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DISCOVERY OF THE NARROW-LINE SEYFERT 1 GALAXY MARKARIAN 335 IN A HISTORICAL LOW X-RAY FLUX STATE

Dirk Grupe,[1] Stefanie Komossa,[2] and Luigi C. Gallo[3]
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ABSTRACT

We report the discovery of the narrow-line Seyfert 1 galaxy Mrk 335 in an extremely low X-ray state. A comparison of *Swift* observations obtained in 2007 May and June/July with all previous X-ray observations between 1971 and 2006 show the AGN to have diminished in flux by a factor of more than 30, the lowest X-ray flux Mrk 335 has ever been observed in. The *Swift* observations show an extremely hard X-ray spectrum at energies above 2 keV. Possible interpretations include partial-covering absorption or X-ray reflection from the disk. In this Letter we consider the partial-covering interpretation. The *Swift* observations can be well fit by a strong partial-covering absorber with varying absorption column density [$N_H = (1–4) \times 10^{23}$ cm^{-2}] and a covering fraction $f_c = 0.9–1$. When corrected for intrinsic absorption, the X-ray flux of Mrk 335 varies by only factors of 4–6. In the UV Mrk 335 shows variability on the order of 0.2 mag. We discuss the similarity of Mrk 335 to the highly variable NLS1 WPVS 007, and speculate about a possible link between NLS1 galaxies and broad-absorption-line quasars.

Subject headings: galaxies: active — galaxies: individual (Markarian 335) — galaxies: Seyfert — ultraviolet: galaxies — X-rays: galaxies

1. INTRODUCTION

Since the mid-1980s narrow-line Seyfert 1 galaxies (NLS1s; Osterbrock & Pogge 1985) have become a field of extensive study in AGN science. NLS1s are crucial for our understanding of the AGN phenomenon, because they are most likely AGNs at an early stage (e.g., Grupe 2004). They possess relatively low-mass black holes and high Eddington ratios L/L_{Edd}. NLS1s are characterized by extreme properties, such as steep soft and hard X-ray spectra, strong X-ray variability, and strong optical Fe II emission (e.g., Boller et al. 1996; Leighly 1999a, 1999b; Grupe et al. 2001, 2004b; Boroson & Green 1992).

The NLS1 Mrk 335 ($\alpha = 00^h06^m19.5^s$, $\delta = +20°12'11.0''$ [J2000.0], $z = 0.026$) is a well-known bright soft X-ray AGN and has been the target of most X-ray observatories. It was seen as a bright X-ray AGN by *Uhuru* (Tananbaum et al. 1978) and *Einstein* (Halpern 1982). Pounds et al. (1987) reported a strong soft X-ray excess found in the *EXOSAT* spectrum, which was confirmed by BBXRT observations (Turner et al. 1993). *Ginga* observations of Mrk 335 suggested the presence of a warm absorber in the source (Nandra & Pounds 1994). During *ROSAT* observations it also appeared bright and with a strong soft X-ray excess (Grupe et al. 2001). The X-ray spectrum during the 1993 *ASCA* observation (George et al. 2000) was either interpreted as the presence of a warm absorber (Leighly 1999b) or as X-ray reflection on the disk (Ballantyne et al. 2001). *BeppoSAX* observations of Mrk 335 also confirm the presence of a strong soft X-ray excess (Bianchi et al. 2001) and a small or moderate Compton reflection component. *XMM-Newton* observed Mrk 335 in 2000 and again in 2006 (Gondoin et al. 2002; Longinotti et al. 2007a, 2007b; O'Neill et al. 2007). Mrk 335 is exceptional in showing evidence for an unusually broad wing in the iron line (Longinotti et al. 2007a). The wing is required if the *XMM* spectrum is explained in terms of reflection; it is not if a partial-covering interpretation is adopted. High-amplitude variability provides important new constraints to distinguish between these different spectral models. Mrk 335 was observed by *Swift* (Gehrels et al. 2004) in 2007 May and appeared to be dramatically fainter in X-rays than seen in all previous observations. In this Letter we report on this historical low X-ray flux state of Mrk 335 and compare the continuum properties of the *Swift* with previous *XMM-Newton* observations.

