Rapid Ultraviolet Variability in NGC 4151

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Abstract. The rapidly variable Seyfert 1 galaxy NGC 4151 was intensively monitored with IUE, ROSAT, CGRO, ASCA, and ground-based telescopes during the period UT 1993 December 0 – 10. This contribution focuses on the continuous IUE monitoring, in which the light curve was sampled an order of magnitude more frequently than in any previous Seyfert 1 campaign. The ultraviolet continuum shows significant variations down to the shortest time scales sampled (a few hours), and an overall peak-to-peak variation of ~35% over the 9.3-day campaign.
The fastest ultraviolet variations occur in the shortest wavebands. The long (e.g., at 2700 Å) and short wavelength (e.g., 1350 Å) continuum light curves exhibit similar general long-term behavior, but they also have clear differences on short time scales. It appears possible that the 2700 Å light curve could be derived from the 1350 Å light curve by convolving it with a transfer function that smooths and delays it on time scales of order hours to tens of hours. This behavior is very different from that seen in previous campaigns on both this and other Seyfert 1s, in which the long and short wavelength light curves were very similar (over longer time scales). Comparison with the preliminary ROSAT light curve (which has much poorer sampling) suggest that the X-ray variations may appear more closely related to those at 2700 Å than at 1350 Å.

The results appear to be consistent with the ultraviolet continuum arising in a thermal accretion-disk in which the long-wavelength emission is produced by reprocessing of shorter wavelength photons. They are also consistent with the hypothesis that the ultraviolet is produced by reprocessing of the hard X-ray continuum. However, both models have problems with the details, which may or may not be resolved by further analysis, and other interpretations are certainly possible at this early stage.

1. Introduction

Because active galactic nuclei (AGN) are too distant to resolve from Earth, we must rely on variability to provide information about their central environs. In recent years, intensive monitoring with the International Ultraviolet Explorer (IUE) has helped clarify our understanding of the structure of the active nucleus. For instance, monitoring of the BL Lac object PKS 2155–304 every 96 min for 4 days (with some gaps), revealed significant variations on time scales as short as a few hours, much more rapid than previously measured (Urry et al. 1993). The ultraviolet and optical light curves tracked almost identically, with cross-correlation analysis revealing no evidence for a lag between 1400 Å and 5000 Å variations. The simultaneous ROSAT light curve (Brinkmann et al. 1994) was also very similar, except that the variations were shifted by a significant amount (∼2 – 3 hr), in the sense that the X-ray variations occurred earlier (Edelson et al. 1994a). The ultraviolet/X-ray lag means that the X-ray photons are not due to synchrotron self-Compton scattering from the ultraviolet, since the X-rays would then be expected to lag or track the ultraviolet, while the lack of a ∼1 day lag between 1400 Å and 5000 Å poses severe problems for the tapered jet model.

In the case of the Seyfert 1 galaxies NGC 5548 (Clavel et al. 1991) and NGC 3783 (Reichert et al. 1994), which were observed only once every 4 days for eight months, the line variations were found to lag closely behind those of the continuum, with generally smaller lags for higher-ionization lines. The good correlation between lines and continuum is generally taken as evidence in support of the standard model in which the gas in the broad-line region (BLR) is heated and photoionized by a central continuum source. It has led to strong constraints
RAPID UV VARIABILITY IN NGC 4151

on the size of the BLR (e.g., it now appears that most of the C iv-emitting gas is located within ~20 lt-day of the center for NGC 5548). The shorter lags for high-ionization lines (such as He ii) suggests that the BLR is not homogeneous but "stratified," with the higher-ionization lines being produced closer to the center than the lower-ionization lines. In fact, the high-ionization lines had such small lags that they could not be measured with the 4-day resolution of the earlier experiments.

An important and unexpected result of the Seyfert 1 monitoring programs was that the ultraviolet and optical continuum variations track closely with no detectable delay (Δt < 4 days). In the standard thermal accretion-disk model, this implied that high radial signal speeds (≥ 0.1c) coordinate the different regions of the disk (Krolik et al. 1991). One possible explanation is that the longer-wavelength emission is due to reprocessing by cooler, outer material of shorter wavelength photons created closer in (Courvoisier & Clavel 1991; Collin-Souffrin 1991), but a rigorous test of this idea requires an order-of-magnitude improvement in sampling, which would allow hypothesized signal propagation in excess of c to be probed.

