THE MASS DISTRIBUTION OF BLACK HOLES IN BL LACERTAE OBJECTS AND EVOLUTION OF ACTIVE GALACTIC NUCLEI

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ABSTRACT

In this Letter, we make an attempt to estimate the masses of black holes and their distributions in BL Lac objects. We show the mass of black hole $M_{BH} \propto \nu_{pk}^{-13/12} L_{pk}^{1/8}$, where $\nu_{pk}$ and $L_{pk}$ are the peak frequency and luminosity in the first bump of continuum, respectively. We find there are two populations of black hole masses in BL Lacs: the first has a lower-mass peak centred at $\sim 7.0 \times 10^4 M_\odot$, composed of high frequency-peaked BL Lacs (HBLs) and the second is a higher-mass ($> 10^6 M_\odot$) population composed of low frequency-peaked BL Lacs (LBLs). We find that the black hole mass distribution in the high frequency-peaked BL Lacs is in good agreement with that of narrow line Seyfert 1 galaxies. Considering the fact that the orientation of BL Lacs close to the sight of observer’s line is the same with NLS1s as well as this agreement, we propose two evolutionary routes among the narrow line Seyfert 1 galaxies (NLS1s), low and high frequency-peaked BL Lacertae objects: 1) HBLs → NLS1s ($m \leq 0.1$) → IBLs, 2) HBLs → NLS1s ($m \geq 5$) → LBLs, strongly depending on the accretion rates in NLS1s.

Subject headings: galaxy - active - BL Lac object - Narrow line Seyfert 1 galaxy

1. INTRODUCTION

The black hole masses and their distributions in active and inactive galaxies are of great interest in astrophysics (Richstone et al. 1998, Kormendy & Gebhardt 2001, Merrit & Ferrarese 2001). BL Lacertae objects are characterized by their powerful featureless continuum radiation spanning from radio to gamma-ray bands (Bregman 1990). They play an important role in the evolution and unification scheme of active galactic nuclei (Urry & Padovani 1995, Antonucci 1993). With extensive studies of the BL Lacs, there has been considerable progress in understanding the properties of their multiwavelength continuum and radiation mechanisms. It is generally believed that synchrotron self-Compton (SSC) emission of high energy electrons in a relativistic jet is responsible for the multiwavelength continuum of the BL Lacs (Urry & Padovani 1995). The emission is highly beamed. The featureless continuum of the BL Lacs only permits us to use timescale of variability $\Delta t$ to estimate black hole mass, $M_{BH} \leq c^3 D \Delta t / G$, where $c$ is the speed of light, $G$ the gravitational constant and $D$ Doppler factor. However this only provides a very crude upper limit of a black hole mass since it is very difficult to determine the shortest timescale, especially when there is an uncertainty of relativistic boosting factor.

There is an unambiguous relation between peak frequencies $\nu_{pk}$ and luminosities $L_{pk}$ in the first bump of continuum, such that $\nu_{pk} \propto L_{pk}^{\beta}$ ($\beta > 0$) (Sambruna et al. 1996, Fossati et al. 1998, Costamante et al. 2001). This relation simply suggests that the lower the peak luminosity the higher is peak frequency. The luminosities of the high-frequency-peaked BL Lacs are much lower than those of the low frequency-peaked BL Lacs. One likely implication of this relation is that the high frequency-peaked BL Lacs contain less massive black holes.

It has been pointed out that the masses of black holes in all the radio-loud quasars of low redshift PG sample exceed $10^9 M_\odot$ (Laor 2000). This suggests the black hole mass controls the radio-loudness $R$, defined as the ratio of radio to optical fluxes. There is growing evidence that some of narrow line Seyfert 1 galaxies are radio-loud objects (Oshlack, Webster & Whiting 2001). The typical mass of the black hole in a narrow line Seyfert 1 galaxy is a few million solar masses. One interesting question arises: do the high frequency-peaked BL Lacs have similar masses to the narrow line Seyfert 1 galaxies?

The main goal of this paper is making an attempt to estimate the mass of black holes in BL Lacs and to provide some arguments to support the possible evolutionary sequence between narrow line Seyfert 1 and BL Lac objects.

