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Statistical properties of extragalactic radio sources*

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In this paper, a large sample of extragalactic radio sources is analysed to show their statistical properties. The core and total radio powers are used to determine the core-dominance parameter for galaxies, BL Lacertae objects and quasars; mutual correlations between core radio power, total radio power, redshift and core dominance parameter are examined for different subclasses. A statistically significant correlation between the total and core radio power is confirmed. There are no obvious correlations between core-dominance parameter and the total power for our whole sample and quasars, but there is a statistically significant anti-correlation for our galaxy sample. Some discussions and comparison of the correlations with those obtained by other authors are also given.

Keywords: extragalactic objects, radio galaxies, BL Lacertae, quasars
PACC: 9850, 9850S, 9850R, 9870J

1. Introduction

As we know, active galactic nuclei (AGNs) approximately harbour a supermassive black hole surrounded by an accretion disc at the centre. But the physical process of producing energy, especially the nature of the central regions, is still not very clear. In the unified model point of view, different viewing angle (the angle between the jet and the line of sight) gives rise to different subclasses of objects, such as BL Lacertae objects, core-dominated quasars, lobe-dominated quasars, highly polarized quasars, and superluminal sources, etc. BL Lacertae objects are presumed to be Fanaroff Riley type I (FRI) radio galaxies,[1] but some evidence also suggests that the parent population of BL Lacs should be FRI and some Fanaroff Riley type II (FRII) radio galaxies (Kollgaard *et al*[2], Fan *et al*,[3] and references therein). Since emissions in the jet are strongly beamed, then the core-dominance parameter, R, should indicate the orientation of the jet. Observations also show that optical polarization ($P_{\rm opt}(\%)$) is associated with R with high polarization corresponding to high R.[4,5]

Some extremely observational properties, such as rapid and high amplitude variations in all wavelength bands, high luminosity, high polarization, and superluminal motion based on radio observations in AGNs lead to the construction of a relativistic beaming model. Very large array (VLA) and very long baseline interferometry (VLBI) observations make it possible to separate the core and the extended components. Therefore, the observed radio emissions of AGNs contain two components: namely, a compact relativistically beamed core component and an unbeamed lobe component, from which people define a core dominance parameter R (the ratio of the core to the extended component) to indicate the beaming effect.[6] Based on the parameter R, the Doppler factor and the superluminal velocity, an important factor for the jet in the source frame was estimated for a sample.[7,8]

Some authors have investigated the relation between flux (or radio power), emission-line luminosity and R or redshift from various samples. For instance, Feretti *et al*[9] and Giovannini *et al*[10] investigated statistical properties of elliptical galaxies and found some statistically significant correlations between the core radio power and total radio power and optical absolute magnitude. Baum and Heckman[11] analysed the correlations between the total radio luminosity and core radio luminosity, the optical narrow emission line luminosity, the broad band optical luminosity and redshift for 38 radio galaxies. Hough and Readhead[12] defined a complete sample of 28 double-lobed radio quasars to make a statistical analysis of

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the large-scale structure to check for consistency with the beaming hypothesis in the central components. It was shown that the core dominance parameter increases with redshift.[13] Murphy *et al*[14] mapped a complete sample of 89 powerful core-dominated radio sources (70 quasars and 19 BL Lacs) with core flux density $S_c^{5GHz} > 1$ Jy at 5GHz. They compared the different distributions of core-dominance parameter, redshift and extended radio luminosity for quasars and BL Lacs. Punsly [15] investigated the extended luminosity of strong radio cores for a sample of 134 ultraluminous radio core quasars. Those quasars have ultraluminous radio cores (core luminosity $P_c > 10^{53}J^{-1}$ in the quasar rest frame from 10MHz to 250GHz). Zirbel and Baum [16] examined the correlations of emission-line luminosity, radio luminosity, core radio power and host galaxy optical magnitude independently for FRI and FRII radio galaxies.