Throughout the paper spectral indexes are denoted as energy spectral indexes with $F_\nu \propto \nu^{-\alpha}$. Luminosities are calculated assuming a ΛCDM cosmology with $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and a Hubble constant of $H_0 = 75$ km s^{-1} Mpc^{-1} corresponding to a luminosity distance $D = 105$ Mpc. All errors are 90% confidence unless stated otherwise.

2. OBSERVATIONS AND DATA REDUCTION

Swift observed Mrk 335 on 2007 May 17 and 25 and June 30 to July 02 for 4.8, 8.2, and 8.7 ks (Table 1), respectively, with its X-Ray Telescope (XRT) in Photon Counting mode (PC mode) and in all six filters of the UV-Optical Telescope (UVOT). X-ray data were reduced with the task `xrtpipeline` version 0.11.4. Source and background photons were extracted with XSELECT version 2.4, from circles with radii of 47″ and 189″, respectively. The spectral data were rebinned with at least 20 photons per bin, `grppha` version 3.0.0. The 0.3–10.0 keV spectra were analyzed with XSPEC version 12.3.1x (Arnaud 1996). The auxiliary response files were created with `xrtmkarf` and corrected using the exposure maps and the standard response matrix *swxpc0to12_20010101v008.rmf*.

The UVOT data were co-added for each segment in each filter with the UVOT task `uvotimsum` version 1.3. Source photons in all filters were selected in a circle with a radius of 5″. UVOT magnitudes and fluxes were measured with the task `uvotsource` version 3. The UVOT data were corrected for Galactic reddening ($E_{B-V} = 0.035$; Schlegel et al. 1998).

XMM-Newton observed Mrk 335 in 2000 and 2006 for 37 and 133 ks, respectively (see Table 1). During the 2000 observation the Optical Monitor (OM) did photometry in the *V*, *B*, *U*, and M2 filters. During the 2006 observation the UV grism was used exclusively. The *XMM-Newton* EPIC pn data were analyzed using the XMMSAS version *xmmsas_20060628_1801-7.0.0*. The

[1] Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802; grupe@astro.psu.edu.
[2] Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse, D-85748 Garching, Germany; skomossa@mpe.mpg.de.
[3] SUPA, School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife KY16 9SS, UK; lgallo@ap.stmarys.ca.

TABLE 1
XMM-Newton and *Swift* Observations of Mrk 335

Mission	T_{start} (UT)	T_{stop} (UT)	T_{exp} (s)
XMM 2000	Dec 25, 17:18	Dec 26, 02:06	36910
XMM 2006	Jan 03, 19:10	Jan 05, 08:03	133251
Swift 001/2007	May 17, 00:32	May 17, 05:37	4860
Swift 002/2007	May 25, 00:01	May 25, 19:23	8084
Swift 003/2007	Jun 28, 00:01	Jun 28, 14:37	2932
Swift 004/2007	Jun 30, 00:13	Jun 30, 14.52	2837
Swift 005/2007	Jul 02, 14:47	Jul 02, 21:18	2979

2000 and 2006 observations were performed in full frame and small window, respectively. Because the 2000 observation was severely affected by pileup, photons from a 20″ source-centered circle were excluded. The source photons in the 2006 pn data were selected in a radius of 1′ and background photons of both observations from a source-free region close by with the same radius. The spectra were rebinned with 100 photons per bin. In order to compare the photometry in the OM with the UVOT we selected five field stars with similar brightness in *V* as Mrk 335. Only in *B* and M2, the OM magnitudes had to be adjusted by −0.10 mag and +0.30 mag, respectively.

3. RESULTS

None of the *XMM-Newton* and *Swift* spectra can be fitted by a single-absorbed-power-law model. In the literature a variety of spectral models have been applied to the X-ray data of Mrk 335, including warm absorption (Leighly 1999a; Nandra & Pounds 1994), partial covering (Tanaka et al. 2005), and reflection (Gondoin et al. 2002; Ballantyne et al. 2001; Crummy et al. 2006; Longinotti et al. 2007a, 2007b). Fits with a warm-absorber model (*absori*) and a blackbody plus power law model yield unacceptable results, while fits to the *XMM-Newton* 2000 data yield acceptable fits by using an absorbed-broken-power-law model with the absorption column density fixed to the Galactic value (3.96×10^{20} cm^{-2}; Dickey & Lockman 1990); the *XMM-Newton* 2006 and *Swift* spectra require additional components. We used a partial-covering absorber model with underlying power-law and broken-power-law spectral models. Table 2 summarizes the results from the X-ray spectral analysis. Figure 1 displays the *Swift* spectra fitted with a power law and partial-covering absorber. Fits to each spectrum were first performed separately. Subsequently all the *Swift* spectra were fitted simultaneously in XSPEC with the power-law spectral slopes tied and the absorber parameters and the normalizations left to vary. The results are listed in Table 2 and suggest a development of the partial-covering absorber over time. The most dramatic change is from the 2006 *XMM-Newton* to the first *Swift* observation when the absorber became nearly opaque and only 2% of the X-ray emission can be seen directly. In this case the absorption column density changes from 5×10^{23} cm^{-2} with a covering fraction of 0.45 during the 2006 *XMM-Newton* observation to about 4×10^{23} cm^{-2} and a covering fraction of 0.98 during the first *Swift* observation.

