COSMOLOGICAL EVOLUTION OF THE SUBMILLIMETRE LUMINOSITY OF HIGH-REDSHIFT RADIO GALAXIES

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Abstract

A systematic survey measuring the submillimetre continuum luminosity in radio galaxies between redshifts \( z \sim 0.1-5 \) is currently in progress. The first results from observations with the bolometer array SCUBA on the JCMT suggest a trend of increasing submillimetre luminosity with redshift out to \( z \simeq 4 \). Assuming the continuum emission at 850 \( \mu \text{m} \) is dominated by thermal radiation from dust heated by young, massive stars, the straightforward interpretation of these data implies that the host galaxies of powerful radio sources, presumably ellipticals or their progenitors, exhibit increased star formation activity with increasing redshift. However a severe bias may distort the true picture since only a subset of 30 galaxies have been observed, which represent the most luminous radio sources (\( P_{151 \text{MHz}} > 10^{27.5} \text{WHz}^{-1}\text{sr}^{-1}) \), whilst the complete sample covers \( 4 \) decades in radio power (\( 10^{25} - 10^{29} \text{WHz}^{-1}\text{sr}^{-1}) \). This on-going observational programme continues to improve coverage of the \( P-z \) plane in an attempt to remove this potential bias towards higher AGN activity and hence understand more fully the relationship between high-z AGN, their level of star formation, and the evolutionary status of their host galaxies.

1 Introduction

The last 12 months have seen submillimetre astronomy make a significant impact on cosmological studies of galaxy formation and evolution. This is primarily due to the technological development of bolometer arrays now operating on the world’s largest submillimetre and millimetre telescopes. There currently exist two distinct, feasible and complementary observational programmes at submillimetre wavelengths which address important questions regarding the evolutionary status of high-redshift galaxies. These can be summarised as:

1. Blank field submillimetre surveys at 850 \( \mu \text{m} \), covering a range of depths (with 3\( \sigma \) detection limits between 1.5 and 8 mJy) and areas (between 0.002 - 0.1 sq. degrees) \[\text{[1] [2] [3] [4]}\], with the aim of determining the cosmological evolution of the starburst galaxy population.

2. Pointed observations of known high-redshift AGN, including radio galaxies \[\text{[5]}\], radio-loud and radio-quiet quasars \[\text{[6]}\], designed to determine the epoch of elliptical galaxy formation, if indeed a unique epoch exists, and the cosmological evolution of dust mass in massive elliptical galaxies.
Figure 1: The radio-luminosity-redshift \((P - z)\) plane of high-z radio-loud galaxies. The entire SCUBA sample of \(>200\) radio galaxies (stars), selected from progressively deeper radio surveys (3C, 6C, 7C, LBDS), covers a large range in radio power and redshift. The circles represent those targets already observed with SCUBA, for which the open and solid symbols indicate non-detections and detections \( (>3\sigma)\) at 850 \(\mu\)m respectively. The subset of completed SCUBA observations have been confined to a region of parameter space defined by \(\log(P_{151 MHz}/\text{WHz}^{-1} \text{sr}^{-1}) > 27.0, z > 0.7\). Using sub-mm observations of the complete sample we can quantify the contribution of an AGN to the rest-frame FIR luminosity, and trace the evolution of gas mass and star-formation rate as function of redshift and radio luminosity.

Both observational programmes are motivated by several lines of evidence, outlined below, that suggest an era of massive star-formation exists at high-redshift.

(i) First, strong evidence exists for a redshift cutoff in the number density of radio-loud sources, indicating that AGN activity peaked at redshifts \(z = 2 - 3\) \([7]\). Second, deep infrared K-band imaging has demonstrated that in the low-z universe \((z < 1)\) luminous radio sources, and all optical quasars (both radio-loud and radio-quiet) more luminous than \(M_V = -24\), reside in giant elliptical galaxies with K-band luminosities \(>2L_\star\) and hence stellar masses \(>5 \times 10^{11} M_\odot\) \([8]\). If it can be assumed that the host galaxies of powerful high-redshift AGN are also massive ellipticals and are fully assembled at \(z \sim 2\), then a sustained star-formation rate (SFR) \(>250 M_\odot/yr\) is required during the previous 2–3 Gyrs of their evolution.

(ii) The elliptical hosts of weak radio sources at \(z \sim 1.5\) show absorption line spectra consistent with stellar populations having a formation epoch \(z_f > 4\) \([9]\).

(iii) The clustered populations of Lyman-limit galaxies at \(z \sim 3\) show modest average SFRs of \(1 - 5 h^{-2} M_\odot/yr\) \([10]\). However these observed SFRs, calculated from rest-frame UV luminosities may significantly underestimate the true SFRs by factors of \(\sim 2 - 15\) due to the efficient absorption of UV radiation by dust \([11]\, [12]\).