In order to obtain light curves with sufficient time resolution to measure lags in the rapidly responding continuum and high-ionization lines, a large, multinational group of observers (the International AGN Watch consortium) made intensive observations of the bright, rapidly variable Seyfert 1 galaxy NGC 4151 with IUE, along with ROSAT, ASCA, CGRO, and ground-based optical telescopes. The goals of the experiment were (a) to measure the lag between short and long-wavelength ultraviolet continuum variations, and thus make a critical test of accretion-disk models, (b) to measure the temporal correlation and lag between continuum wavebands and the broad-band spectral energy distribution, in order to determine the relationship between components emitting in different bandpasses, and (c) to make detailed measurements of the transfer function of the most rapidly responding emission lines, greatly improving the constraints on the distribution of the innermost broad-line gas.

As of the time of this contribution, the IUE continuum data have been almost fully reduced, and a preliminary ROSAT PSPC light curve has also been derived. Therefore, this contribution will focus on the correlation between ultraviolet continuum bands, and in addition their relation to the X-rays. The observations, data and reduction techniques are discussed in the next section, and the light curves presented in §3. These preliminary results are briefly interpreted in §4, and the results are summarized and the requirements and prospects for future continuum monitoring experiments discussed in §5.

2. Observations and Data

2.1. NGC 4151

If one could point to an "archetypal" Seyfert 1 galaxy (and one could argue that there is no such thing), it would almost certainly be NGC 4151. Probably the most "Seyfert-like" of the six peculiar galaxies in Seyfert's (1943) original sample, it exhibits a very bright nucleus, very broad emission lines, rapid variability, and has a very low redshift that makes it relatively easy to study. It is generally either the brightest or one of the brightest AGN in the sky at optical
and all higher frequencies \((V \approx 11)\). Approximately 10% of all AGN papers in *The Astrophysical Journal* include data on NGC 4151. Because it is so bright and strongly variable, it was the obvious choice for this campaign.

Previous *IUE* observations, sampled every 1–4 days, showed continuum variations with doubling times as short as a week or less (e.g., Clavel et al. 1990). Its spectrum shows broad emission lines \((\sim 30,000 \text{ km s}^{-1} \text{ FWZI for C IV})\), several broad \((1000 \text{ km s}^{-1})\), blueshifted \((-820 \pm 100 \text{ km s}^{-1})\), and rapidly variable absorption lines that arise in ions of widely different stages (Bromage et al. 1985), and two unidentified emission lines, known as L1 \(\lambda 1518\) and L2 \(\lambda 1594\), that bracket C IV (Ulrich et al. 1985; Penton, Shull, & Edelson 1994). It also exhibits a complex X-ray spectrum that can be characterized as a power-law continuum modified by a warm or partial absorber, which sometimes extends out to 1 MeV (e.g., Baitz et al. 1984) but at other times turns over at \(\sim 50\text{ keV}\) (Jourdain et al. 1992). It has an additional, apparently non-varying soft X-ray excess (e.g., Yaqoob et al. 1989), which shows up as an extended source in Einstein HRI observations (Elvis, Briel, & Henry 1983).

### 2.2. Observations

*IUE* was used to observe NGC 4151 for a continuous 9.3-day period during UT 1993 December 0 – 10. Because the source was near its historical maximum brightness during the experiment, optimally exposed short and long-wavelength spectra required only \(\sim 10\) and \(\sim 20\) min, respectively. In addition, snapshot spectra were obtained once every day for the 4 days before the intensive period and the 6 days afterwards. This allowed observations in cycles of 80 min per pair of spectra. After accounting for interruptions due to Earth occultations, a total of \(\sim 200\) pairs of spectra were obtained.

Other observatories also observed NGC 4151 during the intensive period, but scheduling constraints and satellite and weather problems meant that the coordination was not always perfect. *ROSAT* observed NGC 4151 approximately once every 12 hours during UT 0.0 – 5.5 December, and again on 9.5 December, but missed the part in between due to gyro problems. Satellite problems also limited *ASCA* to 4 observations on about UT 4.5, 6.0, 7.5 and 10.0 December. The OSSE instrument aboard *CGRO* observed NGC 4151 continuously during the period 2 – 13 December.

### 2.3. IUE Data Reduction

We took great pains to extract the spectra and measure fluxes to produce the highest signal-to-noise ratios obtainable, in order to be able to measure weak features and small variations. The first step was to create a 1-d spectrum using the spectral extraction package TOMSIPS. The procedure applies a novel photometric correction to the raw data frame, and then performs a direct piece-wise “Optimal” extraction (Ayres 1993). The absolute calibration was by reference to the hot white dwarf G191–B2B. The approach is similar to that adopted in NEWSIPS, although the details differ considerably. The resulting spectra are clearly superior to Optimal/SWET or IUESIPS extractions, and comparable to or better than NEWSIPS (see Fig. 1).

