LETTER TO THE EDITOR

The Close AGN Reference Survey (CARS)

What is causing Mrk 1018's return to the shadows after 30 years?⋆

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ABSTRACT

We recently discovered that the active galactic nucleus (AGN) of Mrk 1018 has changed optical type again after 30 years as a type 1 AGN. Here we combine *Chandra*, *NuStar*, *Swift*, *Hubble Space Telescope* and ground-based observations to explore the cause of this change. The 2–10 keV flux declines by a factor of ∼10 between 2010 and 2016 which cannot be caused by varying neutral hydrogen absorption along the line-of-sight up to the Compton-thick level. The optical-UV spectral energy distributions are well fit with a standard geometrically thin optically thick accretion disc model that seems to obey the expected $L \sim T^4$ relation. It confirms that a decline in accretion disc luminosity is the primary origin for the type change. We detect a new narrow-line absorber in Lyα blue-shifted by ∼700 km s^{-1} with respect to the systemic velocity of the galaxy. This could be evidence for the onset of an outflow, a companion black hole with associated gas possibly linked to the accretion rate change, or a fast-moving cloud from the debris of the galaxy merger unrelated to the accretion process.

Key words. Accretion, accretion disc - Galaxies: Nuclei - Galaxies: Seyfert - Galaxies: individual: Mrk 1018

1. Introduction

Active Galactic Nuclei (AGN) and some X-ray binaries and are thought to be powered by accretion of material onto a black hole (BH). They commonly show significant variability at optical-to-X-ray wavelengths on short timescales which can be well described by noise processes (e.g., Nandra et al. 1997; McHardy et al. 2004; Mushotzky et al. 2011). The variability timescale is expected to scale with the mass of the BH and is therefore longest for super-massive BHs (SMBH) reaching up to several hundreds of years (e.g., McHardy et al. 2006). It is therefore difficult or even impossible to directly measure the long-term high-amplitude fluctuations of AGN over the required time scales.

Outbursts or sudden drops in X-ray brightness of orders of magnitude have also been observed in many AGN. These can often be associated with intermittent obscuration by clouds in the torus (e.g., Markowitz et al. 2014), flares from tidal disruption events (TDEs) due to accretion of a star (e.g., Komossa & Bade 1999; Halpern et al. 2004; Merloni et al. 2015), or large intrinsic accretion rate changes (e.g., Denney et al. 2014). AGN in which the strength of the broad Balmer lines from the BLR change drastically compared to the stellar continuum and narrow emission lines are often called "changing-look" AGN. Examples of such "changing-look" AGN with appearing BLR are Mrk 1018 (Cohen et al. 1986), NGC 1097 (Storchi-Bergmann et al. 1993), and NGC 2617 (Shappee et al. 2014), and with disappearing BLR are NGC 7603 (Tohline & Osterbrock 1976), and Mrk 590 (Denney et al. 2014), SDSS J0159+0033 (LaMassa et al. 2015), and SDSS J1011+5442 (Runnoe et al. 2016).

In McElroy et al. 2016 (hereafter Paper I), we reported the surprising discovery that Mrk 1018, which turned from a type 1.9 to a bright type 1 AGN around 1984, has changed back to a type 1.9 nucleus after ∼30 years. The optical continuum brightness dropped by an order of magnitude between 2010 and early 2016. While we discuss in Paper I that a TDE is unlikely to explain the variability of Mrk 1018, several other options including a cloud event still appeared possible. In this Letter, we present follow-up

⋆ Based on Cycle 17 Director's Discretionary Time program (ID: 18789, PI: G. Tremblay) approved by the *Chandra* Director, Dr. Belinda Wilkes. Based on Cycle 23 Director's Discretionary Time observations made with the NASA/ESA Hubble Space Telescope (ID: 14486, PI: B. Husemann) approved by *HST* Director Dr. Kenneth Sembach.

