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The AGN component in deep radio fields: Results from the First Look Survey

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We are currently exploiting the deep radio/optical/IR information available for the extra-galactic component of the Spitzer First Look Survey (FLS) to investigate the physical properties of faint radio-selected AGNs, with the aim of studying the AGN component of sub–mJy radio fields. One of the key unresolved issues is whether, as a function of cosmic epoch, low-power AGNs are more related to efficiently accreting systems (mostly radio-quiet) or to systems with very low accretion rates (mostly radio-loud). Here we present a sample of optically identified radio-emitting AGNs extracted from the FLS. Preliminary results show that at the flux densities probed by the FLS ($S_{1.4\mathrm{GHz}} \gtrsim 100$ μJy) we still have a significant number of radio–loud AGNs, similarly to what found in 'brighter' sub–mJy radio samples. Very interestingly, however, we have also a clear and direct evidence of a population of radio–emitting AGNs in the FLS, whose properties are consistent with those expected from existing radio–quiet AGN modeling. Such AGNs could be recognised as such thanks to the availability of IR colors which proved to be especially useful to efficiently separate radio sources triggered by AGNs, from sources triggered by star-formation. This latter result supports the idea that radio–quiet AGNs are not necessarily radio silent, and very promisingly may indicate that the bulk of the radio–quiet AGN population could emerge from studies of deeper radio samples.

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1. Scientific background

After a decade of multi-wavelength studies of deep radio fields it is rather clear that star-forming galaxies dominate at microJy (μJy) levels, while radio sources associated to early–type galaxies, and plausibly triggered by AGNs, are the most significant source component at flux densities $> 50-100$ μJy ($\sim 60-70\%$ of the total) with a further 10% contribution from broad-/narrow-line AGNs (see e.g. [9, 19, 1, 16, 21]).

The somehow unexpected presence of large numbers of AGN–related sources at sub-mJy fluxes has given a new interesting scientific perspective to the study of deep radio fields. Of particular interest is the possibility of studying the physical and evolutionary properties of such low power/high redshift AGNs. One of the key unresolved issues is for instance whether, as a function of cosmic epoch, the low-power AGNs are more related to efficiently accreting systems - like radio-intermediate/quiet quasars - or to systems with very low accretion rates - like e.g. FRI radio galaxies ([5]). The latter scenario (radio mode) is supported by the presence of many optically inactive early type galaxies among the sub–mJy radio sources; whereas the quasar mode scenario may be supported by the large number of so-called radio-intermediate quasars observed at mJy levels (see e.g. [13]) and by the modeling work of [11], who predict large numbers od radio-quiet AGNs at sub-mJy levels.

Assessing such a question would have relevant impact on topics like: the role played by low accretion/radiative efficiency AGNs in the global black-hole-accretion history of the Universe; the relative contribution of radiative versus kinetic (jet-driven) feedback to the global AGN feedback in models of galaxy formation; and, more generally, would allow us a better understanding of the triggering mechanisms of AGN radio activity.

2. The First Look Survey

The First Look Survey was the first major scientific program carried out by the Spitzer Space Telescope. As part of the extragalactic component of the First Look Survey (FLS), a region covering 4 square degrees and centered on RA=17:18:00, DEC=59:30:00 was imaged, with the aim of studying a low Galactic Background region to a significantly deeper level than any previous large-area extragalactic infrared survey. Such a survey was complemented by a smaller 0.75x0.3 sq. degr. survey ('verification' survey), lying in the same region, observed to a factor of 3 deeper flux levels.

Spitzer images and source catalogues are available at 3.6, 4.5, 5.8, 8.0 μm (IRAC, [14]) and at 24, 70, 160 μm (MIPS, [4, 6]), complemented by a large set of ancillary data taken at different wavebands: from deep optical imaging (R-band, [3]; u*-/g*-bands, [20]) and spectroscopy ([22, 18, 15]) to deep (rms noise level 23-30 muJy) radio images at 1.4 GHz (VLA, [2]) and 610 MHz (GMRT, [7]). A deeper (rms noise level 8.5 muJy) 1.4 GHz mosaic was obtained at Westerbork for a 1 sq. degr. region covering the FLSv ([17]).