The next step was to measure continuum (and line) fluxes, using the pipeline developed at Colorado for the IUEAGN database project. We summa-
Figure 1. SWP 49557, a spectrum from the recent NGC 4151 campaign, reduced by IUESIPS (top), Optimal/SWET (middle), and TOMSIPS (bottom). Note the improvement in the signal-to-noise ratio in the TOMSIPS version; in particular, the improved visibility of the He$\,\text{II}\lambda 1640$ line.
uum fluxes over \( \sim 30 \) Å wide bands centered at 1290 Å, 1350 Å, 1730 Å, 1820 Å, 2700 Å, and 2950 Å. We obtained error levels of \( \sim 1.5\% \), which, as shown in Figs. 2 – 4, are quite repeatable and believable. Line fluxes were measured by fitting multiple Gaussians, and result in somewhat higher error levels (\( \sim 5\% \)). A more detailed description of the data reduction will be given in Crenshaw et al. (1994).

2.4. ROSAT Data

Because, as mentioned earlier, the soft X-ray emission from NGC 4151 is dominated by an extended, non-varying component, it probably has nothing to do with variations measured in this campaign. Therefore, the X-ray light curve is restricted to energies above 1 keV. This should provide a good measure of the level of the variable X-ray continuum in NGC 4151 on time scales shorter than a few weeks.

The ROSAT data presented herein are only preliminary, so a detailed description of the data reduction will not be provided in this paper. Instead, the interested reader should refer to the paper by Warwick et al. (1994), which will give full details of the ROSAT, ASCA, and CGRO observations and data reduction.

3. Results

3.1. Overall Properties of the Ultraviolet Light Curves

The derived light curves are shown in Figs. 2 – 5. The source is clearly variable, with 3 or 4 clear 10 – 20% flux variations in a single day, visible in all bands. Because of the good sampling and high signal-to-noise ratios of the data, small, rapid variations (microvariability) can be seen down to time scales of hours, the shortest times sampled in this experiment. For instance, the 1350 Å flux increased by \( \geq 10\% \) in \( \sim 6 \) hr on 3 December. Although a rigorous comparison requires derivation of the fluctuation power-density spectra, which has not yet been done for these data (but will be in Edelson et al. 1994b), it is already clear that these variations are faster than any seen before in a Seyfert 1 galaxy. For example, the fastest significant change in the first NGC 5548 campaign occurred over time scales of many days or even weeks (Clavel et al. 1991).

3.2. Degree of Variation vs. Wavelength

Table 1 shows the mean flux (in mJy, except in the case of the X-ray data, which at this time are still only on a relative flux scale), average error level (in percent) and normalized variability amplitude (NVA) in each of the measured continuum bands. (The 2950 Å band was not included because of possible problems remaining in the data reduction.) The NVA is defined as the ratio of the rms variability and the mean flux in that band, so it gives a measure of the fractional variability (expressed here as a percentage) that is independent of the flux level or number of data observations. No correction was made for measurement errors, but as long as the NVA is much larger than the mean error, this is not a problem.

Table 1 shows a clear trend, in the sense that the shortest wavelengths show the strongest variations. Put another way, the spectra tend to get harder as the source becomes brighter. Previous long-term monitoring and archival studies
Figure 2. Ultraviolet light curve of NGC 4151, measured at 1350 Å. Error bars of 1 – 2% allow detection of variations on time scales as short as a few hours.
Figure 3. Ultraviolet light curve of NGC 4151, measured at 1820 Å, as in Fig. 2.

Figure 4. Ultraviolet light curve of NGC 4151, measured at 2700 Å, as in Fig. 2.
RAPID UV VARIABILITY IN NGC 4151

NGC 4151

Figure 5. *ROSAT* X-ray light curve measured at \(\sim 10\ \text{Å}\). Flux scale is arbitrary. Compare to Figs. 2 – 4.

show similar behavior for a wide variety of Seyfert 1s (e.g., Edelson, Krolik, & Pike 1991). The fact that the short wavelengths are more strongly variable is consistent with the ultraviolet continuum being made up of two components: a hard, strongly variable component (due, perhaps, to the putative accretion disk) and a softer, less-strongly variable one.

