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ASTRONOMY AND ASTROPHYSICS

On the local radio luminosity function of galaxies

I. The Virgo cluster*

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Abstract. We cross-correlate the galaxies brighter than $m_B = 18$ in the Virgo cluster with the radio sources in the NVSS survey (1.4 GHz), resulting in 180 radio-optical identifications. We determine the radio luminosity function of the Virgo galaxies, separately for the early- and late-types. Late-type galaxies develop radio sources with a probability proportional to their optical luminosity. In fact their radio/optical (R_B) distribution is gaussian, centered at $log R_B \sim -0.5$, i.e. the radio luminosity is $\sim$ 0.3 of the optical one. The probability of late-type galaxies to develop radio sources is almost independent of their detailed Hubble type, except for Sa (and S0+S0a) which are a factor of $\sim$ 5 less frequent than later types at any R_B.

Giant elliptical galaxies feed "monster" radio sources with a probability strongly increasing with mass. However the frequency of fainter radio sources is progressively less sensitive on the system mass. The faintest giant E galaxies ($M_B = -17$) have a probability of feeding low power radio sources similar to that of dwarf E galaxies as faint as $M_B = -13$.

Key words: galaxies: clusters: individual: Virgo cluster – galaxies: fundamental parameters – galaxies: luminosity function, mass function – radio continuum: galaxies

1. Introduction

A robust determination of the local (z=0) Radio Luminosity Function (RLF) of normal galaxies, jointly with similar determinations carried out at cosmological distances (e.g. Prandoni et al. 1998), is the essential tool for addressing several relevant cosmological issues, such as estimating the rate of evolution in galaxies, more directly than by modeling the distribution of the faint radio source counts (see Condon 1989).

Since the seventies this issue received strong attention among the scientific community, culminating with the analyses of elliptical galaxies by Auriemma et al. (1977) and of spiral galaxies by Hummel (1981). The study of the radio properties of late-type galaxies in the Coma supercluster by Gavazzi & Jaffe (1986) contributed establishing that the radio continuum luminosity of these galaxies is to first order proportional to their optical luminosity, and to second order to their current star formation rate. In other words, cosmic ray electron acceleration is provided primarily by type II supernovae explosions (see also Condon 1992) which are more abundant in massive spiral galaxies.

Deep radio surveys, carried out in the nineties with the VLA, provided the mean of re-determining the RLF of elliptical galaxies (Ledlow & Owen 1996), which turned out to be in remarkable agreement with the early determination of Auriemma et al. (1977). Their main finding is that the probability of E galaxies to develop powerful radio sources ($log P_{1.4} > 24\ W Hz^{-1}$) is strongly dependent on their optical luminosity ($L_B^{1.5}$). Below $log P_{1.4} = 24\ W Hz^{-1}$ this dependence becomes weaker with decreasing $P_{1.4}$.

Due to the lack of extensive radio and optical surveys of galaxies of both early- and late-type, the present knowledge is still limited to relatively bright radio sources ($log P_{1.4} > 21\ W Hz^{-1}$) and bright optical luminosities ($M_B < -18.0$), typical of giant galaxies.

To go one step further it seems natural to re-determine the RLF using the Virgo cluster, which contains thousands of galaxies, spanning a large luminosity range, from giant to dwarfs as faint as $M_B = -13$ mag. Surprisingly the latest systematic study of this cluster at centimetric wavelengths dates back 1981, when Kotanyi (1981) carried out with the WSRT a survey of this cluster. Not only these early measurement were limited by the current sensitivity (several mJy/beam), but also they lacked the necessary cluster coverage.

We are now in the position of re-addressing the issue taking advantage of the recent all sky NVSS radio survey carried out with the VLA (Condon et al. 1998) and of the supreme quality of the Virgo Cluster Catalogue (VCC) of Binggeli et al. (1985), which provides us with reliable photometry and classification for over 2000 galaxies. The major improvement of the new radio observations is not primarily their higher sensitivity, which is in fact only few times better than previously available, but mostly the unprecedented homogeneous sky coverage.

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* Table 1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

In this paper we make use of the NVSS data to construct the RLF of an optically complete ($m_B < 18.0$) sample of galaxies extracted from the VCC. With these data we wish to discuss two issues: i) is the dependence of the RLF on Hubble type well determined? ii) does the dependence of the RLF on galaxy mass, which is known to exist for giant galaxies, extend to the dwarf population? Issues i) and ii) are addressed in Sect. 4.

