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The Scale Invariant Synchrotron Jet of Flat Spectrum Radio Quasars

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Abstract. In this paper, the scale invariance of the synchrotron jet of Flat Spectrum Radio Quasars has been studied using a sample of combined sources from FKM04 and from SDSS DR3 catalogue. Since the research of scale invariance has been focused on sub-Eddington cases that can be fitted onto the fundamental plane, while near-Eddington sources such as FSRQs have not been explicitly studied. The extracted physical properties of synchrotron jet of FSRQs have been shown to be scale invariant using our sample. The results are in good agreement with theoretical expectations of Heinz & Sunyaev (2003). Therefore, the jet synchrotron is shown to be scale independent, regardless of the accretion modes. Results in this article thus lend support to the scale invariant model of the jet synchrotron throughout the mass scale of black hole systems.

Key words. Galaxies: jets—galaxies: active—BL Lacertae objects: general—quasars: general—quasars: supermassive black holes.

1. Introduction

The idea of the jet formation process is universal in systems possessing black holes of different masses, from galactic X-ray binaries with $M_{\rm BH} sim M_{\odot}$ to super massive black holes in active galactic nuclei (AGN) with $M_{\rm BH} \sim 10^6 M_{\odot}$ to $M_{\rm BH} \sim 10^9 M_{\odot}$, is inspired by the similarities in morphology of the jets and the radio spectrum of core emission. Based on this idea, a scale invariant model has been established in Heinz & Sunyaev (2003). In a scale invariant jet model, all length scales are proportional to the fundamental scale of the black hole system, $r_g \propto M_{\rm BH}$. This assumption leads to the conclusion that any physical properties f of the jet can be expressed as follows:

$$f(M_{\rm BH}, \dot{m}, a, r) = \phi_f(M, \dot{m}, a)\psi_f\left(\frac{r}{r_g}, \dot{m}, a\right) \quad (1)$$

where $\dot{m}$ is the dimensionless accretion rate, a is the spin parameter, r is the distance to the central engine, ϕ_f is the dependence of f on M_{BH}, and ψ_f is a normalization factor, describes the spatial dependence of f on the similarity variable $\chi \equiv \frac{r}{r_g}$ for a given set of $\dot{m}$ and a.

Employing the standard radiation theory, Heinz & Sunyaev (2003) showed that there exists a non-linear dependence of synchrotron luminosity L_ν at a certain frequency f on black hole mass M_{BH} and accretion rate $\dot{m}$. Meanwhile, the model-dependent complications of jet physics can be canceled out and only model-independent relation left (Heinz & Sunyaev 2003). The relations between the synchrotron luminosity L_ν at a given frequency ν emitted by the jet and the black hole mass M_{BH} and the dimensionless accretion rate $\dot{m}$ are as follows:

$$\frac{\partial \ln(L_\nu)}{\partial \ln(M_{\mathrm{BH}})} = \frac{2p+13+2\alpha}{p+4} + \frac{\partial \ln(\phi_B)}{\partial \ln(M_{\mathrm{BH}})}\left(\frac{2p+3+\alpha p+2}{p+4}\right) + \frac{\partial \ln(\phi_C)}{\partial \ln(M_{\mathrm{BH}})}\left(\frac{5+2\alpha p}{p+4}\right) \tag{2}$$

and

$$\frac{\partial \ln(L_\nu)}{\partial \ln(\dot{m})} = \frac{\partial \ln(\phi_B)}{\partial \ln(\dot{m})}\left(\frac{2p+3+\alpha(p+2)}{p+4}\right) + \frac{\partial \ln(\phi_C)}{\partial \ln(\dot{m})}\left(\frac{5+2\alpha p}{p+4}\right), \tag{3}$$

Here, p is spectral index of the electron power law distribution and α is the spectral index of luminosity L_ν at a certain frequency.