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>Mean Flux (mJy)</th>
<th>Mean Error (%)</th>
<th>NVA (%)</th>
</tr>
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<tbody>
<tr>
<td>10</td>
<td>–</td>
<td>5.1</td>
<td>20.0</td>
</tr>
<tr>
<td>1290</td>
<td>43.9</td>
<td>1.1</td>
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</tr>
<tr>
<td>1350</td>
<td>41.8</td>
<td>0.7</td>
<td>7.7</td>
</tr>
<tr>
<td>1730</td>
<td>30.1</td>
<td>1.4</td>
<td>6.4</td>
</tr>
<tr>
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<td>28.9</td>
<td>1.3</td>
<td>5.1</td>
</tr>
<tr>
<td>2700</td>
<td>17.8</td>
<td>0.8</td>
<td>4.5</td>
</tr>
</tbody>
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3.3. Differences Between Short and Long Ultraviolet Wavelength Light Curves

Perhaps the most unexpected and exciting result is the clear difference in appearance between the long and short-wavelength light curves. Although they

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have overall long-term similarities, the 2700 Å light curve shows less short time-scale structure than at 1350 Å. It appears to the eye that the 2700 Å light curve could result from convolution of the 1350 Å light curve with a transfer function which smoothes and delays it by time scales of order hours to tens of hours. It is possible that some of this effect could arise because the smaller variability and lower signal-to-noise ratio of the long-wavelength data makes them less sensitive to small, rapid variations, but it is unlikely to all be due to this. However, a detailed measurement of the transfer function has not been done, and until it is (Edelson et al. 1994b), this conclusion must be regarded as preliminary. Another difference is that the two light curves appear to diverge towards the end of the intensive monitoring period, with the 1350 Å light curve dipping back down to levels seen at the beginning of the period, while the 2700 Å light curve remained at a higher level.

3.4. Comparison with Previous Observations

Previous, coarser-resolution monitoring of NGC 5548 (Clavel et al. 1991) and NGC 3783 (Reichert et al. 1994) showed no significant differences in the shape of the long and short-wavelength light curves, although the long-wavelength variations always are of smaller amplitude. Our analysis of the many archived 1–2 month monitoring campaigns on NGC 4151, which typically sampled every 1–4 days, also showed no differences in the shape of the short and long-wavelength light curves.

Why, then, do the long and short-wavelength light curves look so different in this experiment? It is unlikely to be due to the higher signal-to-noise ratio and variability levels in the short-wavelength data, since this would affect both the high and low time-resolution data similarly. Likewise, it is unlikely to be due to contamination of the long-wavelength data by a broad pseudo-continuum of FeII emission, since FeII is weak in the spectrum of NGC 4151. Instead, it probably means something about the emission mechanism, as discussed in §4.

3.5. Comparison of X-Ray and Ultraviolet Light Curves

The X-ray light curve in Fig. 5 has much poorer sampling than do the ultraviolet light curves. It appears that the X-rays begin low, then rise at around 3 December, and then level off, although this may be an illusion caused by the gap during 6–9 December. As such, the X-ray data may appear to correspond more closely to the long-wavelength light curve, but the poor sampling of the X-rays compared to the ultraviolet makes it very difficult to reach any firm conclusions. In any event, the X-rays show larger amplitude variations than the ultraviolet (NVA = 20 % in the X-rays, compared with ~8% at 1350 Å).

3.6. Summary of Observational Results

This project has produced three important observational results thus far:

1. The ultraviolet flux of NGC 4151 can change very rapidly, with significant variations on time scales as short as a few hours.

2. Although the overall shape of the ultraviolet light curves are generally similar, the short wavelengths show more rapid variations than the long wavelengths, and the light curves also diverge at the end of the campaign.
3. The X-ray light curve appears similar but not identical to the ultraviolet light curves, and may be more like the long than short-wavelength light curve, but poor sampling prevents any clear comparison.

4. Discussion

4.1. The Blue Bump

The origin of the excess ultraviolet emission seen from most AGN (the "blue bump") is not clear. The two most popular explanations (which could be related) of this emission are that it is: (1) thermal emission from an accretion disk around a black hole (the "intrinsic" model); (2) reprocessed emission from a disk or other structure that is illuminated by a hard X-ray source (e.g., Clavel et al. 1992). The ultraviolet/X-ray variability data reported herein can be used to compare, test and constrain these models.