The availability of both deep radio and far-infrared data is of particular interest, since we can exploit the well-known tight correlation between far-IR and radio luminosities of star-forming galaxies (see e.g. [10, 8]) to efficiently separate radio sources triggered by AGNs. Very useful is also the availability of data at two radio frequencies – 0.61 and 1.4 GHz – which allows us to derive the

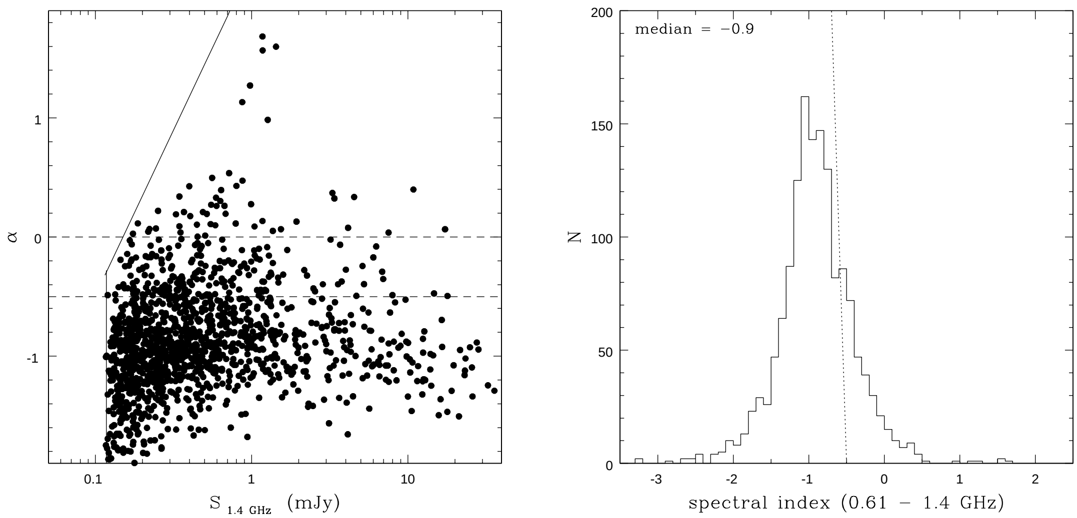

Figure 1: *Left:* $0.61-1.4$ GHz spectral index against 1.4 GHz flux density for the FLS sources. Horizontal lines indicate $\alpha=-0.5$ and $\alpha=0$, i.e. the spectral index values conventionally dividing steep– from flat–spectrum sources and flat– from inverted–spectrum sources. The vertical line indicates the limit of the VLA catalogue ($S_{1.4\mathrm{GHz}}\sim 0.12$ mJy), while the diagonal line indicate the maximum spectral index values to which the present work is sensitive due to the GMRT flux density limit ($S_{0.61\mathrm{GHz}}\sim 0.15$ mJy). *Right:* Distribution of FLS sources as a function of α. The dotted vertical line corresponds to $\alpha=-0.5$.

source spectral index (α). This is important since different accreting regimes may display different spectral signatures in the radio domain.

3. Derivation of source spectral index

Radio sources from VLA and GMRT catalogues were cross-identified, and radio spectral indices between 0.61 and 1.4 GHz were derived (see Fig. 1). As expected, most such objects are steep-spectrum radio sources ($\alpha<-0.5$). Nevertheless the spread in the spectral distribution is wide, with a significant number of flat ($-0.5<\alpha<0$) or inverted sources ($\alpha>0$). This indicates the presence of an heterogeneous population, consisting in a mixture of flat/steep-spectrum AGNs and steep star-forming galaxies. A number of ultra-steep spectrum sources ($\alpha<-1.1$) could be ascribed to a population of high-redshift galaxies.

