# Multiwavelength Monitoring of NGC 4395: Optical Variability, X-ray/UV/Optical Correlations, and Reverberation Mapping

Louis-Benoit Desroches (UC Berkeley), Alexei V. Filippenko (UCB), Shai Kaspi (Technion, Wise), Ari Laor (Technion), Dan Maoz (Wise), Mohan Ganeshalingam (UCB), Weidong Li (UCB), Edward C. Moran (Wesleyan), Brandon Swift (UCB), Misty C. Bentz (Ohio State), Luis C. Ho (Carnegie), Kirpal Nandra (Imperial College), Paul M. O'Neill (Imperial College), Bradley M. Peterson (Ohio State)

## Introduction

NGC 4395 is a uniquely interesting galaxy, whose study is useful in order to understand the early processes of galaxy and black hole formation. Of particular interest are the following properties of NGC 4395:

- It harbours the least luminous known "dwarf" type 1 Seyfert active galactic nucleus (AGN). Because of the low luminosity, the central supermassive black hole (SMBH) is expected to be of low mass compared to other AGNs.
- Despite its low luminosity, the AGN exhibits all the hallmarks of typical type 1 AGNs, such as an X-ray point source, a compact radio core, and a spectral energy distribution (SED) from X-ray to radio similar to other AGNs. It thus appears to be a bona fide type 1 AGN.
- The AGN resides, surprisingly, in an essentially bulgeless, extremely late-type galaxy, contrary to most other AGNs in either early-type galaxies or in the bulge-dominated centers of late-type galaxies.
- The AGN is ideally suited to the technique of reverberation mapping, used to measure the mass of the SMBH, with an expected reverberation timescale of order hours (as opposed to days, months, or even years for higher luminosity AGNs). This timescale defines the size of the broad-line region (BLR).
- NGC 4395 allows us to probe the low-mass end of the SMBH distribution and the $M_{BH}$-$\sigma_*$ correlation. This correlation between the SMBH mass ($M_{BH}$) and the galactic gravitational potential as measured by the central stellar velocity dispersion ($\sigma_*$ ) is a compelling argument linking SMBH formation and growth with galactic formation and evolution. These seemingly unrelated processes appear intimately connected to each other, suggesting joint evolutionary processes.
- The SMBH is a potential candidate for an intermediate mass black hole (IMBH), a black hole mass in a range which is poorly constrained and rarely observed.