Very recently, a larger sample of 661 extragalactic radio sources were compiled and a relation between the 5GHz core luminosity and 1.4GHz total luminosity was discussed.[17] Based on their paper, Fan & Zhang [18] selected a sample of 542 sources with both core and total luminosity, calculated their core-dominance parameters, investigated log$R$ distribution, and discussed the correlation between core-dominance parameter and core radio power for BL Lacertae objects, galaxies, and quasars respectively. In this paper, we mainly discuss some mutual correlations, core-dominance parameter and core radio power, total and core radio power, radio power and redshift for the sample. In Sec.2 we define our sample and give the results. In Sec.3, we compare it with other authors' corresponding results and then discuss some statistical properties of radio sources. Finally, in Sec.4, we give a brief summary.

2. Results

From a paper by Liu & Zhang,[17] a sample of 542 objects with total luminosity (in W·Hz^{-1}) at 1.4GHz and core luminosity at 5GHz were chosen. Out of them, 27 are BL Lac objects, 300 are galaxies, and 215 are quasars (see Ref[18] for detail).

2.1. Correlation between total and core radio power

2.1.1. Distribution of radio power

To compare statistical properties for different subclasses, we give the total radio power and core radio power (logarithms) for each subclass. The mean total radio power for BL Lacertae objects and galaxies and quasars are $<\log P_{Tot}> = 25.77\pm1.14$, 24.86 ± 1.35 and 27.26 ± 0.74, respectively. The mean core radio power for BL Lacertae objects, galaxies and quasars are $<\log P_{Core}> = 25.22\pm1.14$, 23.16 ± 1.22 and 26.27 ± 1.00, respectively. From these values, we can find some apparent differences between different subclasses. Galaxies have obviously the lowest total and core radio powers, and BL Lacertae objects have lower total and core radio power than quasars although there are large overlaps of radio power distribution between the subclasses. In these regions, three subclasses 'coexist'. This difference is illustrated by comparing their distribution of logP_{Tot} and cumulative probability (Kolmogolov–Smirnov (KS) test) in Figs.1(a) and (b), Figs.2(a) and (b) and Figs.3(a) and (b) for BL Lacs and quasars, BL Lacs and galaxies, and quasars and galaxies respectively. The KS test indicates that the null hypothesis (they both being from the same parent population) cannot be rejected at the following confidence level for the different samples, namely $p < 10^{-4}$ for BL Lacs and quasars, p=0.0006 for BL Lacs and galaxies, and $p < 10^{-4}$ for quasars and galaxies. So, neither BL Lacs or quasars are different from galaxies.

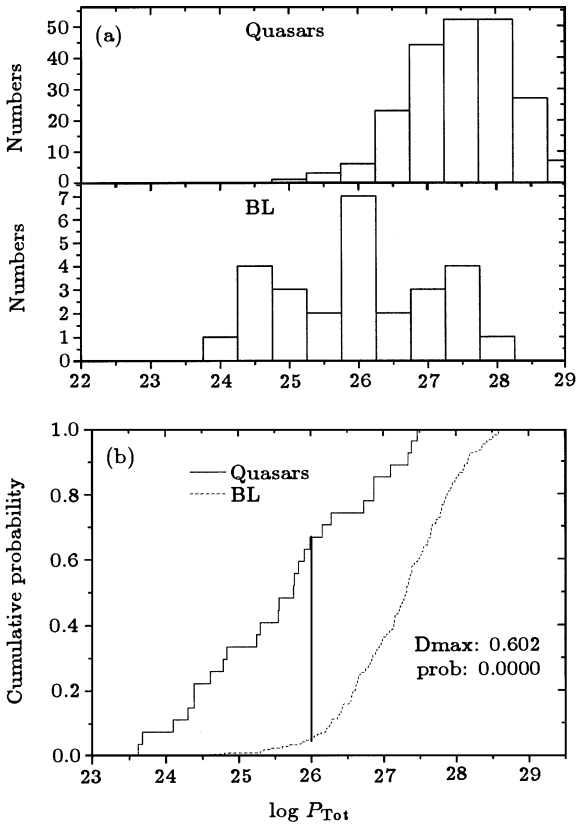


Fig.1. (a) Histogram comparison of total radio power (1.4G) for BL Lacs (lower panel) and quasars (upper panel); (b) KS test for BL Lacs and quasars.

