EVOLUTION OF AGN AND STELLAR FORMATION THROUGH RADIO SURVEYS

LORETTA GREGORINI[1,2], ISABELLA PRANDONI[1]
[1] Istituto di Radioastronomia CNR, Bologna, Italy
[2] Dipartimento di Fisica, Universita di Bologna, Italy

ABSTRACT. The change in the slope of the radio source counts suggests the emergence of a new population of radio galaxies at mJy and sub-mJy levels. Our understanding of such faint radio sources has advanced over the last decade through increasingly sensitive radio surveys and follow-up works at optical wavelength. The sub–mJy 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. Recent results are reviewed and discussed.

1. Introduction

Differential radio source counts derived from deep 1.4 GHz surveys show a flattening below a few milliJanskys (Fig.1). This change in slope is usually interpreted as the result of the emergence of a new population which does not appear at higher flux densities, where the counts are believed to be dominated by the classical powerful radio galaxies and quasars, triggered by an active galactic nucleus (AGN).

To explain the new faint radio population several scenarios have been invoked: strongly-evolving normal spirals (e.g. Condon 1984, 1989); a non-evolving population of local ($z < 0.1$) low-luminosity galaxies (e.g. Wall et al. 1986); actively star forming galaxies (e.g. Rowan-Robinson et al 1993). The latter scenario is strongly supported by extended optical identification works, showing that the counterparts of faint radio sources are often blue, disk galaxies (e.g. Thuan and Condon 1987), with disturbed morphology and/or in merging galaxy systems. The energy source in such galaxies is ultimately stellar, possibly entirely from supernovae explosions, widespread over the whole galaxy.

However, nuclear emission could be important also at low radio fluxes. Both low luminosity AGNs and nuclear star formation have been suggested as possible mechanisms for producing the radio emission. In fact, to determine the dominant source in any galaxy it is necessary to obtain from observations its radio morphology and brightness, together with the morphology and spectrum of the optical counterpart.

2. Active Galactic Nuclei

Radio and optical quasars, Seyfert galaxies, radio galaxies and blazars constitute a variety of astrophysical phenomena which may be interpreted as due to the existence of