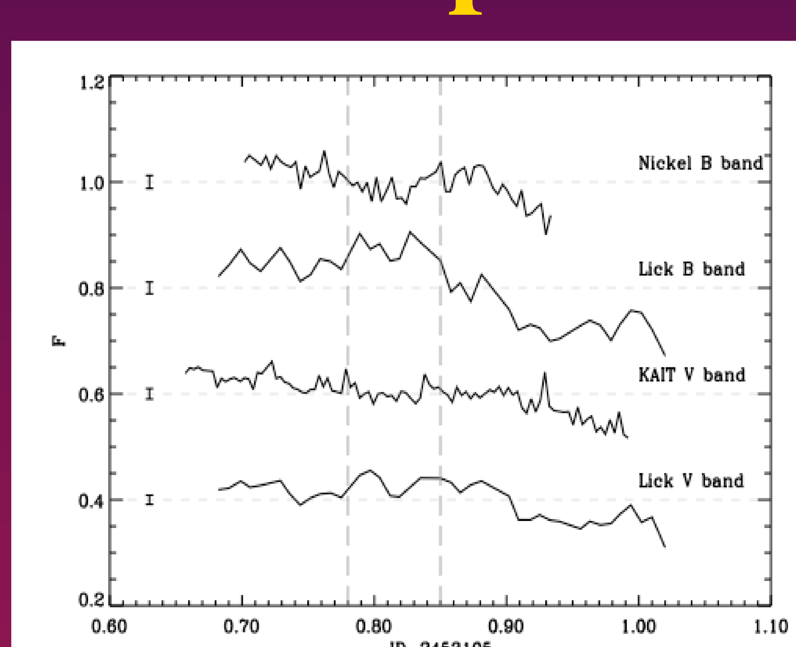
## Observations

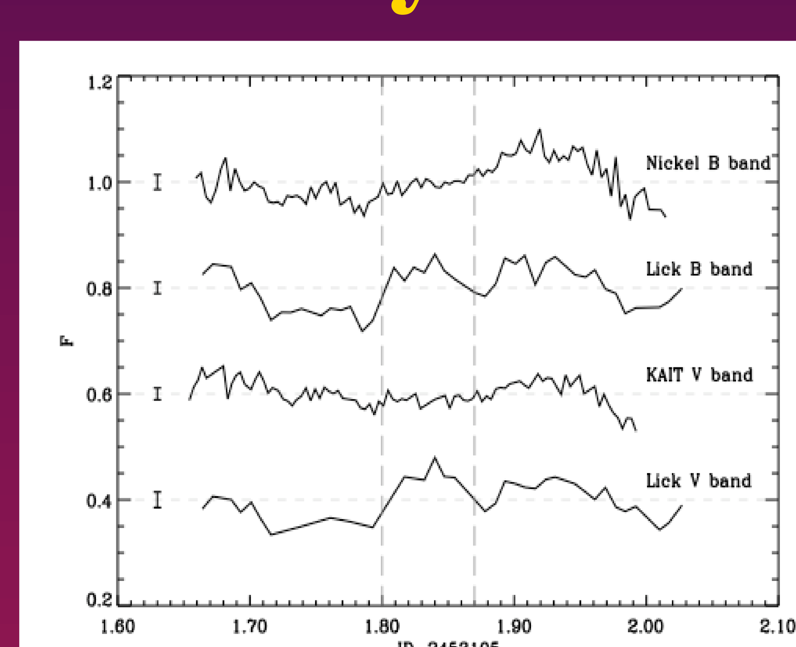
NGC 4395 was observed on 2004 April 10 and 11 UT simultaneously from:

(1) *Hubble Space Telescope* (UV spectra), (2) *Chandra Space Telescope* (X-ray), (3) Shane 3-m Telescope, Lick Observatory (optical spectra), (4) Nickel 1-m Telescope, Lick Observatory (*B* band photometry), (5) KAIT 0.76-m Telescope, Lick Observatory (*V* band photometry), (6) Wise Observatory 1-m Telescope (*V* band photometry), and (7) Mayall 4-m Telescope, KPNO (optical spectra).

Optical spectra were normalized via strong narrow lines, such as [OIII] λλ4959,5007, [OI] λ6300, and [SII] λλ6716,6731, which remain constant. An absolute flux scale was established via a nearby star. The optical photometry was normalized and calibrated to nearby stars of similar magnitude and colour to the nucleus of NGC 4395. UV results are presented in Peterson et al. (2005, hereafter known as Paper I). X-ray results are presented in O'Neill et al. (2006, hereafter Paper II).