We fitted all three *Swift* spectra simultaneously in XSPEC by tying the covering fraction f_c and spectral indices together. This fit suggests a change in the absorption column density

TABLE 2
Spectral Analysis of the *XMM-Newton* and *Swift* X-Ray Data

Observation	Model[a]	$\alpha_{X,soft}$	E_{break}[b]	$\alpha_{X,hard}$	$N_{H,pcf}$[c]	F_{cover}[d]	$\log F_{X,gal}$[e]	$\log F_{X,all}$[f]	χ^2/ν
XMM 2000	a	1.87 ± 0.01	$1.76^{+0.09}_{-0.08}$	1.18 ± 0.04	...	...	−13.10	...	513/419
	b	1.87 ± 0.01	...	...	$7.7^{+1.1}_{-0.9}$	0.58 ± 0.02	−13.10	−12.72	561/419
XMM 2006	a	1.73 ± 0.01	1.82 ± 0.02	1.08 ± 0.01	...	...	−13.17	...	2420/1327
	c	1.74 ± 0.01	1.63 ± 0.03	1.25 ± 0.02	$55.1^{+10.0}_{-8.2}$	$0.45^{+0.04}_{-0.03}$	−13.17	−12.91	1973/1325
	d	1.74 ± 0.01	1.62 ± 0.03	1.25 ± 0.02	$51.0^{+10.2}_{-8.0}$	$0.43^{+0.04}_{-0.03}$	−13.17	−12.93	2611/1910[g]
Swift 001	c	$2.05^{+0.24}_{-0.20}$	...	...	$31.1^{+17.0}_{-13.6}$	$0.98^{+0.02}_{-0.03}$	−14.63	...	9/9
	e	1.74 ± 0.01	1.62 ± 0.03	1.25 ± 0.02	$38.2^{+19.2}_{-19.6}$	$0.95^{+0.04}_{-0.03}$	−14.75	−13.48	2611/1910[g]
	f	1.79 ± 0.10	...	...	$20.0^{+8.9}_{-5.4}$	0.93[h]	−14.71	−13.55	87/85[i]
	g	1.81 ± 0.10	...	...	$20.5^{+8.6}_{-5.4}$	$0.94^{+0.01}_{-0.02}$	−14.70	−13.51	87/86[i]
	h	1.81 ± 0.10	...	...	$12.8^{+2.6}_{-2.2}$	$0.91^{+0.03}_{-0.06}$	−14.72	−13.69	95/86[i]
Swift 002	c	1.78 ± 0.14	...	...	$10.4^{+2.6}_{-2.2}$	$0.93^{+0.02}_{-0.03}$	−14.25	−13.10	52/48
	e	1.74 ± 0.01	1.62 ± 0.03	1.25 ± 0.02	$10.4^{+3.6}_{-2.7}$	$0.88^{+0.02}_{-0.03}$	−14.27	−13.37	2611/1910[g]
	f	1.79 ± 0.12	...	...	$10.4^{+2.6}_{-2.1}$	0.93 ± 0.02	−14.25	−13.10	87/85[i]
	g	1.81 ± 0.10	...	...	$10.9^{+2.4}_{-2.0}$	$0.94^{+0.01}_{-0.02}$	−14.25	−13.06	87/86[i]
	h	1.81 ± 0.10	...	...	$12.8^{+2.6}_{-2.2}$	$0.94^{+0.01}_{-0.02}$	−14.25	−13.02	95/86[i]
Swift 003–005[j]	c	1.75 ± 0.17	...	...	$16.6^{+6.4}_{-4.7}$	$0.93^{+0.02}_{-0.04}$	−14.49	−13.32	23/26
	e	1.74 ± 0.01	1.62 ± 0.03	1.25 ± 0.02	$17.5^{+9.8}_{-6.6}$	$0.89^{+0.04}_{-0.07}$	−14.50	−13.56	2611/1910[g]
	f	1.79 ± 0.10	...	...	$16.4^{+6.1}_{-4.6}$	$0.94^{+0.02}_{-0.03}$	−14.48	−13.28	87/85[i]
	g	1.81 ± 0.10	...	...	$15.8^{+4.0}_{-3.2}$	$0.94^{+0.01}_{-0.02}$	−14.47	−13.28	87/86[i]
	h	1.81 ± 0.10	...	...	$12.8^{+2.6}_{-2.2}$	$0.92^{+0.02}_{-0.03}$	−14.48	−13.36	95/86[i]

