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THE INTERNATIONAL AGN WATCH: A MULTIWAVELENGTH MONITORING CONSORTIUM

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Abstract. The International AGN Watch, an informal consortium of over 100 astronomers, was established to coordinate multiwavelength monitoring of a limited number of active galactic nuclei and thus obtain comprehensive continuum and emission-line variability data with unprecedented temporal and wavelength coverage. In this review, we summarize the principal scientific results from two completed space-based and ground-based campaigns on the Seyfert galaxies NGC 5548 and NGC 3783. We describe a project in progress and outline our future plans.

Key words: Active galactic nuclei, spectroscopy, variability, multiwavelength observations.

1. Introduction

With the launch of the *International Ultraviolet Explorer (IUE)* in 1978, it became possible to observe the strong emission lines in the spectra of relatively low-redshift active galactic nuclei (AGNs) at resolution and signal-to-noise ratios comparable to what could be obtained in the optical spectrum from the ground. At about the same time, with the proliferation of high-quality detectors, AGN spectroscopy ceased to be the sole province of 4-m class telescopes. These two developments resulted in tremendous growth of the field of AGN spectroscopy during the last decade.

One of the notable results of this growth was the realization that continuum and emission-line variability is very common in AGNs. It was widely recognized that variability affords a potentially valuable probe of both the continuum source and the broad-line region (BLR) in these sources. For example, by examining the broad-line response to the variable continuum that drives the line emission, it is possible to determine both the structure and kinematics of the BLR (e.g., Blandford & McKee 1982). A number of groups undertook ultraviolet and optical monitoring programs in an effort to use variability to probe the physics of active nuclei. While these programs were valuable in defining the basic characteristics of AGN variability (see Peterson 1988 for a review of these early efforts), they were unable to resolve most of the key questions that could be addressed with such

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studies, primarily because of limited temporal sampling. Space-based observing time is always at a premium, and so it was virtually impossible for a small group of astronomers to obtain a sufficient number of observations to carry out a completely successful monitoring project. Ground-based astronomers were frustrated not only by these difficulties, but by gaps in temporal coverage on account of unfavorable weather.

In 1987, workshops in Segovia and Atlanta featured lively discussion of results obtained in variability studies. Despite the uncertainty of the results, it had become apparent to the AGN community that the goals of spectroscopic monitoring programs could in fact be achieved if sufficient observing time could be devoted to them. It was also realized that suitable sampling could be achieved only by cooperation of observers on a scale that was unprecedented in extragalactic astronomy. The International AGN Watch was therefore established with the goal of focusing attention on a limited number of AGNs for intensive monitoring efforts. The role of the AGN Watch has been:

1. To define the scientific questions to be addressed, to conceive the observational projects, and to coordinate the submission of the appropriate observing proposals.
2. To ensure that data are collected in a manner consistent with the scientific goals.
3. To reduce the observational data, and to make these data sets available to the entire community.
4. To perform the necessary measurements and analysis of the data, and to publish the primary scientific results.

Detailed and model-dependent interpretations are left to the various individuals or sub-groups of the AGN Watch, as well as to all other interested parties.

In the following sections, we will summarize briefly the major results of the two AGN Watch programs that have been completed as of this time, describe an on-going program, and outline another program planned for late 1993.

2. The AGN Watch Campaign on NGC 5548: Mapping the BLR Structure

The first AGN Watch program was an eight-month monitoring campaign on the Seyfert 1 galaxy NGC 5548. The scientific goals of this program were (1) to measure the continuum–emission-line response times (or "lags") for all of the strong UV and optical emission lines, and (2) to compare the amplitude and phase of continuum variations at different wavelengths. A joint ESA/SERC/NASA *IUE* program was the cornerstone of this campaign, since the UV spectrum is critical to our understanding of the AGN phenomenon. Moreover, space-based observations afford the advantage of regular temporal sampling without interruptions on account of weather. A concurrent ground-based optical effort was also organized in order to enhance the scientific return of the project by providing contemporaneous data on the optical continuum and emission lines.

The *IUE* observations were made once every four days between 1988 December 14 and 1989 August 7 (60 epochs). Ground-based data were obtained between 1988 December 14 and 1989 October 10; the resulting optical data base consists of 246 spectra, 52 photometric observations, and numerous CCD images which have been contributed by observers on more than 20 telescopes around the world. The optical campaign has been sustained in order to investigate variability on longer time scales, and this program is currently in its fifth year.