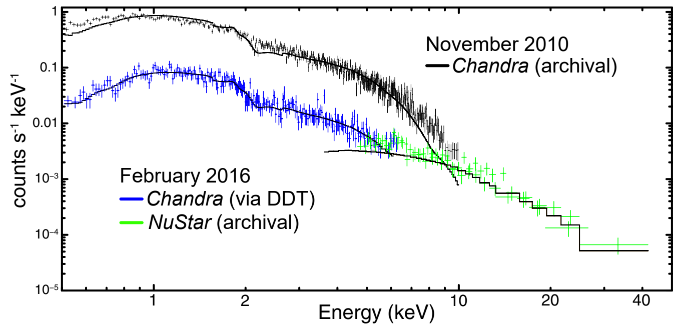

Fig. 1. A comparison of Mrk 1018's X-ray spectrum in November 2010 and February 2016. For all data, we show the best fit model of a simple power-law plus Galactic absorption as a solid black line. The apparent mismatch near 5 keV between the 2016 *Chandra* and 2016 *NuStar* are instrumental effects included in the model. The X-ray flux dropped by a factor of ~10.5 between 2010 and 2016, and both spectra are consistent with no N_H absorption in both epochs.

Director's Discretionary Time (DDT) and archival X-ray and UV spectroscopic data which show that the changing classification is driven by accretion rate changes rather than obscuration events.

2. Observations & Results

2.1. Chandra and NuStar X-ray spectroscopy

Chandra observed Mrk 1018 on 18 February 2016 as part of a DDT request. It was observed on the nominal aimpoint of the back-illuminated ACIS-S3 chip for 27.2 ksec. Mrk 1018 was also targeted on 10 February 2016 with *NuStar* (Harrison et al. 2013) for 21.6 ksec as part of the public shallow Extragalactic Survey so that we can construct the quasi-simultaneous X-ray spectrum combining both observations. The combined *Chandra* and *NuStar* X-ray spectrum covering 0.5-50 keV is shown in Fig. 1 together with an archival *Chandra* observation taken on November 27 2010 (ID: 12868, PI: Mushotzky).

Both *Chandra* spectra were extracted with the *CIAO* package (v4.5) and the latest *CALDB* files (4.7.0) using standard settings for point sources. Similar settings for point sources were also employed for the *NuStar* spectral extraction using the *nupipeline*. All spectra were grouped and minimum binned with 20 counts. We fit an intrinsically absorbed power-law together with absorption by the Galactic neutral hydrogen ($N_{HI,Gal}$ = $2.43 \times 10^{20}\,\mathrm{cm}^{-2}$, Kalberla et al. 2005) to the data. The *Chandra* and *NuStar* spectra from 2016 are fitted simultaneously.

The 2010 and 2016 spectra and their fits are both consistent with no absorption beyond Galactic, in particular even partial Compton-thick absorption is ruled out with *NuStar* in 2016. The best fit parameters and errors on the power-law index (Γ) and 2–10 keV flux are listed in Table 1. The shape of the X-ray spectra indicates that the flux is lower by a factor of ~ 10.5 in 2016 compared to 2010, though the 2010 spectral index is flatter. Furthermore, there appears to be a hint of a weak Fe Kα line at 6.4 keV in the 2016 data.

2.2. Swift X-ray monitoring

While *Chandra* obtained very high S/N spectra of Mrk 1018 it only allows us to probe two epochs. The X-Ray Telescope (XRT) aboard of the *Swift* satellite has targeted Mrk 1018 several times between 2005 and 2016 (see Table 1). These monitoring data allow us to study the evolution of X-ray brightness as well as the amount of absorption and the X-ray spectral power-law index. We use the interactive *Swift* data processing and analysis pipeline of the ASI Science Data Center (*http://swift.asdc.asi.it* Gendre & Giommi 2010) to infer these parameters.