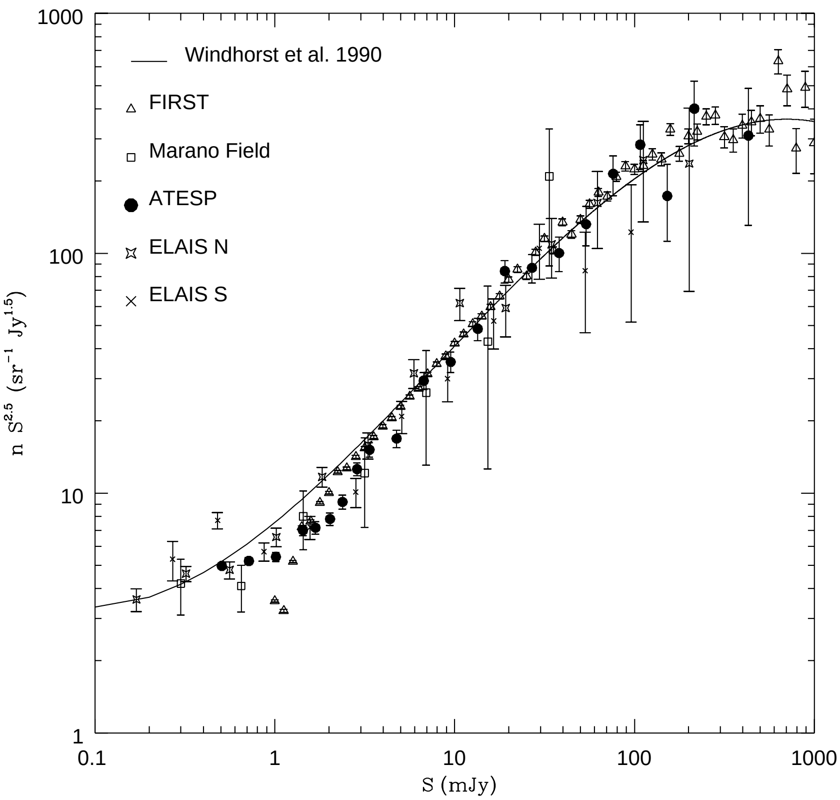

Fig. 1. Radio source counts at 1.4 GHz (normalized to Euclidean ones) as a function of ux for di erent samples (see Tab. 1): FIRST (triangles), Marano Field (squares), ATESP (lled circles), ELAIS North (stars) and ELAIS South (crosses). The t obtained by Windhorst et al. (1990) is also shown (solid line)

a massive black-hole (BH) in galaxy nuclei. Powerful spectrographs and high-resolution imagers on optical (HST) and X-ray telescopes (ROSAT and ASCA) allow to test the presence of a BH (M_{BH} 10^6 3 $10^9 M_{sun}$) in a few nearby galaxies, via gas and stellar dynamics. Models on quasars (e.g. Cavaliere and Padovani 1989) suggest that the AGN phenomenon is short-lived and probably recurrent, implying that a signi cant fraction of massive galaxies should contain a inactive BH. Recently Vercellone and Franceschini (1999) explored the dependence of the galaxy nucleus emissivity at various wavelengths on the BH mass, using estimates of M_{BH} for a sample of nearby galaxies.

Tab. 1
Faint 1.4 GHz Radio Surveys

Survey	References	Survey	References
NVSS	Condon et al. 1998	PDF	Hopkins et al. 1998
FIRST	White et al. 1997		Georgakakis et al. 1999
VLA-NEP	Kollgaard et al. 1994	B93[a]	Benn et al. 1993
ATESP	Prandoni et al. 1999	Marano Field	Gruppioni et al. 1997
LBDS	Windhorst et al. 1984		Gruppioni et al. 1999a
	Kron et al. 1985	Lockman Hole	de Ruiter et al. 1998
ELAIS N	Ciliegi et al. 1999	1300+30	Mitchell & Condon 1985
ELAIS S	Gruppioni et al. 1999b	HDF+HFF[b]	Richards 1999

[a] Sample of radio sources studied by Benn et al. (1993). It collects sources from three deep 1.4 GHz radio fields: 0846+45 (Lynx 3A, Oort 1987), 0852+17 (Condon & Mitchell 1984) and 1300+30 (Mitchell & Condon 1985).
[b] Hubble Deep Fields + Flanking Fields region.

They found a tight relationship of the BH mass with both the nuclear and the total radio flux at 5 GHz, which is thus a very good tracer of a super-massive BH and a good estimator of its mass.

The fraction of sources below 1 mJy associated with elliptical galaxies at $z \sim 1$ found in very deep radio surveys (e.g. Gruppioni et al. 1997; Hammer et al. 1995) may be more distant examples and may offer the possibility to explore the evolution of the mass and distribution of black holes with cosmic epoch.

In a recent paper Ho (1999) used optical spectroscopic information for a sample of nearby early-type galaxies surveyed with the VLA, to establish the physical nature of the low-power radio cores present in these objects. Comparison of the observed radio continuum power with that expected from the thermal gas traced by the optical emission lines implies that the bulk of radio emission is nonthermal. The relation between radio power and line emission observed in this sample is consistent with the low-luminosity extension of similar relations seen in classical radio galaxies and luminous Seyfert nuclei. A plausible interpretation of this result is that the weak nuclear sources seen in these galaxies are simply the low-luminosity counterparts of more distant, luminous AGNs.

