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Nature of UV Variability in NGC 4151 from *IUE*'s Intensive Monitoring Spectroscopic Data

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Abstract

The *International Ultraviolet Explorer* (*IUE*) satellite, launched in 1978 by NASA and ESA, has conducted highly successful long-term monitoring spectroscopic observations of many nearby (low-redshift) bright active galaxies, including NGC 1068, NGC 5548, NGC 7469, Fairall 9, MRK 335 and NGC 4151. Notably, *IUE* has monitored NGC 4151 more intensively than any other active galaxy, obtaining 414 spectra during its campaign from December 1 to 15, 1993. Here, we present results of our recent studies on the emission line and continuum variabilities characterised by the $R_{\rm max}$ and $F_{\rm var}$ parameters. From the analysis of the short timescale, intense monitoring data, we obtained $R_{\rm max}$ values ranging between 2.14 ± 0.02 and 1.62 ± 0.01 corresponding to the UV continua 1270 Å, and 2705 Å, respectively. The corresponding $F_{\rm var}$ values varied from 9.62 ± 0.04 % to 5.19 ± 0.04 %. Furthermore, the $R_{\rm max}$ values for the UV emission lines Lyα, C IV, He II, O III], C III] and Mg II have been found to be 4.09 ± 0.06, 4.55 ± 0.05, 13.65 ± 0.68, 4.78 ± 0.17, 2.76 ± 0.02, respectively. The corresponding $F_{\rm var}$ valued obtained are 2.85 ± 0.01 %, 26.51 ± 0.06 %, 15.59 ± 0.02 %, 48.93 ± 1.79 %, 20.30 ± 0.06 % and 18.68 ± 0.02 %, respectively. These results provide constraints on the amplitude of UV variability and the size of the broad-line region (BLR) in low luminosity Seyfert galaxies. The decreasing $F_{\rm var}$ amplitudes of the UV continuum with respect to increasing wavelengths are significant results of the present study.

Keywords: NGC 4151, short-timescale variability, line and continuum fluxes, $R_{\rm max}$ parameter and $F_{\rm var}$ amplitude

1. Introduction to Ultraviolet Variability in NGC 4151

The spectral variations in the UV and X-ray regions exhibit no simple relationship, making it challenging to set constraints on possible mechanisms to explain the AGN variability phenomenon. Ulrich et al. (1991) attributed the near-simultaneous variations in UV/optical wavelengths to instabilities in the inner part of the accretion disk emitting maximally in the UV/EUV

range. Additionally, the disk irradiation by a variable X-ray source has been considered as an alternative process for the simultaneous UV/optical variability. A systematic study of UV variability would provide information on the range of timescales and structural stratification of the broad emission line (BEL) region (or BLR). Large-amplitude variability in line and continuum fluxes at optical/UV and X-rays is a characteristic feature of Seyfert galaxies and quasars. The broad emission lines such as Lyα, Si IV, CIV, C III], HeII, and Mg II lines observed in the UV spectra are among the most prominent features in Seyfert 1 galaxies and quasars.

NGC 4151 stands out as one of the nearest and brightest Seyfert 1 galaxies, initially studied by Carl K. Seyfert (1943). With a very low redshift ($z = 0.00332 \pm 0.00001$) and an apparent brightness of $M_V = 10.04$ magnitudes in the visual band (de Vaucouleurs et al., 1991), it has been the focus of numerous multi-wavelength variability campaigns spanning both the continuum and emission lines, for example in the X-ray range (Barr et al., 1977) and in the UV range by many authors, such as Boggess et al. (1978a,b), Ulrich et al. (1984), Clavel et al. (1987), and Vedavathi and Doddamani (2018). NGC 4151 has been extensively observed in the visible/optical range by Antonucci and Cohen (1983) and Gill et al. (1984), in near-IR (NIR) by Jarrett et al. (2011), in far-IR (FIR) by Meléndez et al. (2014) and at radio wavelengths by Williams et al. (2020). NGC 4151 is an active galaxy that exhibits strong UV emission lines, such as Lyα, N V, Si IV, C IV, He II, O [III], C [III] and Mg II.

The availability of both long-term and short-term UV spectroscopic data from the *International Ultraviolet Explorer* (*IUE*) for Seyfert galaxies and quasars has motivated us to undertake a systematic and detailed study of the complete dataset to better understand the complex nature of line and continuum variability. Among Seyfert galaxies, NGC 4151 stands out as particularly intriguing due to its small amplitude and rapid variability observed in both line and continuum fluxes. It is the only well-observed Seyfert 1 galaxy by the *IUE* satellite with ~ 1086 spectra, compared to the significantly fewer spectra of the active galaxies Fairall 9 (Recondo-González et al., 1997) and NGC 5548 (Peterson et al., 1991).

