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Probing the Physics of Active Galactic Nuclei by Multiwavelength Monitoring
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B.M. Peterson, R.S. Polidan, and R.W. Pogge

Multiwavelength Monitoring of Active Galactic Nuclei

Bradley M. Peterson

Department of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus, OH 43210

Abstract. By intensive monitoring of AGN variability over a large range in wavelength, we can probe the structure and physics of active galactic nuclei on microarcsecond angular scales. For example, multiwavelength variability data allow us (a) to establish causal relationships between variations in different wavebands, and thus determine which physical processes are primary and which spectral changes are induced by variations at other wavelengths, and (b) through reverberation mapping of the UV/optical emission lines, to determine the structure and kinematics of the line-emitting region, and thus accurately determine the central masses in AGNs. Multiwavelength monitoring is resource-intensive, and is difficult to implement with general-purpose facilities. As a result, virtually all programs undertaken to date have been either sparsely sampled, or short in duration, or both. The potentially high return on this type of investigation, however, argues for dedicated facilities for multiwavelength monitoring programs.

1. Multiwavelength Monitoring

After nearly four decades, the idea that active galactic nuclei (AGNs) are powered by gravitational accretion is becoming quite secure. We do not yet understand, however, the specifics of how gravitational potential energy is converted to primary radiation (and what form that primary radiation takes) and how this primary radiation is reprocessed into other forms. In this regard, multiwavlength monitoring of AGN variability is proving to be an important tool. AGNs, the archetypical multiwavelength sources, are well-studied over the accessible electromagnetic spectrum, and their spectral-energy distributions and variability within each band are comparatively well-characterized. What is missing, however, is key information about how the variations in various bands are coupled; this is the key that will determine the causal relationships, which will then allow us to determine which radiation processes are primary and which are secondary.

Multiwavelength monitoring is an expensive and difficult tool to use, however: it involves time-constrained repeated observations of single sources and coordination of these observations with other facilities, both of which are something of an anathema to the people who have to do the scheduling. Getting a multiwavelength program approved in the first place is very difficult because of the problems of multiple jeopardy (more than one review panel needs to be convinced) and in general each review panel needs to hear a strong argument about the science that can be done solely with the particular proposed facility. There are thus a number of serious sociological and technical constraints that mean that the science return on the investment in a multiwavelength program has to be perceived as very high.

Despite the many difficulties, as a community, we have been very successful at carrying out multiwavelength monitoring experiments. The results have had a powerful impact in how we view AGNs: if the monitoring programs carried out to date have not succeeded in giving us a definitive view of AGN physics, they have certainly led us to reject most of our simple models of how AGNs work. Many of us believe that multiwavelength monitoring holds much promise for the future, but the next generation of monitoring programs will require resources (time and wavelength coverage) that are considerably beyond what has been accomplished thus far. Some of us believe that future programs are so demanding that dedicated observing facilities will be required, partly because more complete time-coverage will be required and partly because we believe that it is unrealistic to expect a large fraction of all existing general-purpose space-based telescopes to spend a large and time-constrained fraction of their operational lifetimes studying individual sources in exquisite detail when this could be done so much more efficiently and cheaply with a well-designed special-purpose platform. But we need to make a powerful scientifically persuasive argument that a dedicated facility is indeed warranted. We therefore decided to hold this workshop with two basic goals in mind:

1. To assess what we have already learned through multiwavelength monitoring programs.
2. To define the most important goals and strategies for future programs.

2. The Major Questions

If indeed we hope to command greater resources for multiwavelength monitoring, either with general-purpose or dedicated facilities, the scientific case must be extremely strong and have broad implications. Therefore, I think it is valuable at this point to step back for a moment and consider briefly what are the most important scientific questions about the nature of AGNs. I would like to make a short list of some of the most basic questions that might be addressable with multiwavelength time series:

1. What are the masses of the central sources in AGNs? Can we be sure that they are in fact supermassive black holes?
2. What are the accretion parameters? Specifically, what is the luminosity relative to the Eddington rate $L/L_{\rm Edd}$, the efficiency ϵ, and the mass accretion rate $\dot{M}$? How much variation is there in these accretion parameters among AGNs, and how do they scale with the black-hole mass?
3. How does the accretion process work? Are there in fact structures that we would identify as accretion disks? What is the role of inefficient emitters (ADAF, ADIOS, or CDAF structures) in AGNs, and what are their observational signatures?

