Monitoring of Active Galactic Nuclei: the Why and the How

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1. Introduction

Over the past twenty years, ground-based optical observations as well as ultraviolet, X-ray, and γ-ray observations from space-borne telescopes have revealed the variable nature of the continuum and emission lines in the spectra of active galactic nuclei (hereafter referred to as AGN). Variability is now recognized as one of the distinctive features of these important but poorly understood objects.

2. The Why of Monitoring Campaigns

2.1 Some basics

In the study of AGN, variability affords a potentially valuable probe of the properties of both the continuum source itself and the broad-line emitting region surrounding it.

Knowledge of the continuum variability pattern in different wavebands from γ-ray to radio wavelengths can provide a way to probe the various physical processes at the origin of the continuum emission. The variation time scales in particular give some indication of the size of the emitting regions, an indirect clue to the likely emission mechanisms. Of potentially greater interest is the possibility of eventually measuring time lags between continuum variations in different wavebands because this can tell us about the connection between various mechanisms producing continuum photons in these systems.

In the framework of the so-called standard model, based on a massive black hole and accretion-disk system, we assume that accreting material is distributed throughout the line-emitting regions: the broad-line region (hereafter BLR) and the narrow-line region (NLR), which are somewhat arbitrarily distinguished by the width of the lines they emit (ranging from as much as a few 10,000 km/s for the broadest lines to only a few 100 km/s for the narrow lines). An important probe of the inner structure of AGNs is provided by measuring in detail how the emission-line fluxes change in response to changes in the continuum flux. The broad emission lines respond with small but measurable time delays (days to weeks) to variations of the central continuum source, making it possible to use the technique of "reverberation mapping" to probe the structure and kinematics of the BLR. In general, the narrow lines do not vary in flux since the size of the NLR is usually too large to provide a coherent response to changes in the level of the continuum flux.

The fundamentals of reverberation mapping were described by Blandford and McKee (1982), but it has been only over the last five years or so that the first tentative applications of this technique to real AGN have been possible, as severe conditions on the amount and quality of the data have to be met (Peterson, 1994).

Some experiments, undertaken by the "International AGN Watch" collaboration, have been conducted in part with telescopes at the European Southern Observatory (ESO), and these form the subject of this report.

Similar programmes, albeit with a sometimes different overall emphasis, have been undertaken by other informal organisations during the same time frame. For example, the European consortium LAG ("Lovers of Active Galaxies") which was initiated by the late M.V. Penston, has carried out a spectroscopic and photometric monitoring of several AGN on the Canary Islands telescopes within the framework of the CCI 5% international time programme (Robinson, 1994).

2.2 A bit of recent history

In the early eighties, a number of groups involved in AGN studies undertook ultraviolet and optical monitoring programmes in an effort to probe the physics of AGN (for a review, see Peterson, 1988). We note in particular the results of the so-called NGC 4151 collaboration (Ulrich et al., 1984; Clavel et al., 1990). One of the major surprises of the monitoring campaigns of the eighties was that the BLR seemed to be an order of magnitude smaller than the value generally predicted by photoionisation equilibrium calculations. This conclusion demanded even denser sampling for AGN variability programmes.

In 1987, two successive workshops in Segovia and Atlanta featured lively discussion of results obtained from AGN variability studies. It became apparent to the community that the goals of spectroscopic monitoring programmes could in fact be achieved only if sufficient observing time could be devoted to such an approach.

Cooperation of observers on a scale that was unprecedented in extragalactic astronomy, i.e. with very large collaborations involving around 100 astronomers, became a necessity.

To deal with a collaboration of this size and a highly time-constrained programme, new ways of working and cooperating had to be invented. The International AGN Watch was therefore established with the goal of focusing attention on a few AGN for intensive monitoring efforts and maintaining communication among the various individuals and groups that carried out the actual observations. A key factor in the success of these efforts has been the ability to communicate and exchange information promptly via modern computer networks. The role of the AGN Watch has been multifold: (a) to define the scientific questions to be addressed, conceive the observational projects and coordinate the submission of the appropriate observing proposals, (b) to ensure that data are collected in a manner consistent with the scientific goals, (c) to reduce the observational data and make these data sets available to the entire community, and (d) to perform the measurement and analysis of the data and publish the primary scientific results.

