Active Galactic Nuclei and Related Phenomena
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Active Galaxies and Cosmic Evolution

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Abstract. The evolutionary history of active galaxies is surveyed and contrasted with recent observations of the evolution of star and element formation rates with cosmic epoch. The problem of taking proper account of the effects of dust obscuration in optical and ultraviolet observations is reviewed. Recent submillimetre surveys have been used to derive the star formation rate as a function of cosmic epoch independent of dust obscuration. These observations suggest that the star formation rate peaked at redshifts $z \sim 2 - 4$, similar to the maximum in the evolution of the populations of active galaxies. The inference of these observations for theories of galaxy formation is discussed.

1. Introduction

Many of the features of the cosmological evolution of active galaxies are now quite well understood and the big challenge is to relate these features to the evolution of galaxies in general. I will therefore summarise briefly these features and then describe evidence on the evolution with cosmic epoch of star formation in galaxies which is crucial for understanding the relation between the evolutionary properties of active galaxies and galaxies in general. The key problem which bedevils many aspects of these studies is the rôle of dust, but there are now ways by which this can be circumvented. The ultimate question we need to answer is whether or not it all hangs together.

2. The Cosmological Evolution of Active Galaxies

It is simplest to begin with the evolution of the radio source population because in many ways these results are less severely affected by insidious selection effects as compared with optically-selected samples. Their great advantage is that the samples are selected according to the radio properties of these active galaxies and so are unaffected by obscuration by dust. An indication of the current state of the art is provided by the models described by Dunlop (1998). In Fig. 1, two examples of models of the evolution of the overall luminosity function of radio galaxies and radio quasars are shown which are consistent with a very wide range of observations of the number counts at different frequencies and the redshift distributions of complete samples of sources at relatively high flux densities. These examples make the key point that there was a maximum in the

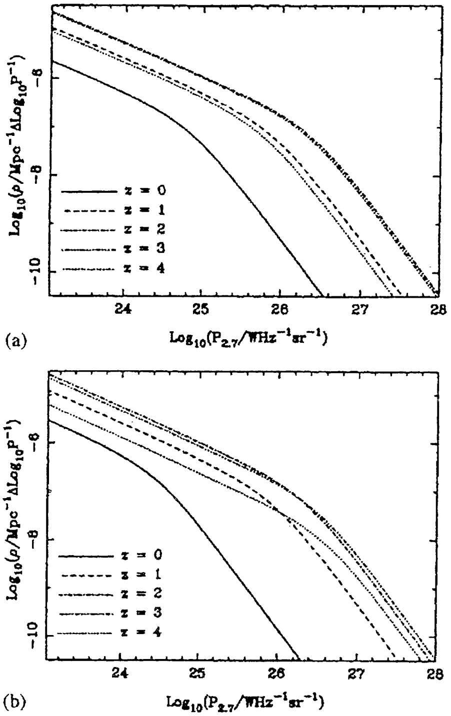

Figure 1. Two examples of the forms of evolving radio luminosity function which can account for the radio source counts and available redshift and identification data (Dunlop 1998). In model (a), the change in the radio luminosity function is described by pure luminosity evolution. In model (b), the changes in the radio luminosity function involve in addition negative density evolution at large redshifts. In both cases, the changes in the form of the radio luminosity function are described in terms of the number densities of sources per unit comoving volume (Dunlop 1998)

radio source activity of these active galaxies at $z \sim 2-3$ and a decline at greater redshifts.

A key issue is the cut-off suggested by the models in Fig. 1. A test of the reality of the cut-off is provided by the redshift distribution of complete samples of radio sources in deep source samples, the results of the 6C-B2 survey and the Leiden-Berkeley Deep Survey being shown in Fig. 2. It can be seen that the inferred redshift distributions are consistent with both models shown in Fig. 1. In particular, in models in which there is no redshift cut-off, the numbers of sources at large redshifts would far exceed the numbers observed, particularly in the Leiden-Berkeley Deep Survey. It therefore seems unambiguous that the radio quasars and radio galaxies flourished at redshifts $z \sim 2-3$ and that this activity declined at greater redshifts.

