AGN and Starburst Galaxies Seen through Radio Surveys

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Abstract. The emergence of a new population of radio galaxies at mJy and sub-mJy levels is responsible for the change in the slope of the radio source counts. This population seems to include both star forming galaxies and classical (AGN-powered) radio sources, but the relative importance of the two classes is still debated. We present results from the ATESP radio survey and its optical follow-up and show that the fraction of starburst galaxies changes from $\sim 15\%$ at fluxes $\geq 1$ mJy to $\geq 50\%$ at lower fluxes.

1. Introduction

Recently, deep radio surveys ($S \lesssim 1$ mJy) have shown that normalized radio counts show a flattening below a few mJy, (see figure 1 for counts at 1.4 GHz). This change of slope is generally interpreted as being due to the presence of a new population of radio sources (the so-called sub–mJy population) which does not show up at higher flux densities (see e.g. Condon 1989), where the counts are dominated by classical radio galaxies and quasars.

The sub-mJy population is essentially composed by low luminosity AGN and starburst galaxies, but their relative contribution is still not firmly established. Unfortunately, due to the long observing times required to reach faint fluxes, the existing samples in the sub–mJy region are generally small.

The identification work and the subsequent spectroscopy are very demanding in terms of telescope time. Typically, no more than $\sim 50 - 60\%$ of the radio sources in sub–mJy samples have been identified on optical images, even though in the $\mu$Jy survey in the Hubble Deep Field and in SSA13 80% of the 111 radio sources have been identified (Richards et al. 1999). On the other hand, the
typical fraction of spectra available is only $\sim 20\%$. The best studied sample is the Marano Field, where 50\% of the sources have spectra (Gruppioni et al. 1999a), which permitted the determination of spectral type and redshift for 29 objects. To alleviate the identification work, regions with deep photometry already available (possibly multicolor) provide a significant advantage. The region we have selected fulfills these requirements at least partially.

2. The ATESP survey

Vettolani et al. (1997) made a deep redshift survey near the SGP by studying photometrically and spectroscopically nearly all galaxies down to $b_J \sim 19.4$. The survey, yielding 3342 redshifts (Vettolani et al. 1998), has a typical depth of $z = 0.1$ with 10\% of the objects at $z > 0.2$ and is 90\% complete.

In the same region a radio survey has been carried out with the ATCA (Australia Telescope Compact Array) at 1400 MHz (Prandoni et al. 2000a,b). It consists of 16 radio mosaics with $\sim 8'' \times 14''$ resolution and uniform sensitivity (1$\sigma$ noise level $\sim 79$ $\mu$Jy) over the whole area of the ESP redshift survey ($\sim 26$ sq. degrees at $\delta \sim -40^\circ$). We detected 2960 distinct radio sources down to a flux density limit of $\sim 0.5$ mJy (6$\sigma$), 1403 being sub–mJy sources.
Figure 2. Redshift distribution for the different spectral classes.

We used the ATESP catalogue to derive the differential ATESP source counts down to 0.70 mJy (Prandoni et al. 2000c). These counts are compared with the most updated previous determinations at 1.4 GHz (see Fig. 1). Also shown is the interpolation determined by Windhorst et al. (1990) from a collection of 10,575 radio sources belonging to 24 different surveys at 1.4 GHz, representing the state of the art at that time (solid line). There is consistency between the ATESP counts and those obtained by other recent surveys, with the exception of the Phoenix Deep Survey (PDF and PDFS, Hopkins et al. 1998), whose counts at $S \geq 0.7$ mJy are systematically higher than the ATESP counts (and also higher than the counts derived from the other surveys presented in the figure).