3. Star Forming Galaxies

The prototype of nearby starburst galaxies is M82 (Muxlow et al 1994) which shows the presence of many compact bright radio sources. Some of these sources show large flux changes over scales of a few years suggesting that they are radio supernovae (SN) associated with the initial supernova explosion; while size measurements (typically 2–3 pc) indicate that the bulk of them are associated with young SN remnants. Typical star formation rates for the sub–mJy/mJy starbursts range from 1 to 100 M_{sun} yr^{-1} (for massive stars with $M > 5M_{sun}$). These star formation rates can only be maintained for short periods ($< 10^{8-9}$yr) before depleting the available gas in these systems. Thus,

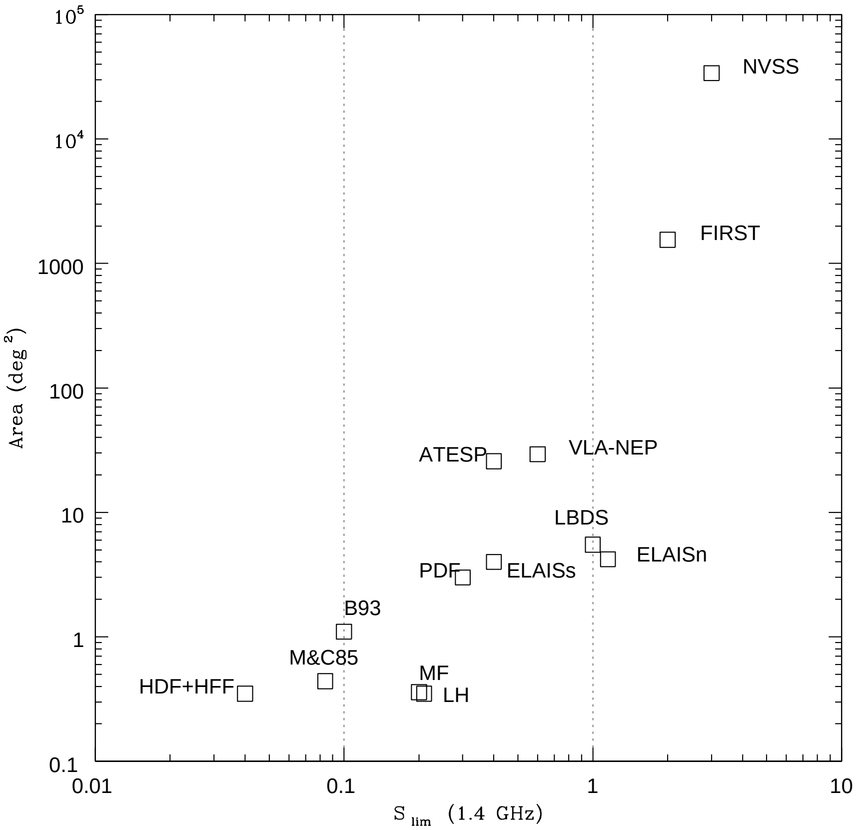

Fig. 2. Largest deep 1.4 GHz radio surveys: area covered (square degrees) vs. (80% completeness) ux limit (mJy). The two vertical lines show the 1 mJy and 0.1 mJy ux limits. Some of the surveys reported here do reach deeper uxes on sub-areas. For simplicity, this extra-information is not plotted. For more information on the surveys see references reported in Tab. 1.

radio emission which is almost extinction-free is a sensitive measure of recent starburst activity, where both UV and H observations are heavily a ected by internal absorption. Its utility relies on the hypothesis that the radio luminosity is directly proportional to the supernova rate. The radio-FIR correlation can be cited as support for this hypothesis. It is noteworthy that FIR samples are also extinction{free, but have very low spatial resolution, making very di cult the identi cation follow{up. Moreover, radio samples allow to study star{forming galaxies at a ux density level considerably deeper than the 60 Jy completeness limit of the IRAS Faint Galaxy Catalog and barely reachable in deep surveys carried out by the ISO satellites ($S_{60\ m}$ 10 20 mJy).