2. *IUE* Observations, Data Reduction and Analysis

NGC 4151 was observed by *IUE* for 15 days during December 1–15, 1993, using a new observational spectroscopic technique. This source is inherently characterized by a low luminosity and rapid variability. The C IV line maintains a high degree of symmetry during the decreasing and increasing flux states of NGC 4151. The observed variations in the broad emission lines over relatively short timescales of several days suggest that the broad-line region (BLR) is on the order of one or two light days, or even less in size.

In this paper, we present our results based on our recent analysis of the unprecedented UV spectroscopic final archival data from *IUE*. During this observational period, NGC 4151 was observed through the SWP/R (1150–1970 Å) and LWP/R (1970–3300 Å) cameras with large apertures ($10'' \times 20''$) in low dispersion mode ($\Delta\lambda = 5$–8 Å). We extracted a total of nearly 414 NEWSIPS processed spectral data from MAST IUE–NED. Crenshaw et al. (1996) previously studied 401 spectra for their $F_{\rm var}$ characterization of NGC 4151. In this study, all spectra

Table 1: UV continuum flux (rest frame) variability data.

Continuum (Å)	Continuum Window Width (Å)	Continuum Flux (average) ($\mathrm{erg\,s^{-1}\,cm^{-2}\,Å^{-1}}$)	R_{max}	F_{var} (%)	Number of Spectra
1270	1260–1280	37.78 ± 0.13	4.66 ± 0.03	9.78 ± 0.07	211
1340	1320–1360	35.24 ± 0.10	4.57 ± 0.02	12.32 ± 0.03	211
1450	1260–1280	33.00 ± 0.14	4.57 ± 0.02	10.95 ± 0.04	211
1700	1440–1460	26.13 ± 0.07	4.79 ± 0.02	11.08 ± 0.02	211
1830	1800–1860	25.63 ± 0.03	3.56 ± 0.01	9.27 ± 0.01	211
2625	2600–2650	21.66 ± 0.07	1.66 ± 0.01	6.14 ± 0.02	198
2705	2690–2720	22.88 ± 0.08	1.62 ± 0.01	6.64 ± 0.04	197
3025	3000–3500	25.14 ± 0.07	1.85 ± 0.01	9.04 ± 0.01	198

Table 2: Strong UV strong emission line flux (rest frame) variability data.

Emission Line	λ_{rest} (Å)	EW (Å)	Emission Line Flux (average) ($\mathrm{erg\,s^{-1}\,cm^{-2}}$)	R_{max}	F_{var} (%)	Number of Spectra
Ly α	1216	75.44	623.60 ± 7.65	5.46 ± 0.10	26.73 ± 0.06	199
N V	1240	25.16	16.32 ± 1.23	8.67 ± 0.92	121.01 ± 1.86	3
C IV	1549	113.94	735.00 ± 1.26	4.55 ± 0.01	17.52 ± 0.02	200
He II	1640	12.16	105.11 ± 1.30	14.79 ± 0.26	57.45 ± 0.12	183
O III]	1663	2.5	13.45 ± 0.38	4.78 ± 0.50	45.48 ± 1.37	24
C III]	1909	37.71	127.03 ± 0.69	3.57 ± 0.03	20.8 ± 0.06	197
Mg II	2798	34.82	100.26 ± 0.27	3.05 ± 0.01	19.48 ± 0.18	187

have been dereddened using $E(B-V) = 0.032$. The reddening-corrected spectra were further reduced for the redshift of $z = 0.00332$ and using the `dopcor` task from IRAF.

The continuum fluxes were measured within new continuum windows with widths ranging from 20 to 60 Å, centered at 1270 Å, 1325 Å, 1450 Å, 1655 Å, 2175 Å, 2625 Å and 2705 Å (see Table 1 for results). The fluxes of strong and broad emission lines, such as Lyα, Si IV, C IV, C III] and Mg II were measured by fitting single Gaussian profiles individually using IRAF tools (see Table 2 for details). The fluxes of the emission lines were determined using the mean continuum level on either side of the lines. For the C IV line flux calculations, a weak overlying absorption feature was removed using IRAF tasks, following a procedure similar to that used by Ulrich et al. (1991) and by Vedavathi and Doddamani (2018).

The F-variance (F_{var}) parameter allows to characterize the variability amplitude in both continuum and line fluxes, by reducing the instrumental and measurement errors. It is defined

