UV Spectroscopic Time Domain Studies of Active Galactic Nuclei

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Overall Goals:

Time domain spectroscopic studies of active galactic nuclei (AGNs) enables:

1) Determination of the structure and kinematics of the gaseous regions in the immediate vicinity of the central supermassive black holes, thereby clarifying the role of this gas in both fueling (inflow) and feedback (outflows).
2) Accurate measurement of the masses of the central black holes.
3) Measurement of luminosity distances to high-redshift quasars and determination of cosmological parameters to high redshift, independent of any other method.

Introduction:

"Reverberation mapping" (Blandford & McKee 1982; Peterson 1993) is a spectroscopic time-domain technique that can be used to determine the structure and dynamics of the broad-line region (BLR) of AGNs. Reverberation mapping can provide us (a) with insights into mass outflows and mass accretion on microarcsecond scales, too small to be resolved by any other direct method, and (b) a means to directly measure the masses of the central black holes in these objects. Moreover, secondary methods anchored by reverberation mapping results allow us to estimate masses in active nuclei to arbitrarily large cosmic distances, addressing the Cosmic Origins goals of determining when supermassive black holes form and how have they affected the evolution of galaxies in which they are found. Indeed, all black hole mass estimates beyond the local universe are based on scaling relationships anchored by reverberation. In addition, the luminosities of AGNs can be inferred by BLR sizes determined by reverberation mapping, providing a direct measure of luminosity distances to quasars and allowing determination of cosmological parameters at redshifts as high as $z = 3$ or more (Watson et al. 2011).

Background:

Supermassive black holes reside at the centers of most, if not all, massive galaxies. Some 5–10% of these black holes are actively accreting mass at a high enough rate to form a radiatively efficient accretion disk. On spatial scales of a several to a hundred gravitational radii ($R_g = GM/c^2$), the accretion disk emits thermal radiation across the electromagnetic spectrum. On scales of a few hundred to thousands of gravitational radii, nebular gas is ionized by radiation from the accretion disk and reprocesses the incident radiation into emission lines that are Doppler broadened to thousands of kilometers per second by the rapid motion of the gas in the deep gravitational potential of the black hole (hence the name "broad-line region"). The radiation from the accretion disk varies irregularly with time and the emission lines respond to these variations, but with a time delay due to the light-travel time across the BLR. Measurement of these time delays, or "lags," is the core of the reverberation mapping technique. The emission-line lag τ is the mean light travel time across the BLR radius $R = c\tau$.

Scientific Results from Reverberation Mapping:

Measurement of emission-line lags has yielded two very important results:

1) By comparing lags and line widths for multiple emission lines in an AGN, we find an inverse relationship between line width ΔV and lag τ that is consistent with the virial prediction $\Delta V \propto R^{-1/2}$ where $R=c\tau$. This means that, up to a projection factor that must be calibrated locally, the product $\Delta V^2 R/G$ yields the mass of the central black hole (Peterson & Wandel 1999, 2000, Kollatschny 2003; Bentz et al. 2009b). Higher ionization lines are broader and have shorter lags than low-ionization lines, demonstrating the ionization stratification of the BLR (Clavel et al. 1991).
2) The size of the BLR as measured for a particular emission line is closely related to the luminosity of the AGN in the approximate form $R \propto L^{1/2}$ (Kaspi et al. 2000, 2005; Bentz et al. 2006, 2009a). This radius–luminosity (or "R–L") relationship is at the present time well-established only for Hβ (Figure 1).

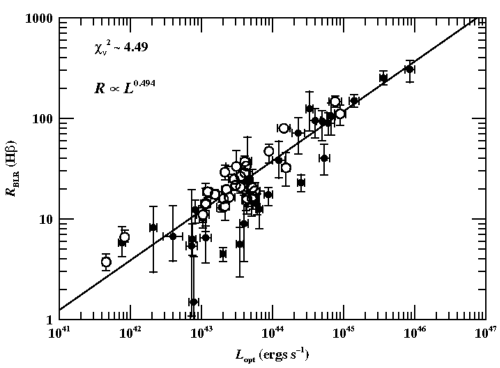

Figure 1. The relationship between starlight corrected optical luminosity and broad-line region radius as measured for the Hβ emission line. The open symbols represent the highest-quality reverberation measurements. Based on Bentz et al. (2009a).