For a synchrotron jet with observed optically thick luminosity labeled as L_{thick}, observed optically thin luminosity as L_{thin} and black hole mass M_{BH}, the above equations predict a relation as follows:

$$\log L_{\mathrm{thin}} = \xi_{\mathrm{thick}} \log L_{\mathrm{thick}} + \xi_M \log M_{\mathrm{BH}} + C, \tag{4}$$

where the coefficients are as given below:

$$\xi_{\mathrm{thick}} = \frac{(p+4)(p+5)}{2(2p+13+\alpha_{\mathrm{thick}}p+6\alpha_{\mathrm{thick}})}, \tag{5}$$

$$\xi_M = 3 - \frac{(p+5)(2p+13+2\alpha_R)}{2(2p+13+\alpha_R p+6\alpha_R)}. \tag{6}$$

Here, p is spectral index of the electron power law distribution and α_{thick} is the spectral index of luminosity L_ν at a certain frequency.

If one of the luminosities L_{acc} originates from the accretion, one has

$$\log L_{\mathrm{acc}} = \xi'_{\mathrm{thick}} \log L_{\mathrm{thick}} + \xi'_M \log M_{\mathrm{BH}} + C' \tag{7}$$

where C', ξ'_{thick} and ξ'_M are constants.

Employing the scale invariance, one obtains the correlation coefficients in equation (7) as follows:

$$\xi'_{\mathrm{thick}} = \left(\frac{\partial \ln \phi_B}{\partial \ln \dot{m}}\right)^{-1}\left(\frac{q(p+4)}{2p+13+\alpha_R p+6\alpha_R}\right) \tag{8}$$

$$\xi'_M = 1 - q\left(\frac{\partial \ln \phi_B}{\partial \ln \dot{m}}\right)^{-1}\left(\frac{\partial \ln \phi_B}{\partial \ln M_{\rm BH}}\right) - \left(\frac{\partial \ln \phi_B}{\partial \ln \dot{m}}\right)^{-1}\left(\frac{q(2p + 13 + 2\alpha_R)}{2p + 13 + 2\alpha_R p + 6\alpha_R}\right), \tag{9}$$

where q is the accretion efficiency, $\dot{m}$ is dimensionless accretion rate, and ϕ_B is the dependence of magnetic field on the black hole mass.

On the other hand, the observationally established fundamental plane (FP) of black hole activity is a linear correlation describing the emissions from a black hole system in the three-dimensional ($\log L_{\rm R}$, $\log L_{\rm X}$, $\log M$) space that has the form:

$$\log L_{\rm X} = \xi_{\rm R} \log L_{\rm R} + \xi_{\rm X} \log M_{\rm BH} + C, \tag{10}$$

here, $L_{\rm R}$ and $L_{\rm X}$ are luminosities from radio and X-ray waveband, respectively. $M_{\rm BH}$ is the black hole mass, $\xi_{\rm R}$, $\xi_{\rm X}$ and C are constants. This relation applies to black hole systems from the $\sim 10 M_\odot$ X-ray binaries (XRBs) to $10^6 \sim 10^8 M_\odot$ super-massive black holes (SMBHs) (Merloni *et al.* 2003; Falcke *et al.* 2004; hereafter MHM03 and FKM04, Done & Gierliński 2005; Nipoti *et al.* 2005; Jester 2005; Körding *et al.* 2006; McHardy *et al.* 2006; Körding *et al.* 2007; Markoff *et al.* 2008; Gliozzi *et al.* 2010; Kelly *et al.* 2011; Plotkin *et al.* 2012). Physically, the FP implies that there exists a fundamental connection between the black hole system, which includes the black hole and accretion disk, and the jet production process and is one of the strongest arguments supporting the idea of scale invariance of jets.

Under the framework of scale invariant jets, from equations (4) and (7), it can be seen that one of the points of the FP study is that by studying the correlation between the flat spectrum radio emission, which is well understood as optically thick emission from a synchrotron jet, and the X-ray emission, which is not *a priori* understood, one gets a new constraint on the efficiency of the X-ray emission process, and a tool by which one can eliminate various competing models for the X-ray emission.