4. Multi-wavelength analysis of FLS radio sources: radio–loud AGNs

The two-frequency FLS radio catalogue was cross-correlated with the Spitzer IRAC multi-color (3.6, 4.5, 5.8, 8.0 μm) catalogue ([14]), with the MIPS 24 μm catalogue ([4]) and with the optical spectroscopy catalogues of [15] and [18]. Identifying the optical counterpart of the sources is crucial to get information on both the galaxy redshift and classification (broad/narrow-line AGN, star-forming or early-type galaxy). An optical identification was found for $\sim 20\%$ of the sources,

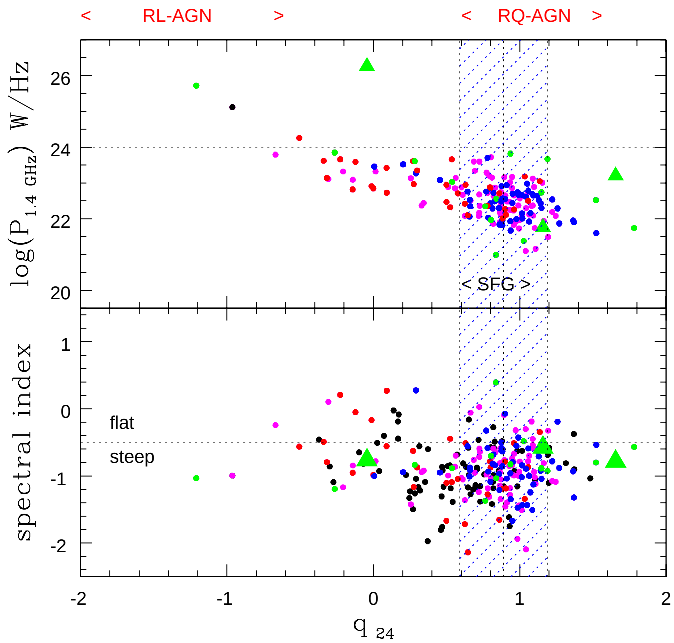

Figure 2: 1.4 GHz luminosity (top) and $0.61-1.4$ GHz spectral index (bottom) as a function of $q_{24} = log(S_{24\mu m}/S_{1.4GHz})$ for the optically identified FLS radio sources. The expected location or star-forming galaxies is shown by the blue shaded region. Symbols refer to optical spectral classification: star-forming galaxies (blue); early-type galaxies (red); broad/narrow emission-line AGN spectra (green triangles/dots); spectra showing narrow emission lines, but whose spectral features do not allow an unambiguous SFG vs. AGN classification (magenta); no spectral information (black).

most of which have a measured redshift. In the following we will focus on the sample of optically identified sources, and use it to extract from the FLS a robust sub-sample of radio-emitting AGNs. A first analysis of the multi-wavelength properties of the optically identified radio sources in the FLS is illustrated in Figure 2, where we plot the 1.4 GHz radio power (top) and the 0.61-1.4 GHz spectral index (bottom) as a function of the so-called q_{24} parameter, defined as the ratio between the 24 μm and the 1.4 GHz source flux density ($q_{24} = log(S_{\rm 24mum}/S_{\rm 1.4GHz}$). The q_{24} value range allowed for star-forming galaxies is shown by the blue shaded region ([15]). Radio-loud AGNs are located at the left side of such region (corresponding to an excess of radio emission with respect to infrared). As found in 'brighter' sub-mJy samples (see e.g. the ATESP sample, [16]) we have a significant fraction of radio-loud AGNs in the FLS, and among them we have several flat-/inverted–spectrum sources, whose properties are currently under further analysis. Such radio–loud AGNs have mostly low radio powers ($P_{\rm 1.4GHz} < 10^{24}$ W/Hz) and are preferentially identified with early-type galaxies (shown in red) or weak narrow line systems (shown in magenta). Such properties are consistent with those of low power (FRI-type) radio galaxies, typically characterized by very low accretion rates.