It was decided that detailed and model-dependent interpretation would be left to individuals or sub-groups of the

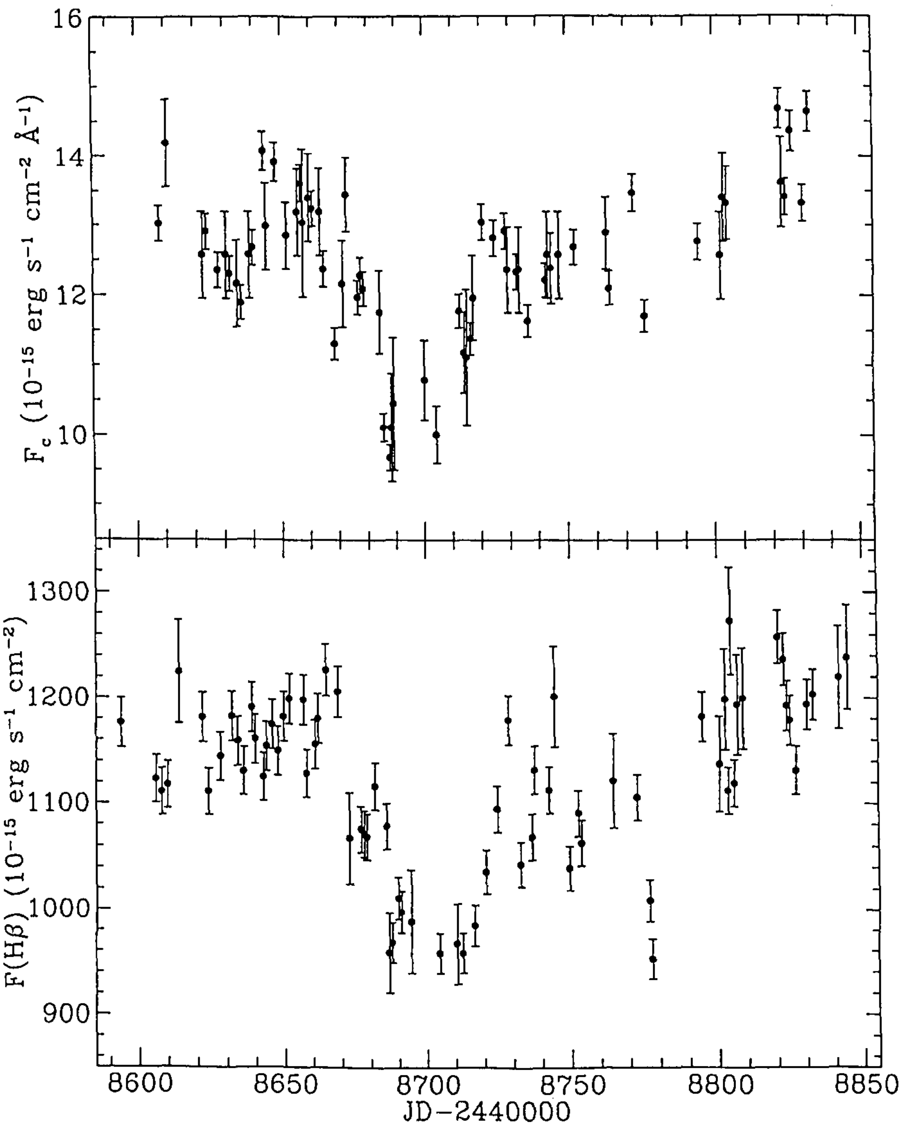

Figure 1: *The light-curves of the optical continuum (top panel) and of Hβ (lower panel) from the AGN in NGC 3783 during the ESO campaign.*

AGN Watch collaboration, as well as to other interested parties. The AGN Watch data are at the disposal of the entire community once the primary scientific results have been published by the collaboration.

The How

As many of the strongest and most important broad lines in AGN spectra are located in the ultraviolet domain, space-based observations are critical for understanding the BLR. Therefore, the initial focus of the AGN Watch efforts was UV spectroscopy using the International Ultraviolet Explorer (IUE) and, later, the Hubble Space Telescope (HST). However, concurrent observations of the optical lines and continuum are essential for a complete description of AGN behaviour, and therefore each of the AGN Watch campaigns was organised to ensure that adequate data would be obtained at both ground-based and space-based observatories.

3.1 First experience, the NGC 5548 campaign

The first AGN Watch project was an eight-month monitoring campaign (AGN Watch campaign I) on the Seyfert 1 galaxy NGC 5548. IUE observations were made once every four days between December 14, 1988 and August 7, 1989, for a total of 60 epochs.