In a companion paper (Gavazzi & Boselli 1999: Paper II) we address another question: iii) is the local RLF of late-type galaxies universal or is it influenced by the environment? To study this issue we compare the RLFs of late-type galaxies in five nearby clusters (Virgo, Cancer, A262, A1367 and Coma) with that of galaxies in less dense regions of the universe at similar distances. $H_o = 75\ km\ s^{-1} Mpc^{-1}$ is used throughout this paper.

2. The sample

2.1. The optical data

The present investigation is based on the Virgo Cluster Catalogue (VCC) by Binggeli et al. (1985). The VCC catalogue contains 2096 galaxies brighter than $m_B = 20.0$. Photographic photometry with $\sim$ 0.35 mag uncertainty and detailed morphological classification are given in the VCC. The VCC coordinates are affected by $\sim$ 10 arcsec uncertainty (Binggeli et al. 1985) or slightly better. The VCC also contains a (morphological) estimate of the membership to the various structures constituting the Virgo cluster: cluster A (M87), cluster B (dominated by M49), W, W', M clouds, and Southern extension. General members and possible members are treated in this work as belonging to the cluster.

We use an updated version of the VCC containing the following improvements: i) for 305 galaxies listed in Binggeli & Cameron (1993) we substitute the eye estimated m_p with B_T obtained on digitized plates. ii) we include the redshift and consequent membership re-assignments given in Binggeli et al. (1993). We complement these data with (few) other redshifts found in the New Extragalactic Database (NED). iii) for 565 galaxies we substitute the celestial coordinates with the more precise ones (few arcsec) listed in NED. By comparing this set of new coordinates with the original VCC ones we find an rms difference of 6.75 arcsec. We extract from the catalogue a subsample of 1342 objects complete to $m_B = 18.0$. Among these, 589 have yet no redshift in the literature (140 are possible members, 379 belong to cluster B and another 70 are background galaxies). Based on the most recent Cepheyds determination, we consider members of clusters A and B, general members, members of clouds W', M and Southern extension at the distance of 17 Mpc. Members of W cloud are taken at 28 Mpc (see also Gavazzi et al. 1999).

2.2. 1.4 GHz continuum data

Radio continuum 1.4 GHz data in the regions covered by the present investigation are available from a variety of sources:

1) Full synthesis and snap-shot observations of specific regions were undertaken with the VLA and with the WSRT ("pointed" observations). Hummel (1980) and Kotanyi (1980) did observations of the Virgo cluster with the WSRT. Condon (1987) and Condon et al. (1990) observed with the VLA nearby galaxies projected onto the Virgo region. These surveys do not generally constitute a complete set of observations.

2) Recently, the all-sky NVSS survey (Condon et al. 1998) carried out with the VLA at 1.4 GHz became available. The D array (FWHM = 45 arcsec) NVSS survey covers the sky north of $\delta > -40°$, with an average rms=0.45 mJy. Except in specific regions of the sky near bright sources, where the local rms is higher than average, this survey offers an unprecedented homogeneous sky coverage. It not only provides us with extensive catalogues of faint radio sources, but also with homogeneous upper limits at any celestial position. The VCC region is covered by 13 NVSS maps which are available via the World Wide Web.

Since radio data from more than one source exist for several target galaxies, we choose between them adopting the following list of priorities:

1) in general we prefer NVSS data to any other source because of its homogeneous character, relatively low flux density limit and because its FWHM beam better matches the apparent sizes of galaxies under study, thus providing us with flux estimates little affected by missing extended flux.

2) For individual bright radio galaxies (e.g. M87) we prefer data from specific "pointed" observations since they should provide us with more reliable estimates of their total flux.

3) in all cases where the flux densities from NVSS are lower than those given in other references we privilege the reference carrying the largest flux density.

2.3. The radio-optical identifications

At the position of all optically selected galaxies we search for a radio-optical coincidence. For the remaining undetected galaxies we compute an upper limit flux using $4 \times rms$. For the purpose of our study we proceed as follows:

1) we pre-select sources from the NVSS data-base, allowing for a maximum radio-optical positional discrepancy of 45 arcsec, because of the large apparent size of the galaxies in this nearby cluster.