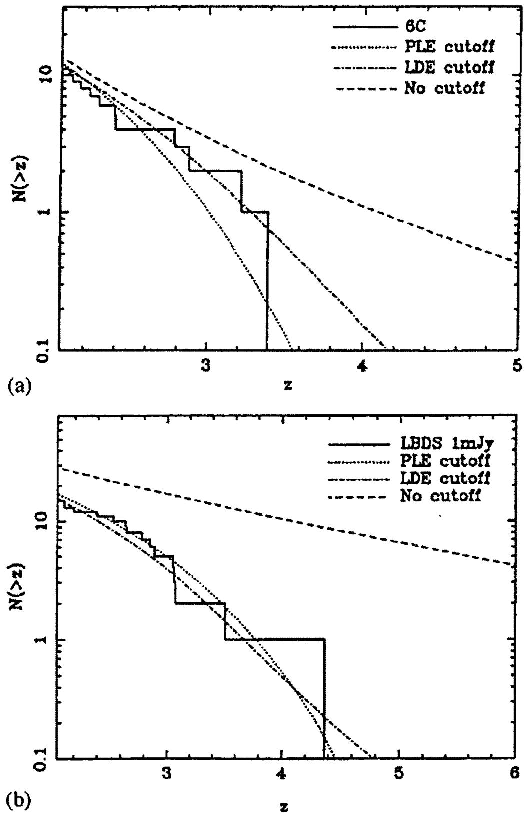

Figure 2. (a) The observed high-redshift cumulative redshift distribution for the complete 6C/B2 samples of Eales, Rawlings and their colleagues (Eales and Rawlings 1996), compared with the large redshift predictions of the two evolution models shown in Fig. 1, and a model in which the comoving luminosity function of the radio sources is constant at redshifts $z \geq 2$. (b) The same comparison for the Leiden–Berkeley Deep Survey (Dunlop *et al.* 1995). For more details, see Dunlop (1998).

A similar picture emerges from studies of complete samples of optically selected quasars. The problem with the optical observations is to ensure that the samples are complete – this is highly non-trivial at redshifts $z > 2$. The surveys of Boyle *et al.* (1991) and Shaver *et al.* (1996) are consistent with the same type of evolutionary behaviour found in the samples of radio sources (Fig. 3). The cut-off at large redshifts has been indicated by the deep surveys of Warren *et al.* (1994), Kennefick *et al.* (1995) and Schmidt *et al.* (1995), as well as by the survey of Shaver *et al.* (1996).

Although many detailed questions still need to be answered, the parent galaxies associated with these active systems are all massive systems, as indicated by the success of unification schemes for the radio galaxies and radio quasars in bright radio source samples and, more directly, by the similarity of the