## Optical Variability

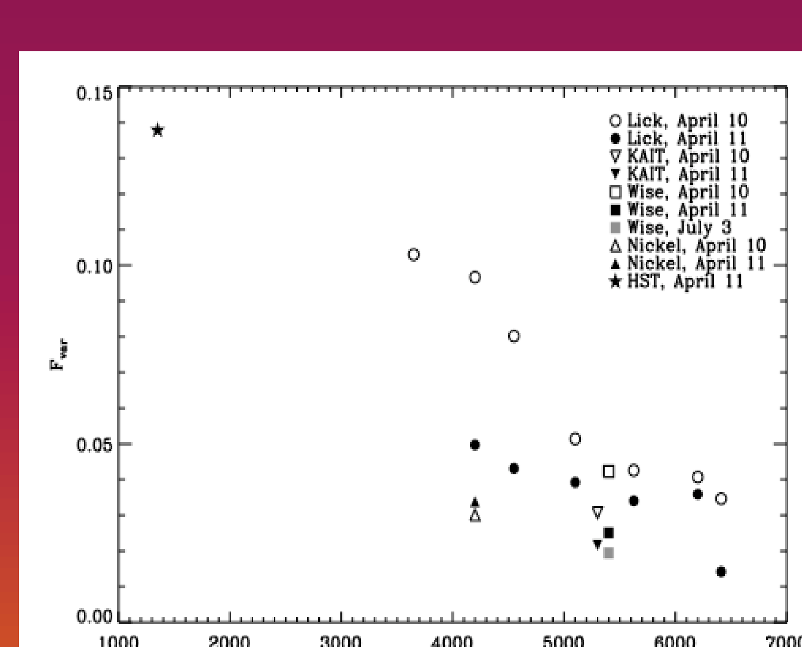



NGC 4395 was in a very low state of activity during this period, with optical continuum flux levels, variability amplitudes, and broad emission-line fluxes all diminished compared with earlier epochs. Despite this, we detect intrinsic continuum variability, from both spectra and broad-band photometry, ranging from about 2% to 10% ($F_{var}$). In general, we clearly see evidence for increased variability toward shorter wavelengths, consistent with other typical type 1 AGNs. This trend extends into the simultaneous UV and X-ray bands. The overall shape of the optical continuum light curves agrees with the simultaneous UV and X-ray light curves. Variability was greatest on April 10, while April 11 exhibited a slightly shallower dependence of variability on wavelength. The monochromatic variability and energetics are consistent with a reprocessing model, in which X-ray photons are the driving force behind UV/optical variability; i.e. we observe

$$\Delta L_X \geq \Delta L_{UV} \geq \Delta L_{opt}$$

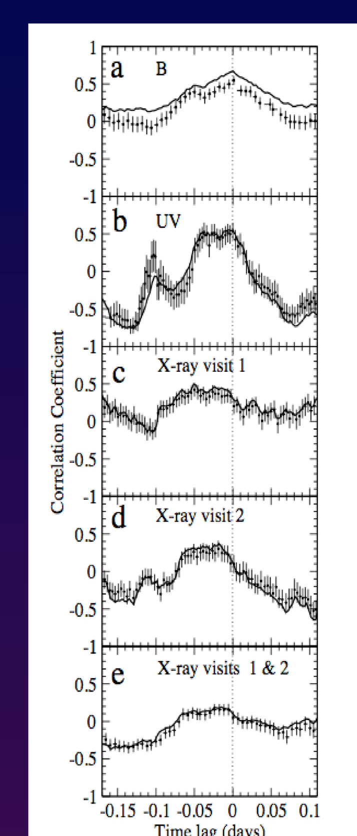
where $\Delta L_X \sim \Delta L_{UV} \sim 2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ at 1 keV and 1350 Å, and $\Delta L_{opt} \sim 6 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ at 5500 Å.

