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# Radio Identifications of Markarian Galaxies and the Correlation between Radio and Far-Infrared Properties

Shao-Guang Luo[1,2] and Xue-Bing Wu[1]

[1] Department of Astronomy, Peking University, Beijing 100871; *luo@vega.bac.pku.edu.cn*
[2] Shenzhen Graduate School, Peking University, Shenzhen 518055

**Abstract** By checking DSS optical images and NVSS radio images, 782 Markarian galaxies were identified to be NVSS radio sources. A comparison of the radio luminosity at 1.4 GHz and the far-infrared (FIR) luminosity for 468 "normal" galaxies shows a tight correlation. Most of the Seyfert galaxies and quasars follow the radio-FIR relation deduced from the "normal" galaxy sample, but with a somewhat larger scatter. A total 167 Markarian galaxies, comprising 100 "normal" galaxies, 66 Seyfert galaxies and one quasar, have either excess radio emission or much lower FIR spectral index $\alpha(25\,\mu\mathrm{m}, 60\,\mu\mathrm{m})$. These galaxies may be classified as "AGN-powered". For "normal" galaxies, the average $q$ value (defined as the log ratio between FIR and radio luminosities) is 2.3. There seems a trend for $q$ to slightly decrease with increasing radio luminosity. This may imply that the ongoing active star formation in galaxies with higher radio luminosities is more efficient in *heating* the cosmic-ray electrons.

**Key words:** galaxies: active – galaxies: Seyfert – galaxies: starburst – radio continuum: galaxies – infrared: galaxies

## 1 INTRODUCTION

The radio and far-infrared properties of normal and star-burst galaxies have been widely investigated since the IRAS infrared sky survey. A tight correlation between the radio and far-infrared luminosities was found in IRAS-selected samples by Lawrence et al. (1986) (313 galaxies), by Unger et al. (1989) (156 galaxies), by Condon et al. (1991a) (313 galaxies), and in an optically selected sample (299 normal and irregular galaxies) by Condon et al. (1991b). A thorough review concerning the radio emission from normal galaxies was given by Condon (1992). While the IRAS survey covered 96% of the sky and detected a myriad of galaxies, the radio survey is time-consuming and therefore all above investigations are based on relatively small samples. The NRAO VLA Sky Survey (NVSS; Condon et al. 1998) at 1.4 GHz covers all the sky with J2000 $\delta > -40^\circ$ and detected $\sim 1.8 \times 10^6$ radio sources with a sensitivity limit of 2.5 mJy. Using this database and IRAS fainter source catalog (FSC), Yun et al. (2001, hereafter YRC) investigated 1809 galaxies with $S_{60\,\mu\mathrm{m}} > 2.0$ Jy. Condon et al. (2002) identified 4583 NVSS sources from the Uppsala Galaxy Catalog (UGC) and investigated the radio and infrared properties of 1966 sources which are located with $|b| > 20^\circ$, stronger than 2.5 mJy at 1.4 GHz and brighter than $m_p = 14.5$ in optical. These two studies with a larger sample verified the conclusion obtained by the previous studies. The study has also been extended to galaxies with high redshifts (Stanford et al. 2000; Garrett 2002) and the same conclusion was obtained.

Markarian Galaxies are galaxies with excess blue and UV emission. Mazzarella & Balzano (1986) compiled a catalog with 1500 entries, of which most are galaxies. This kind of galaxies plays a central role in distinguishing the astrophysically different types of phenomena that occur in AGNs. The excess blue and UV emission is either the signature of a high star formation rate or the presence of an AGN in the central region of the galaxies. If we exclude those galaxies with a "Monster" in their nucleus, this sample should be thought to be a sample mainly consisting of "normal" galaxies. However, the strong blue and UV excess shows that starburst activity is taking place in these galaxies. Izotov & Izotova (1989), Stine (1992) and Marx et al. (1994) compared the radio continuum and far-infrared emissions in a relatively small sample of Markarian galaxies and found a tight correlation. Bicay et al. (1995) first systematically investigated the IRAS properties of Markarian galaxies and found 944 entries are faint IRAS sources. They also studied their radio emission at 4.86 GHz, 1.415 GHz, 10.63GHz and 23.1 GHz using the NRAO 91.4 m telescope at Green Bank, the NAIC 305 m telescope at Arecibo, the 46 m telescope at Algonquin Radio observatory, and the 40 m telescope at Owens Valley radio Observatory. However, the detection rates are relatively low. Comparing these observed results with IRAS FSC, they found the same tight correlation between the radio luminosity and far-infrared luminosity.