4. What is the source, or sources, of the broad emission lines? Does this gas play a role in the accretion process?

5. Why do some AGNs have jets? What is the role of magnetic fields in the accretion procees? Are jets powered by black-hole spin or by accretion?

6. What is the origin and role of the X-ray and UV absorbers in AGNs?

3. Current Status

Here I will attempt to summarize briefly where we are in our pursuit of just a few of the questions raised above.

3.1. Mass of the Central Source

The mass M of the central source can be determined observing motion of some type of tracer in the gravitational potential of the source. This is done by application of the virial theorem

$$M = f(r\Delta V^2/G), \tag{1}$$

where r is the size of the tracing region over which we measure the velocity dispersion ΔV, G is the gravitational constant, and f is a factor of order unity that depends on the details of the geometry and kinematics of the entity we are using as the tracer. Tracers that have been or in principle can be used as virial estimators for AGNs are listed in Table 1. Tracers that can be applied to the smallest scales are the most desireable, since these afford the strongest argument that the central source must be a black hole. Emission-line reverberation affords a strong probe of the black-hole model since the most rapidly responding emission lines respond to continuum variations on time scales shorter than the expected light-travel time $10^3\,R_S/c$; the X-ray Fe Kα line at 6.4 keV is especially intriguing, since it is close enough to the event horizon for relativistic effects to be manifest. Indeed, it has been suggested that relativistic effects produce the redshift and asymmetry of this line (Miyoshi et al. 1995). However, in practice X-ray reverberation will be difficult for a number of technical reasons (see Reynolds, these proceedings).

That AGN virial masses from reverberation of the UV/optical broad emission lines (see papers by Netzer and Horne in these proceedings) can now be trusted is based on evidence for a few AGNs for which time delays have been measured for more than one line and, at least in the case of NGC 5548, on more than one occasion for a single line (Fig. 1). In each case, we see that the data are consistent with the expected virial relationship $V \propto r^{-1/2}$, where the size of the region r is given by the light-travel time delay for each emission line and the line width V is the full-width at half-maximum of the emission line, in this case measured in the root-mean-square spectrum formed from all the monitoring data; this is done to isolate the variable part of the emission line from the constant components.

At the present time, virial masses are available for nearly three dozen AGNs (Wandel, Peterson, & Malkan 1999; Kaspi et al. 2000) and span a range from