2) we inspect the NVSS maps at the position of all candidate radio-optical associations. We discard few spurious radio sources listed in the NVSS database, which turn out to be grating rings associated with strong radio sources. These belong to 3 regions of approximately 40 arcmin radius around M87, NGC 4261 (3C-270), and around the source $12^h30^m + 02$. In these regions we also re-compute the local rms radio noise.

3) at the position of all pre-selected optical-radio matches we compute an "identification class" (ID) according to a criterion which is a slight modification of the one adopted by Jaffe &

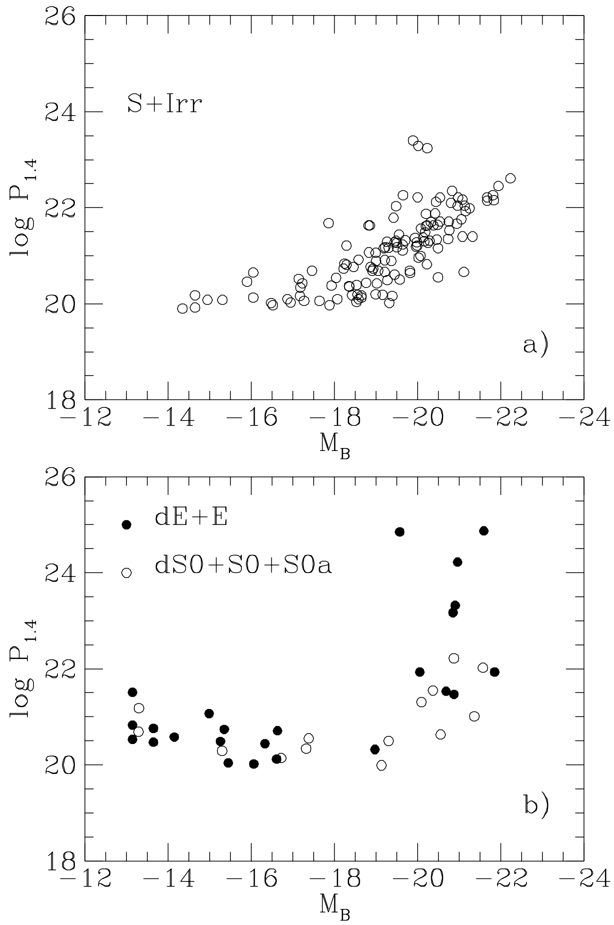

Fig. 1a and b. The correlation betwen the radio and optical luminosity for the detected galaxies. **a** late-type; **b** early-type.

Gavazzi (1986). For each galaxy we calculate the quantity:

$$R^2 = \frac{\Delta^2_{r-o}}{\sigma^2_g + \sigma^2_r} \tag{1}$$

where Δ_{r-o} is the radio − optical positional offset, σ_r is the radio position uncertainty, and σ_g is the uncertainty in the galaxy position. The latter quantity is assumed to be the 3% of the galaxy optical diameter plus the uncertainty in the optical position itself:

$$\sigma^2_g = 0.0009 \times A^2 + \sigma^2_o \tag{2}$$

where A is the galaxy optical major axis, and σ_o is the uncertainty in the optical position (see Sect. 2.1). The errors on the radio positions are assumed to be inversely proportional to the signal-to-noise ratio as:

$$\sigma_r = 0.5 \times FWHM \times \sqrt{rms/flux} + 0.3 \tag{3}$$

Identification class ID=1 includes pointlike radio sources with $R \leq 3$.

Identification class ID=2 are extended sources not meeting the 3σ criterion.

Identification class ID=3 are dubious identifications not meeting the 3σ criterion (not used in the following analysis).

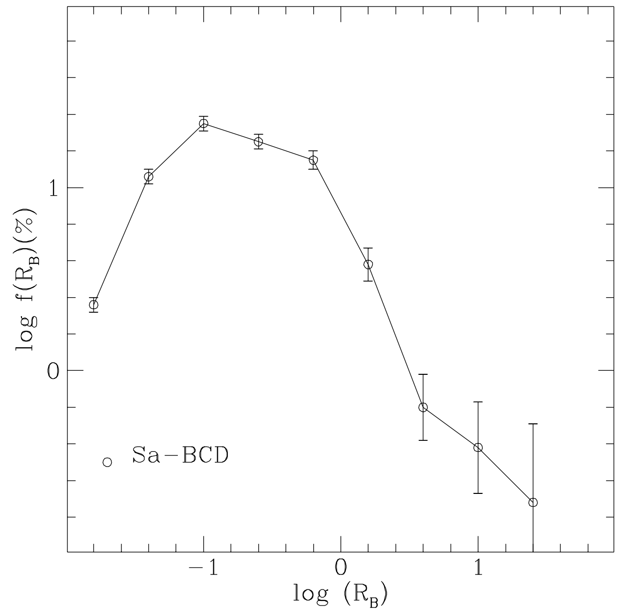

Fig. 2. The differential RLF as a function of the radio/optical ratio R_B for all late-type galaxies (Sa-BCD).