Ground-based observations were collected with various telescopes in the northern hemisphere during this entire period, and the ground-based component of this programme is in fact still continuing. The success of this original programme (see Peterson, 1993, for a detailed summary) led to a similar programme of NGC 3783 (AGN Watch II, described below), and to a follow-up programme on NGC 5548 (AGN Watch III) using both IUE and HST to obtain ultraviolet spectra at a higher rate than in the original programme, once every two days with IUE between March 16 and May 27, 1993; during the second half of this campaign, HST spectra were obtained with an even higher frequency, once per day. Detailed results of the campaigns on NGC 5548 can be found in Clavel et al. (1991), Peterson et al. (1991), Korista et al. (1995) and references therein. The main conclusions reached are as follows:

1. The ultraviolet and optical continua vary with little, if any, phase difference between them. The continuum becomes bluer as it becomes brighter and the shorter-wavelength continuum bands show sharper variations.
2. The variations of the highest ionisation lines (He II, NV) lag behind the variations of the ultraviolet continuum by slightly less than 2 days, implying an inner radius of somewhat less than 2 light-days for the BLR. Its outer radius, from the CIII] and Balmer lines, is somewhat larger than 20 light-days.
3. There are some indications that the higher radial-velocity gas (line wings) responds more rapidly than the lower radial-velocity gas (line core), suggesting a virialised BLR cloud system.

3.2 Where ESO comes on the stage, the NGC 3783 campaign

In order to improve our understanding of the size and structure of the BLR and to test the generality of the NGC 5548 results, it was deemed to be desirable to carry out similar programmes on other AGN in order to map the AGN luminosity vs. BLR size plane.

Therefore, two other targets with different absolute luminosities were selected, NGC 3783 (AGN Watch II) and Fairall 9 (AGN Watch IV), both observable from the southern hemisphere. These AGN Watch campaigns relied heavily on ESO telescopes for the ground-based component.

The AGN Watch campaign II was set up to monitor NGC 3783 with IUE for 69 epochs from December 21, 1991 to July 29, 1992, once every 4 days for the first 172 days and once every 2 days for the final 50 days. Simultaneous optical and near-infrared observations were collected from ESO and CTIO (Chile), CASLEO (Argentina), Lowell Observatory (USA), Vainu Bappu Observatory (India) and SAAO (South Africa). The ground-based campaign started on December 3, 1991 and was completed on August 9, 1992.

An application for the ESO observing programme was submitted through the normal Observing Programmes Committee (OPC) channel, with special requirements regarding the dates to be scheduled and the time-slot to be allocated to the programme, i.e., once every 4 nights (concurrent with the IUE observations), 2 hours of time placed such that NGC 3783 would be at its meridian transit (in order to minimise the air mass).

The project was recommended by the OPC and carefully scheduled by ESO on the 1.5-m telescope. All PIs of other regular successful 1.5-m telescope proposals were informed in advance by ESO about these two-hour blocks of time and were required to schedule their own observations around this interruption. A detailed handbook had been prepared for the AGN Watch observations, describing briefly the purpose of the observations, the experimental conditions to be strictly followed, and providing information for all the necessary contact persons. A group of ESO postdocs, students, and cooperants present at La Silla over this period of time was organised under the responsibility of Dr. B. Altieri to actually take care of the AGN Watch observations. Dr. B. Altieri was also in charge of collecting and reducing all the AGN Watch data on-line in order to ensure that the programme was being carried out as designed and was producing useful data.

This organisation turned out to be extremely satisfactory and efficient. The ESO staff was found to be very cooperative, which was certainly one of the primary reasons for the success of the campaign. The observers of regular proposals had to deal with some interruption of their own programmes and consult with the ESO AGN Watch team with regard to details of the programme in order to carry out both the PI and AGN Watch programmes as efficiently as possible. We are pleased to report that we found a highly cooperative spirit among the regular observers. Altogether, the experience has been quite positive in our relations with the ESO staff and the European astronomical community. We owe them many thanks and certainly some part of the credit for the success of the campaign.

After reduction, the ESO data were then merged with similar data sets collected at other ground-based facilities (Fig. 1). There was in particular a very close collaboration with CTIO, as researchers in charge of the AGN Watch at both sites were in continuing contact.

The NGC 3783 campaign was also distinguished from the AGN Watch campaign I by two important features:

1. The availability of HST allowed us to obtain a high-resolution, high signal-to-noise ultraviolet spectrum that proved to be crucial in disentangling features in the IUE data by using the HST spectrum as a model.