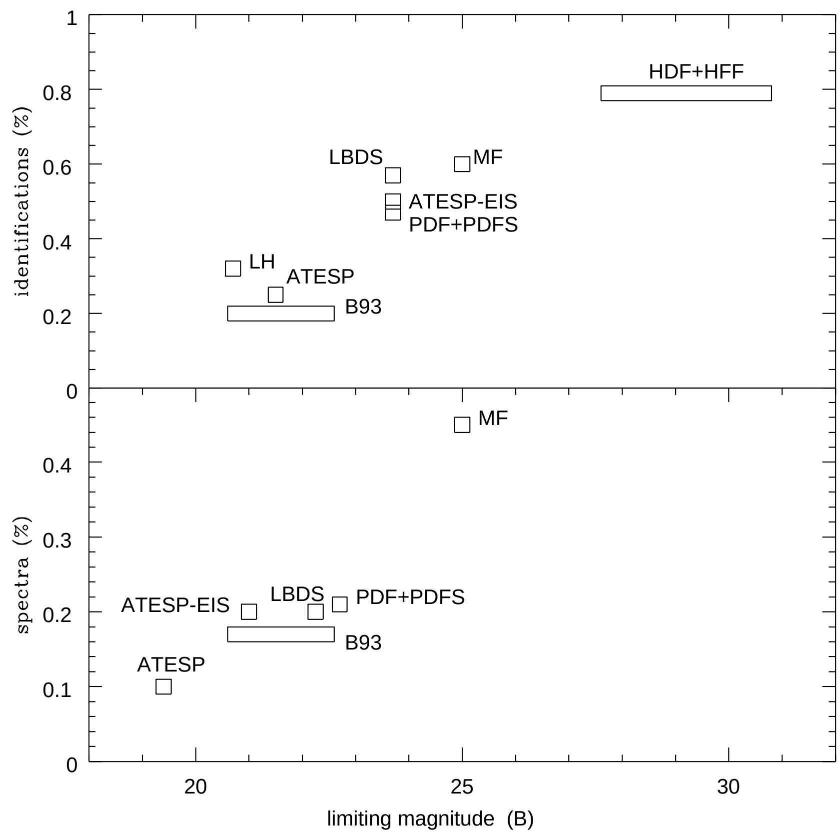

Fig. 3. 1.4 GHz sub-mJy surveys: optical follow-up. Top panel: fraction of radio sources identi ed (i.e. optical counterpart found from imaging) as a function of the limiting magnitude of the images. Bottom panel: fraction of radio sources with spectral information (redshift and possibly spectral classi cation) vs limiting magnitude of spectroscopy. References are reported in Tab. 1.

4. Faint Radio Surveys and Optical Follow{up

Our understanding of the faint radio sources has advanced over the last decade through increasingly sensitive radio surveys and follow{up works at optical wavelengths. The largest faint 1.4 GHz radio surveys available up to now are summarized in Tab. 1 and in Fig. 2, where we plotted the sky coverage versus the ux limit of the survey.

The realization of a survey is time-consuming; therefore the deeper the sensitivity, the smaller the area covered by the survey. For instance the deepest 1.4 GHz survey available (HDF+HFF in Fig. 2) is sensitive to Jy sources (ux limit 40 Jy), but it covers only a fraction of square degree (0.35 sq. degr.).

Tab. 2
mJy Population

survey	early-type %		late(S) %		AGN %		others %		N_{tot}
B93	45	20	27	16	9	9	18	13	11
PDF	62	14	17	7	14	8	7	5	29
ATESP-EIS	47	11	8	5	22	8	24	8	37

The ATESP survey (Prandoni et al. 1999), on the other hand, is a good compromise between flux limit (~ 0.4 mJy) and area covered (about 26 square degrees). This radio survey overlaps the region of the ESO Slice Project (ESP) galaxy redshift survey (Vettolani et al. 1997). The catalogue contains about 3000 radio sources, more than 1000 being sub-mJy sources.

Despite the effort devoted to study the faint radio population there are still open questions: (i) what is the stellar population in the sub–mJy/mJy radio sources; (ii) which is the relation between star–formation activity and radio properties; (iii) which is the relation to the local population of normal galaxies. In order to address these points optical/near-infrared photometry and optical spectroscopy are needed.