Identification class ID=4 include pointlike sources whose radio-optical offset is within the optical extent of the galaxy. These are dubious identifications, which are nevertheless used because off-set radio sources are often found associated with disk galaxies.

The 180 positive radio-optical matches are listed in Table 1 as follows:

Column 1: the VCC (Binggeli et al. 1985) designation.
Column 2: the photographic magnitude corrected for extinction in our Galaxy according to Burstein & Heiles (1982) and for internal extinction following the prescriptions of Gavazzi & Boselli (1996), except that the correction for internal extinction has been omitted for Irr and dwarfs.
Column 3: the morphological classification as given in the VCC.
Column 4: the membership to the individual clusters and clouds in the Virgo area as given in Binggeli et al. 1985 and revised in Binggeli et al. (1993).
Columns 5, 6: the (B1950) optical celestial coordinates of the target galaxy.
Columns 7, 8: the (B1950) celestial coordinates of the radio source.
Column 9: the radio-optical offset (arcsec).
Columns 10: the identification class (see above).
Column 11: the 1.4 GHz total flux density (mJy).
Columns 12, 13: the extension parameters of the radio source (major and minor axes in arcsec).
Column 14: reference to the 1.4 GHz data. All except 12 identifications are based on NVSS data.

All our ID=1 sources are found within 35 arcsec from the central optical coordinates of the parent galaxies. Some (generally fainter than 10 mJy) ID=2 and ID=4 sources lie between 35 and 45 arcsec. An estimate of the number of possible chance-identifications ($N_{c.i.}$) among the 180 sources/galaxies listed in

