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# Accretion Rate Sequence and Unification of Radio-loud AGNs

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**Abstract**

We have assembled a sample consisting of 43 BL Lacs and 37 radio-loud quasars, which have been imaged with the *Hubble Space Telescope (HST)* in order to investigate the relationship of accretion states and jet formation, and the unification model. We find 1) the accretion states are from pure ADAFs to a hybrid of the SS disk and ADAF, SS to super Eddington accretion. This means that jet can be formed in various accretion disks. 2) The extended radio emission strongly correlates with the accretion rates. 3) The SEDs in BL Lacs are correlated with the accretion rates. 4) *All* BL Lac objects are in ADAF regime while RLQs are in standard accretion disk regime. 5) The accretion rate sequence colud explain the Ledlow-Owen diagram of BL Lacs and radio-loud quasars.

## 1.1 Introduction

It has been generally believed that the relativistic jets originate from the accretion disks in radio-loud active galactic nulcei and quasars. There are some clear evidence for the relationship between the jet formation and the accretion disk in X-ray binaries, but it remains open in AGNs. There are several important issues to be addressed:

- What is the relationship between the accretion disk state and jet formation?
- Is there an accretion rate sequence in radio-loud objects in the unification?
- What machenism determines the spectral energy distribution (SED) of the continuum?

These questions are strongly correlated with the masses of the black holes, which are highly uncertain until *HST* observations of quasar's host galaxies. The masses of the black holes can be reliably estimated from the tight relation with the host luminosity. This provides a new clue to understand the central enignes of the radio-loud objects. We assemble a heterogeneous sample of radio-loud AGNs and quasars, which published information on the host galaxies by *HST*, to make an attempt to answer these questions.

## 1.2 Sample and Statistic Properties

The most reliable measurements of quasar host galaxy luminosities currently come from *HST* observations. We collect *all* the radio-loud quasars with *HST* observations in our sample consisting of 37 objects. The sample of BL Lac objects is chosen according to the availability of information on (1) the luminosity of the host galaxy, (2) the luminosity of one or more emission lines, and (3) the fitted peak frequency and luminosity of the SED. The sample is limited mainly by the host galaxy observations. More recently, an *HST* survey of

132 BL Lac objects was completed by Urry et al. (2000). Our sample has 17 HBLs and 26 LBLs. We determine BH masses from the absolute $R$-band magnitudes of the host galaxies, using the relation determined by McLure & Dunlop (2001) from a study of active galaxies: $\log\left(M_{\rm BH}/M_{\odot}\right) = -0.5M_{\rm R} - 2.96$.

The bulk of the line luminosity is photoionized by the accretion disk, $L_{\rm lines}$ should be proportional to the total disk luminosity. The total emission line luminosities are obtain from the quasar spectrum template (Celotti, Padovani & Ghisellini 1997). We define a "line accretion rate" and its dimensionless form as follows:

$$\Lambda = \frac{L_{\rm lines}}{c^2}; \quad \lambda = \frac{L_{\rm lines}}{L_{\rm Edd}}. \tag{1.1}$$

The disk states are descirbed by the dimensionless accretion rate $\dot{m} = \dot{M}/(\eta L_{\rm Edd} c^2)$, where $\eta = 0.1$ and $L_{\rm Edd}$ is the Eddington luminosity. For an ADAF the relation between $\lambda$ and the dimensionless accretion rate is given by $\dot{m} = 2.17 \times 10^{-2}\alpha_{0.3}\xi_{-1}^{-1/2}\lambda_{-4}^{1/2}$, where $\alpha_{0.3} = \alpha/0.3$, $\xi_{-1} = \xi/0.1$ and $\lambda_{-4} = \lambda/10^{-4}$. We assume that $\xi$ is of the same order as the covering factor of the line-emitting clouds ($\sim 0.1$). This expression assumes that the total luminosity from the ADAF is $L_{\rm disk} \propto \alpha^{-2} M_{\rm BH}\dot{m}^2$ (Mahadevan 1997). A necessary condition for the presence of an optically thin ADAF is $\dot{m} \le \alpha^2$, then