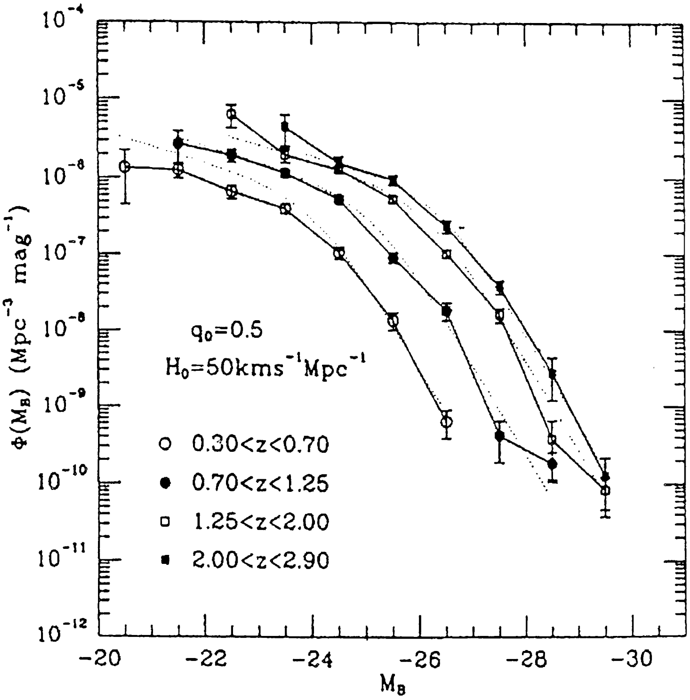

Figure 3. The evolution of the comoving optical luminosity function of radio-quiet quasars in the redshift interval $0.3 < z < 2.9$. The redshift bins have been selected to correspond to equal intervals in $\log(1+z)$. The luminosity functions have been derived from complete samples of quasars and include almost 1000 quasars. The faint dotted lines show the the expectations of a luminosity evolution model in which the luminosities of the quasars change with cosmic epoch as $L(z) \propto (1+z)^{3.5}$ in the redshift interval $0 < z < 2$ and $L(z) =$ constant for redshifts $2 < z < 2.9$ (Boyle *et al.* 1991).

absolute magnitudes of the parent bodies of radio galaxies, radio-loud quasars and radio-quiet quasars (Taylor *et al.* 1996).

It is likely that the number counts of X-ray selected active galaxies display the same form of cosmological evolution, although the redshift information is as yet not as extensive as that in the radio and optical wavebands (Hasinger *et al.* 1996).

3. The Evolution of Element and Star Formation Rates with Cosmic Epoch

There has been remarkable progress in defining element and star formation histories from a wide range of observations over recent years. There are however problems and it is simplest to illustrate these using the analysis of Pei and Fall

(1995), which has been widely quoted. In their programme, they attempt to relate the chemical history of interstellar matter in galaxies, as defined by studies of Lyman-limit absorption line systems in high redshift quasars, to the emission history of star formation, as defined by the characteristic blue continua of star-forming galaxies. As they show elegantly, these histories are related through the equations of cosmic chemical evolution. The results of their studies repay close study and are illustrated in Fig. 4.

In all four panels of Fig. 4, the dashed lines show the observations, uncorrected for the effects of dust obscuration, whereas the solid lines show how these results change once account is taken of the effects of dust obscuration. Panel (b) shows how the density parameter in neutral hydrogen changes with redshift. The observed points are taken from the studies of Lyman-α absorption clouds by Storrie-Lombardi *et al.* (1996) which show that the density parameter in neutral hydrogen at redshifts $z \sim 3-4$ is of the same order as that in the stars in galaxies at the present epoch. It can be seen that the fraction of the baryonic mass in the form of neutral hydrogen in galaxies decreases to only about one twentieth of the overall mass in stars in galaxies by the present epoch. At the same time, panel (c) shows that the abundances of the heavy elements at $z \sim 2$ must have been about an order of magnitude less than the values observed at the present epoch. A good example of the type of analysis, from which this information is derived, is presented by Pettini *et al.* (1996).

The equations of cosmic chemical evolution can be used to predict the star formation rate as a function of cosmic epoch, given the observed rate of depletion of the neutral hydrogen and the build up of the heavy elements. The solid curves shown in panel (d) have been widely quoted and are in reasonable agreement with the star formation rates inferred from the Hubble Deep Field, the numbers of Lyman-α drop-outs observed by Steidel and his colleagues and the analyses of the Canada-France Redshift survey carried out by Lilly and his colleagues.

It can be seen, however, that the results are strongly dependent upon assumptions made about the influence of interstellar dust upon the observations. Dust enters in a number of different ways into the analysis. For example, account has to be taken of the fact that there may be quasars missing from the samples because of dust extinction. The abundances themselves can be strongly affected by the effects of reddening. What I find interesting about these models is that the epoch at which the maximum rate of star formation took place changes according to the assumptions made about the amount of dust extinction present. There is also the key question as to whether or not all the star forming galaxies at large redshifts have been detected. The way of circumventing many of these problems is to make observations in the submillimetre waveband and this has been achieved recently.