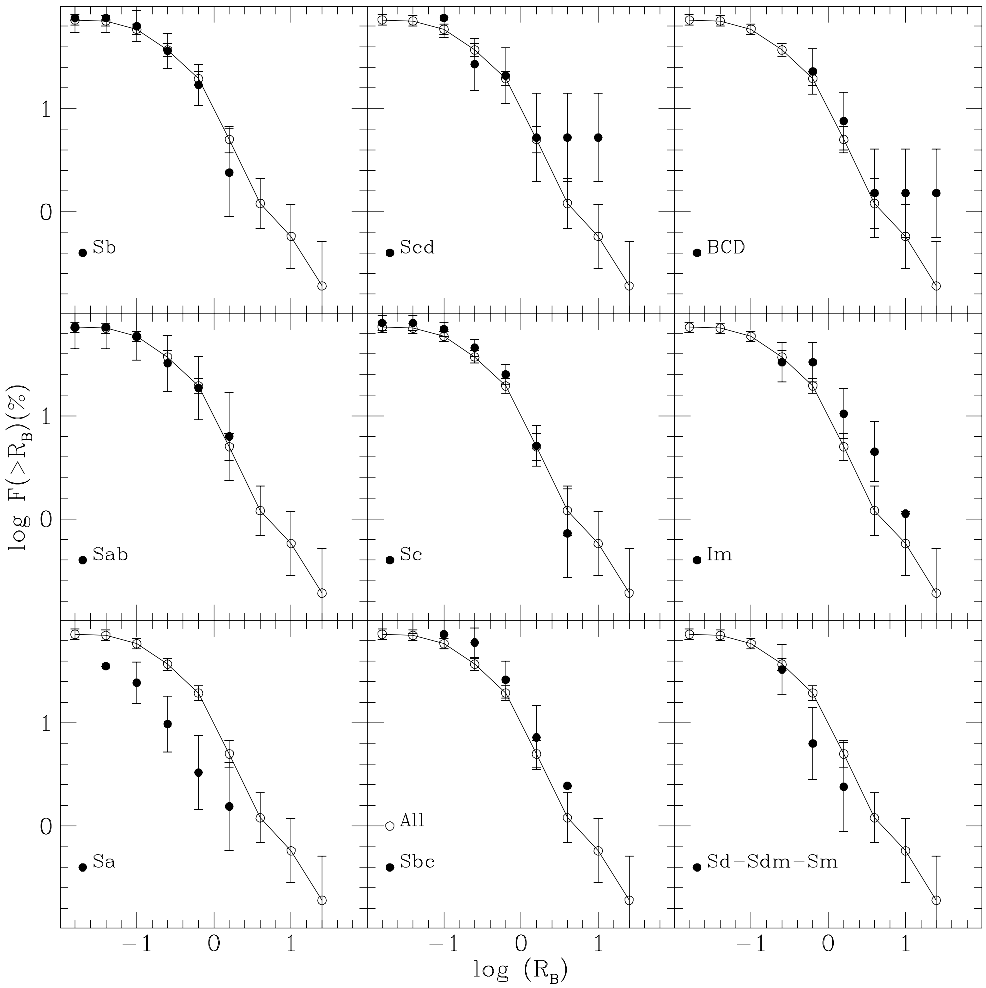

Fig. 3. The cumulative RLF as a function of the radio/optical ratio R_B of late-type galaxies is given separately for each morphology class (filled dots). The distribution of all late-type is also given for comparison (open dots).

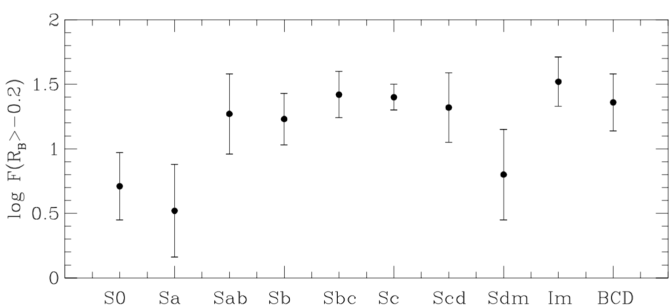

Fig. 4. The cumulative RLF for $logR_B > -0.2$ is given as a function of the Hubble type.

Table 1 is carried out with two independent methods. Using Condon et al. (1998) Fig. 6 we estimate that the probability of finding an unrelated source within 45 arcsec of an arbitrary position is 2%. Thus about 3.6 sources in Table 1 should be spurious associations. An independent estimate is computed according to:

$$N_{c.i.} = 9\pi \times \Sigma\sigma_r^2 \times N_g/A \quad (4)$$

where the summation is extended to all radio sources (approximately 7000) found in the area A ($140deg^2$) containing the Virgo cluster, and N_g is the total number of galaxies considered (1342). $N_{c.i.}$ is 5.3, in good agreement with the previous determination.

3. The radio-optical luminosity

For all galaxies we have a measurement of the total radio flux density $S_{1.4}$ (for 180 detections) or an upper limit S_l (undetected objects). Combining this with the distance to the objects we determine their radio luminosity $P_{1.4}$ (or P_l) in WHz^{-1}.

Let us consider the detected galaxies first. The existence of a correlation between the radio and optical luminosity is well known: (see e.g. Condon 1980; Gavazzi & Jaffe 1986; Gavazzi & Contursi 1994). Figs. 1a and b show this correlation separately for the early and late-types. In spite of a large scatter which indicates that, beside the optical magnitude other quantities determine the radio properties of galaxies, it appears that late-type galaxies obey to an almost direct proportionality between the two quantities. Early type galaxies instead show a strongly non-linear behavior: galaxies fainter than approximately $M_B = -19$ have an average radio luminosity $\sim 10^{21}\ WHz^{-1}$, independent of their optical luminosity. Galaxies brighter than $M_B = -19$ have a radio luminosity strongly increasing with M_B. These are