Table 1. X-ray observations and best-fit results

Date[a]	t_{exp} [b]	θ_{off} [c]	N_{bin} [d]	Γ [e]	$f_{2--10\,\mathrm{keV}}$ [f]
05-08-2005(S)	5.2	2.6	113	1.93 ± 0.05	1.11 ± 0.08
20-06-2007(S)	3.3	4.4	58	1.91 ± 0.08	0.92 ± 0.10
22-06-2007(S)	3.5	6.3	61	1.95 ± 0.08	0.78 ± 0.07
24-06-2007(S)	4.1	5.9	73	1.95 ± 0.07	0.85 ± 0.07
11-06-2008(S)	4.8	1.2	81	1.76 ± 0.06	0.97 ± 0.08
27-11-2010(C)	22.7	0.0	627	1.37 ± 0.02	1.23 ± 0.01
07-06-2013(S)	1.3	2.0	14	1.42 ± 0.18	0.79 ± 0.16
09-06-2014(S)	2.1	4.5	3	1.50 ± 0.60	0.16 ± 0.09
11-02-2016(S)	3.7	3.7	9	1.75 ± 0.27	0.15 ± 0.05
16-02-2016(S)	3.1	3.9	8	1.33 ± 0.26	0.25 ± 0.08
18-02-2016(CN)	27.2	0.0	511	1.62 ± 0.03	0.12 ± 0.01

Notes. [(a)] Date of observations with facility indicated in brackets C-*Chandra*, S-*Swift*, N-*NuStar* [(b)] effective exposure time in ksec [(c)] off axis-angle in arcmin [(d)] Number of bins used for X-ray fitting [(e)] Power-law index with 90% uncertainty range [(f)] Physical flux (Galactic-absorption corrected, on-axis corrected) between 2–10 keV in units of $10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$

Given the individual exposure times of up to a few ksec, only a simple spectral model consisting of a power-law plus Galactic absorption component is fitted. Such a simple model is in good agreement even with the higher S/N *Chandra* observation. We list the best-fit power-law value and the 2–10 keV flux in Table 1. Considering the large uncertainties of the *Swift*-based quantities from Feb 2016, the measurements broadly agree with our DDT *Chandra* observation of much higher S/N around the same time.

In all *Swift* observations with more than 2 ksec, a second fit with a free Galactic absorption parameter leads to smaller values or within the 90% uncertainty range of the Galactic-absorption value. Hence, during 2005 and 2016 the *Swift* data show no signs of additional absorption along the line of sight in agreement with the *Chandra* observations. Interestingly, the variations in Γ are significant ranging from Γ ~ 1.9 in the bright phase down to Γ ~ 1.4 around 2010 which is accompanied with a temporary increase in the X-ray flux, which is not seen in the optical continuum at the same time, but it precedes the dramatic decline of the optical and X-ray flux starting around 2011.

2.3. HST FUV spectroscopy

Hubble Space Telescope (*HST*) FUV spectroscopy of Mrk 1018 was obtained with the Cosmic Origin Spectrograph (COS, Green et al. 2012) on February 27 2016 for 2 orbits granted as Director's Discretionary Time. The G140L grism provides a broad wavelength range covering Lyα and C IV. A 300 s NUV acquisition image was also taken with the Primary Science Aperture and MIRRORB. The reduced COS spectrum is shown in Fig. 3 together with archival *IUE* spectra taken in 1984/86 and *HST* spectra taken with the Faint Object Spectrograph (FOS) in 1996.

All spectra in the bright phase exhibit a FUV continuum flux density of $(1.3 \pm 0.3) \times 10^{-14}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,\AA^{-1}}$ and $7.8 \times 10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,\AA^{-1}}$ seen by COS which is a factor of ~17 fainter. The Lyα line is shown in the lower panel of Fig. 3 after normalizing the adjacent continuum level to 1. The broad line is well modelled with three Gaussians plus single Gaussians for each absorption line. We measure a total Lyα flux of