[a] Spectral models used are (a) absorbed power law, (a) absorbed broken power law, (b) partial covering absorbed with a single power law, (c) partial-covering absorber and broken power law, (d) same as (c) but simultaneous fits to the 2006 *XMM-Newton* and all *Swift* spectra with the broken-power-law parameters tied and the partial-covering absorber parameters left free to vary, (e) same as (b) but *Swift* spectra fit simultaneously in XSPEC with the X-ray spectral index tied and the partial-covering absorber parameters left free to vary, (f) same as (e) but the covering fraction f_c of all three *Swift* spectra tied, and (g) same as (e) but N_H tied and f_c left free. For all models the absorption column density was fixed to the Galactic value (3.96×10^{20} cm^{-2}; Dickey & Lockman 1990).

[b] The break energy E_{break} is given in units of keV.

[c] Absorption column density of the redshifted partial-covering absorber $N_{H,pcf}$ in units of 10^{22} cm^{-2}.

[d] Covering fraction F_{cover}.

[e] Rest-frame 0.2–2.0 X-ray flux $\log F_{0.2-2.0\,keV}$ corrected for Galactic absorption given in units of W m^{-2}.

[f] Rest-frame 0.2–2.0 X-ray flux $\log F_{0.2-2.0\,keV}$ corrected for Galactic and intrinsic absorption given in units of W m^{-2}.

[g] Simultaneous fit to all *Swift* data.

[h] Leaving covering absorber fraction as a free parameter only gives unconstrained results. We therefore fixed the absorption covering fraction to 0.93, which was found in the other *Swift* data.

[i] Simultaneous fit to all *Swift* data.

[j] Co-added data from segments 003 to 005.

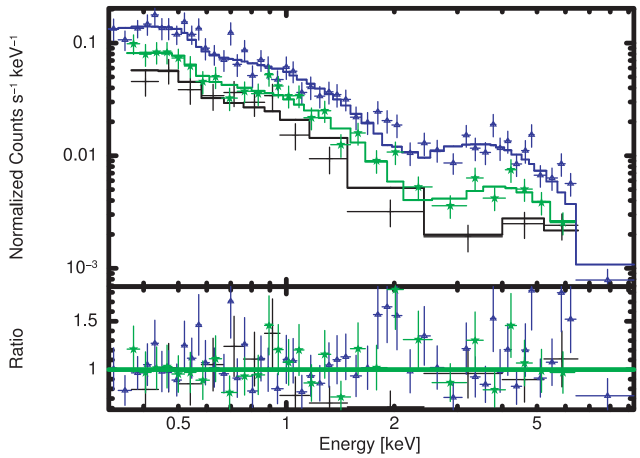

FIG. 1.—*Swift* XRT spectra of Mrk 335 fitted with a power-law model with partial-covering absorber as listed in Table 2. The black spectrum displays the *Swift* segment 001 spectrum, the segment 002 spectrum is in blue (*triangles*), and the segment 003-005 spectrum is in green (*stars*).