There are two discovery papers of FP, MHM03 and FKM04. MHM03 studies a sample containing about 100 AGNs and 50 simultaneous observations of GBHs and find a statistically significant correlation among the radio, X-ray luminosity and the black hole mass, which is entitled as the FP of the black hole activity as follows:

$$\log L_{\rm R} = (0.60^{+0.11}_{-0.11}) \log L_{\rm X} + (0.78^{+0.11}_{-0.09}) \log M + 7.33^{+4.05}_{-4.07}. \tag{11}$$

It is well known that the radio luminosity is from the synchrotron radiation of the jet. The X-ray luminosity might have various origins, such as the jet synchrotron emission, the radiation from radiatively efficient accretion flow, and the radiatively inefficient flow. The authors employ the scale invariance jet to model all the possible cases and compare the results with observations, and find that models of radiatively inefficient accretion flows seem to agree well with observations, the jet origin of the X-ray has marginal consistency, and the radiatively efficient accretion flow seem to fail.

Alternatively, in FKM04's scenario the authors assume that the spectral energy distribution (SED) of significant sub-Eddington systems are dominated by non-thermal emission from relativistic jets (JDAF), whereas near-Eddington black holes will be dominated by emission from the accretion disk. The authors use a sample consisting of GBRs, LINERs, FR I galaxies and BL Lacertae objcets (BL Lacs), which are all significant sub-Eddington, thus are JDAF dominated, according to the above assumption. FKM04 then studies the correlation between the radio and X-ray luminosities. In FKM04's pictures, the radio luminosity studied in the FP actually is optically thick emission, while the X-ray luminosity is the optically thin radiation. For FR Is and BL Lacs with observed X-ray emissions not from optically thin synchrotron radiation, the authors propose to extrapolate the optical band radiation, which can be safely concluded as optically thin, to the X-ray band. Recent work of Plotkin *et al.* (2012) shows that this extrapolation process is necessary and valid. Taking only the radio and X-ray luminosities L_{R} and L_{X} into consideration, there exists no global correlation for all the sources in the sample. However, based on a coupled jet-disk model originated by Blandford & Königl (1979) and updated by Falcke & Biermann (1995), the X-ray luminosity, i.e. the optically thin luminosity L_{X} is then scaled by a term consisting of black hole mass and spectral indices. The theoretically predicted linear relation between L_{R} and scaled, or the equivalent X-ray luminosity L'_{X}, for X-ray binary GX 339-4 then can be well followed by all types of sources in the sample. This obviously supports the scale invariance of low power black hole systems. The relation obtained by FKM04 is

$$\log L'_{\mathrm{X}} = P \log L_{\mathrm{R}} + Q, \tag{12}$$

where P and Q are constants. Expressing the L'_{X} as the combination of L_{X} and M_{BH}, one has

$$\log L_{\mathrm{X}} = P \log L_{\mathrm{R}} + F \log M_{\mathrm{BH}} + Q \tag{13}$$

which is of the form of an FP.

Both MHM03 and FKM04 find observationally a statistically-significant linear correlation between L_{R}, L_{X} and M_{BH} across the entire black hole mass scale, respectively, and explain theoretically the results. Note that MHM03's theoretical model is applicable for any model that is scale invariant (Heinz & Sunyaev 2003) and FKM04's canonical jet model by nature is also scale invariant (Heinz & Sunyaev 2003). The two scenarios have the same theoretical foundation. Furthermore, MHM03 and FKM04 have similar assumptions (Plotkin *et al.* 2012).