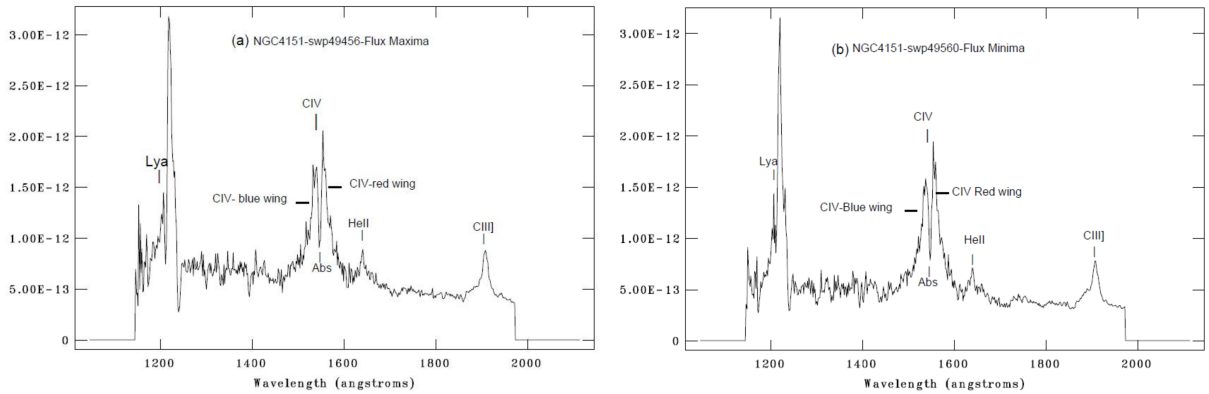

Figure 1: Two short wavelength spectra of NGC 4151 were identified for their high and low UV continuum flux states at 1700 Å observed on December 5, 1993 (*left*) and December 10, 1993 (*right*) by *IUE* from the present study.

as the standard deviation of the fluxes divided by the mean flux in each wavelength band of continuum (or emission line flux). It is furthermore corrected by subtracting the "mean error" in quadrature (Crenshaw et al., 1996). The parameter $R = F_{\rm max}/F_{\rm min}$ provides the relative variability amplitude in the emission line and continuum fluxes. A summary of the variability characteristics obtained in this study is presented in Tables 1 and 2. We identified pairs of spectra corresponding to high and low flux states for different UV continuum windows. One such pair of short-wavelength spectra is presented in Fig. 1. A timescale of five days has been observed for UV variability, comparable to the earlier results for NGC 4151 (Crenshaw et al., 1996) and NGC 5548 (Clavel et al., 1991).

3. Results, Discussion and Conclusions

We have analyzed the final sample of the intensive monitoring of NGC 4151 undertaken with the *IUE* satellite during December 1–15, 1993. Although our methodology for the data analysis differed and has been simpler than that of earlier studies, notably by Crenshaw et al. (1996) and Edelson et al. (1996), we obtained very interesting results. We have obtained $R_{\rm max}$ values ranging between 2.14 ± 0.02 and 1.62 ± 0.01, corresponding to the UV continua at 1270 Å and 2705 Å, respectively (see Table 1). The corresponding $F_{\rm var}$ values for the UV continuum has ranged from 9.62 ± 0.04 % to 5.19 ± 0.04 %. The $R_{\rm max}$ for UV emission lines such as Lyα, C IV, He II, O III], C III] and Mg II were found to be 4.09 ± 0.06, 4.55 ± 0.05, 13.65 ± 0.68, 4.78 ± 0.17 and 2.76 ± 0.02 respectively. The corresponding $F_{\rm var}$ values obtained have been 2.85 ± 0.01 %, 26.51 ± 0.06 %, 15.59 ± 0.02 %, 48.93 ± 1.79 %, 20.30 ± 0.06 % and 18.68 ± 0.02 % respectively (see Table 2). Crenshaw et al. (1996) studied 401 spectra for their $F_{\rm var}$ characterization of NGC 4151. The continuum and emission line variability characteristics obtained here are in good agreement with the results obtained by Crenshaw et al. (1996), Edelson et al. (1996), and recently by Vedavathi and Doddamani (2018) using the same observational data, but now with complete spectral data. These results have provided constraints on the amplitude of the UV variability and the BLR-size in low-luminosity Seyfert galaxies. The

decreasing $F_{\rm var}$ amplitudes of the UV continuum with increasing wavelength are significant results from the present study. *IUE*'s temporal resolution limit of observations with one-hour simultaneity between emission line and UV continuum variability in NGC 4151 thus provides a strict constraint on time-delays compared to the upper limits set on UV lags of $\Delta t \leq 4 \pm 3$ days for the C IV line by Clavel et al. (1991) and 9 ± 2 days for Balmer lines by Maoz et al. (1990) for NGC 4151.

Similar results (in terms of $F_{\rm var}$ and $R_{\rm max}$ parameter values) about the nature of UV variability have been obtained by Clavel et al. (1991) for NGC 5548, and Reichert et al. (1994) for NGC 3783. Our results are in general agreement with previous *IUE* studies of NGC 4151, suggesting that the spectrum at longer wavelengths becomes harder when the flux increases. NGC 4151 is a well-studied active galaxy for short timescale variability across X-ray/UV/optical wavebands. The large-amplitude, rapid variability characteristics presented in this paper could be attributed to the continuum reprocessing of X-rays absorbed by the material in the accretion disk, according to the continuum emission model proposed by Shakura and Sunyaev (1973).

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Further Information

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All the authors have contributed equally towards the analysis and presentation of the results.

Conflicts of interest

The authors declare no conflict of interest.

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