$$\lambda_1 = 1.72 \times 10^{-3}\xi_{-1}\alpha_{0.3}^2. \tag{1.2}$$

Optically thin ADAFs require $\lambda < \lambda_1$. Accretion disks in the optically thick, geometrically thin SS regime obey $\dot{m} = L_{\rm line}/(\xi L_{\rm Edd}) = 10\xi_{-1}^{-1}\lambda$, and the condition $1 > \dot{m} \ge \alpha^2$ gives

$$\lambda_2 = 9.0 \times 10^{-3}\xi_{-1}\alpha_{0.3}^2, \tag{1.3}$$

above which a standard disk can exist. It is interesting to note that in the transition region between $\lambda_1$ and $\lambda_2$ the accretion flow may be in a hybrid state in which a standard disk coexists with an ADAF. The disk structure, however, is complicated in such a regime, largely due to uncertainties in the viscosity. When the accretion rate reaches $\dot{m} \ge 1$, we have

$$\lambda_3 = 0.1\xi_{-1}, \tag{1.4}$$

in which case we use $E_{\rm R} = L_{\rm line}/(\xi L_{\rm Edd})$ to describe the accretion state since $\dot{m} > E_R$ in the super-Eddington accretion (SEA) regime in which photon trapping efficiently lowers the radiated luminosity (Begelman 1978, Wang & Zhou 1999).

## 1.3 Discussion and Conclusions

1) Figure 1 shows that HBLs and LBLs have pure optically thin ADAFs whereas some of RLQs have a hybrid of standard disk and ADAF and some of them have standard disks. This conclusion disagrees with some of theoretical model for jet formation that only favaours ADAF. We improve the current models for jet formation (Wang, Ho & Staubert 2003). Figure 1b also shows a sequence of the accretion rate from BL Lacs to RLQs. This supports a blazar sequence (e.g. Cavalier & D'Elia 2002).

2) Figure 2 shows that the extended radio emission strongly relates with the accretion rates directly indicating the relation between the central engine and the extended radio emission. The correlations are

$$\log L_{\rm 5GHz}^{\rm ext} = (27.57 \pm 0.29) + (0.68 \pm 0.10)\log\lambda, \tag{1.5}$$

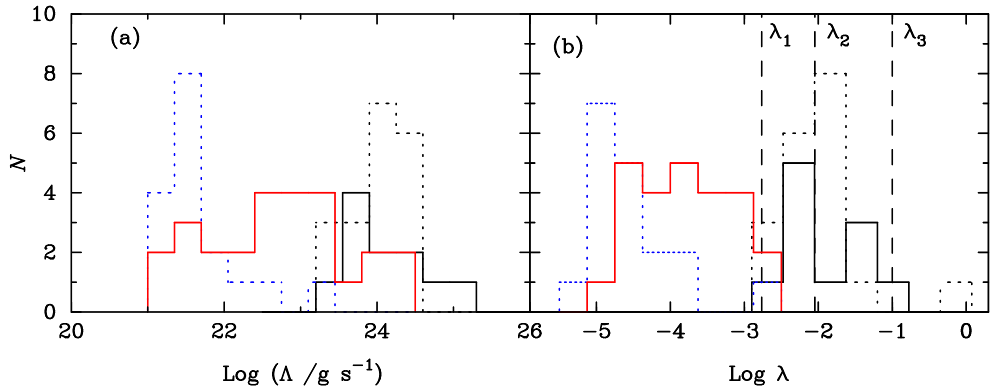


Fig. 1.1. The $\Lambda$ and $\lambda$ distributions in BL Lac objects and radio-loud quasars. The blue dotted histogram represent the HBLs, red solid the LBLs, black dotted SSRQs and solid the FSRQs. The distribution of (*a*) $\Lambda$ and (*b*) $\lambda$. The distribution of $\lambda$ is divided into four regions, corresponding to different states of the accretion disks: (1) $\lambda < \lambda_1$ (pure ADAF); (2) $\lambda_1 \leq \lambda \leq \lambda_2$ (ADAF+SS); (3) $\lambda_2 \leq \lambda \leq \lambda_3$ (SS); (4) $\lambda \geq \lambda_3$ (SEA)