On the other hand, the two discovery papers have differences. Bear in mind that the most significant one is the origin of L_{X}. In FKM04's scenario only the jet properties are focused while in MHM03 there are various origins. Another important difference is that the MHM03 sample consists of high accretion rate objects while the FKM04 sample just contains weakly accreting sources. Also, the notation of the formula in MHM03 and FKM04 is different from each other (Plotkin *et al.* 2012). The study in FKM04 was whether a synchrotron only model was consistent with all low luminosity sources, i.e., can a synchrotron only emission model that works to explain realtime correlations in XRBs be extended to AGN? Their results show that for some low-luminosity AGN it could. However, in the Heinz & Sunyaev (2003) and MHM03 paper, it was shown that this interpretation works primarily because the scaling of synchrotron X-ray is $\dot{m}^2$, and this is also similar to the X-ray efficiency of RIAFs $\dot{m}^{2-2.3}$ so, in fact, several mechanisms are consistent with the data.

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Recently, Plotkin *et al.* (2012) shows that for sub-Eddington black holes the X-ray emission is dominated by optically thin synchrotron radiation from the jet, if their radio spectrum are flat or inverted. The FP obtained is

$$\log L_{\mathrm{X}} = (1.45 \pm 0.04) \log L_{\mathrm{R}} - (0.88 \pm 0.06) \log M - 6.07 \pm 1.10 \qquad (14)$$

with intrinsic scatter $\langle \sigma \rangle = 0.07 \pm 0.05$. Since FKM04, the highly accreting objects are almost excluded in the study of FP. However, since black hole systems with higher accretion rates can still have observable jets, such as Flat Spectrum Radio Quasars (FSRQs) and some Narrow Line Seyfert galaxies (see, e.g., Abdo *et al.* 2009a, b, c; Foshini *et al.* 2010). If there exists a jet in a black hole system, it is reasonable to be uniformly made, regardless of the accretion processes. Therefore, from the viewpoint of scale invariant synchrotron jet, if the synchrotron jet properties of FSRQs can be extracted, a correlation that has the form of equation (4) can be physically expected. However, it is noted that since the FP is defined as the correlation between the observed radio and X-ray luminosity of the sources, this correlation is not a FP.

2. Sample description

In this article, we compile a sample of 88 black hole systems from two papers. There are 41 observations of GBH, Sgr A*, LLAGNs and BL Lacs from FKM04. There are 47 FSRQs from the sample of Chen *et al.* (2009), which is constructed by cross-correlating (Shen *et al.* 2006) SDSS DR3 quasar sample with the Faint Images of the Radio Sky at Twenty Centimeters (FIRST) and Green Bank 6-cm survey (GB6) radio catalogue. The data of FSRQs are listed in Table 1 with synchrotron peak luminosity $(\nu L_\nu)_{\mathrm{syn}}^{\mathrm{peak}}$, synchrotron peak frequency $(\nu L_\nu)_{\mathrm{syn}}^{\mathrm{peak}}$, black hole mass M_{BH}, the 5 GHz radio luminosity and the observed X-ray luminosity $L_{\mathrm{X}}^{\mathrm{obs}}(3\text{–}9\,\mathrm{keV})$. The synchrotron peak frequency and peak luminosity are derived by fitting the multi-band (radio, UV, optical, infrared and X-ray) data following Fossati *et al.* (1998). The black hole mass is estimated by using the empirical relation based on the luminosity and FWHM of broad emission lines (Greene & Ho 2005; Vestergaard & Peterson 2006; Kong *et al.* 2006). The advantage of using this sample lies in two facts. One is that all sources are selected in the same way, the multi-wavelength data are taken from the same observations and black hole masses are estimated with the same method. The other is that all necessary data in our analysis are available for all sources in Chen *et al.* (2009) sample.