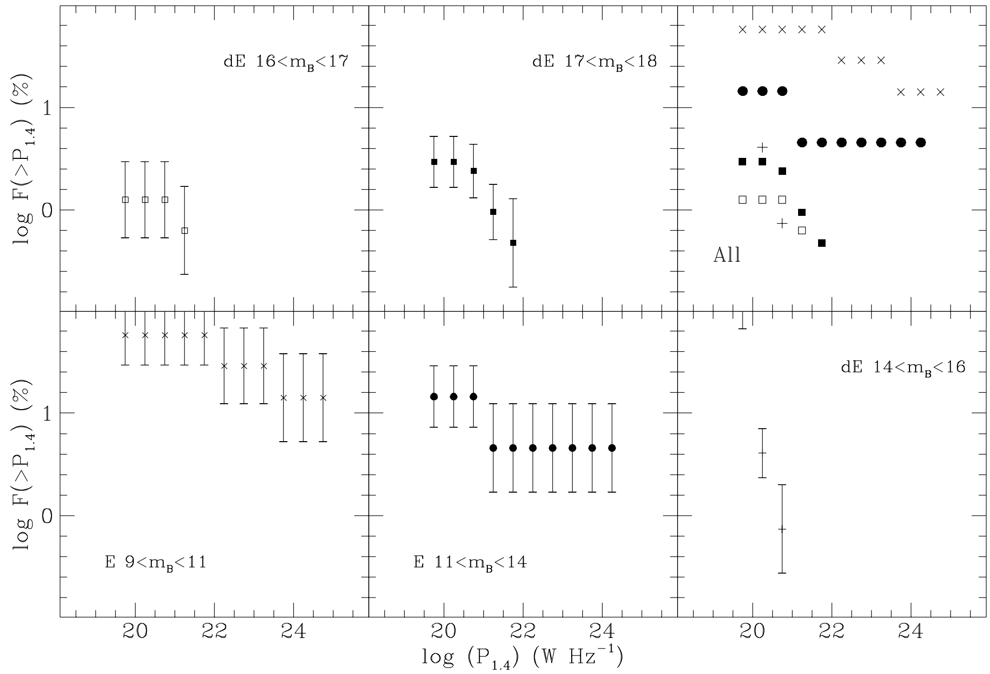

Fig. 5. The cumulative RLF of Elliptical galaxies in five bins of optical luminosity.

the "monster" radio galaxies. It is interesting to notice in Fig. 1b that "monsters" are absent among S0+S0a galaxies.

4. The radio luminosity functions

Given the small number of actual radio detections (180) with respect to the number of optical candidates (1342), Fig. 1 might not give a realistic representation of the radio properties of an optically selected sample of galaxies. More appropriately, that can be derived in the form of the Fractional Radio Luminosity Function (RLF), which gives the probability distribution $f(P)$ that galaxies develop a radio source of a given luminosity ($P_{1.4}$), taking into account the number of detected objects $n_d(P_k)$ in each bin of radio luminosity P_k, as well as the upper limits (see Avni et al. 1980).

The differential distribution can be derived adopting method III of Hummel (1981) which has been shown to be equivalent to the expression given by Avni et al. (1980):

$$f(P_k) = \frac{n_d(P_k) \times (1 - \sum_{j=1}^{k-1} f(P_j))}{n_u(P_l < P_k) + n_d(P \leq P_k)} \tag{5}$$

where: $n_d(P \leq P_k)$ is the number of detected objects with $P \leq P_k$, $n_u(P_l < P_k)$ is the number of undetected objects with $P_l < P_k$.

The uncertainty on $f(P_k)$ is given by:

$$\sigma f(P_k) = \frac{f(P_k)}{\sqrt{n_d(P \geq P_k)}} \tag{6}$$

The cumulative distribution is thus:

$$F(\geq P_k) = \sum_{j=1}^{k} f(P_j) \tag{7}$$

4.1. Late-type galaxies

Spiral galaxies are well known to develop radio sources with an average radio luminosity proportional to their optical luminosity (see Sect. 3). For these objects it is convenient to define the (distance independent) radio/optical ratio: $R_B = S_{1.4}/k \times 10^{-0.4*m_B}$, where m_B is the B magnitude and $k = 4.44 \times 10^6$ is the factor appropriate to transform the broad-band B magnitudes in mJy. R_B gives the ratio of the radio emission per unit light emitted by the relatively young stellar population. The distribution of $f(R_B)$, that is the probability that a galaxy develops a radio source with a radio/optical ratio R_B can be derived similarly to $f(P_{1.4})$ using Eq. (5).

Since the radio/optical ratio is a distance independent quantity, we extend the present analysis to all galaxies in the VCC, including the background objects. The exclusion of these objects reduces significantly the statistics, without changing the results.

The $f(R_B)$ for all galaxies (from Sa to BCD), given in Fig. 2, appears as a normal distribution peaked at Log $f(R_B)$ between -1 and -0.5. About 20% of all galaxies are detected at the peak of the distribution. At the sensitivity of the present radio survey about 70% of Virgo galaxies have $R_B > 0.01$. Let us now consider separately the following 9 morphological type classes: Sa, Sab, Sb, Sbc, Sc, Scd, Sd+Sdm+Sm, Im, and BCD. Barred and ringed spirals are mixed with normal spirals.

