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QSO EMISSION LINES AND BLACK HOLE MASSES

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RESUMEN

La presencia de agujeros negros supermasivos en núcleos de galaxias, tanto activas como inactivas, es un hecho establecido. Los avances que se han hecho en entender la naturaleza de la región de emisión de líneas anchas hacen posible la medición de masas de agujeros negros en un gran número de núcleos de galaxias activas (AGN). Esto permite estudiar las propiedades de los AGN en función de la masa del agujero negro y el cociente de Eddington. Estos estudios nos llevarán a un mejor entendimiento de la física de los AGN. La posibilidad de medir la masa de los agujeros negros en QSOs también nos permite estudiar la relación entre la masa del agujero negro y las propiedades de la galaxia huésped. Resultados preliminares indican que esta relación para QSOs a $z \approx 2$ es similar a la de galaxias cercanas en el presente.

ABSTRACT

The presence of supermassive black holes in galactic nuclei, both quiescent and active, is now well established. Advances in understanding the nature of the broad emission-line region make it possible to measure black hole masses in large numbers of active galactic nuclei (AGN). This in turn allows study of AGN properties as a function of black hole mass and Eddington ratio. Such studies should lead to a better understanding of the physics of AGN. The ability to measure black hole masses in QSOs also allows study of the relationship between black hole mass and host galaxy properties. Early results suggest that this relationship in QSOs at redshifts $z \approx 2$ was similar to that in nearby galaxies today.

Key Words: **GALAXIES : ACTIVE — GALAXIES : NUCLEI — QUASARS : EMISSION LINES**

1. INTRODUCTION

Soon after the discovery of quasars, accretion onto supermassive black holes was suggested to power them (Salpeter 1964; Zeldovich 1964). The idea that the broad emission lines of Seyfert galaxies involve orbital motion in a deep gravitational potential (Woltjer 1959) now had a new context. Yet the obvious goal of measuring the black hole's mass ($M_{\rm BH}$) was frustrated for many years by uncertainty over the radius of the broad line region (BLR) and by the competing idea of radiation driven outflow.

The key step was to measure the BLR radius ($R_{\rm BLR}$) through the use of time variations. The BLR gas is photoionized by the continuum from the central source, and time lags between continuum variations and the response of the line intensities gives $R_{\rm BLR}$. This technique is known as "echo mapping" or "reverberation mapping" (Blandford & McKee 1982). The first results showed that the BLR in Seyfert galaxies was smaller than had been inferred from photoionization models (Ulrich et al. 1984; Peterson et al. 1985). This led to reasonable black hole masses on the assumption of gravitational motions that were now reasonable in the context of other constraints. Virial motions were further supported by the Keplerian relationship between line width and radius deduced from different emission lines in a given AGN as well as the roughly symmetrical variability of the broad line profiles (e.g., Peterson 1993, 1997; Wandel, Peterson, & Malkan 1999).

Subsequent work has measured $R_{\rm BLR}$ in a number of AGN, ranging from Seyfert galaxies to moderate redshift QSOs, typically on the basis of the broad Hβ line. This has led to the recognition that $R_{\rm BLR}$ systematically increases with AGN continuum luminosity (Kaspi et al. 2000, and references therein). This result opens the door to wholesale determinations of $M_{\rm BH}$ in AGN, because the continuum luminosity and broad emission-line widths are easily measured.

Another important advance is the determination of black hole masses in substantial numbers of quiescent and modestly active AGN, opening the way to the study of "black hole demographics." The results, based on kinematics of stars and gas in nearby galaxies, show that $M_{\rm BH}$ is correlated with the luminosity of the bulge component of the host galaxy and the stellar velocity dispersion σ_* (see article by

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Gebhardt in these Proceedings). This intriguing relationship has stimulated much theoretical attention, and it provides another way to estimate black hole masses in AGN. A burgeoning area of research on AGN involves the use of $M_{\rm BH}$ to understand the physics of AGN and the relationship of AGN activity to galaxy formation and evolution.