We have made a cross identification by comparing the NVSS catalogue and Markarian catalogue in order to obtain a homogeneous sample for checking the radio properties of Markarian galaxies. About 800 Markarian galaxies are found to be NVSS sources. By examining the radio and IRAS properties of the sources, a tight correlation between radio luminosity and far-infrared luminosity was confirmed for this larger and more homogeneous sample of galaxies.

## 2 RADIO IDENTIFICATION OF MARKARIAN GALAXIES

A preliminary radio identification was made by comparing the optical positions of the Markarian galaxies and those in the NVSS database using the catalog browser available on the NVSS web site. Usually, when the offset between the optical and radio positions is less than $45''$, they are temporarily identified to be the same. Nevertheless, not all of the identifications based only on the position coincidence are correct. Within the $45''$ FWHM NVSS beam, there may be some other optical objects and the radio emission may not be associated with the Markarian galaxy. So in order to avoid any misidentification, we have made finding charts centered on the optical position of each Markarian galaxy showing both the DSS2 image (gray scale) and NVSS radio contours. Figure 1 presents a few examples of positively identified sources. From the upper right image in Figure 1, we can see that the separation between Mrk 355 and Mrk 356 is $35''$ and the radio emission is associated with Mrk356 rather than Mrk355. In Figure 2 we show a few examples for which the radio identifications are rejected. For Mrk 305, although the offset between the radio and optical positions is about $35''$, the radio emission is obviously from a peculiar SB galaxy, UGC 12066. In the case of Mrk 1236, the radio emission is associated with both Mrk1236 and NGC 3023, although Beck et al. (2000) pointed out that there is a strong 6 cm peak at $09^{\rm h}49^{\rm m}54.359^{\rm s}$ $00^{\rm d}36^{\rm m}59.74^{\rm s}$. Near Mrk 19 there is a galaxy pair KUG 0912+599, so, which one of the pair is associated with the radio emission is not certain. In a few cases, the radio emission from the Markarian galaxy is not separated from nearby strong radio emission which is obviously associated with another object and therefore was also rejected.

By examining the finding charts, we identified 782 Markarian galaxies with NVSS sources. Other 28 Markarian galaxies may also be associated with NVSS sources, but their identifications are suspect. In fact, some doubtfully identified radio sources may be headtail radio sources. A typical example is Mrk 978 as shown in Figure 2. In Table 1 (see *http://www.chjaa.org/2005_5_5.htm*), 167 identified sources are listed. These sources either have an excess radio emission or have an lower FIR spectrum index which may contain a detectable AGN, as will be discussed later. A completed table will be published in electronic version.

Although we set an offset of 45″ as the preliminary criterion, for 90% of the identified sources, the offset in fact is less than 10″. In Figure 3 we show the distribution of offsets for all the identified sources.

## 3 CORRELATION BETWEEN RADIO AND FAR-INFRARED EMISSIONS

Among the 782 Markarian galaxies with NVSS sources, 672 source are found to be IRAS faint sources. For most of these sources the offset between radio and infrared positions is less than 20″, a typical value for IRAS position error. For 59 other sources the offset between centers of radio and infrared emission is larger than 30″, but still less than 60″ (three times the IRAS position error). So we accept these IRAS sources as associated with the identified Markarian galaxies. For some of the IRAS sources, only an upper limit of flux at $60\,\mu$m or $100\,\mu$m was given; these are first excluded from the statistical sample. We also excluded known Seyfert galaxies, quasars and BL Lac objects from this sample because for these, the infrared and radio properties may not be directly associated with the star formation process (but see discussion below). This sample includes 468 entries and will be called the "normal" galaxies sample to distinguish it from the AGN sample. The correlation between the radio luminosity at 1.4 GHz and the far-infrared luminosity for this sample is shown in Figure 4. A least-square analysis yields the following equation:

$$\log L_{1.4\mathrm{GHz}} = (1.123 \pm 0.018) \log L_{\mathrm{FIR}} + (10.47 \pm 0.18). \quad (1)$$

