THE MASSES OF QUASARS AND AGN: CORRELATING THE ACCRETION-DISK AND THE EMISSION-LINE METHODS

Amri Wandel
Center of Space Science and Astrophysics
Stanford University, ERL
Stanford, CA 94305
USA

ABSTRACT. The UV continuum spectrum is used to extract the mass (and accretion rate) of quasars and AGN, assuming the UV is dominated by the emission from a thin accretion disk . This is done by fitting the observed luminosity and spectral slope in the UV by an accretion disk mode, giving the accretion parameters (black hole mass and accretion rate). An independent estimate of the mass is obtained using the emission-line method, which assumes that the velocity dispersion of the broad emission-line s is induced by the gravitational potential of the central compact object. For a sample of 36 quasars and Seyfert 1 galaxies, for which both data, the UV spectrum and the $H\beta$ line width are available, the masses calculated with the two independent methods are in good agreement (within a factor of 2 for 75% of the sample) and highly correlated. Over three orders of magnitude in luminosity, the mass is found to increase less than linearely with luminosity, being in the range $10^8 < M < 10^{10} M_\odot$, with $L(1450A)/L_{Edd}$ ranging from 0.001 for Seyferts to 0.03 for bright quasars.

1. ESTIMATING THE MASS FROM THE UV SPECTRUM

Assuming the UV bump is the spectrum of an accretion disk (as suggested by Malkan 1983), one can relate the observed UV continuum to the black hole mass and accretion rate (Wandel and Petrosian 1988). The spectrum is calculated by integrating the locally emitted spectrum I_ν over the entire disk, $F_\nu = 2\pi \int_{R_{in}} I_\nu(T_s, \rho) R dR$, where R_{in} is the inner disk boundary. In the massive α disk the UV comes mainly from the modified black body regime, while for an α disk with a low viscosity parameter ($\alpha < 0.01$), or with a low accretion rate , the disk spectrum is essentially black body (fig. 1). In the β-disk (viscosity = βP_{gas}) this is the case for any accretion rate and viscosity parameter. We have calculated disk spectra for a grid of accretion parameters (M and $\dot{m}$), and for each one we determine the spectral index (α_ν =-dln$F$/dlnν) and the flux in the far UV band (912-1450A). In order to compare with the observations, we invert this grid, mapping the $M - \dot{m}$ plane onto the $\alpha_{1450} - F(1450A)$ plane. The result is given in curved coordinates, of constant mass or accretion rate , in the observables plane (fig. 2).

For a black body disk the mass may be estimated analytically in terms of the luminosity and the "turnover temperature" (which is related to the spectral slope); the turnover in the black body disk spectrum occurs at a frequency $\nu_m \approx 3kT_m/h$, corresponding to the maximum disk temperature

$$T_m \approx \left(\frac{Q(R_m)}{\sigma}\right)^{1/4} \propto (M\dot{M})^{1/4} R^{-3/4},$$

where $Q(R) = (3/8\pi) GM\dot{M}R^{-3}[1 - (R/R_{in})^{-1/2}]$ is the local energy release from the disk. The black hole mass can be written as

$$M \sim (4.5 \times 10^8 M_\odot) \left(\frac{T_m}{10^5\ {}^\circ\mathrm{K}}\right)^2 L_{46}^{1/2} \left(\frac{\eta}{0.3}\right)$$

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where η is the efficiency (respectively 0.06 and 0.30 for a Schwartzschild and a Kerr black hole).

2. THE DYNAMICAL METHOD

An independent method of estimating the central mass uses the broad emission lines (Dibai 1980; Joly *et. al.* 1985; Wandel and Yahil 1985). Assuming the velocity dispersion measured by the line width is induced by the gravitational potential of the central black hole , one can calculate the mass. The distance of the emission-line gas from the central source is estimated by using the standard photoionization model; for fiducial parameter values one has

$$R = 0.10 \left(\frac{L_{45}}{U_{-1}n_{10}}\right)^{1/2} \text{pc},$$

where $L_{45} = L_{ion}/10^{45}\text{erg s}^{-1}$ is the ionizing luminosity, $U_{-1} = U/0.1$ is the ionization parameter (number of ionizing photons per atom), and $n_{10} = n/10^{10}\text{cm}^{-3}$ is the density of the line-emitting gas. The "dynamical" mass is then found from the Newtonian relation $v^2 = kGM/R$ (k is a kinetic factor, taken as unity),

$$M \approx (1.7 \times 10^9 M_{\odot}) \left(\frac{L_{45}}{U_{-1}n_{10}}\right)^{1/2} \left(\frac{V_{FW0I}(H\beta)}{10^4\text{km s}^{-1}}\right)^2,$$

where the effective velocity dispersion is assumed to be related to the full width at zero intensity by $v_{eff} \sim \sqrt{3}V_{FW0I}/4$.