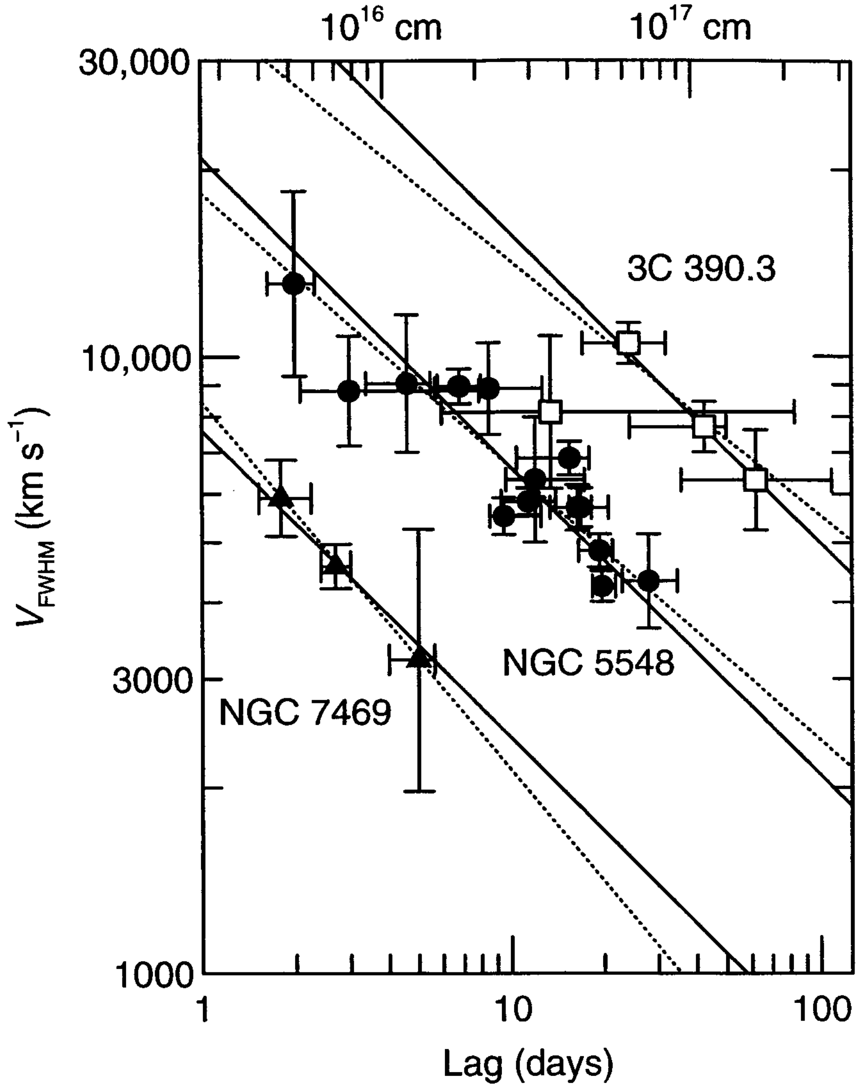

Figure 1. Line width in the rms spectrum plotted as a function of the distance from the central source (upper horizontal axis) as measured by the emission-line lag (lower horizontal axis) for various broad emission lines in NGC 7469, NGC 5548, and 3C 390.3. The dashed lines are best fits of each set of data to the relationship $\log V = a + b \log c\tau$, where V is the full-width at half maximum of the line in the rms spectrum and τ is the emission-line lag for the line. The best-fit slopes are $b = -0.61 \pm 0.35$, -0.44 ± 0.05, and 0.41 ± 0.15 for the three galaxies, respectively. The solid line shows the best fit to each set of data for fixed $b = -1/2$, yielding virial masses of $8.4 \times 10^6\, M_\odot$, $5.9 \times 10^7\, M_\odot$, and $3.2 \times 10^8\, M_\odot$ for the three respective galaxies. From Peterson & Wandel (2000).

Table 1. Virial Estimators for AGNs

Source	Distance from Central Source[a]
X-Ray Fe Kα	3–10 R_s
Broad-Line Region	600 R_s
Megamasers	$4 \times 10^4\, R_s$
Gas Dynamics	$8 \times 10^5\, R_s$
Stellar Dynamics	$10^6\, R_s$

[a] In units of Schwarzschild radius $R_S = 2GM/c^2 = 3 \times 10^{13}(M/10^8\, M_\odot)$ cm.

about 10^6 to $4 \times 10^8\, M_\odot$. Radius–luminosity and mass-luminosity are now beginning to emerge (Kaspi, these proceedings) and the implications explored (Wandel, these proceedings). It must be kept in mind, however, that on account of the unknown geometry and kinematics of the broad-line region (BLR), these masses are uncertain by as much as a factor of several; the factor f in eq. (1) is unknown for the BLR in any AGN (see Fromerth, these proceedings).

The clear path to higher-precision AGN masses is through improved reverberation mapping. At the present time, we are working with one-dimensional transfer functions, i.e., integrated emission-line response as a function of time delay. With some improvements in sampling and signal-to-noise ratios, it will be possible to determine reliably two-dimensional transfer functions, i.e., emission-line response as a function of both line-of-sight velocity V_z and time delay, thus reducing the three spatial and three velocity dimensions of BLR phase space with two constraints. Further constraints can be obtained by incorporation of multiple emission lines and photoionization modeling (Horne, these proceedings).