The cumulative $F(\geq R_B)$ distributions are shown in 9 panels of Fig. 3 respectively. All panels show, for comparison, also the distribution of all late-type galaxies together (open dots connected with a solid line). It is striking that, within the statistical uncertainties, all RLFs are consistent among each other, except for the Sa's. The Sa's develop radio sources, at any given value of R_B, about 5 times less frequently than all others late-type galaxies. Sd+Sdm+Sm are slightly underluminous than average, but

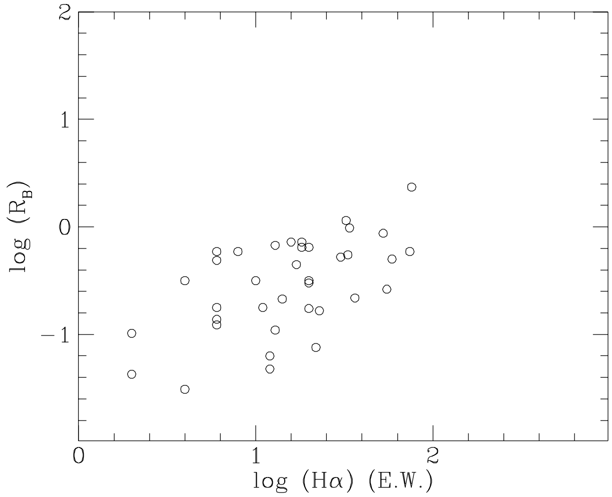

Fig. 6. The relation between the radio/optical ratio R_B and the equivalent width of the H_α line for the late-type detected galaxies.

this difference is barely significant. We have also computed the $F(\geq R_B)$ distribution of S0+S0a (not shown in Fig. 3), which results identical to that of Sa galaxies.

Fig. 4 summarizes the dependence of the radio properties on Hubble type using the cumulative fraction $F(> R_B = -0.2)$. These results are in full agreement with the findings of Hummel (1981).

4.2. Early-type galaxies

Early-type galaxies do not develop radio sources with a radio luminosity proportional to their optical luminosity (see Sect. 3). For these objects the radio/optical ratio is meaningless. This is consequent to the very existence of radio galaxies. These galaxies develop radio sources with a broad range of power, whose nature is nuclear, thus it is only indirectly related with the total luminosity of their host galaxies. For early-type galaxies it is convenient to analyze the "bivariate" (i.e. per interval of optical luminosity) distribution of radio luminosity. Obviously this analysis is restricted to the members of Virgo, disregarding the background objects.

The cumulative representation $F(> P_{1.4})$ is shown in Fig. 5 in 5 bins of optical luminosity, such that each of them contains a significant number of objects: $9 < m_B < 11$ (7); $11 < m_B < 14$ (22); $14 < m_B < 16$ (141); $16 < m_B < 17$ (159) and $17 < m_B < 18$ (211). Within the range of radio power covered by the present analysis ($20 < logP_{1.4} < 25\,WHz^{-1}$) it appears that the probability for E galaxies to develop radio sources decreases steeply with the optical luminosity only above $m_B = 16$ (which corresponds to $M_B = -15$). Below this optical luminosity, where dEs dominate, the fraction $F(> P_{1.4})$ becomes independent of the optical luminosity.

5. Discussion

A clearcut result of the present investigation is that spiral-Irr galaxies develop extended radio sources whose luminosity scales with the optical luminosity, independently of the detailed Hubble type. Their radio/optical ratio is linearly correlated with their current, massive star formation rate, as derived from their H_α emission line intensity (Kennicutt, 1999). Fig. 6 shows that, among the detected galaxies, the relation between R_B and the equivalent width of the H_α line is one of direct proportionality, implying that cosmic-ray acceleration is primarely associated with type II supernovae.