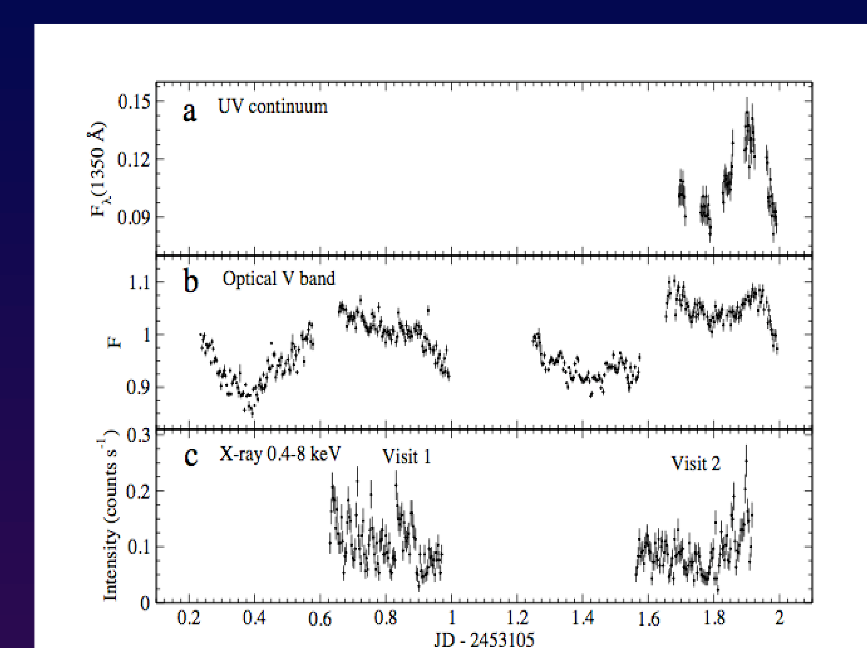


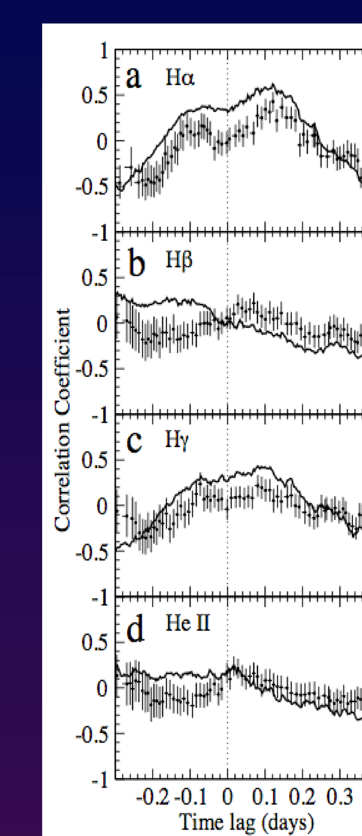

*Top left*: *B* and *V* band variability on April 10, 2004, comparing Nickel and KAIT photometry with spectroscopically derived broad-band light curves. F is in arbitrary units. Vertical dashed lines denote a time frame near transit in which electronic difficulties on the 3-m resulted in slightly compromised spectra. These difficulties, however, did not affect the rest of our results. *Top right*: *B* and *V* band variability on April 11, 2004. *Bottom right*: Continuum $F_{var}$ measurements as a function of wavelength. Not shown are the values for the 0.4-8.0 keV X-rays, which are 0.35 and 0.36 on April 10 and 11, respectively.

For further details, see:
Desroches et al., 2006, ApJ, 650, 88

## X-ray/UV/Optical Correlations




*Top*: Continuum light curves used in our CCF calculations. $F_\lambda$ is in units of $10^{-14}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. F is in arbitrary units. *Left*: CCFs of the *B* band, UV, and X-ray light curves with the *V* band optical light curve. Solid lines are the ICCF method, and points are the ZDCF method. *Right*: CCFs of the optical emission-line light curves with the V band light curve. We only formally detect a lag for Hα.

For all cross-correlations, we use the interpolated cross-correlation function (ICCF) along with the Monte Carlo flux randomization/random subset selection (FR/RSS) method. This allows us to build up a cross-correlation centroid distribution and estimate uncertainties. As a check, we also use the z-transform discrete correlation function (ZDCF).

Cross-correlation of the various continuum light curves suggests that the optical emission lags behind the UV emission by $24^{+7}_{-9}$ min, and the optical emission lags behind the X-ray emission by 44 ± 13 min. There is no formal detection of any lag between the UV and X-ray emission, as described in Paper II, nor between the *B* and *V* bands (9 ± 11 min). The X-ray/UV lag has a 95% upper limit of ± 1 hour. These results are consistent with the reprocessing model, in which X-ray photons are reprocessed into UV and optical photons. Our high sampling frequency has allowed us to make these measurements, which have previously been very difficult to achieve. This trend appears to extend into the IR, where Minezaki et al. (2006) measure a near IR lag behind the *V* band of $7.2^{+15.8}_{-8.6}$ min.