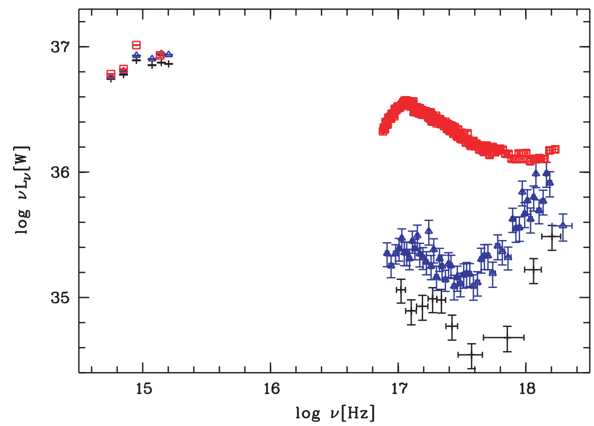

FIG. 2.—Spectral energy distributions of Mrk 335. The black crosses are from the *Swift* observation segment 001, blue triangles from segment 002, and red squares from the 2000 *XMM-Newton* observation. The *Swift* segments 003–005 spectrum would be between the 001 and 002 spectra.

$N_{\rm H,pcf}$ of the partial-covering absorber by a factor of 2 within a week between the 2007 May 17 and 25 observations. Alternatively, we also fitted the spectra with $N_{\rm H,pcf}$ tied and f_c left as a free parameter. An *F*-test gives an *F*-value of 7.8 that these two fits are different and a probability $P = 0.006$ of a random result. Leaving $N_{\rm H,pcf}$ free gives a significantly better result than leaving f_c free to vary. In the rest-frame 0.2–2.0 keV band the observed fluxes (only corrected for Galactic absorption) seem to be highly variable and between the *XMM-Newton* 2000 and the first *Swift* observation we found variability by a factor of 30. However, when correcting also for intrinsic absorption the unabsorbed rest-frame 0.2–2.0 keV fluxes from *ROSAT* and *Swift* are comparable. During the *ROSAT* All-Sky Survey observation a flux of 4×10^{-14} W m^{-2} was found (Grupe et al. 2001). Correcting for a partial-covering absorber in the *XMM-Newton* and *Swift* spectra we found that the flux varied only by factors of 4–6, as listed in Table 2.

The X-ray spectra of Mrk 335 in the higher and more typical flux state can be well described as arising from an incident power law and reflection component (e.g., Crummy et al. 2006; Longinotti et al. 2007a). However, the low-flux spectra are difficult to reproduce by simply rescaling the high-state models or by varying the relative contribution of each component. A modified reflection model that self-consistently describes the high- and low-flux states is being investigated and is presented in L. C. Gallo et al. (2007, in preparation).

As shown by the spectral energy distribution (SED) in Figure 2, there was no dramatic variability in the UV data between the 2000 *XMM-Newton* OM and 2007 *Swift* UVOT observations, although during the 2007 May 17 observation Mrk 335 was about 0.2 mag fainter. The UV/optical spectral slopes are on the order of $\alpha_{\rm UV} = -0.4$, except for the 2007 May 17 observation, when it was $\alpha_{\rm UV} = -0.3$. The UV to X-ray spectral slope $\alpha_{\rm ox}$[4] was significantly steeper during the *Swift* observations with $\alpha_{\rm ox} = 1.91$ and 1.65 during the *Swift* segments 001 and 002, respectively. During the 2000 *XMM-Newton* observation, however, an $\alpha_{\rm ox} = 1.32$ was measured, consistent with the value given by Gallo (2006).

4. DISCUSSION

We report the *Swift* observations of the NLS1 Mrk 335 when it was in its lowest X-ray flux state ever observed. Historically, Mrk 335 has exhibited X-ray variability by about a factor of a few (e.g., Turner et al. 1993; Markowitz & Edelson 2004), although the source has always[5] remained rather bright at least until the last X-ray observation with *Suzaku* in 2006 June (J. Larsson 2007, private communication). However, sometime between 2006 June and 2007 May the observed flux dropped by a factor of more than 30, including a dramatic change in its SED. The X-ray spectrum has become progressively more complex as the X-ray flux has diminished, indicative of either absorption or reflection (e.g., Gallo 2006). The 2–10 keV high-flux spectrum in 2000 did not appear overly complex and the high-energy continuum could be simply fitted with a power law. The 2006 *XMM-Newton* data, however, can be fitted with a partial-covering absorber model (see also O'Neill et al. 2007), suggesting that the absorber started moving in the line of sight before 2006 January.