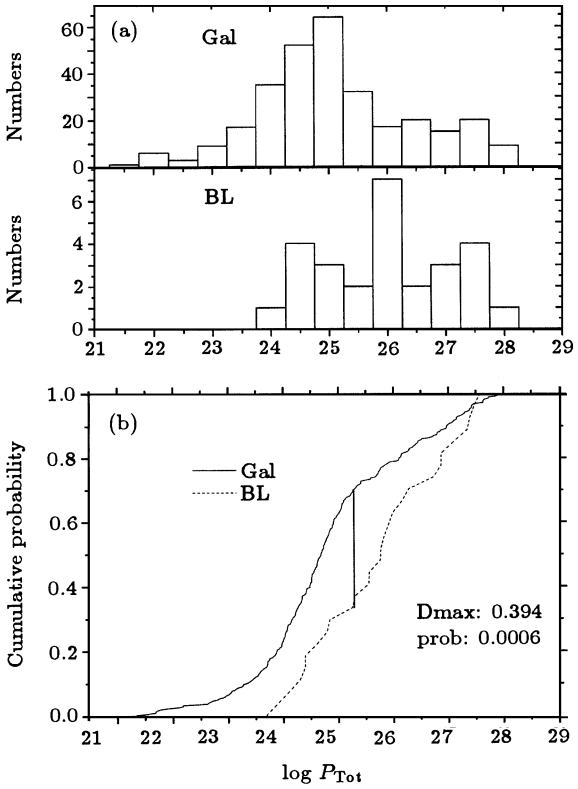


Fig.2. (a) Histogram comparison of total radio power (1.4G) for BL Lacs (lower panel) and galaxy (upper panel); (b) KS test for BL Lacs and galaxies.

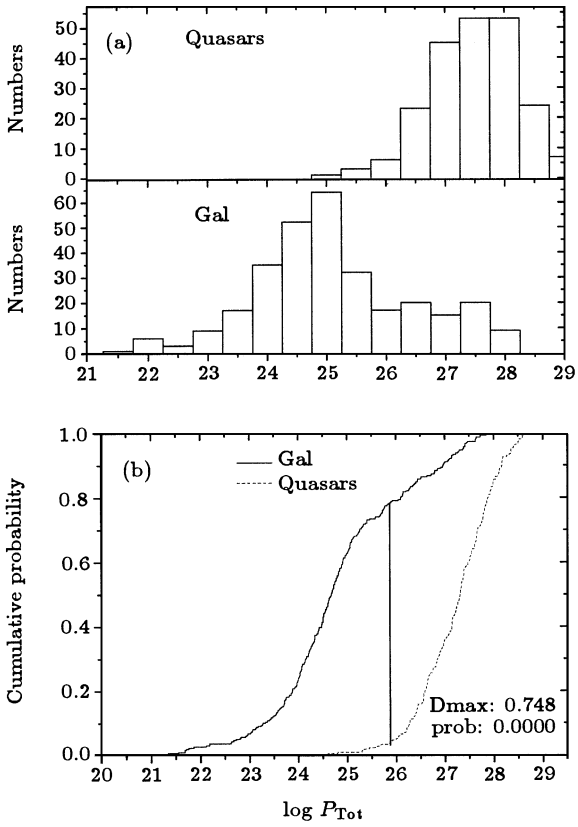


Fig.3. (a) Histogram comparison of total radio power (1.4G) for quasars (lower panel) and galaxies (upper panel); (b) KS test for galaxies and quasars.