2. DETERMINATION OF BLACK HOLE MASSES IN AGN

Determinations of $M_{\rm BH}$ in AGN assume virial motions of the broad line gas, so that $M_{\rm BH} = v^2 R_{\rm BLR}/G$. One adopts some measure of the line width and a radius that is hoped to go with the velocity. The radius is derived, directly or indirectly, from echo mapping results. The virial velocity appropriate to this radius is parametrized as $v = fW$, where W is the FWHM of the adopted broad emission line. A common assumption is $f = \sqrt{3}/2$, appropriate for isotropic motions. However, McLure & Dunlop (2001) considered a disk model for the BLR. Ideally, echo results will be available for an object of interest. Even then, there are issues of geometry and correspondence between the variable and time-averaged line profiles. Further uncertainty arises when one uses the empirical scaling of $R_{\rm BLR}$ with luminosity. Arguments based on photoionization physics (e.g., Baldwin et al. 1995) and survival of dust grains (Netzer & Laor 1993) suggest $R_{\rm BLR} \propto L^{0.5}$, and values of $M_{\rm BH}$ based on scaling $R_{\rm BLR}$with L are sometimes called "photoionization masses". Laor (1998) found consistency between photoionization masses and QSO host galaxy luminosities. Kaspi et al. (2000) analyzed echo results for 34 Seyfert galaxies and QSOs, giving a wide range of luminosity. They found $R_{\rm BLR} \propto L^{0.7}$. McLure & Jarvis (2002) found $R_{\rm BLR} \propto L^{0.6}$. However, given the scatter in the echo results, use of $L^{0.5}$ may be reasonable. Shields et al. (2003, S03) used the $L^{0.5}$ fit shown in Figure 6 of Kaspi et al. (2002). Adjusted to a cosmology of $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_{Lambda} = 0.7$, this gives

$$M_{\rm BH} = (10^{7.69}\ M_\odot) v_{3000}^2 L_{44}^{0.5}, \tag{1}$$

where $v_{3000} \equiv v/(3000\ \mathrm{km\ s^{-1}})$ for Hβ and $L_{44} = \lambda L_\lambda(5100$ Å. McLure & Jarvis (2002) and Vestergaard (2002) discuss the use of lines other than Hβ.

3. BLACK HOLE MASSES AND AGN PHYSICS

The availability of black hole masses in AGN provides an important constraint on models of the presumed accretion disk. Historically, fits to the energy distribution of QSOs in terms of thermal emission from a disk provided estimates of the black hole mass (e.g., Shields 1978; Malkan 1983; Mathur, Kuraszkiewicz, & Czerny 2001). Models have progressed from a black body approximation to the local emission from the disk surface to elaborate NLTE models (e.g., Hubeny et al. 2001, and references therein). Parameters that characterize such models include $M_{\rm BH}$, the accretion rate $\dot{M}$, the disk inclination i, and the black hole angular momentum parameter $a \equiv J/M$. Observation constraints include the continuum luminosity, continuum shape, and possible spectral features such as the Lyman edge. Currently our ability to exploit spectral details to constrain disk models is limited largely to the possible presence of a continuum slope change associated with the Lyman edge in the local disk emission, heavily Doppler broadened by the relativistic disk rotation (Shields & Coleman 1994; Hubeny et al. 2001). Clearly, a reduction in the number of free parameters in the model is most welcome. From a simplified point of view, the characteristic effective temperature of the disk scales as $T_{disk}^4 \propto (\dot{M}/M_{\rm BH}^2)$. The disk bolometric luminosity is given by $L = \epsilon c^2 \dot{M} = (10^{45.76}\ \mathrm{erg\ s^{-1}})\epsilon_{-1}\dot{M}_0$, where $\dot{M}_0 \equiv \dot{M}/(1\ M_\odot\ \mathrm{yr}^{-1})$ and $\epsilon_{-1} \equiv \epsilon/10^{-1}$. The efficiency for a disk around a black hole is $\epsilon \approx 0.1$, depending on the black hole spin. If both $M_{\rm BH}$ and L can be derived independently, the derived T_{disk} implies a continuum shape that can be compared with observation. This could give information on the black hole spin or disk inclination, or perhaps even the validity of the disk model. An example of fitting detailed disk models to specific objects is the work on 3C 273 by Blaes et al. (2001).