The most important improvement that needs to be made in emission-line reverberation is better temporal sampling. Fortunately, simulations seem to indicate that with realistic enhancements in sampling, accurate transfer functions, and hence strong constraints on the BLR geometry and kinematics, are achievable (Collier, these proceedings).

3.2. Accretion-Disk Structure

Continuum variations across the spectrum also provide us with a probe of the structure of the continuum-generating regions, specifically the putative accretion disk and surrounding corona. We consider two specific examples:

Wavelength-Dependent Continuum Lags in NGC 7469 The first intensive long-duration UV/optical monitoring experiment on the Seyfert 1 galaxy NGC 5548 (Clavel et al. 1991; Peterson et al. 1991) showed that the UV and optical continuum variations were simultaneous to within the measurement accuracy of the experiment, about $\sim$ 2 days (Peterson et al. 1998). This confirmed what had been suspected before, namely that the UV and optical continuum variations were too closely coupled in time to be attributable to instabilities propagating through the disk viscously, since the time scales for variations to propagate through the disk should be measured in years for AGNs. Thus, whatever agent causes the continuum variations, the signal must propagate radially outward at light speed (Courvoisier & Clavel 1991; Collin-Souffrin 1991; Krolik et al. 1991; Molendi, Maraschi, & Stella 1992).

Not long after this conclusion had been reached, independent evidence in the X-rays led to what became known as "reprocessing models". The large equivalent width of the 6.4 keV Fe Kα line and the strength of the Compton reflection component at energies $E \gtrsim 10\,\mathrm{keV}$ suggested that approximately 50% of the sky as seen by the hard X-ray continuum source must be covered by "cold" material, and a simple assumption was that this cold material is the accretion disk itself (Nandra et al. 1991). A completely heuristic model that would explain the X-ray spectral features consists of a hard X-ray source somewhere above the accretion disk. Radiation from the hard X-ray source then gets "reprocessed" into continuum and emission lines. This suggests that the variable hard X-ray source may in fact be responsible for the variations at shorter wavelengths. There was some evidence that in fact that hard X-ray and lower-energy continuum variations are coupled somehow (Edelson et al. 1996 and references therein). Also, the UV/optical continuum variations are lower amplitude and smoother than those in the hard X-rays, as one would expect from a more spatially extended region. But such a model clearly predicts that the hard X-ray variations should be closely coupled in time to those at lower energies. Specifically, the X-rays should be driving the variations at lower frequencies. If the continuum variations are produced by local perturbations in a temperature-stratified region such as a thin accretion disk, it is clear that the variable radiation from the outer, cooler regions will lag behind the variable radiation from the inner, hotter regions.

This effect was searched for in every AGN that was carefully monitored in the UV/optical, and it was finally detected in NGC 7469 (Wanders et al. 1997; Collier et al. 1998; Kriss et al. 2000). Relative to the shortest observed wavelength, variations at longer wavelengths should follow those at shorter wavelengths with time lags $\tau \propto \lambda^{4/3}$, consistent with what has been observed (Fig. 2). For a standard thin accretion disk, the time lag is proportional to $(M/\dot{M})^{1/3}$, so that the NGC 7469 result at least in principle can be scaled straightforwardly to other objects. This shows that previous experiments had not been sufficiently well-sampled for wavelength-dependent time lags to be detectable (Peterson et al. 1998).

While the UV/optical result for NGC 7469 seemed to be consistent with reprocessing scenarios, comparison with the hard X-ray fluxes observed with *RXTE* did not support this interpretation: the hard X-ray light curve was formally uncorrelated with the UV/optical continuum light curves (Nandra et al. 1998). While the minima in the light curves seemed to occur at the same time, the peaks in the hard X-ray fluxes seemed to *lag behind the UV continuum by* ~ 4 *days*, clearly strongly at odds with reprocessing, and arguing strongly against it. Wavelength-dependent continuum lags were also undetected in NGC 3516 (Edelson et al. 2000), a case in which detection was expected based on naive scaling relative to NGC 7469.