3. RESULTS

We have calculated the UV and dynamical masses for a sample of 36 quasars with IUE spectra and Hβ line data. The two mass estimates are well correlated (fig.3), and for 27 out of the 36 objects in our sample, they agree within a factor of 2. The correlation is surprisingly tight, considering the uncertainties in both methods. Although there are no evident selection effects that could induce the tight correlation between the two masses, empirically the correlation is at least in part due to the similar functional dependence of the two mass estimates on the luminosity. It should also be cautioned that the numerical coefficient for the mass (that is, the normalization) in the above methods is quite uncertain, as it depends on several poorly known factors (geometry, kimenatic factor, ionization data in the dynamical method; inclination, black hole spin, viscosity law in the accretion disk method) and is model dependent.

The Eddington ratio (fig. 4) varies from 0.001 for low luminosity Seyfert 1 nuclei, to 0.03 for the brightest quasars in the sample. This is comparable to Wandel and Yahil (1985) but lower than Wandel and Petrosian (1988) because they used a Schwartzschild black hole and had in their sample high redshift quasars not present in ours.

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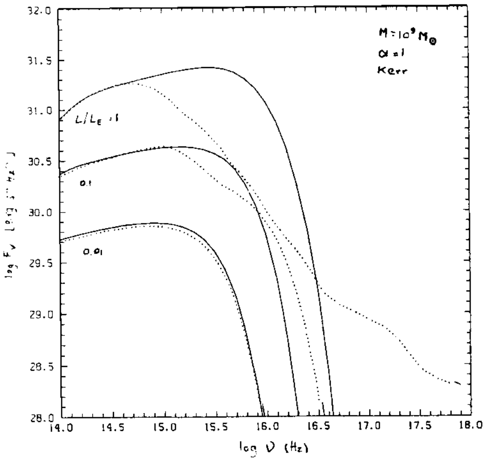

Fig 1. Calculated disk spectra for various Eddington ratios (or accretion rates). Continous curves show a multiple black body spectrum, dotted curves show a modified black body spectrum with Comptonization. All spectra are for $\alpha = 1$ and for a $10^9 M_{\odot}$ maximally rotating Kerr black hole .

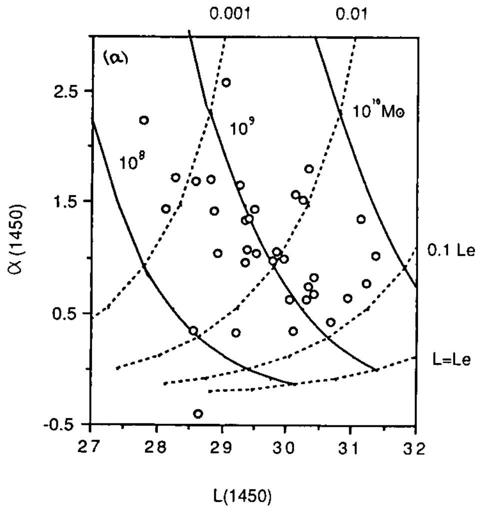

Fig 2. Mapping of the accretion disk parameter space ($M - \ell$) onto the observable UV plane (spectral index in the 1000-1450A band vs. UV luminosity L(1450A)). A maximally rotating black hole is assumed. Continous lines are curves of constant black hole mass, dashed lines denote constant Eddington ratio ($\ell = L_{disk}/L_{Edd}$).

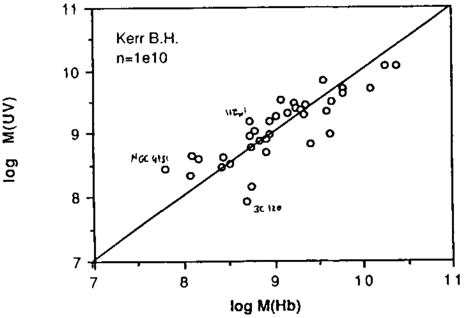

Fig. 3. The UV mass (calculated for $\alpha = 1$ and a Kerr black hole) vs. the dynamical mass (calculated from the $H\beta$line, assuming a density of $n = 10^{10}\mathrm{cm}^{-3}$. The diagonal line denotes $M(H\beta) = M(UV)$.

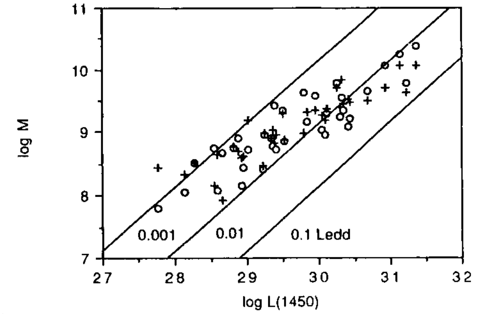

Fig. 4. Mass vs. UV luminosity. Circles denote the dynamical mass estimate, while plus signs denote the UV mass. The diagonal lines indicate a constant Eddington ratio ($\nu F_{\nu}(1450A)/L_E$