2.1.2. Correlation of total and core radio power

To understand the energy emission of extragalactic radio sources, it is necessary to study the correlation between core and total radio power (or extended radio power). Obviously, a large sample of radio sources with a wide range of total power (or core power) for statistic analysis of correlation will be very helpful. Our sample meets the criteria (a large sample containing 542 sources and $19< \log P_{\rm Core}<29$ in units of $\mathrm{W}\cdot\mathrm{Hz}^{-1}$). We investigate core and total power correlation for the whole sample and individual subclass respectively. Our results are shown in Fig.4, in which

$\log P_{\rm Core} = (1.06\pm0.02)\log P_{\rm Tot} + (-2.90\pm0.55)$, for the whole sample with the correlation coefficient r=0.91, and the probability being greater than 99.99%;

$\log P_{\rm Core} = (0.77\pm0.03)\log P_{\rm Tot} + (3.91\pm0.68)$, for galaxies with the correlation coefficient r =0.86 and the probability being greater than 99.99%;

$\log P_{\rm Core} = (0.94\pm0.07)\log P_{\rm Tot} + (0.70\pm1.85)$, for quasars with the correlation coefficient r =0.69 and the probability being greater than 99.99%;

$\log P_{\rm Core} = (0.95\pm0.01)\log P_{\rm Tot} + (0.70\pm1.66)$, for BL Lacs with the correlation coefficient r =0.95 and the probability being greater than 99.99%.

From the above results, we can find that the correlation slopes of core and total radio power are near unity for both the whole sample and the subclasses except for galaxies, whose correlation slope is 0.77 ± 0.03.

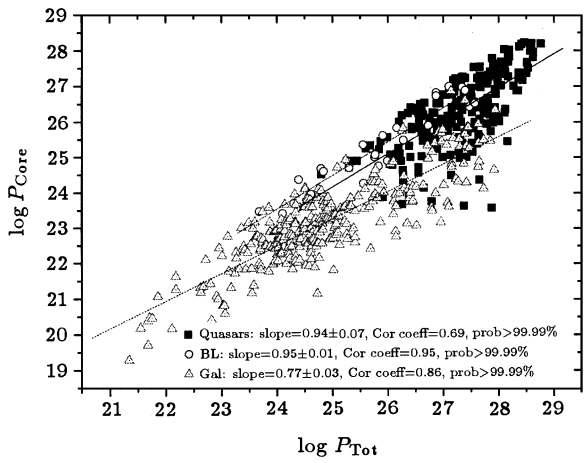


Fig.4. The correlation of core radio power (logarithm) and total radio power (logarithm).

2.1.3. Correlation between radio power and redshift

Figure 5 shows the correlation between total radio power (logarithm) and redshift (logarithm) for each

subclass. For all subclasses, the best linear fit regression slope are all near 2, namely

$\log P_{\rm Tot} = (2.06 \pm 0.04)\log z + (27.22 \pm 0.04)$, for the whole sample with the correlation coefficient r =0.92 and the probability being greater than 99.99%;

$\log P_{\rm Tot} = (1.86 \pm 0.07)\log z + (26.92 \pm 0.09)$, for galaxies sample with the correlation coefficient r=0.83 and the probability being greater than 99.99%;

$\log P_{\rm Tot} = (1.99 \pm 0.10)\log z + (27.32 \pm 0.03)$, for quasars with the correlation coefficient r =0.81 and the probability being greater than 99.99%;

$\log P_{\rm Tot} = (2.10 \pm 0.18)\log z + (27.34 \pm 0.16)$, for BL Lacs sample with the correlation coefficient r=0.92 and the probability being greater than 99.99%.