The case of NGC 7469 is discussed elsewhere in these proceedings. Nandra shows how spectral analysis of the *RXTE* data suggests that the *soft* X-ray flux is correlated with the UV flux (see also Nandra et al. 2000). Korista and Goad

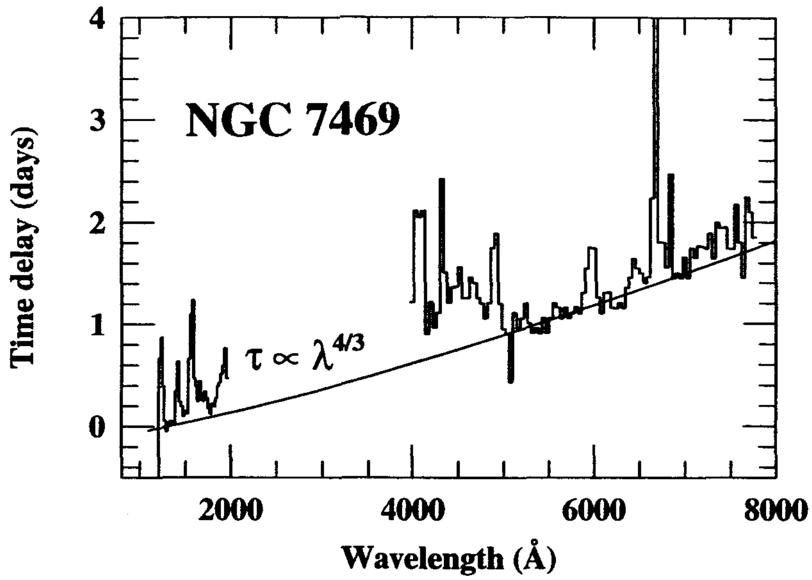

Figure 2. The "lag spectrum" for NGC 7469. The average flux in each wavelength band is cross-correlated with the 1315 Å continuum, yielding a plot of time delay versus wavelength. The peaks above the "continuum" are wavelengths contaminated by strong emission lines, which have time delays of days. The expected dependence for an externally irradiated thin accretion disk, $\tau \propto \lambda^{4/3}$, is also shown. Based on data from Wanders et al. (1997) and Collier et al. (1998).

(these proceedings) suggest diffuse emission from broad-line clouds as alternative explanation for the origin of the wavelength-dependent lags, and more complete wavelength coverage of the variations, especially across the critical Balmer jump, could provide the critical test.

The Narrow-Line Seyfert 1 Galaxy NGC 4051 Recent combined *RXTE* and ground-based observations of the narrow-line Seyfert 1 (NLS1) galaxy NGC 4051 have rather serendipitously afforded an alternative probe of the continuum-generating regions of an AGN (Peterson et al. 2000). This source was observed as part of Ian McHardy's (these proceedings) on-going *RXTE* monitoring program, with ground-based support provided by the International AGN Watch. During 1996 and 1997, the source behaved in a "normal" fashion for NLS1s, with rapid, violent X-ray variability and more modest optical variations. During 1998, however, NGC 4051 went into a very low X-ray state, with mean hard X-ray fluxes about an order-of-magnitude fainter than usual. The optical continuum was slightly fainter than usual, and it was still variable. A remarkable result is seen in the line spectrum, however, as shown in Fig. 3.

Optical spectra obtained during this monitoring campaign can be combined to form a "mean spectrum" and a "root-mean-square (rms) spectrum" — the latter effectively isolates the variable part of the spectrum. In panel (b) of Fig. 3, the rms spectrum shows that the optical continuum and the Hβ and He II λ4686 emission lines were all varying strongly. Panel (c) shows the rms spectrum obtained during the X-ray low-state in 1998; here again we see that the optical