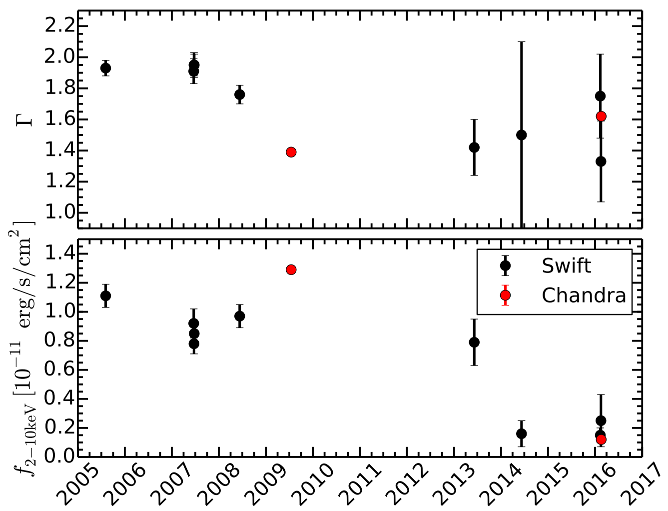

Fig. 2. Time evolution of the X-ray power-law index Γ and the 2–10 keV flux from 2005 until 2016 based on the *Swift* and *Chandra* data.

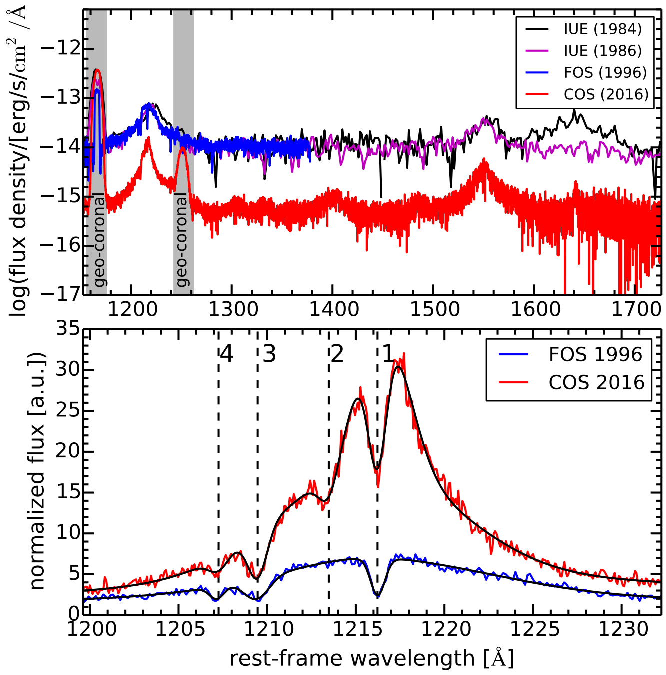

Fig. 3. *Upper panel:* FUV spectra of Mrk 1018 taken between 1984 and 2016 with IUE as well as *HST* FOS and COS. *Lower panel:* Comparison of the Lyα emission-line shape in 1996 and 2016. The spectra are normalized so that the adjacent continuum level is one. The solid black lines are the best-fit model as described in the text.

16×10^{-13} erg s^{-1} cm^{-2} and 2.2×10^{-13} erg s^{-1} cm^{-2}, respectively, which is a factor of ~7 brighter than in 1996. The Lyα line width becomes narrower from 4170 ± 62 km s^{-1} to 1330 ± 122 km s^{-1} in FWHM. This is conceptually consistent with the resonant nature of the line. The Lyα photons produced in the last 30 years are continuously absorbed and re-emitted and thereby able to scatter to larger distance with more quiescent kinematics. This may also explain why the broad Lyα line appears more symmetric compared to the asymmetric Balmer lines as reported in Paper I.

Three Lyα narrow absorption lines (NALs) can be identified in the FOS spectrum taken in 1996. Surprisingly, an additional Lyα NAL appears 20 years later. As indicated in Fig. 3, we label them with numbers from 1 to 4. NAL 1 has an equivalent width (EW) of 0.65Å right at the systemic redshift of Mrk 1018. The new NAL 2 is blue-shifted by ~700km s^{-1} with respect to the systemic redshift and has an EW of 0.32Å. Absorbers 3+4 are blue-shifted by more than 1500 km s^{-1} with EWs of 0.9Å and 0.4Å and less variable. It is unclear if they are intervening absorption systems or still related to the environment of the host galaxy. Only absorber 1 can be detected in C IV, while absorber 2 remains undetected. The lower EW of absorber 2 combined with the lower S/N at C IV during the fading phase may simply prevent a clear detection. Although we cannot detect C IV for the new NAL the short time variability of the line at this strength can only be produced by neutral gas within the host galaxy.