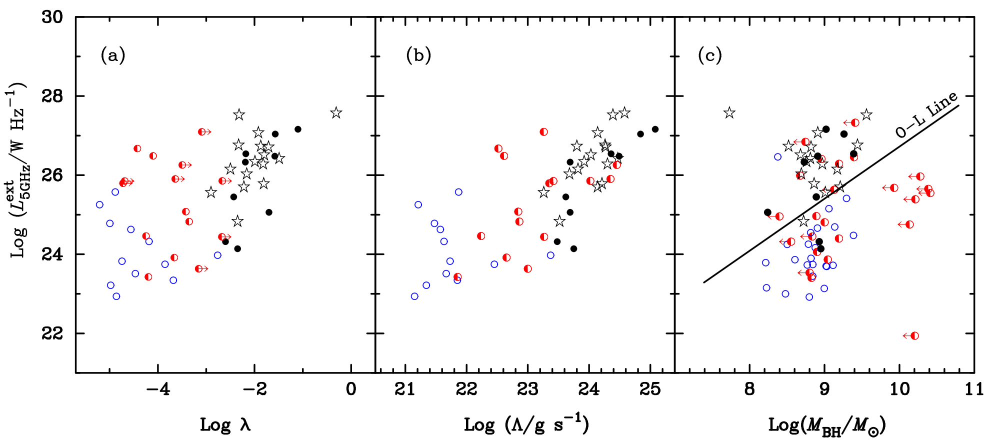


Fig. 1.2. The distribution of extended radio power at 5 GHz versus the (*a*) $\lambda$, (*b*) $\Lambda$, and (*c*) $M_{\rm BH}$. The black filled circles show the FSRQs, and SSRQs are denoted as open stars. The blue open and red semi-filled circles represent high frequency-peaked (HBL) and low frequency-peaked (LBL) BL Lacs, respectively; the radio data for these objects are taken from Urry et al. (2000), and values for $\lambda$, $\Lambda$, and $M_{\rm BH}$ are taken from Wang, Staubert, & Ho (2002). The diagonal line is the empirical division between FR I and FR II radio galaxies in the diagram of extended radio power at 1.4 GHz versus optical *R*-band absolute magnitude, as presented by Ledlow & Owen (1996).

with $r = 0.65$ and $p = 2.6 \times 10^{-10}$, and

$$\log L^{\rm ext}_{\rm 5GHz} = (4.18 \pm 2.70) + (0.92 \pm 0.11) \log \Lambda, \tag{1.6}$$

with $r = 0.76$ and $p = 2.1 \times 10^{-15}$. In the above correlation analysis of $(\lambda - L^{\rm ext}_{\rm 5GHz})$, we excluded the upper limit sources of BL Lacs. These correlations are striking in that they provide fairly direct evidence that the extended jet emission is somehow closely coupled to the central engine via the accretion disk. Our model can explain these correlations (Wang, Ho & Staubert 2003).

3) The Owen-Ledlow diagram (Fig. 2c) shows that the unification of radio-loud quasars