Here $L_{1.4\mathrm{GHz}}$ is in W Hz$^{-1}$ and $L_{\mathrm{FIR}}$ is in $L_\odot$. The correlation coefficient is 0.94 and the standard deviation is 0.20. This relation is almost the same as the one obtained by Condon et al. (1991a) for 258 infrared-selected bright galaxies not known to contain AGNs. The linear relation between radio and IR luminosity spans about five orders of magnitude. It is especially interesting that the HII galaxy Mrk71 with the lowest radio luminosity of $10^{18.7}$ W Hz$^{-1}$ and IR luminosity of $10^{7.15} L_\odot$, is located slightly above the regression line. This contrasts with the result in YRC, where they found a systematic tendency for galaxies with $\mathrm{L}_{60\,\mu} \lesssim 10^9 L_\odot$ to be located below the regression line.

Among the 782 Markarian galaxies identified as NVSS radio sources, 148 are Seyfert galaxies, five are quasars and three are BL Lac objects. However, only 109 galaxies have qualified $60\,\mu$m and $100\,\mu$m flux densities and we will call them the AGN sample of Markarian galaxies. The Seyfert galaxies and other AGNs, like BL Lac objects and quasars, usually have radio-excess and present a much greater scatter in the radio-FIR plot (Fig. 5). They all have much higher radio and IR luminosities. However, as seen from Figure 5 most of the Seyfert galaxies are still located in the very vicinity of the best regression line. This fact shows that the dominant processes in these galaxies for both radio and infrared emission are still starburst rather than "Monster". Two known quasars (Mrk205, Mrk1014) in the AGN subsample are almost precisely located on the best regression line; the other three quasars and three BL Lac objects were excluded because of no qualified FIR data.

Helou et al. (1988) have defined a "$q$" parameter to express the nonlinearity in the dispersion of the radio-FIR correlation. Here, $q$ is defined as:

$$q = \log \left[ \frac{FIR/(3.75 \times 10^{12} \mathrm{W\ m^{-2}})}{S_{1.4\ \mathrm{GHz}} (\mathrm{W\ m^{-2}\ Hz^{-1}})} \right], \quad (2)$$