3. Discussion

3.1. Inconsistency with a cloud event

We speculated in Paper I whether a dense cloud is moving into our line-of-sight causing the dimming of the nucleus. Such a scenario could explain the potential periodicity of such an event. For a black hole mass of $M_{\mathrm{BH}} \sim 7\times10^7 M_\odot$ (Paper I) an orbital period of 30yr would correspond to a velocity of 3300 km s^{-1} at a mean distance of 0.03 pc. The combined high-quality *Chandra* and *NuStar* spectrum clearly shows that such a scenario can be reliably ruled out because no significant neutral hydrogen column density can be detected. In particular, the high energies probed by *NuStar* highlight that even Compton-thick obscuration can be excluded. The significant time evolution in Γ and flux favours a scenario in which the physical state of the accretion disc underwent a significant change or reconfiguration. It is unclear if the flattening of Γ around 2010, right before the decline in optical flux, is linked to the origin of the fading accretion disc.

3.2. Accretion disc changes probed by the Spectral Energy Distribution

GALEX observations in the NUV and FUV were taken 2008 October 21 as part of the medium imaging survey when Mrk 1018 was still in the bright phase. Within 100 days it was targeted by *Swift* in the X-rays and *U* band as well as by the Palomar Transient Factory in the *r* band. The corresponding SED of the nucleus is shown in Fig. 4. The SED significantly changes spectral shape in the optical-FUV range when Mrk 1018 was fading as revealed by the *HST* observation in combination with quasi-simultaneous *u* and *r* band photometry (see Paper I).

We model the optical/UV radiation as a local black body radiation from a geometrically thin, relativistic accretion disc (Page & Thorne 1974). Relativistic effects are included by using the GRTRANS ray tracing code (Dexter 2016). For simplicity, we assume a Schwarzschild BH with fixed $M_{\mathrm{BH}} = 10^8 M_\odot$ and $i = 15°$ and fit for $\dot{M}$ at each epoch. The best fitting models with $\dot{M} \simeq 0.004$ and $0.05 M_\odot\,\mathrm{yr}^{-1}$ are shown in Fig. 4. The simple model provides a satisfactory explanation for the change in SED shape, and the inferred factor $\simeq 10$ drop in $\dot{M}$ agrees with the observed decrease in $f_{2--10\,\mathrm{keV}}$.

The good agreement between a static disc model and the spectra with a difference of a factor $\simeq 10$ in luminosity implies that $L \sim T_{\mathrm{eff}}^4$ (equivalent to a constant inner radius). This relation is frequently seen in BH X-ray binaries (e.g., Davis et al. 2006), but previously has not been found in samples of AGN. Their spectra typically peak at $\lambda \simeq 1000$ Å (Laor & Davis 2014), close to our fit for Mrk 1018 in the bright phase ($T_{\mathrm{eff}} \sim 1300$ K). The

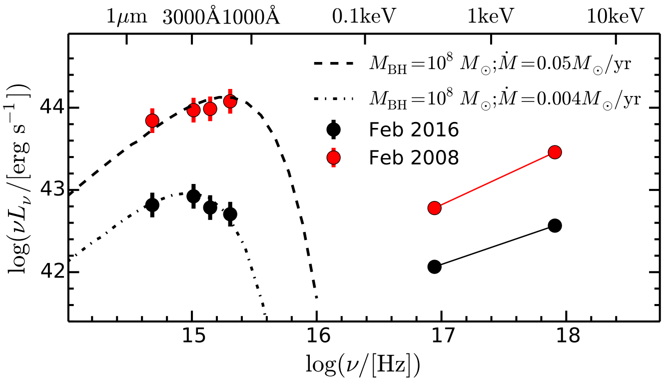

Fig. 4. Optical to X-ray SED for Mrk 1018 for two epochs. Shown are the photometry of the nucleus in the SDSS *r* and *u* band (see Paper I), the NUV and FUV from *GALEX* and *HST* observations as well as the unabsorbed power-law X-ray spectrum from *Chandra*. The black dashed line represents a model for a geometrically thin, relativistic accretion disc as described in the text.

drop to $T_{\rm eff}$ ~3 300 K, coincident with the decline in luminosity, provides strong evidence for an optically thick accretion disc.