The principal results of the program are presented by Clavel *et al.* (1991), Peterson *et al.* (1991, 1992), Maoz *et al.* (1993), and Dietrich *et al.* (1993), and have been summarized by Peterson (1993). The light curves for the continuum and strong emission lines are shown in Fig. 1. Three well-resolved continuum "events" were observed. The emission lines show the same variations as the continuum, but with a small lag which can be quantified by cross-correlation of the continuum and emission-line light curves; the continuum–emission-line cross correlation functions are also shown in Fig. 1. These results are summarized in Table I, which gives the location of the peaks of the cross-correlation functions obtained by cross-correlating the various light curves with the ultraviolet continuum light curve. From these data, several important conclusions can be reached:

1. There is no significant phase difference between the UV and optical continuum variations.
2. The UV continuum varies with greater amplitude than does the optical continuum, even after allowance is made for dilution of the optical continuum by starlight.
3. The emission-line lags are all quite small, and show a pattern of increasing lag with decreasing ionization level; i.e., the BLR shows radial ionization stratification.

The simultaneity of the UV/optical continuum variations is contrary to what is expected in thin accretion disk models, and the small emission-line lags indicate BLR sizes about an order of magnitude smaller than previously estimated on the basis of photoionization equilibrium calculations.

3. The Second AGN Watch Campaign: NGC 3783

Following the success of the NGC 5548 program, it was decided that a second program on another galaxy was desirable in order to test the generality of the NGC 5548 results, to expand the wavelength coverage, and to resolve questions that would require even higher temporal sampling than was achieved in the first program. A second program was carried out between 1991 December and 1992 August, again based on regularly spaced *IUE* observations, with concurrent ground-based support from a number of observatories. The results of this campaign are presented by Reichert *et al.* (1994) and Stirpe *et al.* (1994). The light curves and cross-correlation functions produced by this campaign are shown in Fig. 2, and the lags are given in Table I. Inspection of the light curves shows continuum behavior

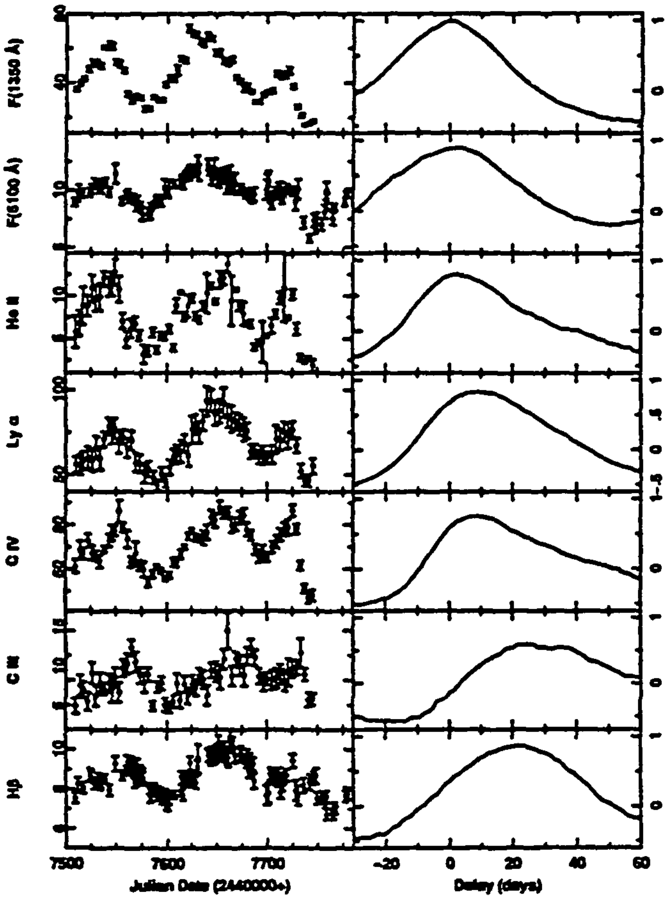

Fig. 1. The left column shows the light curves for the continuum and strong emission lines in NGC 5548 during the first AGN Watch campaign. The right column shows the cross-correlation functions produced by cross-correlating the light curve to the immediate left with the 1350 Å continuum light curve shown in the top panel (the top right panel is the continuum autocorrelation function).

that is different from what was observed in NGC 5548; considerable short time scale variability was seen in NGC 3783, in contrast to the well-resolved events seen in the first campaign. Nevertheless, the data are sufficient to obtain reasonable cross-correlation results. The lags measured in this case are also very short, close to the limit of our ability to resolve them from zero lag, at least in the case of the strong UV lines. The evidence for ionization stratification is weaker than in NGC 5548, but still compelling.