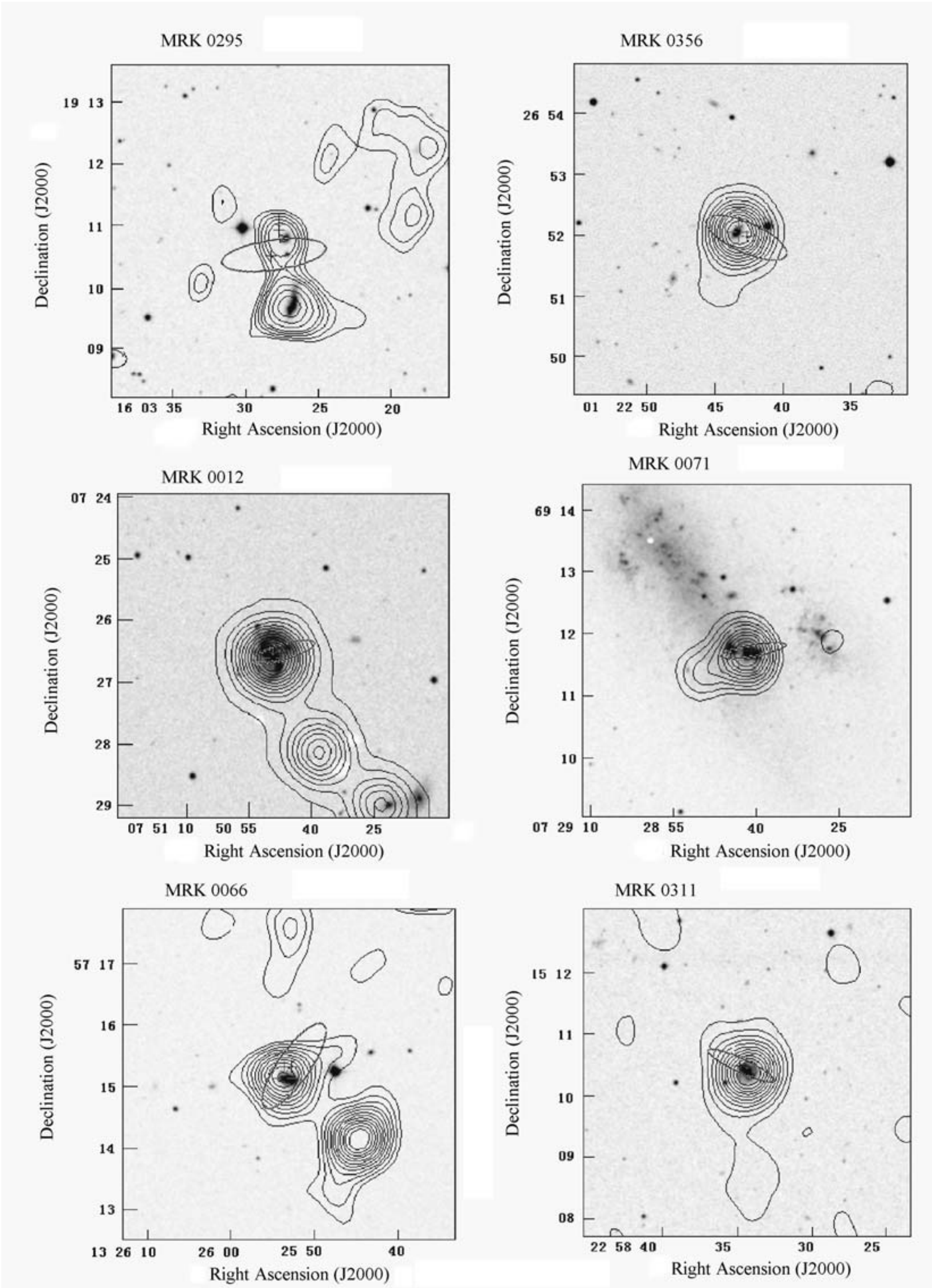


**Fig. 1** Sample finding charts of Markarian galaxies with NVSS contours drawn over the DSS images. The NVSS contours are in arbitrary units. The 3 time IRAS position error ellipses are also plotted.