4. Submillimetre Observations of Distant, Dusty Galaxies

The importance of observations in the submillimetre waveband are well known. Star-forming galaxies have a characteristic flat emission spectrum in the optical-ultraviolet wavebands, but the regions in which stars form are also the dustiest regions we know of in the Universe. As pointed out by Weedman at this meeting, local star-forming galaxies emit much more of their luminosities in the far-

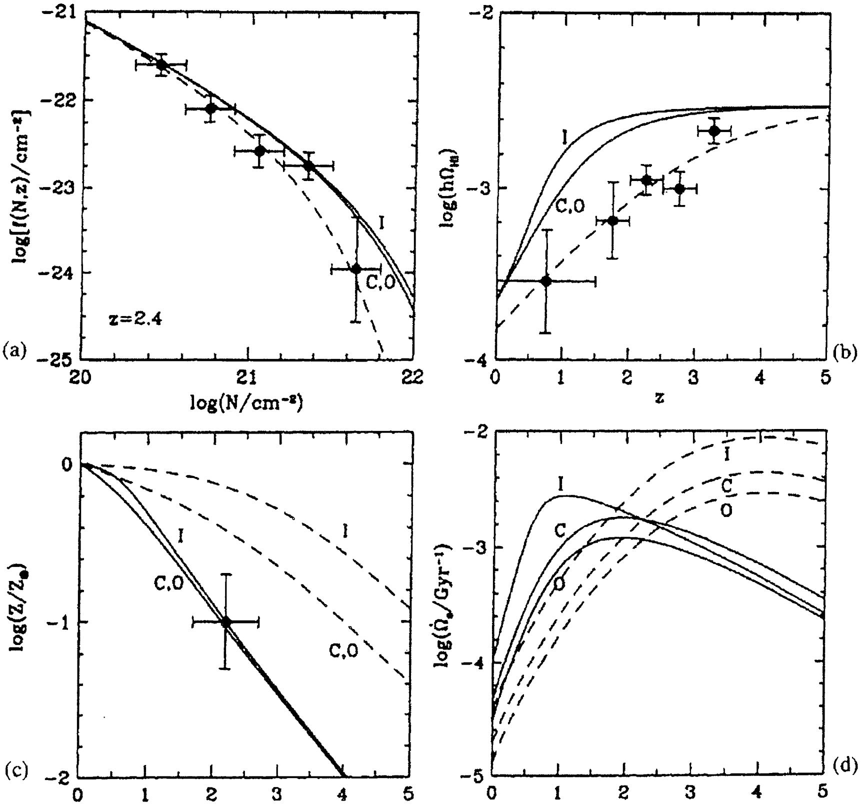

Figure 4. Illustrating the cosmic chemical evolution of models with $\Omega_g(\infty) = 4 \times 10^{-3} h^{-1}$, $\nu = 0.5$ and $\Omega_0 = 1$ (for details, see Pei and Fall 1995). (a) The distribution of HI column densities at $z = 2.4$; (b) the comoving density of neutral hydrogen as a function of redshift z; (c) the mean metallicity Z of the interstellar gas relative to its present value Z_0 as a function of redshift; (d) the predicted comoving rate of star formation as a function of redshift. The solid curves represent the true values for three models described by Pei and Fall: C – closed box model, I – inflow model, O – outflow model. The dashed curves in (a) and (b) represent the corresponding observed quantitites, while the dashed curves in (c) and (d) show the effects of neglecting dust extinction in each of the models. The data points in (a), (b) and (c) are from Lanzetta *et al.* (1991), Lanzetta *et al.* (1995) and Pettini *et al.* (1994), respectively.

infrared rather than in the ultraviolet region of the spectrum. This is because the dust grains, which are essential in enabling a gas cloud to collapse, absorb the optical-ultraviolet radiation, the temperature of the emission corresponding to that to which the dust grains are heated. Observations in the submillimetre waveband have the great advantage that the spectrum of dust has a very steep inverted spectrum through these wavebands and so the 'K-corrections' are large and negative (Blain and Longair 1993, 1996). The result is that a standard dusty star-forming galaxy has more or less the same flux density throughout the redshift interval $1 < z < 10$.