(iv) The traditional interpretation of number counts in the deepest optical surveys suggests that the star formation density peaked at \(z \sim 1 - 1.5\), a factor of 10 greater than the present-day value, and declined at higher redshift. However there is now conflicting evidence, based on deep

\[1h = 100 \text{ kms}^{-1} \text{Mpc}^{-1}\]
submillimetre surveys \cite{1} and corrections for incompleteness at high-z in the optical surveys \cite{12}, which suggests that the rate of star formation may remain high \((0.2 \, hM_\odot yr^{-1} Mpc^{-3})\) at \(z \sim 3\).

Thus regardless of whether one is considering the most luminous AGN, weak radio sources, Lyman-break galaxies or starburst galaxies identified in submillimetre surveys it appears that active star formation may have proceeded in the most massive systems at a rate \(\gg 100 M_\odot/yr\) in the early universe.

2 The evolution of star formation rate in massive elliptical galaxies

Whilst dust is a disadvantage in the optical/UV, the presence of dust heated by young, massive stars means that at early epochs elliptical galaxies can be expected to be not only bright in the rest-frame FIR \cite{13}, but also to show a significant evolution in their FIR luminosities from their formation to the present epoch. At the highest redshifts this FIR spectral peak is shifted into the submillimetre regime making observations at 850 \(\mu\)m a powerful method to quantify the starformation history of the massive elliptical galaxies that host radio-loud high-z AGN.

The spectral shape of a typical starburst galaxy in the submillimetre/FIR means that a large negative K-correction is produced at submillimetre wavelengths. At 850 \(\mu\)m this effect is so great that a galaxy of fixed FIR luminosity has a approximately constant flux density over the redshift range \(z \sim 1 - 10\) \cite{14}. Consequently the bolometer array SCUBA \cite{14}, operating on the 15-m JCMT, is now able to detect in a few hours a galaxy undergoing a burst of star formation similar in intensity to that in the low-z ULIRG Arp220 at any redshift out to \(z \sim 10\) \cite{15}.

In this paper we expand on our earlier work \cite{5} and present the first results from an extensive series of SCUBA observations aimed at measuring the rest-frame FIR properties of a large sample of high-z, steep-spectrum, radio-loud AGN covering the radio-luminosity:redshift \((P-z)\) plane \((25.0 < \log P_{151\text{MHz}}/\text{WHz}^{-1}\text{sr}^{-1} < 28.9, 0.1 < z < 5)\), as shown in figure 1.

Submillimetre measurements of radio-loud sources selected from various surveys (6C, 7C, 8C, LBDS) lead to an estimate of the dust masses, gas masses, FIR luminosities and SFRs in high-z elliptical galaxies, as well as the dependence of these physical properties on redshift (for a fixed radio luminosity) or AGN luminosity (for a given redshift bin).

The preliminary SCUBA observations of 30 radio galaxies, whilst concentrating on the highest radio-power sources at all redshifts \(z > 0.7\), have also endeavoured to provide a sub-sample with a narrower range (less than a factor 3) in radio luminosity and a similarly broad range in redshift \((z \sim 1 - 5)\). Whether one considers the weighted-mean 850 \(\mu\)m flux densities, binned in redshift, of all observed radio galaxies spanning a range of \(\sim 45\) in radio power, or the subset drawn from a significantly smaller range of radio power \((28.0 < \log P_{151\text{MHz}}/\text{WHz}^{-1}\text{sr}^{-1} < 28.5)\), both samples show a trend of increasing submillimetre flux density with increasing redshift (figure 2), extending to \(z > 3\).

The data obtained to date thus suggest that the dust enshrouded star formation in the massive ellipticals which host radio-loud AGN increases monotonically with redshift out to \(z > 3\). This result would clearly be consistent with a primary formation epoch of massive ellipticals at \(z \sim 4\). However, we caution that at present sub-mm luminosity and radio luminosity remain correlated in our sample (although less strongly correlated than \(S_{850,\mu\text{m}}\) and redshift). Further sub-mm observations should allow us to remove this bias and exploit high-redshift radio-galaxies as unbiased tracers of the evolution of SFR in massive ellipticals in general.
Figure 2: Submillimetre flux density vs. redshift for radio-loud AGN. The weighted-mean 850 µm flux densities of the entire sample of radio galaxies (solid circles) observed to date and the subset confined to a narrow band of AGN power, \((\log P_{151MHz}/\text{WHz}^{-1}\text{sr}^{-1}) = 28.0 \pm 28.5\), shown as open stars), are binned in redshift. In both cases the overall trend is for submillimetre flux density to increase with redshift and hence the result may be independent of AGN power. Given the strong negative K-correction at 850 µm which results in a galaxy of fixed rest-frame FIR luminosity having approximately constant flux density between redshifts \(z \sim 1\) – 10, this increase in submillimetre flux density suggests an increase in the star-formation rate in elliptical galaxies or their progenitors with redshift. The dotted-dashed and solid curves represent the 850 µm flux-density for the redshifted spectrum of Arp220 assuming \(\Omega_0 = 1.0\) and 0.1 respectively.

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