Partial covering of the central light source has been invoked since the early days of AGN X-ray spectroscopy (e.g., Holt et al. 1980), and quite often to describe the X-ray spectrum of NLS1s (e.g., Gallo et al. 2004; Grupe et al. 2004a; Tanaka et al. 2005). Its presence is also indicated by narrow absorption lines (which appear to be saturated but do not reach zero intensity) in UV spectra of broad-absorption-line (BAL) quasars (e.g., Barlow et al. 1997; Hamann 1998; Wills et al. 1999). However, the geometry and physics of partial coverers are still not well understood. One possible geometry consists of thick blobs of gas, partially covering parts of the accretion disk (e.g., Guilbert & Rees 1988). In the case of Mrk 335, the clouds must cover only the inner parts of the disk, since we find that the UV emission is not highly variable between the *XMM-Newton* observation in 2000 and the *Swift* observations in 2007,

[4] The X-ray loudness is defined by Tananbaum et al. (1979) as $\alpha_{\rm ox} = -0.384 \log (f_{2\,{\rm keV}}/f_{2500\,\rm Å})$.

[5] Except for an episode in 1983 when it had a rather low X-ray flux during its *EXOSAT* observation as reported by Pounds et al. (1987).

while the X-rays vary dramatically.[6] Note that the fits to the May 17 and May 25 *Swift* spectra suggest a change in the partial-covering absorber column densities by a factor of about 2. This timescale is consistent with, e.g., the absorber toy model suggested by Abrassart & Czerny (2000), where thick clouds at 10–100 Schwarzschild radii partially obscure the central region, causing the X-ray variability.

Alternatively, a partial-covering situation may arise if our line of sight passes through an accretion-disk driven wind which is launched at intermediate disk radii (e.g., Elvis 2000; Proga 2007). If such a wind varies with time and/or is inhomogeneous, different parts of the central source would be covered at different times. In both partial-covering geometries, the physics is still uncertain. In the case of dense blobs, how are they confined and what is their origin (e.g., Kuncic et al. 1997)? In case of disk-driven winds, what is the driver of these massive outflows (e.g., Proga 2007)?

The high column density we need in our *Swift* spectral fits is similar to those frequently observed in BAL quasars (e.g., Green & Mathur 1996; Gallagher et al. 2002; Grupe et al. 2003). In this context, it is interesting to note that similarities between NLS1 galaxies and BAL quasars have been pointed out repeatedly (e.g., Mathur 2000; Brandt & Gallagher 2000; Boroson 2002). In one specific case, that of the X-ray transient NLS1 galaxy WPVS 007, the onset of heavy X-ray absorption (Grupe et al. 2007) is indeed accompanied by the onset of UV BALs (K. M. Leighly et al. 2007, in preparation). When correcting for the effects of intrinsic absorption we found that the X-ray flux of Mrk 335 originating from the central engine has been very similar in the rest-frame 0.2–2.0 keV band between the *ROSAT* observations and the most recent *Swift* observations. Using these fluxes, the intrinsic variability is only a factor of about 4–6, which is quite normal for an AGN, in particular for a NLS1. The change in intrinsic flux between the first and second *Swift* observations is about a factor of 3 within a week. If a partial-covering absorber is the correct model this flux change implies that the soft X-ray scattering region can only be a few light-days in diameter, which is consistent with the Abrassart & Czerny (2000) toy model. The deep low state of Mrk 335 discovered with *Swift* provides us with a rare chance to scrutinize the properties of X-ray low-state AGNs in general. Mrk 335 is unique with respect to being relatively bright during its low state. Therefore, follow-up observations of Mrk 335 in its current low state are highly encouraged. We will continue our monitoring with *Swift* in order to find the timescales on which the AGN switches from a low to high state, but also deep *XMM-Newton* observations, optical spectroscopy, and spectropolarimetry are needed to clarify the nature of the current low state.

[6] We note that historic light curves from *IUE* and *HST* did show that Mrk 335 has been variable in the UV between 1978 and 1985 (Dunn et al. 2006; Edelson et al. 1990) by a factor of 2. The *UBVRI* photometry of Mrk 335 as reported by Doroshenko et al. (2005) (see also Czerny & Janiuk 2007) also suggests that the AGN is intrinsically highly variable. However, because of the lack of simultaneous X-ray observations during these time periods we do not know whether the UV variability was caused by changes in the flux of the central engine or was caused by absorption.

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