The NGC 3783 campaign was also distinguished from the first campaign by two important features: (1) the availability of *Hubble Space Telescope (HST)* allowed us to obtain a high resolution, high signal-to-noise UV spectrum that proved to be

TABLE I
Cross-Correlation Results

Feature	Lag (days) NGC 5548	NGC 3783
Optical continuum	2	0
N v λ1240	2	...
He II λ1640	2	1
"Small blue bump"	6	...
He II λ4686	7	...
Ly α λ1215	10	4
C IV λ1549	10	5
He I λ5876	11	...
Hγ λ4340	13	...
Hα λ6563	17	...
Hβ λ4861	20	8
C III] λ1909	25	9

crucial in disentangling features in the *IUE* data by using the *HST* spectrum as a model, and (2) under the auspices of the "World Astronomy Days" program, it was possible to arrange a nearly simultaneous multiwavelength snapshot of NGC 3783 which includes observations from *GRO*, *ROSAT*, *Voyager*, *IUE*, optical and IR ground-based telescopes, and the *VLA* (Alloin *et al.* 1994).

4. An On-Going AGN Watch Campaign: A More Intensive Study of NGC 5548

While the first two AGN Watch campaigns represent a significant step forward in AGN variability studies, there are still a number of key questions that remain unresolved, particularly regarding the shortest time scale variations. Among the most important outstanding questions are:

1. Is there a small, but measurable, phase difference between the UV and optical continuum variations? The first two programs indicate that the optical continuum variations follow those of the UV continuum by less than ~2 days, and it is important to determine whether indeed the variations in the different wavebands are truly simultaneous.
2. What is the velocity field of the BLR? The combination of the rapid response of the strong UV lines and the relatively low signal-to-noise ratio of the *IUE* data makes it difficult to use line profile variations to determine the velocity field of the BLR gas.

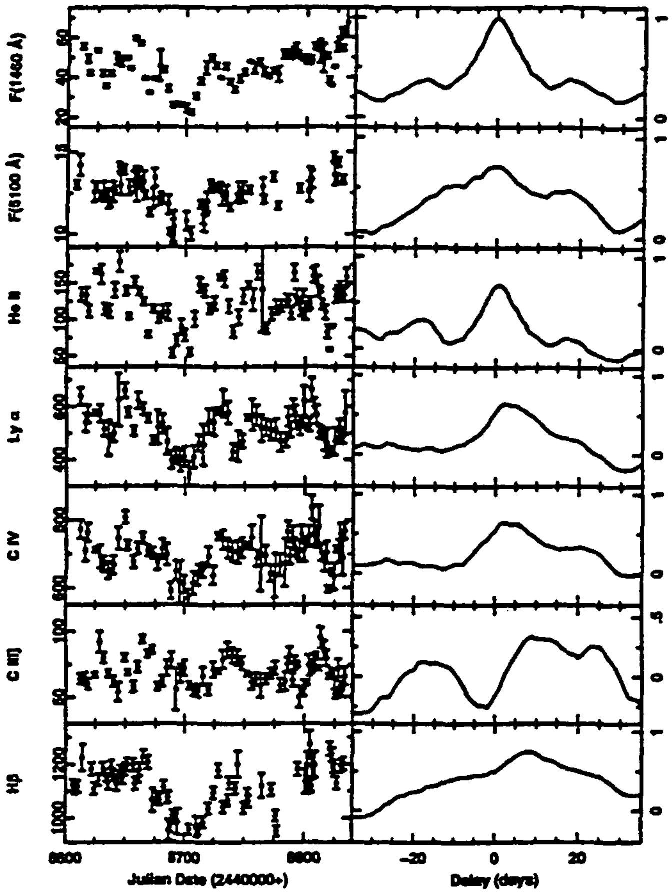

Fig. 2. The light curves and cross-correlation functions from the NGC 3783 campaign, in the same format as in Fig. 1.

3. What is the response time of the most rapidly varying high-ionization lines (such as He II λ1640 and N V λ1240)?

All of these questions require both higher signal-to-noise ratios and denser temporal sampling than had been achieved with *IUE* in the previous campaigns.

In order to address these important issues, a new program using both *IUE* and *HST* was initiated in 1993 March, and is in progress at the time of this conference. *IUE* observations are being made once every two days for a 72-day period, and beginning on 1993 April 19, FOS spectra are being obtained with *HST* once per day for 39 days. Preliminary analysis of the data available at the time of writing reveals that sufficient variability has occurred during the campaign that it should be possible to address each of the above questions; for example, quick-look analysis of the light curves gives a lag of around 1.5 days for He II λ1640, which is a considerable improvement on the 2 ± 2 day result found in the first campaign.