The great breakthrough of the last year has resulted from the commissioning of the SCUBA submillimetre common-user bolometer array on the James Clerk Maxwell Telescope in Hawaii (Holland *et al.* 1999). This is the first time a 'camera' has become available on a large submillimetre telescope and the results are startling. Of the various surveys already published in the literature (Smail *et al.* 1997, Barger *et al.* 1998, Hughes *et al.* 1998), I will concentrate upon the results from surveys of clusters of galaxies and those from the Hubble Deep Field.

The first report of a large population of distant submillimetre sources was presented by Smail *et al.* (1997) who observed clusters of galaxies which were known to be strong gravitational lenses. Six background sources were discovered in the fields of two clusters and their subsequent observations of five other clusters have increased the known numbers of submillimetre sources to 10 at the 4σ level and 17 at the 3σ level. The image of the Hubble Deep Field published by Hughes *et al.* (1998) is the deepest submillimetre image ever made and reaches the confusion limit of the JCMT. Five sources have been observed with good significance in the field.

These results have been synthesised by Blain *et al.* (1999) who have used all the information available on the number counts and background radiation in the submillimetre and far infrared wavebands. A number of key results come out of this analysis. First of all, the total background radiation due to sources already detected in the deep surveys is very close to the integrated background radiation in the submillimetre waveband as derived from observations by COBE. Therefore, there is unlikely to be a large population of dusty galaxies beyond those which have already been observed. Indeed, Blain *et al.* (1999) find that by a flux density of 0.1 mJy at 850 μm, the number counts of submillimetre sources is converging, the integral source count having slope -1.

Second, the data can be used to estimate the variation of the star formation rate with cosmic epoch. This is not a trivial exercise, because of the lack of complete redshift information for these faint submillimetre sources, but their properties are reasonably well constrained by all the information now available from the ISO satellite, as well as the properties of the IRAS population of galaxies. The results of these model computations are shown in Fig. 5. It can be seen that the inferred star formation rates exceed those derived from optical-ultraviolet observations at redshifts $z \sim 2-4$, even when the latter are corrected for the effects of obscuration. The inference is that there are substantial populations of star forming galaxies missing from the Hubble Deep Field – these must be highly obscured objects, probably at large redshifts, although probably not at redshifts greater than 5 (Smail *et al.* 1998).