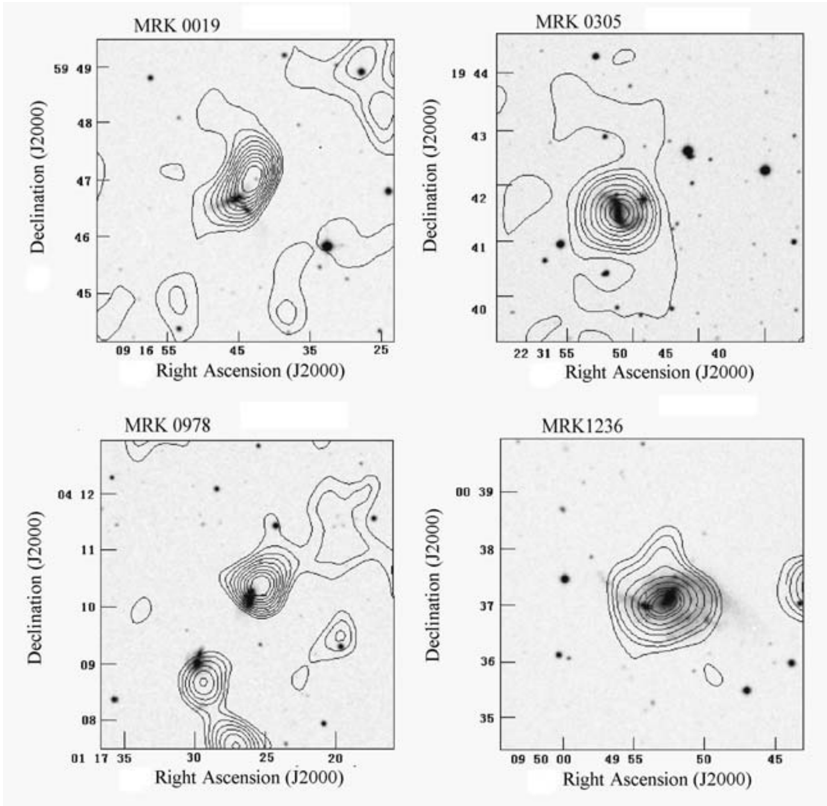


**Fig. 2** Sample finding charts of Markarian galaxies with NVSS contours drawn over the DSS images for few rejected identifications.

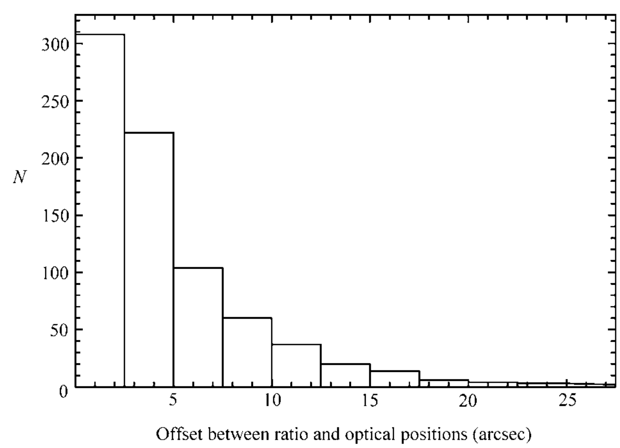


**Fig. 3** Distribution of offsets between Radio and Optical positions of identified Markarian galaxies.

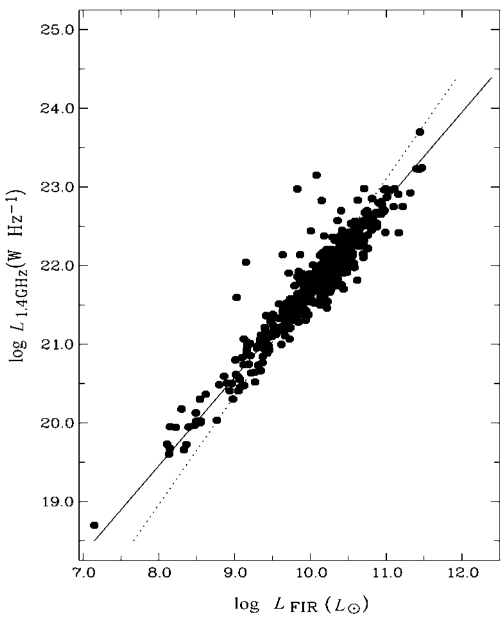


**Fig. 4** A Plot of 1.4 GHz radio luminosity vs. IRAS luminosity for 468 Markarian galaxies. The solid line is the regression line for the "normal" Markarian galaxy sample and the dotted line is for all 577 Markarian galaxies.

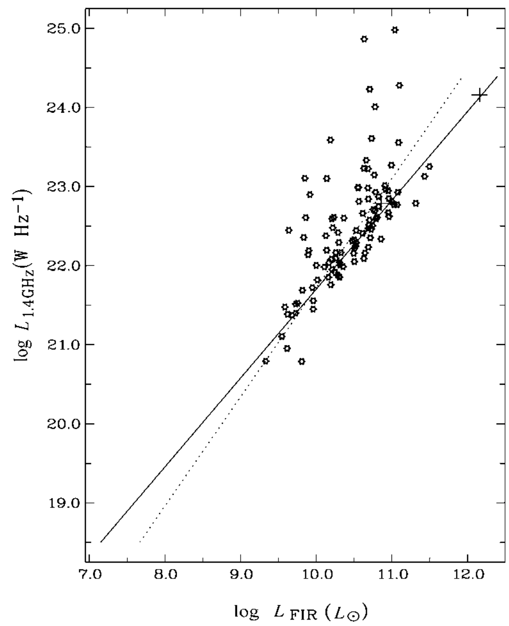


**Fig. 5** A plot of 1.4 GHz radio luminosity vs. IRAS luminosity for 109 Markarian galaxies classified as Seyfert galaxies and QSOs. The solid line and dotted line are the same as in Fig. 4. QSO Mrk205 and Mrk1014 are shown as crosses.