We only formally detect an emission-line lag between the Hα light curve and the *V*-band light curve. Although all other emission-line light curves are consistent with zero lag, the trend as a whole is quite suggestive. In particular, averaging the Balmer-line correlations with the optical continuum yields an emission-line lag of 80 ± 68 min behind the continuum. While not very significant, this result is consistent with the relations of Kaspi et al. (2005) for the size of the BLR. The optical emission-line lag is also about 1.5 times larger than the UV emission-line lag behind the UV continuum (Paper I). We have seen this behavior in other AGNs, which indicates NGC 4395 is behaving typically, albeit faintly, for an AGN.

## Reverberation Mapping

The technique of reverberation mapping exploits the fact that broad emission lines in AGN spectra are powered by the strong continuum radiation arising in the accretion disk surrounding the SMBH. Any change in continuum flux levels will propagate to the broad lines, with a time delay that can be measured. This provides a physical scale to the BLR. The width of the broad lines provides a circular velocity, and together these measurements are used to estimate the SMBH mass.

In Paper I, we measured the mass of the SMBH to be $M_{BH} = (3.6 \pm 1.1) \times 10^5\ M_\odot$ . The lag was calculated from the C IV emission-line light curve and the 1350 Å continuum light curve, using the same cross-correlation method described above. The mass was obtained using:

$$M_{BH} = f\sigma^2 c\tau/G$$

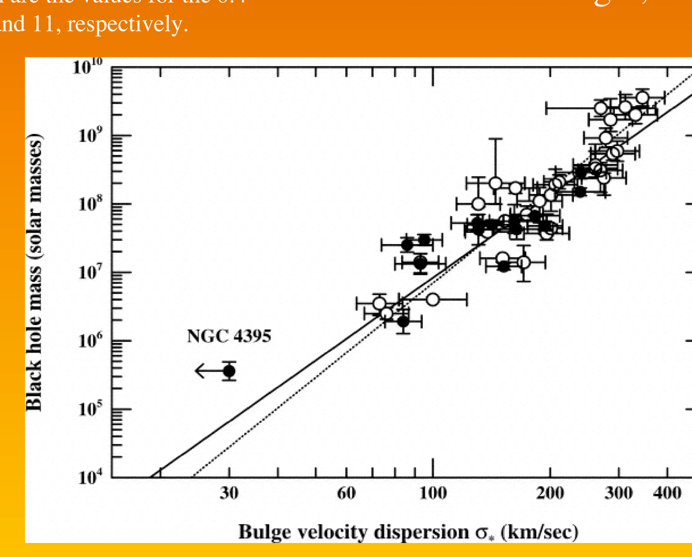
Where τ is the time lag, σ the C IV line dispersion, c the speed of light, G the gravitational constant, and *f* a scale factor which depends on unknown geometry and kinematics of the BLR. We use $f = \langle f \rangle = 5.5$ as found by Onken et al. (2004).

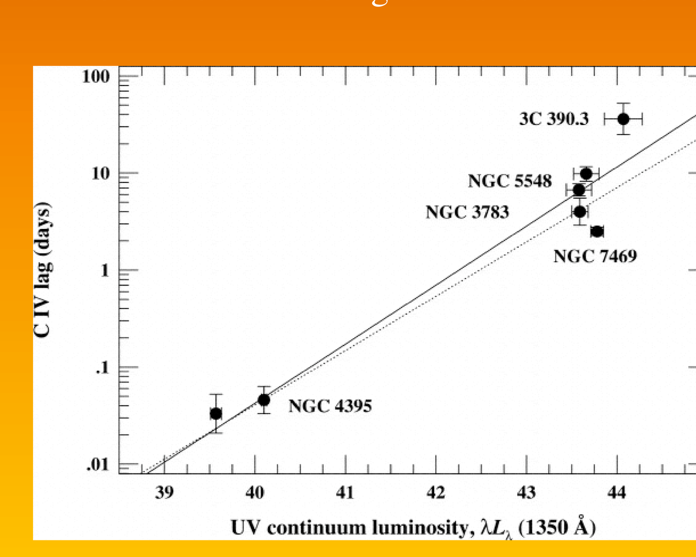
Although variability in the optical was not very strong, we can roughly estimate the SMBH mass using optical data to compare with the UV-derived value above. The average Balmer emission-line lag is τ = 80 ± 68 min and the FWHM of the variable broad-line region is roughly 2300 km s$^{-1}$. Here we assume FWHM ~ σ, as was the case for the C IV line (the broad lines are not strictly gaussian). Using the same formula above, we therefore estimate the mass of the SMBH to be $M_{BH} \sim 3 \times 10^5\ M_\odot$ , which although not very significant, is consistent with the UV result. These results are also consistent with other independent estimates and limits on the SMBH mass.