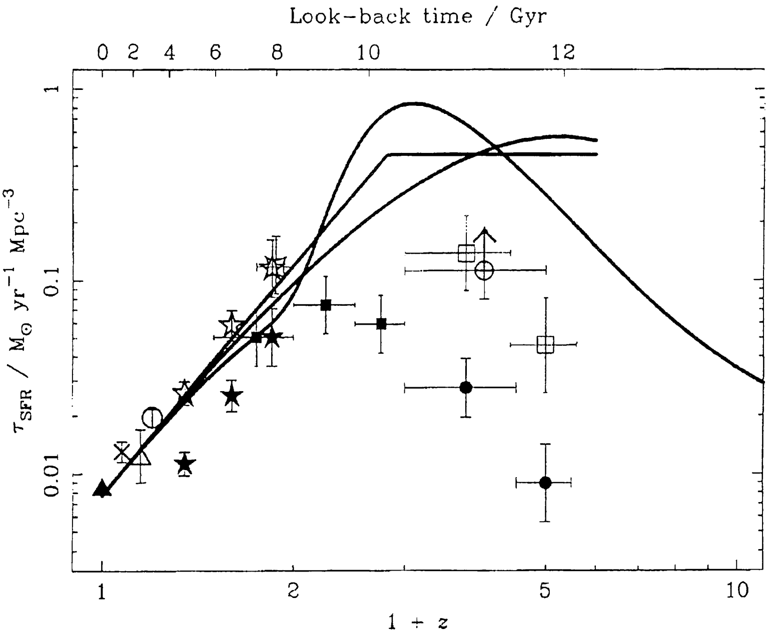

Figure 5. Comparison between the inferred star formation rate as determined by optical-ultraviolet observations and those carried out in the submillimetre waveband. The solid lines are examples of models of the star formation rate with cosmic epoch which are consistent with the number counts of faint submillimetre and far infrared sources and the limits to the background intensity due to discrete sources in the submillimetre waveband (from Blain *et al.* 1999)

These results are very important for understanding the formation of the stellar populations of galaxies. For example, they would strongly affect the rate at which the heavy elements are inferred to be built up with cosmic epoch and they have consequences for the formation of the overall population of low-mass stars. The key observations now are the determination of the redshifts of the faint submillimetre sources. It is now known that two of the background objects have redshifts of 2.5 and 2.8 (Ivison *et al.* 1998), but it is a struggle to find the identifications and then the redshifts of these distant star-forming galaxies.

5. The Active Galaxies Revisited

How do these observations impact the study of the evolution of active galaxies with cosmic epoch? There are several striking features which have come out of the observations described above which are directly related to evolution of the population of active galaxies.

1. The first is the obvious similarity between the evolutionary behaviour of the population of active galaxies and the evolution of the star formation rate with cosmic epoch. Both of these were very much greater at redshifts

$z \sim 2-4$ as compared with the present epoch. In my opinion, this is unlikely to be a coincidence.

2. The second key aspect is the direct evidence that much more of the baryonic matter at redshifts $z \sim 2-4$ was in the form of diffuse gas as compared with the present epoch. Thus, there were certainly large amounts of gas present to fuel active galactic nuclei as a by-product of the process of star formation in galaxies.

3. There is direct evidence for strong interactions between the radio jets of 3CR radio galaxies and their environments from observations of the alignment effect, the coalignment of the radio jets with the optical emission structures (Best, Longair and Röttgering 1998, Best, this volume). The origin of the optical emission is not yet fully understood, but all the viable models involve the interaction of the powerful radio jets with cool interstellar or intergalactic clouds in the vicinity of these massive galaxies.

4. We know that, in both the quasars and the radio galaxies, there must be $10^9\,M_\odot$ black holes in their nuclei. In this regard, the remarkable diagram of Rawlings and Saunders (1991) for the 3CR radio galaxies shows that, for the most luminous radio galaxies in the sample, the rate of total energy production corresponds closely to the Eddington luminosity of $10^9\,M_\odot$ black holes.

From the perspective of galaxy formation, the key result is that these massive black holes must have formed by the epoch when the maximum amount of star formation activity was taking place. In this regard, the analyses of Efstathiou and Rees (1988), Haehnelt and Rees (1993) and Efstathiou (1996) are of particular interest. According to the favoured hierarchical picture of the formation of galaxies and larger scale structures, the most massive objects are formed by the clustering of lower mass objects. According to their calculations, the cut-off to the quasar population at large redshifts is associated with the fact that, by a redshift of 4, there are relatively few massive galaxies and, since there is evidence that the central black hole mass is proportional to the total mass of the galaxy, there would be correspondingly fewer massive enough black holes in the nuclei of galaxies at these redshifts.

The sense of these arguments is that there is now a much closer relation between the evolution of the populations of active galaxies and studies of the formation and evolution of galaxies than in the past. It has been suspected for a long time that the origin of the strong cosmological evolution of active galaxies was related to the formation of galaxies in general, and this can now be placed on a much firmer observational and astrophysical basis.

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