2. Under the auspices of the "World Astronomy Days", sponsored by ESA in the context of the International Space Year, it was possible to arrange a nearly simultaneous multi-wavelength snapshot of NGC 3783 which included observations from GRO, ROSAT, Voyager, IUE, HST, optical and infrared ground-based telescopes, and the VLA. These data were also essential to a better understanding of the continuum source in NGC 3783 and complemented the AGN Watch data set.

The results of AGN Watch campaign II are described in detail by Reichert et al. (1994), Stirpe et al. (1994), and Alloin et al. (1995). We note here the salient conclusions:

1. As in the case of NGC 5548, significant variations were detected, both in the continuum and in the emission-line fluxes. We observe in NGC 3783, however, rapid fluctuations of relatively higher amplitude than in NGC 5548, while the longer-term modulations appear to be comparatively less well defined.

2. The continuum fluxes appear to vary simultaneously in all four measured ultraviolet/optical bands. The slope of the ultraviolet continuum is found to vary in the sense that the fractional amplitude of the continuum variations decreases with increasing wavelength.

3. Cross-correlation analysis indicates strikingly short time delays for most of the strong emission lines. The peaks of the cross-correlation functions occur at lags of 0 ± 3 days for He II+OIII], 4 ± 2 days for Lyα and CIV, 8 ± 3 days for Hβ, and 8–30 days for Si III] and CIII].

4. The continuous emission of the genuine AGN in NGC 3783 appears to be rather flat from soft γ-ray to infrared wavelengths with index $\alpha \approx 1$. The ultraviolet and near-infrared excesses can be understood in terms of thermal emission from an accretion-disk surface and a hot dust component, respectively.

3.3 A high luminosity object, the Fairall 9 campaign

AGN Watch campaign IV was devoted to an AGN of much larger absolute luminosity, Fairall 9, which was already known to exhibit long-term large-amplitude variability (Clavel et al., 1989). In the ultraviolet, this object was observed with IUE once every 4 days from April 30 to December 26, 1994. Because Fairall 9 is a southern source, again the 1.5-m ESO telescope played a key role in the ground-based effort. Again the standard procedure of time application through the OPC channel was followed, without calling for a key project. Time was granted to the campaign, 2.5 hours once every 4 days from May 2 to September 27,1994 but with two consecutive epochs missing due to a large block of time scheduled with an instrument which was not suitable for our project. Again, the ESO schedule matched as well as possible the IUE observation times, with special care being taken to maintain the regular sampling that is desirable in these monitoring programmes. The AGN Watch observations were scheduled even when the telescope was otherwise idle, and we greatly benefitted from this high level of cooperation by ESO.

The on-site organisation of the campaign was roughly similar to that set up for AGN Watch II, with Dr. C. Mendes de Oliveira and Dr. E.Chatzichristou being successively responsible for the interaction with PIs of the regular proposals scheduled on the 1.5-m telescope at every AGN Watch epoch, and for the data collection. Again, the campaign went on smoothly as the ESO staff and most of the regular observers were extremely cooperative and helpful.

Data from the ground-based campaign, from all participating observatories, are now being reduced and will be compared soon to the ultraviolet continuum and emission-line light-curves. Preliminary results from the IUE campaign show that Fairall 9 did vary significantly and that high frequency variations are superimposed on the longer-term trend.

4. Conclusions

Although the observational effort demanded in such campaigns is quite large, the AGN community is convinced that the scientific returns are sufficiently important that such campaigns are worth the trouble. Through these large-scale coordinated efforts, we have been able to acquire data sets of high quality and reasonable homogeneity which are suitable for further statistical analysis. The AGN Watch data sets are available to the entire community, and there is no doubt that they will be used by many more astronomers in the future.

The AGN Watch campaigns have demonstrated that there is no delay, to the accuracy measurable so far, between the ultraviolet and optical continua. This result rather argues in favour of reprocessing models and seems to rule out simple, geometrically thin, optically thick accretion-disk models for AGN. In at least three AGN, it has been confirmed that the size of the BLR is an order of magnitude smaller than predicted on the basis of the standard photoionisation equilibrium models of AGN. In NGC 3783, it is found that the BLR extends from about 1 to 2 light-days upwards to around 30 light-days, and is radially structured with the highly ionised material closest to the centre.