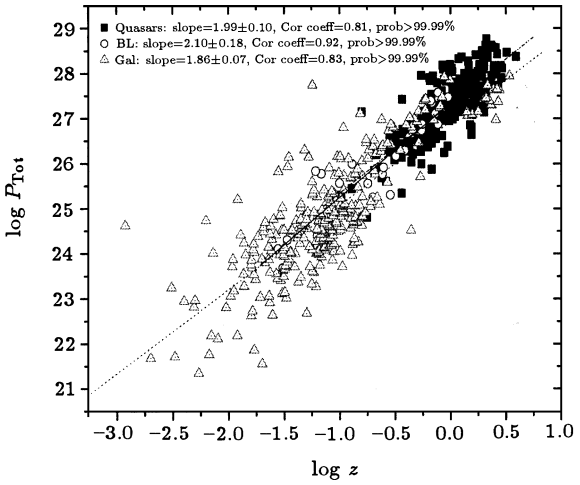


Fig.5. The correlation of total radio power (logarithm) and redshift (logarithm).

2.2. The core-dominance parameter

Using the same method as Fan & Zhang,[18] we assume that the core spectral index is $\alpha_{\rm C} = 0.0$ ($S_\nu \propto \nu^{-\alpha}$), and the extended spectral index is $\alpha_{\rm E} = 0.5$ and 1.0 respectively, to calculate the core-dominance parameter at 5GHz. Therefore, we have that the 1.4GHz core radio power is equal to the 5GHz core radio power, $P^{\rm C}_{\rm 1.4GHz} = P^{\rm C}_{\rm 5GHz}$, and the 1.4GHz extended radio power is the difference of the 1.4GHz total and core radio power, $P^{\rm E}_{\rm 1.4GHz} = P^{\rm T}_{\rm 1.4GHz} - P^{\rm C}_{\rm 5GHz}$, then $P^{\rm E}_{\rm 5GHz} = P^{\rm E}_{\rm 1.4GHz} \times (1.4/5)^{\alpha_{\rm E}}$. In this sense, the core-dominance parameter $R = \dfrac{P_{\rm C}}{P_{\rm E}} = \dfrac{P_{\rm C}}{P^{\rm T}_{\rm 1.4GHz} - P^{\rm C}_{\rm 5GHz}}(1.4/5)^{-\alpha_{\rm E}}$.

We find that the distributions of log$R$ obtained from different extended spectral indices ($\alpha_{\rm E}$) are different. The steeper the spectrum the larger the R; and there is a tendency that the BL Lacs have higher R than quasars, and quasars have higher R than galaxies; the average log$R$ are as follows: log$R$=0.01±0.65 for BL Lac objects, log R=–1.41±0.74 for galaxies, log R=–0.53±0.92 for quasars.

2.2.1. Correlation between R and total radio power

The relations between log$R$ and core and extended power (logarithm) were analysed in Fan & Zhang.[18] For our quasars sample, there is a correlation between core-luminosity (log$P_{\rm C}$) and log$R$ and an anti-correlation between extended luminosity (log$P_{\rm E}$) and R. The relationships have been explained using a beaming model.

Here we consider the correlation between log$R$ and log$P_{\rm Total}$ (total radio power) for the whole sample and individual subclass respectively (only taking into account the $\alpha_{\rm E} = 0.5$ case). The corresponding diagrams are shown in Fig.6. There is no obvious correlation between log$R$ and log$P_{\rm Tot}$ for the whole sample and quasars, but there is an obvious anti-correlation for galaxies, i.e. $\log P_{\rm Tot} = -(0.77 \pm 0.09)\log R + (23.78 \pm 0.15)$. The correlation coefficient is –0.43 and the probability is larger than 99.99%.

For BL Lacs, we get $\log P_{\rm Tot} = -(0.24 \pm 0.35)\log R + (25.77 \pm 0.22)$. The correlation coefficient equals -0.14 and the probability equals 50.04%.