2. FORMULATION

We intend to connect the mass of central black hole with the two available observables, the peak frequency $\nu_{pk}$ and its luminosity $L_{pk}$, rather than to fit the continuum. As the first step, we express the Doppler factor as a function of $\nu_{pk}$ and $L_{pk}$. For the simplicity, we assume a spherical geometry for the radiation region and a monoenergetic distribution of relativistic electrons responsible for the continuum emission, namely, $n(\gamma) = n_0 \delta(\gamma - \gamma_0)$, where $n_0$ is the electron density and $\gamma_0$ the Lorentz factor of electrons. Using the standard formula for synchrotron emission in [Pacholczyk (1970)], $\epsilon_{\nu'} = n_0 c_3 B F(\nu)$, where $c_3 = 1.87 \times 10^{-23}$, we have the peak luminosity $L_{pk}$ in an observer’s frame

$$L_{pk} = D^2 \frac{4}{3} \pi R_0^3 \nu_{pk} \epsilon_{\nu'} \nu_{\nu'}^4,$$

where $F(\nu) = x \int_0^x K_{5/3}(z)dz$, $K_{5/3}$ is the modified Bessel function with of order 5/3, $x = \nu' / \nu_{\nu'}$ and $\nu' = 4.2 \times 10^6 B \gamma_0^3$. The primed parameters are in the co-moving frame of the jet. The peak frequency is given by $d[x F(x)] / dx = 0$, namely, $\nu_{pk} = \cdots$
where the peak frequency and luminosity, we have $\epsilon_i \propto \nu_{pk}^{-1/2} L_{pk}^{-5/2}$. Then we get

$$L_{BJ} = \epsilon_{BJ} M^2_{BH},$$

where $M$ is the accretion rate of a black hole with maximum spin (Armitage & Natarajan 1999). The ADAF dominates when the accretion rate is below the critical value $M_{Edd} \leq \alpha^2 M_{Edd} = \frac{4\pi G M_{BH}/\eta c^3}{\epsilon_{ej}}$, the electron scattering opacity $\kappa_{esc} = 0.34$ and $\eta = 0.1$ (Narayan & Yi 1995). This condition works within a few hundred Schwarzschild radii for massive black holes, for which it is independent of the black hole mass (Narayan & Yi 1995). According to the model of their main sequence, the blazars’ phenomena can be understood in terms of different levels of $\eta$. The accretion rate in BL Lac should be of order $\sim 10^{-3}$ (Cavaliere & D’Elia 2001) (here we use different definition of Eddington limit). For all the BL Lacs, it may be a good approximation that the critical value of the dimensionless accretion rate may be the same $\dot{m} \approx \alpha^2$. This condition then yields a lower limit of black hole mass via $L_{BH} = L_{BL}/\dot{m}$. The powerful emission from the relativistic jet originates from the efficient extraction of energy from the black hole spin by the Blandford-Znajek process. Although it has been shown that this process in geometrically thin disk is not so efficient to pump the energy from black hole spin (Livio, Ogilvie & Pringle 1999), it may dominate over the emission from the accretion disk in the ADAF regime. With the self-similar solution of the optically thin ADAF of Narayan & Yi (1994), the output power of the BZ process is
3. Masses of Black Holes in BL Lacs

There is a largest sample including the high and low frequency-peaked BL Lacs composed of 1 Jy and Slews Survey BL Lacs, in which the peak frequency and its luminosity are given by fitting the SED with a polynomial (Cosmatute et al. 2001). There are three exceptional objects, Mrk 501, IES 2344+514 and IES 1426+428 that show highly variable properties. Their peak frequencies change by as much as $10^{15.2}$ Hz and peak luminosities from $10^{43.3}$ erg/s. We exclude the data of these three objects in their high states to leave 100 data.

The uncertainty in eq. (9) is due to the parameter $\xi$, namely, $\alpha$ and $\langle \epsilon^{+\nu}_{\nu} \rangle$. However we can use their typical values, $\alpha = 0.01$ and $\langle \epsilon^{+\nu}_{\nu} \rangle = 2.5 \times 10^5$, then $\xi = 1$. We find the high mass peak is in good agreement with Laor’s limit, which he find the mass of black hole in radio-loud quasar should exceed $10^9 M_\odot$ (Laor 2000). Thus we think $\xi = 1$ is reasonable. We then determine the low mass distribution with $\xi = 1$ as shown in Fig 1.

It is interesting to find there is evidently a low peak of black hole mass populations centered roughly at $7.0 \times 10^8 M_\odot$ from $(1.0 \rightarrow 3.0) \times 10^8 M_\odot$ when the high peak reconcile with the Laor’s limit. The mass of black hole in Mrk 421 has been estimated to be $\approx 10^9 M_\odot$, with accretion rate $\dot{m} \sim 10^{-3}$ (Celotti, Fabian & Rees 1998). The present result overlaps this estimation.