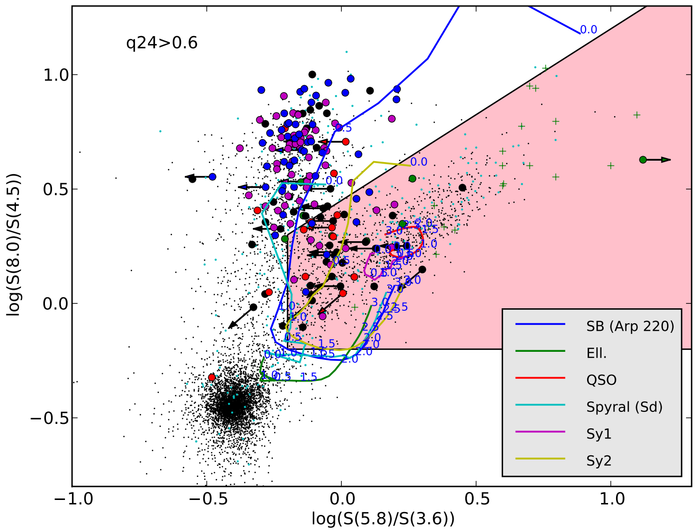

Figure 3: IRAC color-color plot of the FLS radio sources with $q_{24} > 0.6$ (filled symbols), i.e. for sources with infrared-to-radio ratios consistent with the ones of star-forming galaxies and/or radio-quiet AGNs. Colors refer to optical spectral classification as in Figure 2. Arrows indicate upper/lower limits. The expected IRAC colors as a function of redshift for different source types are shown by different lines (see legenda in the plot). The expected location for AGNs is highlighted in pink. For reference we also show IRAC colors of: *a)* all FLS IRAC-identified radio sources (no optical identification selection applied, cyan dots); *b)* the entire FLS IR-selected star/galaxy population (no radio selection applied, black dots); and *c)* a sample of high redshift obscured (type-2) quasars (see Martinez-Sansigre et al. 2006, green crosses).

5. Multi-wavelength analysis of FLS radio sources: radio–quiet AGNs

As shown in Figure 2 the bulk of the FLS radio sources are characterized by $q_{24} > 0.6$, i.e. by q_{24} values consistent with the sources being star-forming galaxies. Nevertheless only a fraction of such objects is optically classified as star-forming galaxy (blue points). A few sources are instead optically classified as AGNs (green points). Such AGNs represent a first very clear direct evidence of a radio-quiet AGN population showing up at the radio flux levels of the FLS. In addition we have a few sources classified as early-type galaxies (red points) and a significant fraction of sources displaying narrow emission lines, which do not have a secure classification (magenta points). Among such sources we may have several other hidden radio–quiet AGNs.
In order to better disentangle radio sources triggered by star formation from those triggered by AGNs, we exploit the available IRAC colors. Figure 3 shows the IRAC color-color plot for FLS sources with $q_{24} > 0.6$. As expected sources optically classified as star-forming galaxies (blue points) are confirmed as such by their IRAC colors, together with many of the sources with no secure optical classification (magenta points). Nevertheless we have a fraction of sources with typical AGN IRAC colors (objects falling in the pink region), which can be considered as genuine radio-quiet AGNs. Their radio properties ($P_{1.4GHz} < 10^{24}$ W/Hz; steep radio spectrum, see Figure 2) are fully consistent with those expected for the radio-quiet AGN population and, as expected, they are

mostly associated to galaxies showing emission lines in their optical spectra ([11, 12]).

6. Conclusions

We are currently exploiting the deep radio/optical/IR information available for the FLS to investigate the physical properties of faint radio-selected AGNs. Such a study is to be included in a more general analysis of several radio deep fields with multi-wavelength information available, with the aim of studying the AGN component of the sub-mJy radio fields.
Preliminary results show that the availability of IR colors proves to be very useful in disentangling star-forming galaxies from AGNs, allowing us to uncover a population of radio-quiet AGNs, which does not emerge from the radio/optical analysis only. The FLS radio-quiet AGN sample represents a first very clear direct evidence of a radio-quiet AGN population showing up at 1.4 GHz flux densities of the order of $S \sim 100\ \mu$Jy, supporting the idea that radio-quiet AGNs are not necessarily radio silent. This result is very promising, possibly indicating that the bulk of the radio-quiet AGN population may be discovered going to deeper radio flux densities than the FLS flux limit.

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