In Fig. 3 we summarize the optical follow-up available for the sub–mJy radio surveys shown in Fig. 2 (for references see Tab. 1). It is clear that for large radio samples it is very difficult to obtain deep optical imaging and spectroscopy and the fraction of sources identified is small. For instance $\sim 25\%$ of the ATESP radio sources have been identified, and only for $\sim 10\%$ spectra have been obtained. Nevertheless deeper imaging and spectroscopy is available for a sub-sample covering ~ 3 sq. degr. (ATESP-EIS, see Nonino et al. 1999). Typically, no more than $\sim 50-60\%$ of the radio sources in sub–mJy samples have been identified, even though in the Hubble Deep Field (HDF+HFF) an identification rate of about 80% is reached. On the other hand the typical fraction of spectra available is only $\sim 20\%$. The best studied sample is the Marano Field, where $\sim 45\%$ of the sources have spectral information.

5. Results

When discussing the results about the nature and physical properties of the mJy and sub–mJy population, the numbers reported above must be kept in mind. All the conclusions reached on the faint radio sources are based on samples, for which photometry and spectroscopy are only available for a fraction of the whole population and selection effects can introduce serious biases.

It is therefore very important to compare homogeneous samples, i.e. with same radio flux limit and same limiting magnitude for the optical counterparts. The role played by selection effects is clear when comparing the results obtained in the Marano Field and the ones reached by Benn et al. (1993). Gruppioni et al. (1999a) identified 44% of all the radio sources fainter than 1 mJy with early-type galaxies; on the contrary, Benn et al. (1993) found a dominance of blue narrow emission line objects, identified as

Tab. 3
sub–mJy Population

survey	early-type %	late(S) %	AGN %	others %	N_{tot}
$R < 18.5$					
B93	4 3	64 12	13 5	18 6	45
PDF	20 5	54 9	10 4	17 5	71
$R > 18.5$					
PDF	24 5	31 5	15 4	31 5	103
MF	47 16	37 14	16 9	–	19

star–forming galaxies, and a percentage of early-type galaxies of only about 8% . This apparent discrepancy is probably due to the deeper optical magnitude reached in the identification work by Gruppioni et al.: the fraction of sub-mJy early-type galaxies in the Marano Field increases around $B = 22.5$, which is approximately the magnitude limit reached by Benn et al.

In order to compare the results obtained from different works we classified the faint radio galaxy population in three main classes: (a) early-type galaxies (ellipticals and S0); (b) late(S) (star–forming galaxies); (c) AGN (objects with nuclear energy source, i.e. Seyfert 2, Seyfert 1 and QSO); (d) others (objects which cannot be classified in one of the three previous classes).

In Table 2 we summarize the composition of the mJy population, according to the data presented in the most recent works (see Tab. 1 for references). The survey name is in the first column; the fraction (%) of objects in each class is given in the following columns. To make a correct comparison of the different works we selected homogeneous sub–samples ($S_{1.4GHz} > 1$ mJy and magnitude $R < 18.5$). The last column of Tab. 2 lists the number of objects belonging the each sub–sample.

The comparison of the data presented in Tab. 2 shows that about 50% of the mJy population is represented by early-type galaxies. For the other components the values are not in complete agreement, even if we must underline that the differences are not statistically significant, due to the large errors. It is noteworthy that the high number (24%) of objects which could not be classified in the ATESP-EIS is paradoxically due to the high quality of the spectra. Most of them are peculiar objects with very complex spectral features, which makes difficult their classification. However the analysis of the radio and optical properties of these objects has shown that probably this class is equally composed by early-type galaxies, late(S) galaxies and AGN.

Table 3 lists the same quantities as in Tab. 2 for the sub-mJy sources. Here we distinguish between two optical magnitude bins ($R < 18.5$ and $R > 18.5$). The $R < 18.5$ bin in Tab. 3 can be directly compared with the statistics reported in Tab. 2. It is evident that there is a change in the dominant class going from mJy to sub–mJy sources: now star forming galaxies constitute half of the population. This result is in agreement with the hypothesis that the mJy population is the faint tail of the population (ellipticals and AGN) which dominate at high fluxes; while in the sub-mJy region a new population emerges where the radio emission is due to star formation phenomenon.