Another use of black hole masses is to assess the "Eddington ratio", that is, the bolometric luminosity relative to the Eddington limit, $L_{\rm E} = 10^{46.1} M_8$ erg s^{-1}, where $M_8 \equiv M_{\rm BH}/(10^8\ M_\odot)$. This ratio is significant in a number of ways. For $L/L_{\rm E}$ approaching unity, the idea of a geometrically thin disk fails. The growth timescale for a black hole is related to $L/L_{\rm E}$, so that $t_{grow} \equiv M_{\rm BH}/\dot{M} = (10^{7.66}\ \mathrm{yr})\epsilon_{-1}(L_{\rm E}/L)$. The spectral properties of AGN appear to depend on Eddington ratio. Important correlations between AGN line and continuum properties are expressed by "Eigenvectors 1 and 2" (EV1, EV2) of Boroson & Green (1992). EV1 involves, among other things, increasing intensity of the broad optical Fe II lines together with decreasing intensity of the narrow O III lines at $\lambda\lambda 5007, 4959$. Boroson & Green suggested that EV1 might involve the Eddington ratio, stronger Fe II going with higher $L/L_{\rm E}$. This is borne out in a study by Boroson (2002a), in which $M_{\rm BH}$ is used to assess $L/L_{\rm E}$ for

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a sample of AGN. EV1 does indeed correlate with $L/L_{\rm E}$ in the suggested way. There is also evidence that AGN with broad absorption lines (BALs) have relatively high $L/L_{\rm E}$. The qualitative trends are illustrated in Figure 7 of Boroson (2002a).

4. BLACK HOLE DEMOGRAPHICS

A review of black hole demographics is given by Kormendy & Gebhardt (2001). Kormendy & Richstone (1995) suggested a proportionality of black hole mass to bulge mass or luminosity. This relationship became widely known with the work of Maggorian et al. (1998), who found $M_{\rm BH}/M_{bulge} \approx 0.006$. Subsequent work has led to a smaller value $M_{\rm BH}/M_{bulge} \approx 0.002$ (Kormendy & Gebhardt 2001). This relationship has considerable scatter, with a 1 σ dispersion in log $M_{\rm BH}$ at fixed M_{bulge} or L_{bulge} of about 0.5. A tighter correlation between $M_{\rm BH}$ and σ_* was found by Gebhardt et al. (2000a) and Ferrarese & Merritt (2000). Tremaine et al. (2002) express this as $M_{\rm BH} = (10^{8.13}\ M_{\rm BH})\sigma_{200}^{4.02}$, where $\sigma_{*200} \equiv \sigma_*/(200\ {\rm km\ s^{-1}})$ and the dispersion is only $\sim 30\%$. The $M_{\rm BH}$–M_{bulge} and $M_{\rm BH}$–σ_* relationships have inspired a variety of theoretical explanations. The low value of $M_{\rm BH}/M_{bulge} \approx 0.002$ is consistent with most of the black hole growth resulting from luminous accretion during AGN episodes (Yu & Tremaine 2002). This suggests that the black hole mass is limited by some sort of feedback between $M_{\rm BH}/M_{bulge}$ and the mechanism for fueling the black hole, as discussed for example by Silk & Rees (1998). The small dispersion of the $M_{\rm BH}$–σ_* relation suggests a mechanism capable of fairly fine tuning.

The tightness of the $M_{\rm BH}$–σ_* relationship makes it a useful tool. Gebhardt et al. (2000b) showed that black hole masses derived from echo mapping in AGN with known σ_* agree well with the relationship. This implies that echo masses are not seriously in error and that values of $M_{\rm BH}$ in active galaxies do not systematicaly differ from those in quiescent galaxies. For galaxies without echo mapping results but with known σ_*, one can estimate $M_{\rm BH}$ for use in the ways noted above.

5. EVOLUTION OF THE $M_{\rm BH}$–σ_* RELATIONSHIP

The small scatter of the $M_{\rm BH}$–σ_* relationship suggests the possibility of looking for evolution in this relationship over cosmic time. Yu & Tremaine (2002) find that high mass black holes acquire most of their mass from luminous accretion. Half of the mass in supermassive black holes today was accreted before redshift $z \approx 1.8$ and only $\sim 10\%$ before $z = 3$. Thus, high redshift quasars offer an opportunity to look back to times when the typical supermassive black hole had only a fraction of its present-day mass. The cause of the tight $M_{\rm BH}$–σ_* relationship is unknown, and measurements of this relationship at high redshift might shed light on the comparative rate of black hole and bulge growth.