The FSRQs are selected from Chen *et al.* (2009) as follows: first, the whole sample in Chen *et al.* (2009) consists 185 sources, 118 of which are non-thermal emission dominated. We use only non-thermal dominated sources, because the thermal radiation from accretion disk or host galaxy might contribute significantly to the SED in the optical band, therefore, might introduce bias when extrapolating the fitted synchrotron peak frequency and luminosity to obtain the X-ray luminosity (see below). Second, the red-shift of sources in the non-thermal dominated sources range

Table 1. Radio luminosity vs. real and extrapolated X-ray luminosities.

Source	z	$\log M_{\rm BH}$	$\log(\nu L_\nu)^{\rm peak}_{\rm syn.obs}$	$\log \nu^{\rm peak}_{\rm syn}$	$L_{5\ \rm GHz}$	$L^{\rm obs}_{\rm X}$	$L^{\rm ext}_{\rm X}$
J013352.7 + 011343.6	0.308	8.56	44.75	14.41	41.68	45.164	46.262
J074541.7 + 314256.6	0.461	9.66	46.14	14.93	43.35	45.604	47.444
J083148.9 + 042939.2	0.174	7.42	45.86	12.46	42.76	45.454	48.152
J093200.1 + 553347.0	0.266	8.92	44.87	14.22	41.49	44.734	46.458
J093309.3 + 461534.6	0.778	9.39	45.73	15.33	42.3	46.034	46.874
J094857.3 + 002225.6	0.585	8.41	45.43	14.38	42.92	45.684	46.954
J095738.2 + 552257.9	0.895	9.11	46.52	13.23	44.38	46.174	48.504
J095855.1 + 423703.8	0.664	8.8	45.39	14.79	42.36	45.834	46.75
J101027.5 + 413238.9	0.612	9.56	46.1	14.68	43.43	46.314	47.504
J101557.1 + 010913.7	0.78	9.85	46.36	14.95	43.08	45.604	47.656
J102235.6 + 454105.4	0.743	8.63	45.06	13.2	42.44	45.564	47.056
J103025.0 + 551622.3	0.434	8.81	45.5	14.98	42.11	45.344	46.784
J104146.8 + 523328.4	0.678	9.53	46.07	15.21	43.5	46.004	47.262
J104732.3 + 483531.3	0.866	8.93	45.6	14.84	42.73	45.824	46.94
J105654.2 + 051713.2	0.456	8.94	45.15	15.07	42.02	45.394	46.398
J121347.5 + 000130.1	0.962	9.4	46.18	15.04	42.72	46.234	47.44
J122106.9 + 454852.2	0.525	9.26	45.62	15.59	42.21	46.154	46.66
J122452.4 + 033050.3	0.956	9.24	46.03	13.3	44.17	45.964	47.986
J125500.5 + 034043.2	0.437	8.86	45.29	15.96	42.35	46.314	46.182
J130217.2 + 481917.5	0.874	9.09	46.07	14.11	43.2	46.334	47.702
J133245.3 + 472222.6	0.669	8.62	45.7	13.69	43.13	45.724	47.5
J133437.4 + 563147.9	0.343	8.11	44.51	14.32	42.15	44.704	46.058
J134357.6 + 575442.6	0.933	8.93	45.77	14.7	43.17	45.894	47.166
J134934.7 + 534116.8	0.979	9.65	46.35	15.03	44	46.314	47.614
J135054.6 + 052206.6	0.442	9.3	45.27	14.64	42.11	45.244	46.69
J135726.4 + 001543.8	0.662	9.11	45.45	14.86	42.84	45.824	46.782
J141159.7 + 423950.4	0.886	9.6	46.25	14.85	42.79	45.824	47.586
J141324.2 + 530525.7	0.456	8.1	44.57	13.34	42.45	45.114	46.51
J145859.4 + 041614.1	0.392	8.2	45.35	12.76	43	44.924	47.522
J150324.7 + 475830.4	0.345	7.49	45.28	16.27	41.97	46.514	46.048
J153404.8 + 482340.7	0.543	8.52	45.17	14.73	42.93	45.324	46.554
J154929.4 + 023701.1	0.414	8.95	45.4	14.75	43.38	45.054	46.776
J160226.9 + 274141.6	0.938	9.45	46.09	14.48	42.62	46.134	47.574
J160623.6 + 540555.7	0.876	9.4	46.12	15.36	43.09	46.514	47.252
J160658.3 + 271705.9	0.934	9.01	45.77	15.16	43.28	46.074	46.982
J160822.1 + 401217.9	0.628	8.33	45.14	13.49	43.01	45.534	47.02
J160913.2 + 535429.7	0.992	9.72	46.16	14.52	42.83	46.364	47.628
J162229.3 + 400643.5	0.688	9.04	45.49	14.51	42.45	45.874	46.962
J162330.6 + 355933.1	0.866	9.32	45.85	14.5	43.29	45.704	47.326
J162901.3 + 400759.6	0.272	8.06	44.71	15.35	41.14	44.794	45.846
J163709.3 + 414030.6	0.76	10.05	46.06	14.84	41.92	45.854	47.4
J164258.8 + 394837.2	0.593	9.21	46.75	13.33	44.53	45.524	48.694
J164829.2 + 410405.9	0.852	9.38	45.62	14.15	43.26	46.194	47.236
J165005.5 + 414032.6	0.585	9.05	45.56	15.31	42.79	45.884	46.712
J165931.9 + 373529.0	0.771	9.59	45.94	15.23	42.23	45.864	47.124
J170425.1 + 333146.1	0.29	8.3	44.68	14.71	41.23	44.824	46.072
J172732.4 + 584634.1	0.844	9.03	45.62	14.97	43.08	45.794	46.908

