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

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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 \([N_H = (1-4) \times 10^{23} \text{ cm}^{-2}]\) and a covering fraction \(f_c = 0.9-1.0\). 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; Borson & Green 1992).

The NLS1 Mrk 335 (\(\alpha = 00^h06^m19.5^s, \delta = +20^\circ12'11.0''\) \([J2000.0], z = 0.026\)) 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 \(F_s \propto \nu^{-\alpha}\). Luminosities are calculated assuming a \(\Lambda\)CDM cosmology with \(\Omega_m = 0.27\), \(\Omega_{\Lambda} = 0.73\), and a Hubble constant of \(H_0 = 75 \text{ km s}^{-1}\text{ Mpc}^{-1}\) corresponding to a luminosity distance \(D = 105 \text{ Mpc}\). 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, in circles with radii of 47, 189, and 378 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 sxwpc0to12_20010101v008.rmf.

The UVOT data were co-added for each segment in each filter with the UVOT task uvotimsun 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 xmmmsas_20060628_1801-7.0.0. The
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; Nakamura & 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 (absor) 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

| Observation | Model | $\alpha_{\text{abs}}$ | $E_{\text{break}}$ | $\alpha_{\text{hard}}$ | $N_{\text{H,abs}}$ | $F_{\text{cont}}$ | log$F_{\text{X-abs}}$ | log$F_{\text{X-abs}}$ | $\chi^2$/dof |
|-------------|-------|----------------------|---------------------|------------------------|-------------------|-----------------|-----------------|-----------------|---------------|
| XMM 2000    | a     | 1.87 ± 0.01          | 1.76 ± 0.00         | 1.18 ± 0.04            | ...               | ...             | ...             | ...             | 513/419        |
|             | b     | 1.87 ± 0.01          | ...                 | ...                    | 7.7 ± 1.0         | 0.58 ± 0.02     | ...             | ...             | 513/419        |
| XMM 2006    | a     | 1.73 ± 0.01          | 1.82 ± 0.02         | 1.08 ± 0.01            | ...               | ...             | ...             | ...             | 2420/127       |
|             | c     | 1.74 ± 0.01          | 1.63 ± 0.03         | 1.25 ± 0.02            | 55.1 ± 3.5        | 0.45 ± 0.04     | ...             | ...             | 1973/125       |
|             | d     | 1.74 ± 0.01          | 1.62 ± 0.03         | 1.25 ± 0.02            | 51.0 ± 2.1        | 0.43 ± 0.03     | ...             | ...             | 2611/1910      |
|             | e     | 1.74 ± 0.01          | 1.62 ± 0.03         | 1.25 ± 0.02            | 38.2 ± 1.0        | 0.95 ± 0.03     | ...             | ...             | 2611/1910      |
|             | f     | 1.79 ± 0.10          | ...                 | ...                    | 20.0 ± 4.5        | 0.93 ± 0.03     | ...             | ...             | 14.71 ± 3.5    |
|             | g     | 1.81 ± 0.10          | ...                 | ...                    | 20.5 ± 4.9        | 0.94 ± 0.03     | ...             | ...             | 14.70 ± 3.5    |
|             | h     | 1.81 ± 0.10          | ...                 | ...                    | 12.8 ± 3.5        | 0.91 ± 0.03     | ...             | ...             | 14.72 ± 3.5    |
|             | i     | 1.81 ± 0.10          | ...                 | ...                    | 12.8 ± 3.5        | 0.91 ± 0.03     | ...             | ...             | 14.72 ± 3.5    |
|             | j     | 1.78 ± 0.14          | ...                 | ...                    | 10.4 ± 3.6        | 0.93 ± 0.03     | ...             | ...             | 14.25 ± 3.10   |
|             | k     | 1.74 ± 0.01          | 1.62 ± 0.03         | 1.25 ± 0.02            | 10.4 ± 2.9        | 0.86 ± 0.03     | ...             | ...             | 14.27 ± 3.37   |
|             | l     | 1.79 ± 0.12          | ...                 | ...                    | 10.5 ± 3.6        | 0.95 ± 0.02     | ...             | ...             | 14.25 ± 3.10   |
|             | m     | 1.81 ± 0.10          | ...                 | ...                    | 10.9 ± 3.5        | 0.94 ± 0.03     | ...             | ...             | 14.25 ± 3.06   |
|             | n     | 1.81 ± 0.10          | ...                 | ...                    | 12.8 ± 3.5        | 0.94 ± 0.03     | ...             | ...             | 14.25 ± 3.12   |
|             | o     | 1.75 ± 0.17          | ...                 | ...                    | 16.6 ± 5.0        | 0.93 ± 0.04     | ...             | ...             | 14.49 ± 3.32   |
|             | p     | 1.74 ± 0.01          | 1.62 ± 0.03         | 1.25 ± 0.02            | 17.3 ± 5.0        | 0.89 ± 0.04     | ...             | ...             | 14.50 ± 3.56   |
|             | q     | 1.79 ± 0.10          | ...                 | ...                    | 16.4 ± 4.6        | 0.94 ± 0.03     | ...             | ...             | 14.48 ± 3.28   |
|             | r     | 1.81 ± 0.10          | ...                 | ...                    | 15.8 ± 4.3        | 0.94 ± 0.03     | ...             | ...             | 14.47 ± 3.28   |
|             | s     | 1.81 ± 0.10          | ...                 | ...                    | 12.8 ± 3.5        | 0.92 ± 0.02     | ...             | ...             | 14.48 ± 3.36   |

### Notes

- Spectral models used are (a) absorbed power law, (b) absorbed broken 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 $N_{\text{H,abs}}$ 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).
- The break energy $E_{\text{break}}$ is given in units of keV.
- Absorbed column density of the redshifted partial-covering absorber $N_{\text{H,abs}}$ in units of 10^{23} cm^{-2}.
- Rest-frame 0.2–2.0 X-ray flux log$F_{\text{X,abs}}$ corrected for Galactic absorption in units of 10^{23} cm^{-2}.
- Rest-frame 0.2–2.0 X-ray flux log$F_{\text{X,abs}}$ corrected for Galactic and intrinsic absorption given in units of 10^{23} cm^{-2}.
- Simultaneous fit to all Swift data.
- 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.
- Simultaneous fit to all Swift data.
- Co-added data from segments 003 to 005.
$N_{\text{H,pcf}}$ 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 $N_{\text{H,pcf}}$ 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 $N_{\text{H,pcf}}$ 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 $4 \times 10^{-14}$ 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 $\alpha_{\text{UV}} = -0.4$, except for the 2007 May 17 observation, when it was $\alpha_{\text{UV}} = -0.3$. The UV to X-ray spectral slope $\alpha_{\text{ox}}$ was significantly steeper during the Swift observations with $\alpha_{\text{ox}} = 1.91$ and 1.65 during the Swift segments 001 and 002, respectively. During the 2000 XMM-Newton observation, however, an $\alpha_{\text{ox}} = 1.32$ was measured, consistent with the value given by Gallo (2006).

4 The X-ray loudness is defined by Tananbaum et al. (1979) as $\alpha_{\text{ox}} = -0.384 \log (f_{\text{2-10 keV}}/f_{\text{0.2-2 keV}})$.

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. 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-disc 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 2004; 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.

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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.