Measurement of σ_* in QSOs at high redshift is difficult, but the narrow lines in the AGN spectrum provide an alternative. The narrow line region (NLR) of AGN emits forbidden lines such as [O III] with profiles having full width at half maximum (FWHM) ~ 500 km s^{-1}. The NLR has a radius ~ 100 pc in Seyfert galaxies and likely larger in QSOs. Nelson & Whittle (1996) found that the widths of the [O III] lines, expressed as $\sigma_{[O\ III]} \equiv FWHM([\rm O\,III])/2.35$, agrees on average with σ_*, albeit with considerable scatter. This suggests that the NLR gas is orbiting in the gravitational potential of the bulge. Nelson (2000) showed that echo measurements of $M_{\rm BH}$ in AGN follow a $M_{\rm BH}$–$\sigma_{[O\ III]}$ relationship that agrees with the $M_{\rm BH}$–σ_* relationship, further confirming the correspondence of $\sigma_{[O\ III]}$ with σ_*.

The use of $\sigma_{[O\ III]}$ in place of σ_* opens the door to studies of the $M_{\rm BH}$–σ_* relationship in distant QSOs. S03 used $\sigma_{[O\ III]}$ and photoionization masses to study the $M_{\rm BH}$–σ_* relationship at high black hole mass and to explore its redshift dependence. From a combination of published and unpublished spectra of Seyfert galaxies and QSOs covering the Hβ and [O III] region, they derived black hole masses using equation (1) above. The resulting plot of $M_{\rm BH}$ vs. $\sigma_{[O\ III]}$ shows considerable scatter; but in agreement with Nelson (2000), the results center fairly well on the $M_{\rm BH}$–σ_* relationship of Tremaine et al. (2002). From an unpublished set of high quality observations of PG QSOs, S03 found a 1 sigma dispersion of 0.5 dex in $M_{\rm BH}$ at fixed σ_*. S03 included a number of objects with redshifts in the range $z = 1$ to 3. These are very luminous objects with large $M_{\rm BH}$ and $\sigma_{[O\ III]}$, and on average they agree with an extrapolation of the $M_{\rm BH}$-σ_* relationship. This suggests that at redshifts ~ 2, when much of the growth of supermassive black holes lay in the future, black holes and bulges already obeyed a relationship similar to the present one. A number of improvements are needed however. The high redshift data used by S03 involved QSOs more luminous than those at lower redshifts, and conclusions involving evolution would benefit from comparisons at the same luminosity. Also, the high redshift data available to S03

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had marginal signal-to-noise ratio and spectral resolution for measuring the [O III] width. Some of the values for $M_{\rm BH}$ and $\sigma_{[O\ III]}$ found by S03 exceed the parameters of galaxies in the nearby universe. This must to some extent involve measurement error and intrinsic scatter in the use of photoionization masses for $M_{\rm BH}$ and $\sigma_{[O\ III]}$ for σ_*, and it does not necessarily undermine the conclusion that high redshift QSOs on average obey the present-day $M_{\rm BH}$–σ_* relationship. Clearly, however, there is a need for high quality observations at high redshift, including lower luminosity objects, and comparable observations at low redshift.

The potential uses of $\sigma_{[O\ III]}$ in place of σ_* warrant careful examination of the reliability of this surrogacy. Boroson (2003) examined the $M_{\rm BH}$–$\sigma_{[O\ III]}$ relationship for a sample of 107 QSOs with $z < 0.5$ from the Early Data Release (EDR) of the Sloan Digital Sky Survey (SDS, http://www.sdss.org). Using photoionization masses (with $M_{\rm BH} \propto L^{0.7}$), he found that a plot of $M_{\rm BH}$ vs. $\sigma_{[O\ III]}$ showed large scatter but centered on the $M_{\rm BH}$–σ_* relationship of Tremaine et al. (2002). The dispersion in $M_{\rm BH}$ at fixed $\sigma_{[O\ III]}$ was ~ 0.7 dex. This degree of scatter suggests that only broad inferences involving averages of large samples are possible. Boroson (2002b) looked for predictors of the offsets of individual objects in this sample from the mean $M_{\rm BH}$–$\sigma_{[O\ III]}$ trend. Objects on the broad [O III] side of the trend have relatively strong Fe II emission. This suggests a correlation of the offset with EV1, but the interpretation is unclear. The correlation is not strong enough to give a major reduction in the scatter of the $M_{\rm BH}$–$\sigma_{[O\ III]}$ plot.

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