In addition to the implications for photoionization physics, the *R*–*L* relationship is particularly important because it affords a viable short-cut to estimating AGN black hole masses (Wandel, Peterson, & Malkan 1999), although at the present time these are accurate to only a factor of three or so and possible systematics, such as the possible (probably minor) role of radiation pressure (Marconi et al. 2008), are still under investigation. From a single spectrum, we can measure the luminosity (and thus infer the BLR size *R*) and combine this with the emission-line width ΔV to estimate the black hole mass.

Another potentially important application of the BLR radius–luminosity relationship has emerged recently, namely as a "standard candle" for cosmological investigations. We can use reverberation mapping to measure the BLR size in distant quasars and then infer the intrinsic AGN luminosity from the *R*–*L* relationship. By comparing this with the measured AGN flux, we infer the luminosity distance D_L (Watson et al. 2011). Reverberation mapping of quasars at high redshift will allow us to probe the equation of state of the universe at redshifts $2 < z < 3$, beyond the reach of supernovae, and will provide an important cross-check on the results from measuring the baryon acoustic oscillations scale at these redshifts using QSO absorption lines.

Velocity–Delay Maps:

Beyond the measurement of a mean time delay for each emission line, transformational developments are possible by improving the delay resolution through high-cadence monitoring sufficient to support high-fidelity velocity-delay mapping. With enough high-quality data, it is possible to resolve the time-delayed emission-line response to continuum changes as a function of Doppler velocity and obtain a "velocity-delay map" (Figure 2). Velocity-delay maps can then be modeled to determine the geometry and kinematics of the broad-line region (Horne et al. 2004; Pancoast, Brewer, & Treu 2011). The emission-line variations, as a function of time *t* and Doppler velocity *V* can be written as

$$L(V,t) = \int_{-\infty}^{+\infty} \Psi(V,\tau)\ C(t-\tau)\ d\tau,$$

where $C(t)$ is the continuum light curve, τ is the time delay, and $\Psi(V,\tau)$ is the velocity-delay map. It is apparent by inspection that $\Psi(V,\tau)$ is the observed emission-line response to a delta function continuum outburst. The goal of a reverberation experiment is to recover the velocity-delay map from the observables, i.e., the continuum $C(t)$ and velocity-resolved emission-line $L(V,\tau)$ light curves. By obtaining velocity-delay maps for multiple broad emission lines spanning a range in ionization level and hence distance from the central source, we can model the structure and kinematics of the BLR gas.

There are multiple lines of evidence, supported by current reverberation studies, that the BLR is a manifestation of the inflow and outflow processes in AGNs. In principle, recovery of velocity-delay maps for different emission lines allows us to determine in detail the structure of the gas flow because the different ionization potentials mean that the different lines probe regions at different distances from the black hole. In particular, the low-ionization lines are thought to arise principally in a disk-like inflow that may be an extension of the accretion disk structure, while the higher-ionization lines may have a component that arises in an outflowing wind. The observed ionization stratification of the BLR means that the mostly optical low-ionization lines arise in the outer BLR while the mostly UV high-ionization lines arise in the inner BLR. Both optical and UV velocity-delay maps are necessary for a complete picture of the BLR structure and kinematics.

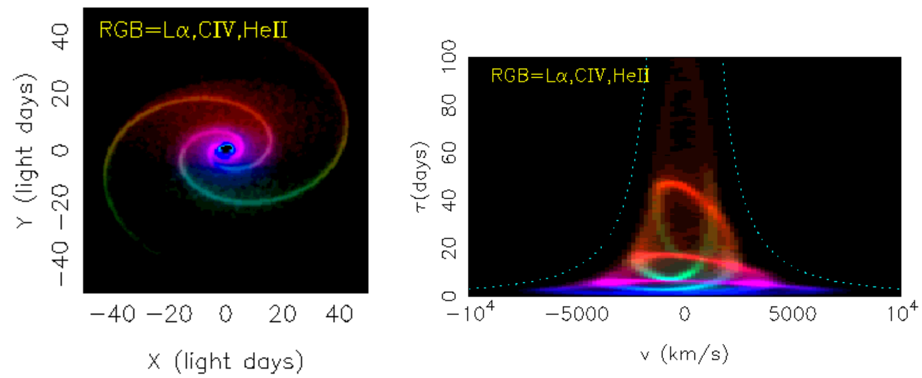

Figure 2: A photoionization model of a hypothetical BLR as a two-armed spiral disk is shown on the left, with red representing Lyα emission, green C IV λ1549 emission, and blue He II λ1640 emission. The panel on the right shows this disk transformed into a velocity-delay map. The structure of the disk is entirely arbitrary, but the velocity-delay map shows clearly how multiple emission lines are required to see the full structure of the BLR. From Horne et al. (2004).