Many intermediate BL Lacs have been found in the RGB (Laurent-Muehleisen et al. 1998), DXRBS (Perlman et al. 1998) and REX surveys (Caccianiga et al. 1999). Simulations show that the IBL content, even the deeper ones, is affected more strongly by the sample flux than by intrinsic properties (Gioi et al. 2000). We have not an homogeneous complete sample composed of HBLs, IBLs and LBLs. It is still unknown the unbiased occurring of BL Lacs according to peak frequency $\nu_{\text{pk}}$. It may have two possible cases. First if the IBL fraction to the total of BL Lacs is still smaller than that of HBL and LBL, the bimodal distribution of BL Lacs still holds. Second, this fraction is comparable with the other two, then the gap between the two peaks will be filled up. There is no available data of peak frequency and peak luminosity for a sample of intermediate BL Lacs, but we presume an arbitrary distribution of the second case of IBL for illustration in Figure 1.

Recent studies of host galaxies of radio-loud quasars and BL Lacs show that the basic properties of these hosts are indistinguishable from those of quiescent, evolved, low-redshift ellipticals of comparable mass (McLure & Dunlop 2001, Dunlop et al. 2001), although the host galaxies of BL Lacs are normal giant ellipticals (Scarpe et al. 2000, Urry et al 2000). With this conclusion, the low mass peak of the distribution of black holes in the BL Lacs reminds us of narrow line Seyfert 1 galaxies, which are special members of the Seyfert family. It would be motivated to compare the mass distributions with narrow line Seyfert 1 galaxies.

4. Black Holes in Narrow Line Seyfert 1 Galaxies

The distinguished features of narrow line Seyfert 1 galaxies (NLS1s) can be explained by the hypothesis that they contain less massive black holes with relatively high accretion rates, close to or even super-Eddington, and disks which are face-on to the observer (Boller, Brandt & Fink 1996). In addition, the jet of the BL Lac is generally close to the line of sight of the observer, so they have the same orientation as the NLS1s. There is increasing evidence for the presence of radio-loud narrow line Seyfert 1 galaxies according to radio loudness $R$ although their radio emission flux is usually weak (Ulvestad, Antonucci & Goodrich 1995). These objects are PKS 2004-447 ($R > 1700$) of $5 \times 10^9 M_\odot$ (Oshlack, Webster & Whiting 2001), PKS 0558-504 ($R = 27$) and RGB J0044+193 ($R = 31$) (Siebert et al. 1999) and RX J0134.2-4258 ($R = 71$) (Grue et al. 2000). These objects evidently comprise a special population in the plot of radio loudness and black hole mass (Laor 2000). Thus, it would be very interesting to compare the bimodal distribution of black hole masses in BL Lacs with that in the NLS1s.

A heterogeneous sample of 59 NLS1 galaxies with good spectroscopic observations is provided (Veron-Cetty, Veron & Goncalves 2001). The masses of black holes in NLS1s can be easily obtained from their H$\beta$ width. Using the estimations by Wang & Lu 2001, we plot the mass distribution in Figure 1. It is surprising that the mass distribution of black holes in high frequency-peaked BL Lacs overlaps that of the narrow line Seyfert 1 galaxies. Are there evolutionary connections between black holes in the high frequency-peaked BL Lacs and narrow line Seyfert 1 galaxies?

There are some pieces of evidence that the accretion rates in NLS1 are relatively high, close to or even exceeding Eddington limit (Mineshige et al. 2000). The spins of the black holes in NLS1 are probably very fast as evidenced by the iron K$\alpha$ profiles (Ballantyne, Iwasawa & Fabian 2001). It has been shown that the accreting matter, by itself, would spin the black hole up to the specific angular momentum $a \approx 1$ after a modest amount of accretion $\Delta M_{\text{BH}}/M_{\text{BH}} = 1.5$ (Bardeen 1970) or within the $e$-folding timescale of black hole growth in NLS1. This is given by $t_{\text{edd}} = \eta M c / (4 \pi G M) = 3.86 \times 10^7 m^{-1} \text{yr}$, when $\eta = 0.1$. If the accreting rate ($\dot{m}$) is assumed to hold a constant, the evolution of mass and spin owning to accretion can be described by

$$ M_{\text{BH}} = M_{\text{BH}}^* e^\tau; \quad \tau = 0.82 e^{-\tau} \left[4 - (18 e^{-2\tau} - 2)^{1/2}\right]. \quad (10) $$

where $\tau = t/t_{\text{edd}}$, $M_{\text{BH}}^*$ is the initial mass of black hole and the initial spin is taken to be zero. If the radiation emitted by the disk and swallowed by the black hole produces a counteracting torque, this can prevent spin-up beyond a limiting state of $a \approx 0.998$ (Thorne 1974).