and

$$\mathrm{FIR(Wm^{-2})} = 1.26 \times 10^{-14}[2.58\mathrm{S}_{60\,\mu\mathrm{m}} + \mathrm{S}_{100\,\mu\mathrm{m}}], \tag{3}$$

where $S_{60\,\mu\mathrm{m}}$ and $S_{100\,\mu\mathrm{m}}$ are IRAS $60\,\mu$m and $100\,\mu$m band flux densities in Jy. In Figures 6 and 7, we show the $q$ vs. radio luminosity plot for the "normal" and AGN samples. The average $q$ value is 2.30 for "normal" Markarian galaxies, comparable with the 2.34 derived by Yun et al. (2001). Including the AGNs slightly decreases the average $q$ value to 2.24. From Figure 6, it is evident that most of the "normal" Markarian galaxies have $q$ values between 1.60 and 2.99, (five times below and above the average value). Only seven objects in the normal Markarian galaxy sample have excess radio emissions. In contrast, 17 Seyfert galaxies are radio excess objects and Mrk1506 (3C 120), a famous radio source with superluminal motion (Zensus 1989), has the lowest $q$ value of $-0.29$ in the sample. Mrk1330, a Sy1 galaxy, has a marginal FIR-excess, with the largest $q$ value of 3.02 in whole the sample.

The $q$ vs. radio luminosity plot for the "normal" galaxy sample seems to show a correlation between the two: with increasing radio luminosity, $q$ slightly decreases (Fig. 6). The same trend was also noted by Condon et al.(1991a). They showed that the observed FIR-radio flux ratio $q$ is correlated with the quantity

$$q_b = \log(L_{4400}/L_{1.4\mathrm{GHz}}), \tag{4}$$

where $L_{4400}$ is the spectral luminosity at $\lambda$=4400 Å and $q_b$ measures the blue-radio luminosity ratio. When $q_b$ <0, $q$ is almost constant. With the increase of $q_b$ at $q_b > 0$, $q$ increases, and for $q_b > 1$, $q$ increases more rapidly (see their fig. 5). They explained this correlation by a two-component model. For those systems with lower $q$ values, the dominant *heating* is from currently

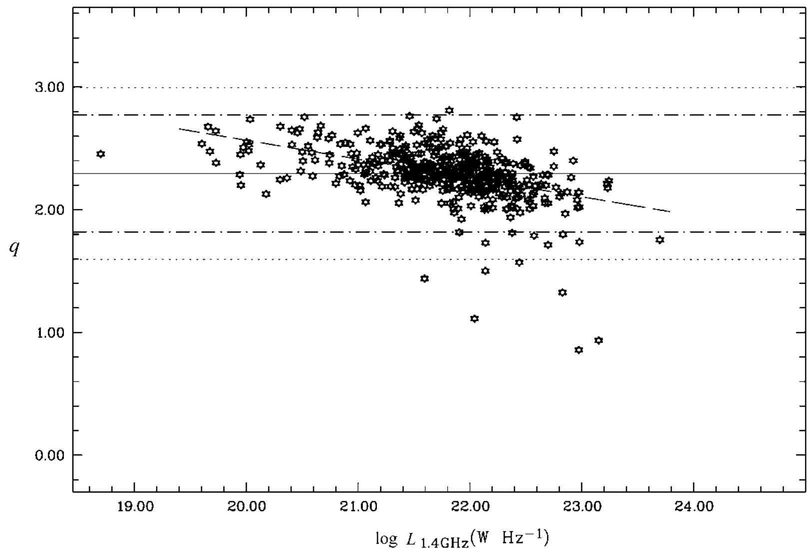


**Fig. 6** Distribution of $q$ values plotted as a function of 1.4 GHz radio luminosity. The solid line marks the average value of q=2.30, while the dotted lines delineate the 5 times radio and FIR excess values. The dash-dot lines delineate the 3 times radio and FIR excess values. The long dash line is a best-regression line of $q$ vs. radio luminosity for "normal galaxy" sample.

