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

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Introduction

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

- It harbors at least luminous known “dwarf” type I Seyfert active galactic nuclei (AGNs). 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 I AGNs, such as an X-ray point source, a complex X-ray spectrum, and a special 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 varies, 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 time-scale of other hours to days months, or even years, for higher luminosity AGNs. This timescale defines the size of the broad-line region (BLR).
- NCG 4395 allows us to probe the low-lum end of the SMBH distribution and the M(lum) - correlation. This correlation between the SMBH mass (M(BH)) and the galactic gravitational potential as measured by the central stellar velocity dispersion (σ) 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 (SMBH), a black hole mass in a range which is poorly constrained and early observed.

Observations

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

- Mayall 4-m Telescope, KPNO (optical spectra).
- The Wise Observatory 1-m Telescope (UV spectra), GALEX (UV photometry), and Chandra Space Telescope (X-ray photometry).
- KAIT 0.76-m telescope (UV photometry), and KAIT B band optical light curve.
- The 2m K~band photometry, and Keck I (H band photometry).
- Wise Observatory 1m Telescope (optical spectra).
- Top: Continuum light curves used in our CCF calculations. The lag was calculated from the C IV line dispersion, c the speed of light, G the gravitational constant, and σ the C IV line dispersion. The time lag, τ, is the time lag, f 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 = (f) = 0.38 by found by Onken et al. (2004).
- The lag was calculated from the C IV emission line light curve and the 150 Å continuum light curve, using the same cross-correlation method described above. The mass was obtained using:

M(BH) = (f) erg cm

where τ is the time lag, f 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 = (f) = 0.35 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 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 ± 1.1) × 10^7 M☉. The lag was calculated from the C IV emission line light curve and the 150 Å continuum light curve, using the same cross-correlation method described above. The mass was obtained using:

M(BH) = (f) erg cm

Comparisons to other AGN

The SMBH mass of NGC 4395 falls above the extrapolated M(σ) = relation established by Tremaine et al. (2002) and Ferrarese et al. (2002), although Greene & Ho (2006) and Wyile (2006) show that the M(σ) = 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, where NGC 4395 appears unique amongst other AGNs. Further study is clearly warranted. Where NGC 4395 appears unique amongst other AGNs, which indicates NGC 4395 is behaving typically, albeit faintly, for an AGN.