Cutting the fuel supply of the accretion disc would propagate down to smaller radii on the inflow timescale, $\gtrsim 10^2$ years for the optical emitting region in AGN, much longer than in Mrk 1018. This timescale is however consistent with the disc thermal time, and thermal fluctuations can explain the optical/UV variability properties in AGN accretion discs (Kelly et al. 2009). For Mrk 1018 the thermal fluctuation would have to be global, decreasing the temperature across large parts of the disc rather than small patches (Dexter & Agol 2011).

3.3. What is the nature of the new Lyα NAL?

The most surprising result of our follow-up observations is the appearance of a new associated NAL in Lyα that was absent 20 years ago. While it appears natural that this feature is linked to the changing-look AGN event of Mrk 1018, it may also be completely unrelated. Below we discuss three potential scenarios for the origin of the NAL, but it may also be something unexpected.

Given the significant variability of the NAL strength and the radial motion of 700 km s^{-1} towards us, the first obvious possibility is that we see an outflow (e.g., Hamann et al. 2012). Assuming a constant outflow velocity implies a maximum distance of 0.01 pc, which is rather close to the nucleus. However, the background source may not be the accretion disc continuum, but the broad wing in Lyα which has larger surface area potentially reaching up to pc scales due to resonant scattering. The NAL could then originate from a much faster wind if it is slightly offset from the accretion disc along the line-of-sight with some inclination. The outflow scenario is attractive because it may be responsible for temporarily limiting the gas inflow by pushing gas outwards far beyond the outer disc. Disc winds seen in thermal states of BH X-ray binaries (e.g., Ponti et al. 2012) have estimated outflow rates comparable to or larger than the inflow rate. The appearing asymmetry towards the blue-side of Hα and Hβ as reported in Paper I could be a signature of some BLR clouds being pushed outwards which, however, needs to be confirmed via reverberation mapping techniques.

Another option is that the NAL is not from clouds associated with the accreting SMBH, but orbiting around a companion SMBH. This could explain the blueshift with pure gravitational motion if the approaching side of clouds around this second SMBH is just moving into our line-of-sight towards the accretion disc. Since Mrk 1018 is an advanced major merger such a binary SMBH scenario appears possible as speculated in Paper I. The appearing asymmetry towards of Hα and Hβ could also be signature of the gravitational interactions in the binary SMBH system as opposed to an outflow.

Alternatively, the new NAL may be simply produced by a fast-moving cloud being debris from the major merger. In this scenario the NAL would be disconnected from the accretion rate change. However, the speed of the cloud towards our line-of-sight would require a hyperbolic orbit around the SMBH.

4. Conclusions

Based on follow-up X-ray observations we rule out an obscuring cloud event as the cause for the change of type again after 30yrs as discovered in McElroy et al. (2016). All observations, in particular the optical-UV SED, are consistent with a declining accretion rate of a geometrically-thin, optically-thick accretion disc. Based on the appearance of a new NAL in Lyα we speculate whether the onset of an outflow or a putative binary SMBH system is driving instabilities in the accretion disc causing the declining luminosity. However, the NAL could also be completely unrelated to the accretion disc changes. Continuous monitoring from the radio to X-rays is needed to further constrain the nature of the dramatic changes at the heart of the nucleus.

Acknowledgements. GRT acknowledges support from the NASA through Einstein Postdoctoral Fellowship Award Number PF-150128, issued by the Chandra X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of NASA under contract NAS8-03060. MK acknowledges support by DFG grant KR 3338/3-1. MAPT acknowledges support from the Spanish MINECO through grants AYA2012-38491-C02-02 and AYA2015-63939-C2-1-P. TAD acknowledges support from a Science and Technology Facilities Council Ernest Rutherford Fellowship. Parts of this research were conducted by the Australian Research Council Centre of Excellence for All-sky Astrophysics (CAASTRO), through project number CE110001020.

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