forming short-lived massive star with masses $> 8M_{\odot}$, while for those systems with higher $q$ values the dominant *heating* is from the longer-lived population with masses $< 8M_{\odot}$. Our result is consistent with this interpretation. Because the radio emission from these star-formation galaxies is non-thermal synchrotron radiation dominated, it is possible that the cosmic-ray electron acceleration is more efficient in galaxies with ongoing active star formation. We note that for the AGN sample, $q$ also rapidly decreases with increasing radio luminosity (Fig. 7).

## 4 AGN-POWERED GALAXIES

The energy source powering the radio emission of a galaxy is either star formation or an AGN. Because the FIR emission also predominantly originated from star formation process, a tight correlation between radio and FIR emissions is expected for those galaxies in which star formation process is active. Checking the relation between radio and FIR emissions from galaxies can supply some clues to their energy sources. From an infrared-selected galaxy sample including 1809 entries, Yun et al. (2001) classified 23 objects as potential AGN hosted galaxies from their lower $q$ values. The authors concluded that radio AGNs occur quite rarely in the IR-selected galaxy sample. Based on a sample including 1966 UGC galaxies brighter than $m_p = 14.5$ and $S_{1.4\,\mathrm{GHz}}$>2.5 mJy, Condon et al. (2002) found 262 AGNs and 32 possible AGNs. They used a rather different criterion from the one Yun et al. (2001) used and found a much higher fraction of AGNs; but if we take $q < 1.64$ as did Yun et al. (2001), then the number of radio AGNs will drop to 46. In our sample there are 26 galaxies with $q < 1.64$. The fraction of radio-excess galaxies we found is slightly higher than both Condon et al. (2002) and Yun et al. (2001). The higher fraction of radio-excess galaxies is certainly caused by our specially selected sample,

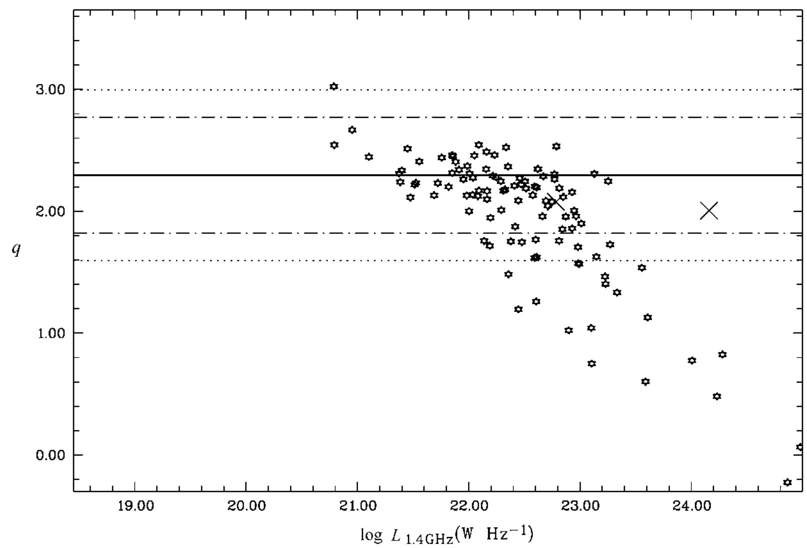


**Fig. 7** Distribution of $q$ values plotted as a function of 1.4 GHz radio luminosity for 107 Seyfert galaxies and two QSOs. The solid line, dotted lines and the dash-dot lines are the same as in Fig. 6. Two QSOs are marked with crosses.