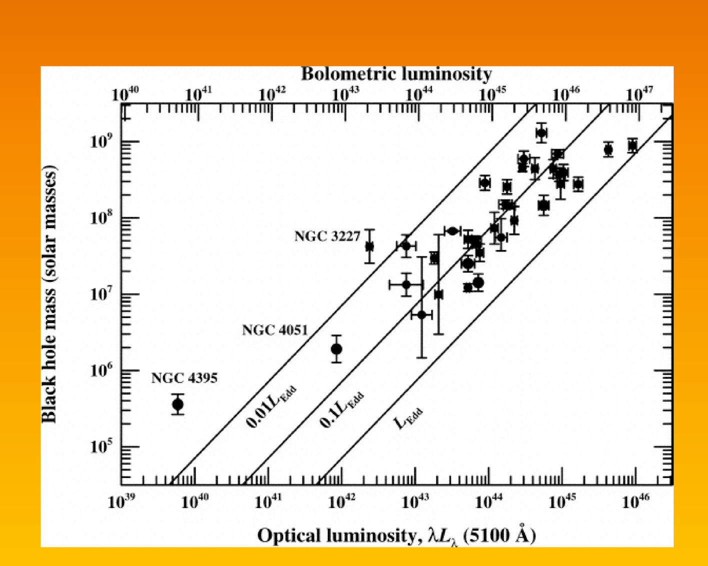
## Comparisons to other AGN

The SMBH mass of NGC 4395 falls above the extrapolated $M_{BH}$-$\sigma_*$ relation established by Tremaine et al. (2002) and Ferrarese et al. (2002), although Greene & Ho (2006) and Wyithe (2006) show that the $M_{BH}$-$\sigma_*$ relation appears flatter at lower masses, and is much better fit with a log-quadratic form. This suggests that perhaps NGC 4395 is perfectly normal, if very faint, among the AGN population. NGC 4395 is also consistent with the BLR radius-UV luminosity relation of Kaspi et al. (2005). The bulgeless nature of NGC 4395, however, renders the definition of $\sigma_*$ problematic, though it does argue that a bulge is not a necessary condition for a SMBH. It is also possible that the statistical scale factor *f* used in our SMBH mass estimates is not the correct factor for the geometry of NGC 4395, leading to an overestimate of the SMBH mass. Further study is clearly warranted. Where NGC 4395 appears unique amongst other AGNs is with its inferred low accretion rate based on its low luminosity. It should be noted, however, that most reverberation-mapped AGNs to date tend to be bright, and are thus biased towards higher accretion rates.

*Left*: The $M_{BH}$-$\sigma_*$ relation. Filled circles represent masses determined via reverberation mapping. Open circles represent other techniques. The solid line is the Tremaine et al. (2002) fit and the dotted line is the Ferrarese et al. (2002) fit.
*Center*: The C IV BLR radius-luminosity relation. NGC 4395 agrees well with other galaxies.
*Right*: $M_{BH}$ vs. optical luminosity. NGC 4395 appears to be radiating far below Eddington, more so than any other AGN.

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