possible early type galaxies from the Hubble Deep Field, redshifts are available for 21 galaxies, and photometric redshifts for a further 32. It proves impossible to reproduce the $f_{616}-f_{814}$ colours of the HDF galaxies using passive models. Instead, they can be well fitted using active models, in which the star formation rate decays exponentially with a characteristic time of about 1 Gyr up until a cut–off time when the galactic wind expels the gas and prevents further star formation.
One further problem in interpreting the evolution of early type galaxies is that the more luminous galaxies have redder colours, which is usually explained by arguing that these have later cut–off times for their galactic winds, but that brighter galaxies also have higher Mg/Fe indices which would require shorter cut–off times. One resolution of this contradiction is if the most massive galaxies have IMFs which are peaked towards the most massive stars. In this model, both of the above effects can be reproduced, and the change in mass–to–light ratio along the fundamental plane ($M/L \propto L^{0.2}$) is also explained.
The on–going star formation and different IMFs proposed for these massive galaxies may have a significant influence upon the interpretation of the K$-z$ relationship.

5 Discussion

Much progress has been made on the questions raised at the start. Outstanding questions and areas to be tackled now appear to be:

1. How rich are clusters at redshift $z \gtrsim 1$, for example those around the 3CR radio galaxies? Whilst spectroscopy on the number of objects required is not currently practical, an estimate of the clustering strength might be possible using multicolour imaging with the new wide–field camera on the INT. Although Mark Dickinson has done similar work, he has not published any of it, and the new camera should give improved results. Together with existing data, this could be used to place tight constraints on galaxy evolution models.

2. Detailed comparisons of the observations should be made of the various different types of galaxy at high redshift. According to the results presented today, at redshifts $z \sim 1$ the brightest cluster galaxies and the 3CR galaxies are remarkably similar apart from the fact that the 3CR galaxies contain powerful radio sources. Can we get any handle on what induces the radio activity by comparing the two classes of object, for example by comparing the major merger rates predicted by the models with the fraction of galaxies which are radio loud?

3. Rather than investigate the clustering properties around radio sources, perhaps a less problematic method would be investigate the radio properties of an X–ray defined sample of sources. The Einstein medium sensitivity survey might be used to define such a sample.

Please note that this is the author's account of what was reported at the meeting, and should be taken as a guide rather than as a definitive work! I apologise for any major omissions or inaccuracies in describing the work presented by others.

Philip Best, 12/02/97.