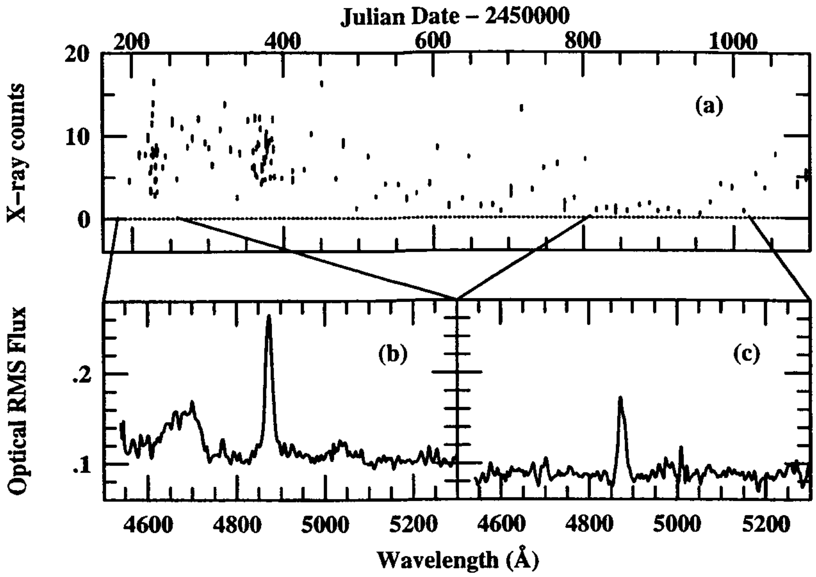

Figure 3. Comparison of hard X-ray and optical spectral variations in NGC 4051 in different X-ray states. Panel (a) shows the 2–10 keV flux measured with *RXTE* as a function time for the three-year period 1996–1998. Panel (b) shows the rms optical spectrum during an X-ray active period in 1996, Panel (c) shows the rms optical spectrum during an X-ray quiescent period in 1998. Note the absence of strong He II λ4686 emission in panel (c). From Peterson et al. (2000).

continuum and the Hβ emission line are variable, but the He II line has vanished from the rms spectrum, meaning that it is absent or constant. Whether or not it has completely vanished is difficult to determine on account of the blending of He II with strong Fe II emission in the mean spectrum, but an attempt to remove the Fe II emission by subtraction of a template indicates that most of the He II emission must have vanished during 1998.

The absence of the He II line in 1998 shows that not only was the hard X-ray emission missing during this period, but softer EUV emission (at He$^+$ ionizing wavelengths, $\lambda < 228$ Å) was gone as well. But at the same time, the optical continuum was still present and variable, and from the variability of Hβ, we can infer that the FUV H-ionizing continuum ($\lambda < 912$ Å) was also present and varying. This suggests that what we may be seeing here is the result of the inner regions of an accretion disk undergoing a transition to a low radiation-efficiency state (like an ADAF, for example), while the outer disk remains in a more-or-less normal state. The transition radius lies somewhere between the regions that produce the bulk of the EUV and the FUV.

4. The Future

In the last section, we showed two specific examples from multiwavelength monitoring programs on AGNs. The NGC 7469 result, based on what is arguably the most intensive multiwavelength campaign ever undertaken, shows that we do not understand clearly even the *phenomenology* of interband variability, especially how the hard X-rays relate to everything else. And we must understand the phenomenology before we can hope to understand the physics.

On the other hand, our understanding of emission-line variability has become quite sophisticated, though we are still grasping at the physics. We have gleaned a number of important results from the emission-line variability data, notably the masses of the central objects on projected scales of tens of microarcseconds, and we have a very good idea how to design and execute the kinds of reverberation experiments that will lead to a fundamental improvement in the results, specifically by determining the line-response as a function of line-of-sight velocity. Improved reverberation results are of obvious important in that this technique can in principle yield high-precision black-hole masses, and is extendable to higher-luminosity quasars where other techniques are far less likely to succeed.

There is little question about the scientific value of multiwavelength monitoring; indeed it is *only* way in the foreseeable future that we can hope to probe AGN structure on microarcsecond angular scales and thus, for example, measure the temperature structure of accretion disks, determine the relative roles of X-ray reprocessing and Compton upscattering, and obtain more precise masses for the central objects.

As we noted earlier, there are many of us who feel that the time is ripe to design a mission dedicated to multiwavelength monitoring; a suitable multiwavelength platform would have a great impact on several areas of astronomy, but the impact on AGN science would be tremendous.

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