Elliptical galaxies develop radio sources whose nature is nuclear. Auriemma et al. (1977) determined the RLF of E galaxies brighter of $M_B = -18$. They found that the RLF shows a pronounced break at the radio luminosity $logP^*_{1.4} = 24\,WHz^{-1}$, independent of the galaxy optical luminosity. Beyond the break $F(> P_{1.4})$ scales with the optical luminosity as $L_B^{1.5}$. Below $P^*_{1.4}$, instead the dependence of $F(> P_{1.4})$ on L_B is weaker. The RLF determined in this work extends to optical luminosities 5 magnitude fainter than Auriemma et al. (1977). However, it does not comprise radio luminosities greater than $logP_{1.4} = 24\ WHz^{-1}$. The only powerful radio galaxy in Virgo is M87, which is in fact right above $P^*_{1.4}$. With our data we can study how the radio properties of E galaxies scale with the optical luminosity below $P^*_{1.4}$. The dependence of the probability for E galaxies to develop radio sources with $logP_{1.4} > 20.75\,WHz^{-1}$ is represented in Fig. 7 as a function of the optical luminosity. Together with our data, Fig. 7 also represents the results of Auriemma et al. (1977) (dotted line, adapted from their Fig. 5) which appear in full agreement with ours. The three brightest points ($9 < m_B < 16$) are well represented by $logP_{1.4} \sim L_B^{1.0}$; however, below $m_B = 16$, the data are consistent with no further dependence from L_B. It is instructive to compare Fig. 1b with Fig. 7, which contain complementary information: Fig. 1 shows the dependence of the radio on the optical luminosity of the detected objects, while Fig. 7 adds the information on the frequency at which Early-type galaxies develop radio sources (with a given radio luminosity) as a function of the optical luminosity. We conclude that, while the frequency with which E galaxies feed the "monsters" in their nuclei is strongly related to their total mass, that of fainter radio sources is progressively less sensitive on the system mass. In fact it does not decrease from $M_B = -16$ to $M_B = -13$. The faintest giant E galaxies have similar probability of feeding low power radio sources than dwarf E galaxies 3–4 mag fainter.

6. Summary

In summary the present investigation brought us to the following empirical results:

1) Late-type galaxies develop radio sources with a probability proportional to their optical luminosity. In fact their radio/optical ratio is a gaussian distribution centered at $R_B \sim -0.5$, i.e. the radio luminosity is ~ 0.3 of the optical one. About 20% of all spiral galaxies is detected at the peak of the distribution.

2) The probability of late-type galaxies to develop radio sources is almost independent of their detailed Hubble type, except that

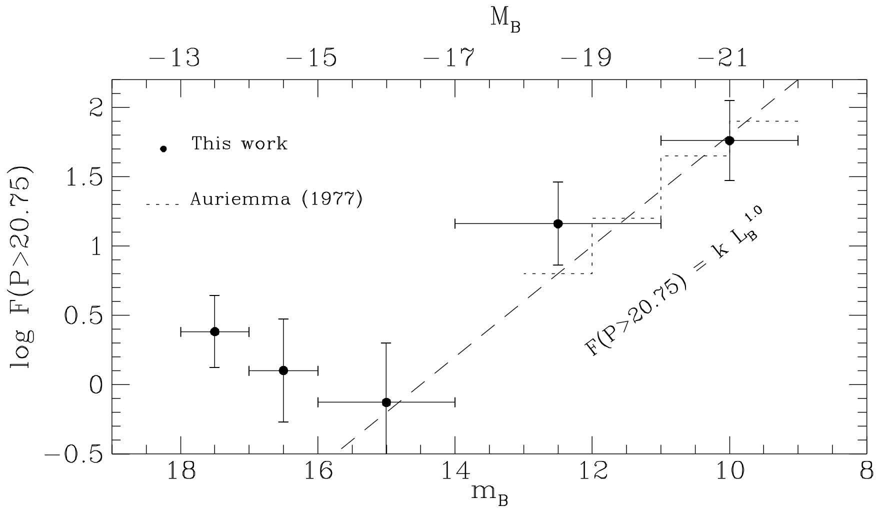

Fig. 7. The cumulative fraction of elliptical galaxies with radio luminosity $logP_{1.4} > 20.75$ as a function of optical luminosity. This work (filled dots); Auriemma et al. (1977) (dotted line).

Sa (and S0+S0a) are at least a factor of $\sim$ 5 less frequent at any value of radio/optical.

3) The relation between R_B and the equivalent width of the H_α line is of direct proportionality.

4) The luminosity of radio sources associated with Early-type galaxies increases non-linearly with the optical luminosity of their parent galaxies.

5) The probability of finding low luminosity ($logP_{1.4} > 20.75\,WHz^{-1}$) radio sources associated with Early-type galaxies scales non-linearly with the optical luminosity.

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