The ATESP counts are in very good agreement with the FIRST counts (White et al. 1997), which are the most accurate available today over the flux range 2–30 mJy. The ATESP survey, on the other hand, provides the best determination of the counts at fainter fluxes ($0.7 < S < 2$ mJy), where the FIRST becomes incomplete. The ATESP counts can thus provide an useful observational constraint on the evolutionary models for the mJy and sub–mJy populations.
Table 1. Composition of faint radio population

| Type          | All | $S < 1$ mJy | $S \geq 1$ mJy |
|---------------|-----|-------------|----------------|
|               | $N$ | $N$         | $N$            |
|               | %   | %           | %              |
| Ell+liner     | 34  | 7 (29%)     | 27 (60%)       |
| AGN           | 5   | 1 (4%)      | 4 (9%)         |
| Spiral disks  | 14  | 6 (25%)     | 8 (18%)        |
| SB + post-SB  | 16  | 10 (42%)    | 6 (13%)        |
| All           | 69  | 24 (35%)    | 45 (65%)       |

3. The ATESP-EIS Sample

In the same region lies the EIS (ESO Imaging Survey, Nonino et al. 1999) Patch A (3.2 sq. degr.), consisting of deep images in the I band out of which a galaxy catalogue to $I=22.5$ has been extracted. For 218 out of 384 radio sources ($S \geq 0.5$ mJy) in 2.97 square degrees of the EIS-A an optical identification was found; we obtained spectra at the ESO 3.6m telescope of a complete sample of 69 galaxies brighter than $I = 19.0$. The high signal to noise ratio of these spectra permits an unambiguous spectral classification of the whole sample. We divided the galaxy-identifications into several standard groups; this classification, based on spectral type, essentially distinguishes between AGNs, which, for weak radio sources, are mostly elliptical galaxies without strong emission lines (although also a few Seyfert type spectra are present), and starburst galaxies (McCall et al. 1985), which are often spiral galaxies in a particularly active phase of star formation. As expected, we found a number of these starburst galaxies, which are characterized by high excitation $H II$ region-like spectra, but also some post-starbursts. The latter have either strong $H\delta$ absorption on top of a K-type spectrum without emission lines, or show $H\alpha$ and $H\beta$ in emission and higher order lines (from $H\delta$ on) strong but in absorption. In addition some spectra are characteristic of galaxy disks of late type spirals: in those cases some emission is present ([OIII],[OII], $H\alpha$ and NII) but at a lower level than in the starburst galaxies. Finally, one typical LINER (Heckman 1980) was found.

Figure 2 shows the redshift distribution of the different spectral classes. The mean redshift distribution of the whole sample is $z=0.20$; in particular starburst and post-starburst galaxies are nearer than ellipticals, in good agreement with the results from FIRST (Magliocchetti et al. 2000).

4. The mJy and sub-mJy Population

The faint radio source composition resulting from the ATESP-EIS spectroscopic sample classification is presented in Table 1, where sub-mJy and mJy regimes have been considered separately. We notice that the good quality of the spectra allowed us to classify all objects (in previous spectroscopic studies of sub-mJy samples about 15-20% of the objects were not classified due to poor spectroscopy).

Our data clearly show that the AGN contribution does not significantly change
Figure 3. Flux density versus I magnitude; lines represent constant radio to optical ratio, defined as: \( R = \frac{S_{1.4 \text{GHz}}}{10^{0.4(I-12.5)}} \). Symbols represent the different classes of objects: Ell. + Liners (circles), spiral disks (squares), SB + post-SB (stars) and AGN (triangles).

Going to fainter fluxes (from 9% to 4%), that early-type galaxies largely dominate (60%) the mJy population, while star-formation processes become important in the sub-mJy regime: SB and post-SB galaxies go from 13% at \( S \geq 1 \) mJy to 42% at \( S < 1 \) mJy. Nevertheless, at sub-mJy fluxes, early-type galaxies still constitute a significant fraction (29%) of the whole population. As shown in Fig. 3 where we plot the radio flux densities against the I magnitudes for the whole sample, this seems to be particularly true going to fainter magnitudes. In fact at \( I > 18\) 40% (2/5) of the sub-mJy sources are early-type galaxies (circles) and the fraction of starburst galaxies (stars) in only 20% (1/5).