There is clear evidence for a non-linear relation between black hole mass and bulge mass (Laor 2001, Czerny et al. 2001, Mathur et al. 2000), showing the black hole mass is much lower than that given by the Magorrian et al. relation (Magorrian et al. 1998). If black hole masses in NLS1 were to satisfy this relation through accretion with a rate $\dot{m} = 0.1$, it would take $\tau \approx 5$ to increase the mass, namely five times of Eddington time, about $2 \times 10^8 \text{yr}$. This time is much longer than the typical lifetime of a quasar ($10^9 \text{yr}$) (Blandford 1990). According to the standard hierarchical cosmologies (Haehnelt, Natarajan & Rees 1998), the bright quasar phase only lasts about $10^8 \text{yr}$. This is supported by recent statistical studies (Kuhn et al. 2001). Most likely, NLS1s are also as short-lived as quasars. There is a shortage of accreting matter after a timescale $t_{\text{edd}}$. Then its mass becomes $e$-folding times, but still in the low peak range. Such a narrow line Seyfert 1 galaxy becomes a high frequency-peaked BL Lac because its spin is guaranteed to be maximal. Under such a circumstance, there may be $\tau$ recylcings from NLS1 to high frequency-peaked BL Lacs and contrariwise. If this were true, the gap between the two peaks would be filled up by gradual accretion growth of the black holes. A narrow line Seyfert 1 galaxy will finally evolve into an intermediate BL Lac after $\tau$ recylcings. It is thus expected that narrow line Seyfert 1 galaxy...
ies are the progenitors of intermediate BL Lacs. However, does an IBL to evolve into a LBL? This remains open.

On the other hand, there are some pieces of evidence that some of the narrow line Seyfert 1 galaxies may have extreme high accretion rate $m \gg 1$ (Mineshige et al. 2000). If the accretion rate is $m \approx 5$ in a narrow line Seyfert 1 galaxy, during a typical lifetime of quasar $3 \times 10^7 \, \text{yr}$, $\tau \approx 5$, the mass will grow by a factor of $e^\tau \approx 170$. When the accreting matter is almost exhausted, it will appear as a low frequency-peaked BL Lacs because its black hole mass will exceed $10^6 M_\odot$. This corresponds to that there is no recycling between high frequency-peaked BL Lacs and narrow line Seyfert 1 galaxies. The only alternative is for the high frequency-peaked BL Lacs to be the progenitors of narrow line Seyfert 1 galaxies, that is high frequency-peaked BL Lacs are just in a phase at the beginning of accretion when the accretion rate is rather low. During its transition from a narrow line Seyfert 1 to a low frequency-peaked BL Lac, a galaxy may spend time as a radio-loud active galactic nuclei. It may then appear in the upper right corner in the Figure 5 of (Ghisellini & Celotti 2001), where the photon trapping process efficiently lowers the radiated luminosity of the accretion disk (Wang & Zhou 1999). The formation of a powerful jet is not understood in such a case because the very efficient energy extraction spins down the black hole rather fastly.

5. CONCLUSIONS AND DISCUSSIONS

This study shows that there are two populations of black holes in high and low frequency-peaked BL Lacs. The mass distribution of black holes in high frequency-peaked BL Lac objects is similar to that of the narrow line Seyfert 1 galaxy, implying some evolutionary connections between the two. It is pointed out that narrow line Seyfert 1 galaxies play a key role in the evolution of BL Lacs. We summarize them as, 1) HBLs $\leftrightarrow$ NLS1s ($m \leq 0.1$) $\rightarrow$ IBL. 2) HBLs $\rightarrow$ NLS1s ($m \geq 5$) $\rightarrow$ LBLs, strongly depending on the accretion rates in NLS1s.

Ghisellini et al. (1998) suggest an evolutionary consequence using a large sample of blazar broadband spectra: HBLs $\rightarrow$ LBLs $\rightarrow$ FSRQ (flat spectrum radio quasar). The model is de-

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Fig. 1.— The mass distribution of black holes in BL Lac objects (solid line). The high ($\nu_{pk} \geq 10^{15}$ Hz) and low ($\nu_{pk} \leq 10^{15}$ Hz) frequency-peaked BL Lacs are usually referred to as blue and red BL Lacs, respectively. There is a bimodal mass population of black holes in HBLs and LBLs. It is very interesting that the mass distribution of black holes in narrow line Seyfert 1 galaxies (dotted line) overlaps that of high frequency-peaked BL Lac objects. The gap between the two populations strongly implies an evolutionary sequence: HBLs $\rightarrow$ NLS1 $\rightarrow$ LBLs if the accretion rate in NLS1 is moderate supper-Eddington limit (slim disk). The second evolutionary route is HBL $\leftrightarrow$ NLS1 $\leftrightarrow$ IBLs if the accretion rate is sub-Eddington limit. The population of IBLs is postulated if the fraction of IBLs to the toatal BL Lacs is comparable with the two others.