since Markarian galaxies endowed with excess blue and UV emissions. In order to compare with their result, we classified those galaxies with radio emission more than three time the value expected from the mean radio-FIR relation or with $\alpha(25\,\mu\text{m}, 60\,\mu\text{m}) < 1.5$ as "AGN-powered". Here $\alpha(25\,\mu\text{m}, 60\,\mu\text{m})$ is defined as

$$\alpha(25\,\mu\text{m}, 60\,\mu\text{m}) = \frac{\log(\text{S}_{60\,\mu\text{m}}/\text{S}_{25\,\mu\text{m}})}{\log(60/25)}. \tag{5}$$

A total of 167 Markarian galaxies, comprising 100 "normal" galaxies, 66 Seyfert galaxies and one quasar, satisfied these criteria. They are listed in Table 1. Among them, 46 are radio selected, 159 are FIR color selected with 38 satisfying both selection criteria. We note that 114 galaxies are not included in the result of Condon et al. (2002). If further observation of these galaxies identify them to host an AGN, then the fraction of AGN-powered objects among Markarian galaxies would be as higher as 29%.

A few Markarian galaxies are of especial interest in some aspects. Mrk1226 has the lowest $q$ value of 0.86 and a relatively low FIR spectral index among the normal galaxies. Condon et al. (1995) have observed this source at 4.85 GHz and classified it as "Monster-powered". At 4.85 GHz the flux density is 109 mJy and a $q$ parameter defined at 4.85 GHz is 0.66. This means that the ratio between radio and FIR emissions is over 100 times higher than the mean value (the mean $q$ value for 354 sources is 2.74). Drake et al. (2003) also classified this object as radio-excess. In the original catalogue of Markarian galaxies, Mrk796 is classified to be a normal emission line galaxy, but Yun et al.(2001) classified it as a Sy2 galaxy and listed it as a radio-excess object (see also Drake et al. 2003). Although the q value of this object is not so low, the FIR spectral index $\alpha(25\,\mu\text{m}, 60\,\mu\text{m}) = -1.605$ shows the presence of much hotter dust in the central region of the galaxy. Condon et al. (1995) have also classified this object as

"Monster-powered", although the $q$ value at 4.85 GHz is 1.8. Another special object is Mrk 1218. Nagar & Wilson(1999) showed it to be interacting with its nearest neighbor at a distance of $1'$. This galaxy has a relatively lower $q$ value of 1.042 and FIR spectral index of 0.276. Mrk 617 has a much lower FIR spectral index $\alpha(25\,\mu\text{m}, 60\,\mu\text{m}) = -1.326$ and a slightly lower $q$ value of 1.326. Drake et al. (2003) investigated this galaxy but did not list it as "radio-excess".

## 5 CONCLUSIONS

By checking the DSS optical images and NVSS radio contours, 782 Markarian galaxies were identified to be NVSS radio sources. Most of these galaxies have faint IRAS counterparts. We selected 468 "normal" galaxies, 107 Seyfert galaxies, two quasars as a sample to study their radio and FIR emission properties. All these galaxies have available $60\,\mu$m and $100\,\mu$m flux density quantities. A comparison of the radio luminosity at 1.4GHz and FIR luminosity shows that they are tightly correlated for 468 "normal" Markarian galaxies. For Seyfert galaxies and quasars, most of them follow the radio-FIR relation deduced from the "normal" galaxy sample, but with a larger scatter. This result implies that, for most Seyfert galaxies and quasars in this sample the radio and FIR emissions are still powered by star formation rather than by AGN. However, about 30% of the sources have either excess radio emission or much lower FIR spectral index $\alpha(25\,\mu\text{m}, 60\,\mu\text{m})$, this implies the presence of very warm ($T >$100 K) dust near the central region of the galaxy. These galaxies can be classified to be AGN-powered, but a more sophisticated survey is needed to confirm or reject this conclusion.

For "normal" galaxies, the average $q$ value is 2.3. However, there seems to be a trend for $q$ to decrease slightly with increasing radio luminosity. This may imply that the ongoing active star formation in galaxies with higher radio luminosities is more efficient in *heating* the cosmic-ray electrons.

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