The latter result, even though based on a very small number of objects, is in agreement with the result obtained from the analysis of the Marano Field sub-mJy sample (Gruppioni et al. 1999a), and suggests that star-forming galaxies dominate the sub-mJy population only at bright magnitudes. Deeper spectroscopy for the ATESP-EIS sample will be crucial in order to verify this indication on a reliable statistical basis.

Fig. 3 also indicates a possible physical interpretation of this result: star-forming galaxies are characterized by smaller radio to optical ratios (\( 10 < R < 100 \)), that is have weaker intrinsic radio emission, than early-type galaxies (\( R \geq 100 \)). If this behaviour holds going to fainter fluxes, a larger fraction of star-forming
galaxies is expected in $\mu$Jy samples. This hypothesis is supported by the study of the $\mu$Jy sources in the Hubble Deep Field, the majority of which seem to be associated with star-forming galaxies (Richards et al. 1999).

5. Perspectives

In order to improve our knowledge of the sub-mJy population it is crucial to obtain deeper optical images and/or fainter radio samples. The first step will be to analyze the UBVRI images of DEEP-1 field (EIS survey) which overlaps a sub-region of the ATESP survey. At a limiting magnitude of about $I=26$ we estimate to identify 70-80\% of the 135 radio sources present in the field. Furthermore the same region will be observed at 5 GHz with the ATCA; radio spectral index and radio source structure will provide important clues on the nature of sub-mJy sources and put strong observational constraints on evolutionary models.

The next step is to have a $\mu$Jy sample with high quality spectroscopy; the VLA data at 1.4 GHz for the deep field of the VIRMOS spectroscopic survey (Le Fèvre, these proceedings) fulfill these requirments.

References

Ciliegi P., McMahon R.G., & Miley G., et al. 1999, MNRAS, 302, 222
Condon, J.J. 1989, ApJ, 338, 13
de Ruiter, H.R., Zamorani, G., Parma, P., et al. 1997, A&AS, 319, 7
Gruppioni, C., Zamorani, G., de Ruiter, H.R., et al. 1997, MNRAS, 286, 470
Gruppioni, C., Mignoli, M, Zamorani, G. 1999a, MNRAS, 304, 199
Gruppioni, C., Ciliegi, P., Rowan-Robinson, M., et al. 1999b, MNRAS, 305, 297
Heckman, T.M. 1980, A&A, 87, 152
Hopkins, A.M., Mobasher, B., Cram, L., & Rowan-Robinson, M. 1998, MNRAS, 296, 839
Magliocchetti M., Maddox, S.J., Wall, J.V., et al. 2000, MNRAS, submitted
McCall, M.L., Rybski, P.M., & Shields, G.A. 1985, ApJS, 57, 1
Nomino, M., Bertin, E., da Costa, L., et al. 1999, A&AS, 137, 51
Prandoni, I., Gregorini, L., Parma, P., et al., 2000a, A&AS, in 146, 31
Prandoni, I., Gregorini, L., Parma, P., et al., 2000b, A&AS, 146, 41
Prandoni, I., Gregorini, L., Parma, P., et al., 2000c, A&A, in press
Richards, E.A. 2000, ApJ, 533, 611
Richards, E.A., Kellerman, K.I., Fomalont, E.B. et al. 1999, ApJ, 526, L73
Vettolani, G., Zucca E., Zamorani, G., et al. 1997, A&A, 325, 954
Vettolani, G., Zucca E., Merighi, R., et al. 1998, A&AS, 130, 323
White, R.L., Becker, R.H., Helfand, D.J., & Gregg, M.D. 1997, ApJ, 475, 479
Windhorst, R.A., Mathis, D., & Neuschaefer, L. 1990. In: Kron R.G. (ed.) Evolution of the Universe of Galaxies, ASP Conf. Ser., 10, 389