The $R > 18.5$ bin in Tab. 3 shows how the sub–mJy population changes going from bright ($R < 18.5$) to fainter magnitudes. While the fraction (10–15%) of AGN is almost independent on the optical magnitude, the contribution of star forming galaxies decreases in this faint optical bin from $\sim 1/2$ to $\sim 1/3$ of the whole population. However there is not complete agreement on the dominant class: the MF sample is dominated by early-type galaxies, whereas in the PDF sample (Georgakakis et al. 1999) the importance of star–forming and early–type galaxies is very similar. Nevertheless, it is worth to note that the fraction of $R > 18.5$ objects which are not classified in the PDF becomes very large (31%), making very difficult to draw any firm conclusion about the relative importance of the different classes in this sample. To summarize, it seems that:

a) radio sources with $S < 1$ mJy and bright optical counterpart are mainly star forming galaxies;

b) radio sources with $S < 1$ mJy and faint optical counterpart are mainly early-type galaxies.

Discrepancies are found also at fainter fluxes. The population in the microJy range was investigated by Hammer et al. (1995) and Richards et al. (1998). Again the samples are complete but very small (36 and 29 objects respectively) and the statistics very poor.

Hammer et al., using redshifts color and radio spectral indices, found that 40% of the sources probably lie at $z > 1$, and nearly half are early-type galaxies, frequently containing a low-power AGN nuclear source. They concluded that, since the space density of AGN-driven sources apparently overtakes those powered by stellar emission, the contribution of AGN light to the faint source counts should be re-evaluated.

On the contrary, Richards et al. concluded that the microJy radio galaxies are distributed over a wide range of redshifts ($0.1 < z < 3$) and are primarily composed of spiral and irregular/merging systems (70–90%) at modest redshifts ($0 < z < 1$). They concluded that the microJy sources are mainly located in nearby normal host galaxies, whose bolometric luminosity is dominated by starlight rather than an AGN.

To conclude, it is clear that more work is needed in order to understand nature and distance distribution of the faint radio population. In particular it is important to get complete identification and (good quality) spectroscopy follow–up for a deep radio sample, large enough to allow a reliable statistical study.

Aknowledgements The authors thank their collaborators: P. Parma, H. de Ruiter, M. Wieringa, R. Ekers and especially G. Vettolani, who read and commented an earlier version of this manuscript.

References

Benn C.R., Rowan-Robinson M., McMahon R.C., Broadhurst T.J., Lawrence A.: 1993, Mon. Not. R. Astr. Soc. 263,, 98.

Cavaliere A., Padovani P.: 1989, Astrophys. J. 340,, L5.

Ciliegi P., McMahon R.G., Miley G., Gruppioni C., Rowan-Robinson M., Cesarsky C., Danese L., Franceschini A., Genzel R., Lawrence A., Lemke D., Oliver S., Puget J-L., Rocca-Volmerange B.: 1999 Mon. Not. R. Astr. Soc. 302,, 222.

Condon J.J.: 1984 Astrophys. J. 287,, 461.

Condon J.J.: 1989 Astrophys. J. 338,, 13.

Condon J.J., Cotton W.D., Greiser E.W., Yin Q.F., Perley R.A., Taylor G.B., Broderick G.B.: 1998, Astron. J. 115,, 1693.

Condon J.J. & Mitchell K.J.: 1984, Astron. J. 89,, 610.

Cram L., Hopkins A., Mobasher B., Rowan-Robinson M.: 1998 Astrophys. J. 507,, 155.

Georgakakis A., Mobasher B., Cram L., Hopkins A., Lidman C., Rowan-Robinson M.: 1999, Mon. Not. R. Astr. Soc. 306,, 708.

Gruppioni C., Zamorani G., de Ruiter H.R., Parma P., Mignoli M., Lari C.: 1997 Mon. Not. R. Astr. Soc. 286,, 470.

Gruppioni C., Mignoli M., Zamorani G.: 1999a Mon. Not. R. Astr. Soc. 304,, 199.