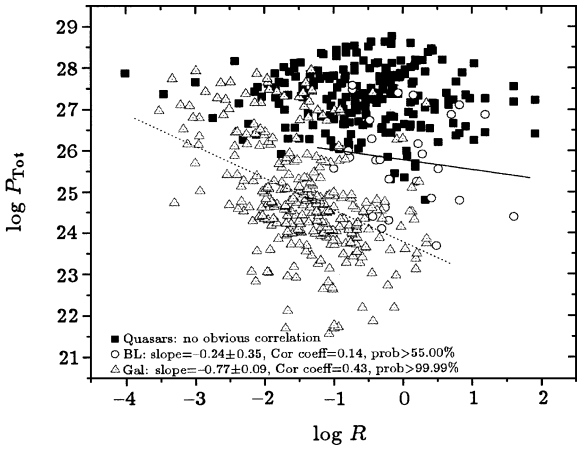


Fig.6. The correlation of total radio power (logarithm) and core dominance parameter (logarithm).

3. Discussion

In AGNs, the emissions are composed of two components. The ratio of R of the beamed core power to the unbeamed extended power is an important parameter showing the orientation of the jets. Many authors have investigated the correlation between observation

parameters including R. In the present paper, we discussed some correlations for a large sample containing 542 sources.

Power and Power Correlation: For this correlation, different authors give differently dependent results based on their own sample. Feretti *et al*[9] investigated a sample of 138 radio galaxies taken from the B2 and the 3CR catalogues and obtained a correlation slope between the core and total radio power of 0.57. Giovannini *et al*[10] investigated statistical properties of radio cores for 187 elliptical galaxies and found the correlation slope between the core and total radio power to be 0.47. Baum and Heckman[9] analysed the correlations between the total radio luminosity, core radio power, the optical narrow emission line luminosity, the broad band optical luminosity and redshift for 38 radio galaxies; they found the correlation slope of the core and total radio power to be 0.66. Zirbel and Baum[16] looked for the correlation of core radio power and total radio power for FRI and FRII radio galaxies: the slope of correlation is 0.56. Fabbiano *et al*[19] studied a sample of 43 3CR radio galaxies: the slope of correlation between core and total radio power for the complete sample is 0.75. For our galaxies sample, the results indicate that the correlation slope between core and total radio power is 0.77 ± 0.03, which is consistent with the results mentioned above. For radio galaxies, the slope of the correlation is less than unity, i.e. the core radio luminosity of radio galaxies increases less rapidly than the total radio luminosity. The physical reason for the correlation (i.e. the slope being less than unity) is currently not clear. Giovannini *et al*[8] supposed that a high power radio source has a more efficient engine than a low power radio source, and the core emission is due to dispersions in the energy transport and/or production. Therefore, the fraction of emission that we see in the core decreases when the total emission increases.

Fanti *et al*[20] suggested that a correlation, $L_{\rm Core} \propto L_{\rm Tot}^{k}$, $k \leq 0.5$ may exist for quasars. Giovannini *et al*[10] suggested that it is possible that the correlation of core radio power and total radio power found for galaxies is also valid for quasars if there is a large complete sample of quasars. But Fabbiano *et al*[19] inspected FRII sources given by a paper of Laing *et al*[21] and found a slope of unity for this correlation when the full variety of optical types are represented. For our quasars and BL Lacs samples, the slope of correlation between the core and total radio power for quasars and BL Lacs are all near unity. This is consistent with Fabbiano *et al*'s result.[19] It shows that the correlation of core and total radio power (i.e. the slope being less than unity) found for galaxies is not valid for quasars or BL Lacs, i.e. the slope of correlation between the core and total radio power for galaxies is less than unity while those for quasars and BL Lacs are both near unity. Maybe different subclasses of extragalactic radio sources have different energy transport mechanisms. Whatever the case, here the statistically significant correlation between core radio power and total radio power has been confirmed. The correlation supports the proposal that radio jets from the core supply energy to extended lob emission.[21]

Power and Redshift Correlation: We found a correlation slope of 2; this kind of correlation might be induced by the dependence of radio power on redshift. Zirbel and Baum[16] also looked at the correlation of total radio power (logarithm) and redshift (logarithm) for FRI and FRII radio galaxies. Their regression slopes are 1.03 for FRIs and 1.92 for FRIIs. For the FRI sample, the slope is much less than 2; we think this was probably caused by the absence of high redshift sources in their FRI sample, because when we analyse the galaxies with lower redshift of our sample alone, we find the slope of regression line for the correlation becomes less.