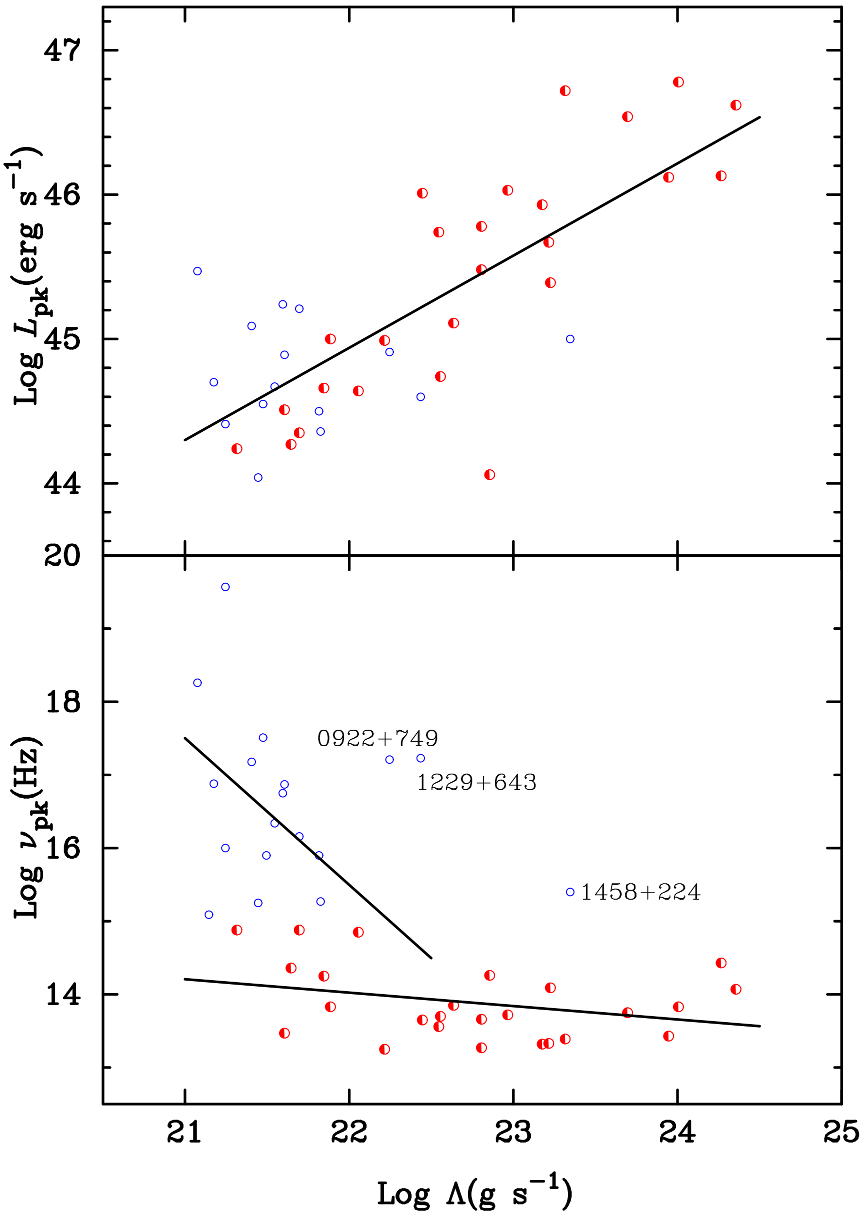


Fig. 1.3. The correlations among the parameters $\nu_{pk}$, $L_{pk}$, and $\Lambda$. The red semi-filled and blue open symbols denote LBLs and HBLs, respectively. The linear regression gives: $\nu_{pk} \propto \Lambda^{-3.02\pm1.19}$ for HBLs and $\nu_{pk} \propto \Lambda^{-0.25\pm0.11}$ for LBLs.

has a sequence of accretion rates. The Owen-Ledlow line indicates a transition of the accretion disk from standard model to ADAF.

4) Figure 4 shows a moderate strong correlation of the SEDs in BL Lacs on the accretion rates. We explain this dependence is caused by different radiative efficiency.

For HBLs, we consider the limiting case that most of the energy is radiated, we have the observed peak frequency is

$$\nu_{\rm pk} \propto \dot{M}^{\frac{\gamma+1}{2(3-\gamma)}} \propto \Lambda^{\frac{\gamma+1}{4(3-\gamma)}} \propto \Lambda^{-(2.3\sim3.0)}, \tag{1.7}$$

where $\gamma = 2.6 \sim 2.7$ is the index of the energy dustribution of electrons. This is consistent with the empirical results for HBLs. Since LBLs have lower peak frequencies, their radiative efficiencies are lower, and we postulate that in this case the kinetic luminosity dominates over the radiative luminosity. The maximum energy of the relativistic electrons will be given by the balance between energy loss and gain. This yields

$$\nu_{\rm pk} \propto \dot{M}^{\frac{n-5}{2(n+1)}} \propto \Lambda^{\frac{n-5}{4(n+1)}}. \tag{1.8}$$

For the Bohm limit ($n = 1$) the relation is $\nu_{\rm pk} \propto \Lambda^{-0.25}$ and not very efficient acceleration (e.g., $n = 2$) the relation will be $\nu_{\rm pk} \propto \Lambda^{-0.50}$. This, too, is roughly consistent with the empirical correlation for LBLs. Celotti & Fabian (1993) found the radiative efficiencies distribute a wide ranges in radio-loud quasars and BL Lacs. Here we suggest the radiative efficiency may explain the dependence of SED on accretion rate (Wang, Staubert & Ho 2002).

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