Carrying on such large campaigns requires good will, excellent organisation and communication among the astronomers involved in the pilot group, and a broad consensus in the community on the importance of the project. We have been fortunate in benefitting from the interest, encouragement, and support of the staff of various observatories at which these observations have been made. In addition to the tangible scientific return from these programmes, we believe that the large-scale international collaborations in the AGN field have greatly enhanced the mutual interactions of the astronomers involved in the project, have led to a *much more efficient use of telescope* time, and have resulted in a better coordination of programmes, thus leading to faster and unquestionable progress in our understanding of the AGN phenomenon.

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On the Variability of Narrow-Line Seyfert 1 Galaxies

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1. Introduction

Narrow-line Seyfert 1 (NLS1) galaxies are characterised by the relatively low projected velocities of their line-emitting nuclear gas. We describe a spectroscopic programme based on a search for variability, which attempts to constrain the causes of their difference with respect to other Seyfert 1 galaxies.

Active galaxies which are classified as Seyferts (characterised by a luminous nucleus of stellar appearance, with a non-stellar blue continuum and strong emission lines) are divided into two categories according to the widths of their lines: in Seyfert 2 galaxies, forbidden and permitted lines all have the same width (~ 1000 km s^{-1}), while in Seyfert 1 galaxies the permitted lines have an additional component of much greater width (~ 10^4 km s^{-1}). The difference is attributed to the presence of both a broad line region (BLR) and a narrow line region (NLR) in the nuclei of Seyfert 1's, while only the latter is present, or visible, in Seyfert 2's. The BLR is characterised by higher densities, higher velocities of the gas which forms it, and by a smaller size than the NLR: in fact, BLRs are so compact ($\ll$ 1 pc) that even in the closest active galactic nuclei (AGN) they cannot be resolved spatially. The large velocities present in the BLR are generally attributed to the gravitational effects of a massive ($>10^7$ $M_\odot$) accreting black hole, which is the prime cause of the nuclear activity.

The distinction between type 1 and type 2 Seyferts is by no means clearcut. Spectropolarimetry (e.g. Antonucci & Miller, 1985) has revealed that several (though not necessarily all) Seyfert 2's contain BLRs which are hidden to conventional spectroscopy by obscuring material (possibly a dust torus). This has sparked a debate on the possibility that all Seyferts may be described within a unified model, in which the orientation of the nuclear axis determines the aspect of a source's spectrum, and therefore its classification. Within this framework, Seyfert 2 nuclei are viewed at large inclination angles, and Seyfert 1's at medium and small ones.

1.1 What is a narrow-line Seyfert 1 galaxy?

The broad components of Seyfert 1's display a great variety of profiles and widths (e.g. Osterbrock & Shuder, 1982, Stirpe, 1990), and it is tempting to explain it on the basis of projection effects. In particular, the so-called 'narrow-line Seyfert 1 galaxies' (Osterbrock & Pogge, 1985) are at the lower end of the broad line width distribution in the Seyfert 1 class. While they are clearly distinct from Seyfert 2's because of the different widths of permitted and forbidden lines, and because of the presence of Fe II lines (which are not emitted by the NLR and are therefore absent in Seyfert 2 spectra), the width of their broad components is barely larger than that of the forbidden lines[1] (FWHM $\leq$ 1000 km s^{-1}). Studies of NLS1s have shown that the broad components of the lines have ratios similar to those of 'normal' Seyfert 1's and, on average, lower equivalent widths (Osterbrock & Pogge, 1985, Goodrich, 1989); this last property, however, is the extension to low FWHM of a trend observed throughout the Seyfert 1 population. Some NLS1 galaxies present in their spectra high ionisation iron lines like [FeVII] λ5721, λ6087 and [Fe X] λ6375 (Osterbrock, 1985, Osterbrock & Pogge, 1985), in some cases with high intensity: these are properties common in Seyfert 1 galaxies, but quite rare in Seyfert 2's. NLS1s comprise approximately 10% of optically selected Seyfert 1's, but a significantly higher percentage ~ 16–50%) of soft X-ray selected Seyfert 1 samples (Stephens, 1989, Puchnarewicz et al., 1992). Boller et al. (1995) report the observation with ROSAT of a sample of NLS1s, finding that the objects in this class have generally steeper soft X-ray continuum slopes than normal Seyfert 1's, and rapid soft X-ray variability.

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[1] It is important to realise that we are referring to objects whose maximum observed velocities from the BLR are low, not to objects in which the broad component of the emission lines is very weak compared to the narrow component, but also very broad: the FWHM of the permitted line (broad + narrow component) can be similar in objects of these two types, and sometimes a low signal-to-noise ratio in a spectrum can mask a weak but very broad component, and cause an object to be misclassified.