EXTREMELY RED GALAXIES IN THE PHOENIX DEEP SURVEY

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Abstract
The Phoenix Deep Survey (PDS) is a multiwavelength survey based on deep 1.4 GHz radio observations used to identify a large sample of star forming galaxies to \( z = 1 \). Here we present an exploration of the evolutionary constraints on the star-forming population imposed by the 1.4 GHz source counts, followed by an analysis of the average properties of extremely red galaxies in the PDS, by using the “stacking” technique.

Keywords: galaxies: evolution — galaxies: starburst — radio continuum: galaxies

1. Introduction
The study of galaxy evolution in recent years has included a strong focus on the star formation properties of galaxies. Many of these studies are based primarily on selection at ultraviolet (UV) and optical wavelengths, and are known to be strongly affected by obscuration due to dust. It has been shown that selection at these wavelengths results in samples of star forming systems that omit a significant fraction of heavily obscured galaxies [11]. There have in addition been suggestions that the most strongly star forming systems suffer the most obscuration [1, 8, 3, 12, 7]. Using radio selection to construct a star forming galaxy sample allows the detection of such systems, and the average obscuration in this case is significantly higher than in optically selected samples [1, 8].

To identify a homogeneously selected catalogue of star forming galaxies, unbiased by obscuration effects, and spanning a broad redshift range \((0 < z < 1)\), the Phoenix Deep Survey (PDS) uses a deep 1.4 GHz mosaic image, based on observations with the Australia Telescope Compact Array. This has been used to construct one of the largest existing deep 1.4 GHz source catalogues [6] (see http://www.atnf.csiro.au/people/ahopkins/phoenix/) from which the star forming galaxy sample will be drawn. The PDS has already been highly suc-
successful in providing a basis for several investigations of the nature of star forming galaxies and their evolution (see references in [6]). Throughout the present investigation we assume a ($\Omega_M = 0.3, \Omega_\Lambda = 0.7, H_0 = 70$) cosmology.

2. 1.4 GHz source counts and models

The PDS 1.4 GHz source counts have already been explored in detail [6]. Here we explore source count models based on local luminosity functions (LFs) and their assumed forms of evolution. We assume an evolving LF for AGNs [5] (converted to our assumed cosmology), since we are interested here in exploring the properties of the star-forming (SF) galaxies. We then use a measured local 1.4 GHz LF for SF galaxies [10], and compare the observed source counts with the model predictions subject to a range of both luminosity evolution, $L(z) \propto (1 + z)^Q$, and density evolution, $\phi(z) \propto (1 + z)^P$, for the SF population. The $\chi^2$ estimator for each combination of ($P, Q$), gives the statistical likelihood, and contours showing the region of maximum likelihood in the ($P, Q$) plane are shown in Figure 1. There is a clear degeneracy, with maximum likelihood occurring for any ($P, Q$) satisfying $Q \approx 2.7 - 0.6 P$ (note that only positive ($P, Q$) have been considered in this analysis). This sort of degeneracy has also been shown in investigations of optically selected galaxies [9].

To illustrate the effect of the degeneracy, Figure 2 shows the predicted source counts compared with the observations for five ($P, Q$) pairs, indicated by the positions a-e in Figure 1. The redshift distributions predicted by these models, however, are significantly different, and photometric redshifts are now being utilised in order to differentiate between the different evolutionary models.
3. Extremely red galaxies

A sample of over 400 extremely red galaxies (ERGs) has been compiled from PDS observations, using the colour criterion $R - K > 5$. Of these, about 20 are detected at 1.4 GHz, while the majority (over 90%) remain undetected. In an effort to understand more about the properties of these systems, the “stacking analysis” technique often used at X-ray wavelengths has been adopted. We extract sub-images from the radio mosaic at the location of the non-detected ERGs, and construct the weighted average of the sub-images (weighted by $1/rms^2$, to maximise the resulting signal-to-noise, since the radio mosaic has a varying noise level over the image). Sub-images where low S/N emission ($> 1.5 \sigma$) is present at the location of the non-detected source are excluded from the stacking, in order to avoid biasing the stacking signal result by the presence of a small number of low S/N sources. A further 22 (out of 399 candidate non-detected ERGs) were excluded in this manner, leaving 377 to contribute to the stacking signal. The stacked image, shown in Figure 3, has an rms noise of 1.1 $\mu$Jy, and a $\approx 6 \sigma$ detection at 6.5 $\mu$Jy. While the actual redshift distribution of these objects is unknown, a significant fraction of ERGs appear to be dusty starbursts at $z \approx 1$ [11]. Assuming that the average redshift of these sources is $z \approx 1$, the inferred average ERG 1.4 GHz luminosity is $3.5 \times 10^{22}$ W Hz$^{-1}$. This corresponds to an average star formation rate (assuming the ERGs are all star-forming systems) of $\approx 20 M_\odot$ yr$^{-1}$ (adopting the recent calibration of Bell 2003 [2]; this value doubles if the calibration of Condon 1992 [4] is used). Clearly these results rely on a large number of assumptions, but they serve the useful purpose of providing a preliminary esti-
Figure 3. Stacked image, incorporating 377 ERO candidates, from the PDS radio mosaic. The image rms is about $1.1 \, \mu Jy$, and the stacked signal is detected at $\approx 6 \sigma$ with a flux density of $6.5 \, \mu Jy$.

mate for the average properties of these systems in order to support proposals for further, more detailed investigation.

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