from 0.174 to 3.946. In order to avoid biases introduced by evolutionary effects and Malmquist (or other kind of) biases, we choose sources within the red-shift range $0.174 < z < 1$, which turns out to be 47 FSRQs.

3. Statistics and results

To test the scale invariance of synchrotron jet of FSRQs, we follow FKM04's scenario to obtain the optical thick and optical thin luminosities. It is safe to take the $L_{\rm R}$ at 5 GHz as the optically thick luminosity. It is also obvious that the observed X-ray luminosity can not be used as optically thin emission because it could have originated from IC processes, not from synchrotron process (see also Körding *et al.* 2006; Plotkin *et al.* 2012). Therefore, an extrapolation from synchrotron radiation at lower frequency to obtain the optically thin emission is necessary.

In FKM04, the authors pick the optical band for extrapolation for the equivalent X-ray luminosity. However, for FSRQs, one has to be cautious because the optical emission could be from the jet as well as from the disk (e.g. Chen *et al.* 2009, Plotkin *et al.* 2012). Therefore, an alternative band for extrapolation is necessary.

According to the standard radiation theory, the typical spectrum of synchrotron emission from a set of power law distributed energetic electrons is a piece-wise power law shape (i.e. in the $\log \nu L_\nu - \log \nu$ plot the SED is of a piece-wise linear shape), with the optically thick part at lower frequency and the optically thin part at higher frequency (see e.g. Rybicki & Lightman 1979) and the latter is followed by a cut-off or another power-law (broken power-law) segment (see e.g. Tavecchio *et al*. 1998, Finke *et al.* 2008). On the whole, the SED in the $\log \nu L_\nu - \log \nu$ plot can be fitted using parabolic or third degree polynomial curves (e.g. Landau *et al.* 1986, Tanihata *et al.* 2004, Massaro *et al.* 2004, Nieppola et al. 2006).

Practically, the SED of blazars is often fitted from multi-band observations using polynomial (e.g. Fossati *et al.* 1998, Abdo *et al.* 2010). However, this does not necessarily mean that the shape of the SED is exactly the curve described by the polynomial. It is worth noting that the fitting curve is only the envelope, mathematically, of the SED. Physically, in the scale independent model, the real SED of the blazars is of piece-wise power-law shape (piece-wise line in a $\log \nu L_\nu - \log \nu$ plot). The result of fitting just helps to find the peak of the synchrotron emission.