Current Limitations:

The rest-frame ultraviolet is the most important part of the spectrum for reverberation mapping of AGNs. The strong C IV λ1549 line, in particular, which is expected to show a strong outflow signature, is in this part of the spectrum, as are other important emission lines, He II λ1640, N V λ1240, and Lyα λ1215, which are all known to have relatively short reverberation time scales. Also, the observable UV continuum (~1350Å) is expected to be a much better proxy than the optical continuum (~5100Å) for the hydrogen-ionizing continuum shortward of 912Å that actually drives the emission lines; indeed the UV and extreme UV are known to be highly correlated (Marshall et al. 1997).

Unfortunately, very few UV spectroscopic time series for reverberation mapping exist, and these are mostly for nearby low-luminosity AGNs that were observed with the *International Ultraviolet Explorer* prior to its termination in 1996.

The situation with velocity-delay maps is, of course, even poorer. Intensive ground-based optical campaigns have begun to yield credible velocity-delay maps (Bentz et al. 2010; Denney et al. 2011; Grier et al., in preparation), but UV velocity-delay maps (e.g., Ulrich et al. 1996; Wanders et al. 1997) give only hints of the structure of the high-ionization BLR. Despite the difficulties involved[1], optical ground-based reverberation mapping of

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[1] Reverberation mapping at high redshift presents additional challenges: (1) Timescales are expanded by time dilation, requiring spectroscopic monitoring programs longer by a factor of $(1 + z)$ compared to local AGNs of the same luminosity. (2) The reverberation timescales are longer for the more easily monitored high luminosity sources as their BLRs are larger. Moreover, compared to lower luminosity AGNs, the amplitude of continuum variability is lower in high luminosity objects and the continuum signal is

the rest-frame UV in high-redshift AGNs will be needed for a cosmology program. But UV reverberation mapping of relatively local AGNs is a critical first step in order to establish the radius-luminosity relationship for C IV over a large range of luminosity. Moreover, reverberation mapping of C IV in local sources is required to effect a direct comparison of black hole mass measurements based on Hβ with those based on C IV. The inescapable conclusion is that UV observations are required to meet any of the science goals described below.

Proposed Science Programs:
There are three distinct reverberation mapping programs that should be carried out:

1) Intensive monitoring campaigns to obtain high-fidelity velocity-delay maps for high ionization lines in the UV. The main scientific goal of this program is to obtain velocity-delay maps of the high-ionization lines to determine the structure and kinematics of the high-ionization BLR. To get a sense of the requirements, bright local Seyfert 1 galaxies might require 1–2 observations per day for up to 6–8 months (Horne et al. 2004). The cadence translates directly into the spatial resolution of the BLR. The necessary duration of a monitoring campaign should scale with BLR size ($\tau = R/c \propto L^{1/2}$).
2) Moderately high cadence UV spectroscopic monitoring campaigns of low-redshift AGNs over a broad range of luminosity. The goal of this scientific program is to establish the BLR radius–luminosity relationship for the C IV emission line as this will be essential for (a) estimating quasar black hole masses at larger redshifts and (b) enabling cosmological applications.
3) Moderately high cadence UV spectroscopic monitoring campaigns of AGNs at redshifts up to about 1.5 in order to use the C IV BLR radius–luminosity relationship to establish luminosity distances and thus measure cosmological parameters. Quasars at larger redshifts can be studied from the ground.

Requirements:
The technical requirements for reverberation mapping are fairly modest, with the most important attribute being the ability to obtain spectra with a relative flux calibration that is accurate at the 1% level. This requirement primarily impacts pointing stability. A two-meter class telescope (or even smaller for some of the more local applications) and a spectrograph with resolution $R > 600$ (higher is better) covering the spectral range 1100 – 3000 Å (or a long wavelength cutoff ~2000 Å to execute only the first two proposed programs) would be sufficient to meet the science goals outlined here, though a larger aperture would decrease exposure time and/or increase the number of sources that could be observed.

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geometrically more diluted over the larger BLR, making the line variations smaller and harder to measure accurately. (3) Reverberation observations of high-redshift AGNs of luminosity comparable to those studied locally will require large time allocations on very large telescopes.

Summary:
Reverberation mapping is an indirect imaging method that assembles the time-resolved spectroscopic data into a two-dimensional velocity-delay map of emission line regions photoionized by the accreting black hole. Just as radio interferometry lets us "see" the jets and radio lobes generated by AGNs, velocity-delay maps sharpen our view of AGN emission-line regions, delivering microarcsecond resolution, with revolutionary potential for our understanding of these enigmatic objects.

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