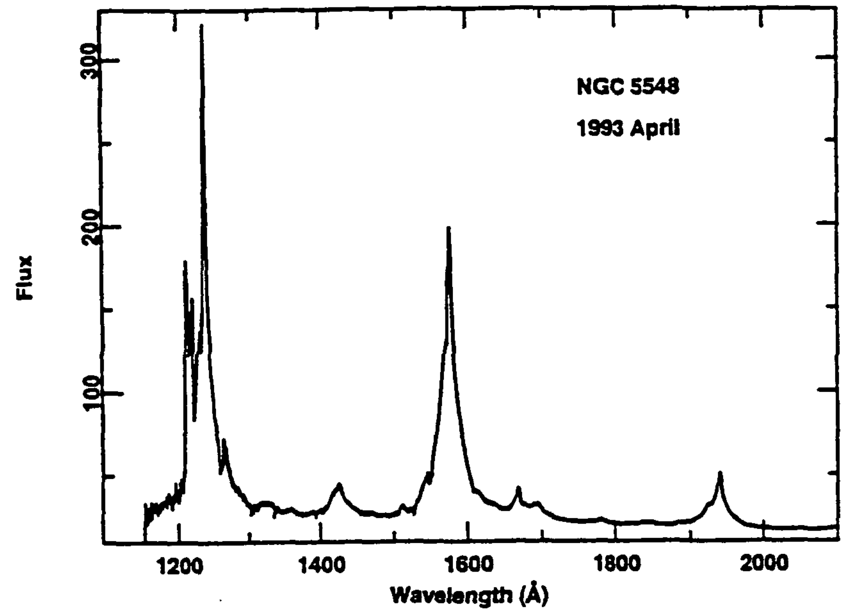

Fig. 3. Mean of the first 18 FOS spectra of NGC 5548 obtained during the 1993 monitoring campaign with *HST*.

The FOS spectra are of extremely high quality and will be useful in addressing problems beyond the planned program. The *summed* spectrum from all 39 observations will result in an AGN spectrum of unprecedented signal-to-noise ratio, as seen in Fig. 3. The summed spectrum reveals the presence of several weak emission lines, as well as many weak absorption features which arise both in the vicinity of the NGC 5548 nucleus and in the halo of our own Galaxy (although the Galactic reddening along the line of sight to NGC 5548 is negligible).

5. A Project in the Planning Phase: Continuous Monitoring of NGC 4151

NGC 4151 is one of the closest and brightest Seyfert 1 galaxies, and has been extensively studied with *IUE* (see Clavel *et al.* 1990, and references therein). The continuum and emission lines are known to vary on short time scales, which makes it an appropriate target for campaigns of limited total duration.

In 1993 December, the AGN Watch will carry out a very intensive multiwavelength monitoring program on NGC 4151. The heart of the campaign will be a 10-day period of continuous monitoring by *IUE*. In addition to the usual extensive ground-based coverage, frequent regular observations will be made by *ROSAT* and *GRO*. The scientific goals of this program are:

1. To measure any possible wavelength-dependent phase difference in the continuum variations.
2. To determine empirically the relationship between X-ray/γ-ray and UV/optical continuum variations, which are known to be at least weakly correlated, based on earlier multiwavelength coordinated observations.
3. To measure the instantaneous bolometric luminosity of the nucleus at various times and to determine how this is related to the emission in the various individual wavebands.
4. To examine the response of the UV emission lines to continuum variations in unprecedented detail, which will greatly improve constraints on the physical conditions of the gas in the immediate vicinity of the central engine.

Although the total duration of the campaign is very limited (less than one month), the intensive nature of this program will produce more data than any previous AGN Watch program.

6. Concluding Remarks

The International AGN Watch has demonstrated that large multiwavelength coordinated efforts are not only feasible, but can provide a high scientific return; the value of coordinated multiwavelength studies is far in excess of the sum of the individual parts. While there are significant sociological and operational barriers to managing large-scale projects which involve over 100 individuals who are geographically widely distributed, there are a number of clear advantages to this mode of operation as well: the range of scientific and technical expertise within the consortium is great, which has enabled us to deal successfully with most of the problems that have arisen, and the level of communication among the AGN Watch membership is extremely high, which has expanded the scientific interaction of many of the participants. Moreover, in addition to the immediate scientific return, coordinated efforts such as the AGN Watch produce multiwavelength archives that will be of great value long after the models which they were intended to address have been superseded.

Acknowledgments

The success of the International AGN Watch has been in large measure due to the support it has received from NASA, ESA, and SERC through the *IUE* and *HST* programs, as well as from the directors of many ground-based observatories and the agencies that fund their operation. We are grateful for the widespread enthusiasm shown for these demanding monitoring programs. We also wish to take this opportunity to acknowledge the significant role played by the observatory staffs at the Space Telescope Science Institute and at the *IUE* Observatories at Goddard and Vilspa, and in particular to thank the schedulers for the valiant efforts that have assured the success of these programs. We thank K.T. Korista and G.A. Kriss for providing the early results on the *HST* campaign.

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