Since the peak of the SED can be estimated by the fitting curve, the peak luminosity of the synchrotron component $L_{\rm syn}^{\rm peak}$ of FSRQs obtained by fitting can safely give a reliable estimate of the optically thin luminosity at the peak frequency. Thus, an extrapolation using the power law spectral index $\alpha_{\rm thin}$ from $L_{\rm syn}^{\rm peak}$ to the X-ray band (3–9 KeV as that in FKM04) is applicable. Also, as stated above, although at the peak of the synchrotron component the fitting curve has a slope of 0.0, physically, the spectrum index for extrapolation should be the optically thin one.

Based on above considerations, we propose a SED-based method slightly different from that of Plotkin *et al.* (2012). We use the fitted synchrotron peak luminosity $(\nu L_\nu)_{\rm syn}^{\rm peak}$ and the fitted peak frequency $(\nu L_\nu)_{\rm syn}^{\rm peak}$ together in extrapolation to obtain the X-ray luminosity. Using typical value of $\alpha_{\rm thin} = -0.6$ (Markoff *et al.* 2003; Falcke *et al.* 2004; Körding *et al.* 2006; Plotkin *et al.* 2012) and simple algebra, the extrapolated X-ray luminosity at $3 - 9$ KeV (i.e. the same as that of the FKM04) is given as

$$\log L_{\rm X}^{\rm ext} = 7.28 + (\log(\nu L \nu)_{\rm syn}^{\rm peak} - 0.40(\log \nu)_{\rm syn}^{\rm peak}) \tag{15}$$

and the values of $L_{\rm X}^{\rm exp}$ are also listed in Table 1.

The reason we use a sample including not only FSRQs but also various black hole systems, is similar to what has been noted by Plotkin *et al.* (2012), i.e., fitting the FP just for the sample of FSRQs in this article leads to regression coefficients different slopes as the limited dynamical range of the sources and relatively large intrinsic scatter.

To test whether the 47 FSRQs in our sample can be fitted onto the FP and statistically determine the thickness of the plane, we employ the multivariate regression method of Kelly (2007, hereafter K07), which is also used in Plotkin *et al.* (2012). K07 uses a Bayesian approach towards linear regression, estimating the probability distribution of the FP parameters with given observations (mlinmix_err.pro in the IDL Astronomy Users Library, http://idlastro.gsfc.nasa.gov/). As has been concluded by Plotkin *et al.* (2012), the K07 approach has advantage in accounting for correlated errors and capability providing statistical information for not just unknown FP parameters, but also the intrinsic scatter, i.e. the thickness of the FP. Moreover, the K07 method is suitable for handling heterogeneously selected data sets with large measurement uncertainties, and the measurement errors in the independent variables do not need to be of similar magnitude.

We use the error budget described in Plotkin *et al.* (2012) and the K07 method gives the following regression relation

$$\log L_{\rm X}^{\rm ext} = (1.42 \pm 0.05) \log L_{\rm R} - (0.89 \pm 0.08) \log M_{\rm BH} - (5.4 \pm 1.4) \qquad (16)$$