Core-Dominance Parameter: Ghisellini *et al*[22] compiled a sample of extragalactic sources and found that the average $\log R$ in BL Lacs is larger than that in flat spectrum radio quasars (FSRQs). However, Murphy *et al*[14] obtained a distribution of $\log R$ for a core-dominated radio source sample (56 quasars and 18 BL Lacs) with the 5GHz core flux densities being greater than 1Jy. They found that there is a tendency for BL Lacs to have lower R than quasars in their sample. Although the difference is not significant, the results do not support the argument that BL Lacs are quasars with more highly beamed cores. More detailed discussion can be found in Fan.[8] Our present results show a tendency that BL Lacs have higher R than quasars, and that quasars have higher R than galaxies.

De Ruiter *et al*[23] analysed the radio properties of a complete sample of 101 low luminosity radio galaxies. They got an anti-correlation of the median $\log R$ (core-dominance parameter) as a function of $\log P_{\rm Tot}$ (total radio power), i.e. $\log R_m = -0.55 \log P_{\rm Tot} + 11.76$. Zirbel and Baum[16] also analysed the correlation between $\log R$ and $\log P_{\rm Tot}$ for FRI and FRII radio galaxies, and found the same anti-correlation for both

FRI and FRII, i.e. the R-parameter decreases as a function of the total radio power. The slope of regression line for this correlation is –0.33±0.12. Our results show, for our galaxies sample, that there is an obvious anti-correlation. The correlation of log$R$ and log$P_{\rm Tot}$ is significant at the >99.99% level. The slope of regression line for this correlation is –0.77 ± 0.09 with a correlation coefficient r=–0.43. This is consistent with their results.[16,23]

However, there are no obvious correlation between log$R$ and log$P_{\rm Tot}$ for our quasars sample. For BL Lacs, we do not have enough reasons to confirm the existence of correlation due to the lower correlation coefficient (–0.14) and lower confidence level (prob=50.04%). There are only 27 BL Lacs in our sample. More sources may be helpful to test the correlation for BL Lacs. These results are in accordance with previous *Power and Power Correlation* results. For galaxies, the slope of correlation between core and total radio power is less than unity, i.e. the core radio luminosity of radio galaxies increased less rapidly than the total radio luminosity. So, the core-dominance parameter ($R = P_{\rm Core}/P_{\rm Tot}$) decreases as the total radio power increases. But for quasars and BL Lacs, the slopes are all near unity, i.e. the core radio luminosity of radio galaxies increases as fast as does the total radio luminosity. So there is no obvious correlation between log$R$ and log$P_{\rm Tot}$ for quasars.

4. Summary

From the above results and discussions, we draw the following conclusions:

1) Obviously, the galaxies have both the lowest total and core radio power, BL Lacs are median and the quasars have the largest values. But there are large regions of overlap in radio power distribution between subclasses. In these regions, three subclasses 'coexist'.

2) A statistically significant correlation is confirmed between the total and core radio power. The slope of correlation between core radio power and total radio power for galaxies is less than unity, and those for quasars and BL Lacs are both near unity.

3) There are no obvious correlations between log$R$ and log$P_{\rm Tot}$ for the whole sample or quasars, and there is not enough evidence to confirm the correlation for our BL Lacs sample. But a statistically significant anti-correlation is confirmed for our galaxy sample.

Acknowledgments

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