4.2. The Intrinsic Accretion-Disk Model

In what we will consider to be the "intrinsic" accretion-disk model, the central black hole is surrounded by a optically thick, geometrically thin disk of material flowing inward. The system is powered by the release of gravitational potential energy of the infalling material. The innermost material moves the fastest, and because of viscosity, such a system will naturally develop a temperature structure which is hottest near the center.

The temperature structure is relatively model independent, and in the case of NGC 4151, most of the 1350 Å emission would be expected to arise from a ring a few light hours in radius, and most of 2700 Å emission would come from about twice that distance. The time scale for a disturbance in the disk to propagate from the 1350 Å emitting region to the 2700 Å region is quite long (days to months) if the process is dominated by viscous or dynamical time scales. As with NGC 5548 (Krolik et al. 1991), the strong overall correspondence on time scales of days between the 1350 Å and 2700 Å light curves can pretty much rule out this model, because it would predict that they would by very different.

Instead, because the 1350 Å and 2700 Å emitting regions are only light hours apart, and the transfer function has a width of hours as well, one is forced to conclude that the signal must propagate through the putative disk at near the speed of light. (A quantitative estimate will be given in Edelson et al. 1994b). While this does not rule out the accretion-disk model, these data clearly require rethinking of the energy transport mechanism and allow strong, previously unavailable constraints on its structure.

4.3. Producing the Ultraviolet by Reprocessing the X-Rays

An alternative idea that has recently gained a great deal of currency is the reprocessing model of Clavel et al. (1992). (See also Nandra, this volume, for a good discussion of this model.) In this picture, the primary power source of the entire system is an X-ray continuum source that illuminates a body of gas (which may or may not be an accretion disk), as well as being visible directly to us because it lies above the emitting gas. The blue bump, as well as the hard X-ray tail and iron fluorescence line, arises because the primary X-ray emission
is absorbed and reprocessed by the gas and re-emitted as "secondary" emission at other wavelengths. (Hence, calling the hard X-ray excess a "reflection tail" is a bit of a misnomer.)

This model predicts a strong correlation between the ultraviolet and X-ray light curves, and the good observed overall correlation certainly supports this model. Beyond that, it may have a problem with the lack of any apparent delay between the X-rays and the ultraviolet. Indeed, it would be difficult to understand how the X-rays could appear to be more closely related to the 2700 Å light curve than the 1350 Å light curve, since the 1350 Å emitting region should be closer to the X-ray source than the 2700 Å region. However, this is a preliminary conclusion, and a more detailed analysis may find either a way to reconcile this or that the undersampled X-ray light curve may not be adequate to make strong claims about the model.

5. Summary

Intensive monitoring of NGC 4151 has produced ultraviolet light curves of unprecedented temporal resolution and detail. On short time scales, they show rapid variability and clear, unexpected differences between long and short-wavelength variations that lower-resolution monitoring was unable to find. While the X-rays seem to follow the long wavelengths better than the short wavelengths, the poor resolution of the X-ray light curve rules out any detailed comparison.

The good overall correlation between the long and short-wavelength ultraviolet light curves is incompatible with the intrinsic accretion-disk model if the signal propagates at viscous or dynamical time scales. Instead, a possible explanation is that the short-wavelength emission is produced in a hot region near the central engine, which then propagates at the speed of light to cooler, more distant outer regions that produce the long-wavelength radiation. For signal propagation speeds this high, these data appear consistent with intrinsic accretion-disk model, but contradictions may emerge during the analysis that will be done in the upcoming months.

The good correlation observed between the ultraviolet and X-ray light curves is a prediction of the reprocessing model, although there may be problems with the details. In particular, if further analysis shows the X-ray light curve is more closely related to the long wavelengths than the short wavelengths, or if the delay between the ultraviolet light curves is found to be smaller than between the ultraviolet and X-rays, it would be difficult to explain with the simplest reprocessing models.

These data will be fully analyzed in the coming months, and will clearly lead to further constraints on the emission mechanisms. Eventually, they will also be correlated with CGRO OSSE γ-ray data, and combined with ground-based, ASCA, and CGRO data to produce the optical through γ-ray spectral energy distribution, which will be used to study the relationship between components emitting in different regimes. The IUE data will also be used to measure the transfer functions of the highest ionization and most rapidly responding emission lines, which should strongly constrain the distribution of the innermost broad-line gas. However, the currently available ultraviolet light curves alone, with little interpretation or further analysis, point up the need for further coordinated
multi-wavelength monitoring of AGN, at the highest sampling rate obtainable, to probe variations that are clearly occurring on very short time scales.

References