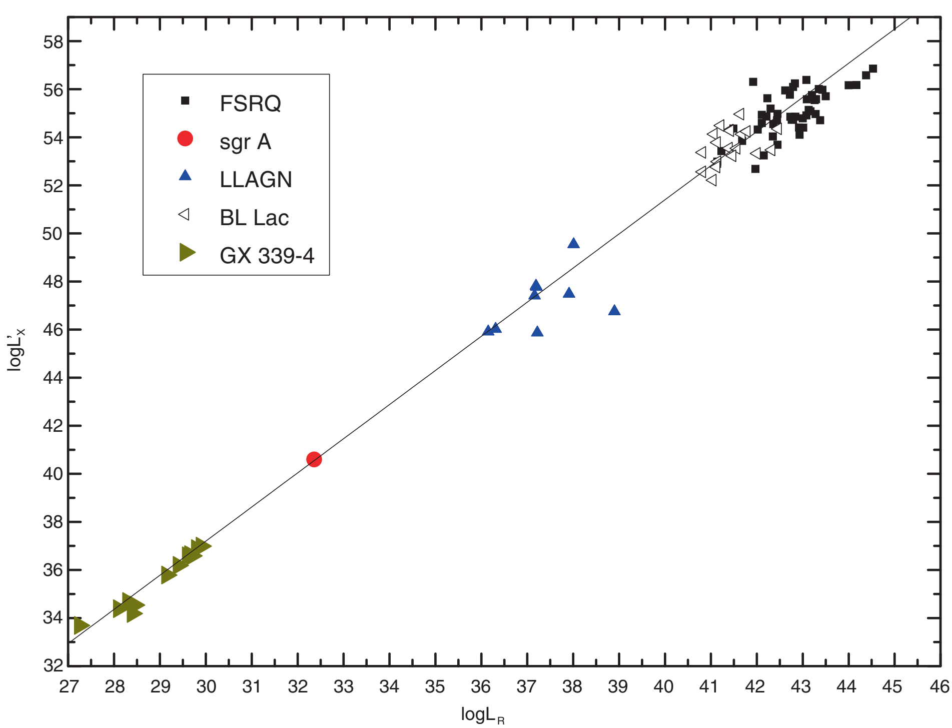

Figure 1. The result in this article illustrated in the way of FKM04, a 2 dimensional projection. The data points represent sample in this article. The thin solid line is the best fitting FP in equation (16). The definition of $L'_{\rm X}$ is in (17).

and an intrinsic scatter of $\langle\sigma_{\mathrm{int}}\rangle = 0.14 \pm 0.06$. From equations (5) and (6), the theoretical expectations of slopes are $\xi_{\mathrm{R}} = 1.38$ and $\xi_M = -0.81$. Hence, the above regression is in agreement with the scale invariant model in Heinz & Sunyaev (2003) and result in Plotkin *et al.* (2012) (14) within 1σ range.

For illustrative purpose we show a projection of FP (16) obtained above in the way of FKM04 in Figure 1. Here, the luminosity L'_{X} is the equivalent X-ray luminosity defined as

$$L'_{\mathrm{X}} = L_{\mathrm{X}}^{\mathrm{ext}} \log M_{\mathrm{BH}}^{0.88}, \tag{17}$$

this is the counterpart of FKM04's equation (7). In Figure 1, the FSRQs nicely follow the trend of weakly accreting black hole systems in FKM04 and represent the high end of the mass scale. Therefore, the above statistical results are in agreement with scale invariant model and, therefore, lend support to it. This confirms that highly accreting jets are scale invariant, which are similar to weakly accreting jets and are physically expected. If the jet exists, then its synchrotron emission might be similar regardless of the accreting rate. In other words, the jets associated with black holes at different mass scales follow basically the same physical principles. Physically, our result lends support to the idea of unification of systems with different black hole masses.

4. Conclusions

In this paper, the scale invariance of the synchrotron jet of FSRQs' has been studied using a sample of combined sources from FKM04 and from SDSS DR3 catalogue. Since the research of scale invariance has been focused on sub-Eddington cases that can be fitted onto the FP and near-Eddington sources such as FSRQs have not been explicitly studied, the extracted physical properties of synchrotron jet of FSRQs have been shown to be scale invariant with our sample. The results are in good agreement with theoretical expectations of Heinz & Sunyaev (2003). Therefore, the jet synchrotron is shown to be scale independent, regardless of the accretion modes. In a word, results in this article lend support to the scale invariant model of the jet synchrotron throughout the mass scale of black hole systems. The possible link to the blazar sequence has also been discussed.

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