Gruppioni C., Ciliegi P., Rowan-Robinson M., Cram L., Hopkins A., Cesarsky C., Danese L., Franceschini A., Genzel R., Lawrence A., Lemke D., McMahon R.G., Miley G. Oliver S., Puget J-L., Rocca-Volmerange B.: 1999b Mon. Not. R. Astr. Soc. 305,, 297.

Hammer F., Crampton D., Lilly S.J., Le Fevre O., Kenet T.: 1995, Mon. Not. R. Astr. Soc. 276,, 1085.

Ho L.C.: 1999 Astrophys. J. 510,, 631.

Hopkins A., Afonso J., Cram L., Mobasher B.: 1999 Astrophys. J. 519,, 59.

Kron R.G., Koo D.C., Windhorst R.A.: 1985 Astron. Astrophys. 146,, 38.

Kollgaard R.I., Brinkmann W., Chester M.M., Feigelson E.D., Hertz P.L., Reich P., Wielebinski R: 1994, Astrophys. J. Suppl. 93,, 145.

Mitchell K.J., Condon J.J.: 1985, Astron. J. 90,, 1957.

Muxlow T.W.B., Pedlar A., Wilkinson P.N., Axon D.J., Sanders E.M., de Bruyn A.G.: 1994 Mon. Not. R. Astr. Soc. 266,, 455.

Nonino M., Bertin E., da Costa L., Deul E., Erben T., Olsen L., Prandoni I., Scodeggio M., Wicenec A., Wichmann R., Benoist C., Freudling W., Guarnieri M.D., Hook I., Hook R., Mendez R., Savaglio S., Silva D., Slijkhuis R.; 1999, Astron. Astrophys.,, in press.

Oort M.J.A.: 1987, PhD Thesis, Univ. Leiden.

Prandoni I., Gregorini L., Parma P., de Ruiter H.R., Vettolani G., Wieringa M.H., Ekers R.D.: 1999, in Looking Deep in the Southern Sky eds. Morganti and Couch, p. 114.

Richards E.A.: 1999, in A&SS issue The Evolution of Galaxies on Cosmological Time Scale, in press. (the Universe at 2 < z < 5), eds. Holt and Smith, p. 350.

Richards E.A., Kellermann K.I., Fomalont E.B., Windhorst R.A., Partridge R.B.: 1998, Astron. J. 116,, 1039.

Rowan-Robinson M., Benn C.R., Lawrence A., McMahon R.G., Broadhurst T.J.: 1993, Mon. Not. R. Astr. Soc. 263,, 123.

de Ruiter H.R., Zamorani G., Parma P., Hasinger G., Hartner G., Treumper J., Burg R., Giacconi R., Schmidt M.: 1997, Astron. Astrophys. 319,, 7.

Vercellone S., Franceschini A.: 1999, Mem. R. Astr. Soc. 70,, 107.

Vettolani G., Zucca E., Zamorani G., Cappi A., Merighi R., Mignoli M., Stirpe G.M., MacGillivray H.T., Collins C.A., Balkowski C., Cayatte V., Maurogordato S., Proust D., Chincarini G., Guzzo L., Maccagni D., Scaramella R., Blanchard A., Ramella M.: 1997, Astron. Astrophys. 325,, 954

Thuan T.X., Condon J.J.: 1987, Astrophys. J. 322,, L9.

Wall J., Benn G., Grue G., Vigotti M.: 1986, in Highlights Astron., ed. Swings, p. 345.

Windhorst R.A., van Heerde G.M., Katgert P.: 1984, Astron. Astrophys. Suppl. Ser. 58,, 1.

Windhorst R.A., van Heerde G.M., Katgert P.: 1984, Astron. Astrophys. Suppl. Ser. 58,, 39.

Windhorst R.A., Mathis D., Neuschaefer L.: 1990, in Evolution of the Universe od Galaxies, ed. R.G. Kron, p. 389.

White R.L., Becker R.H., Helfand D.J., Gregg M.D.: 1997 Astrophys. J. 475,, 479.