Insight into “Changing-look” AGN Mrk 1018 from the Fe Kα Line: The Reprocessing Gas Has Yet to Fully Respond to the Fading of the AGN

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Abstract

Mrk 1018 is a “changing-look” active galactic nucleus (AGN) whose optical spectrum transitioned from a Type 1.9 to a Type 1 between 1979 and 1984, and then back to a Type 1.9 in 2015. This latest transition was accompanied by a decrease in X-ray flux. We analyze the Chandra spectra from 2010 and 2016 and NuSTAR spectra from 2016, with a careful treatment of pileup in the Chandra spectrum from 2010, and self-consistently model absorption, reflection, and Fe Kα line emission in the X-ray spectra from 2016. We demonstrate that while the 2–10 keV X-ray flux decreased by an order of magnitude \((1.46^{+0.10}_{-0.11} \times 10^{-11} - 1.31^{+0.09}_{-0.10} \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2})\), the Fe Kα equivalent width (EW) increased from \(0.18^{+0.12}_{-0.11}\) to \(0.61^{+0.27}_{-0.24}\) keV due to a depressed AGN continuum. We jointly fit the Chandra and NuSTAR spectra from 2016 using the physically motivated MYTorus model, and find that the torus orientation is consistent with a face-on geometry and that lines of sight intersecting the torus are ruled out. While we measure no line-of-sight absorption, we do measure a column density of \(N_{\text{H}} = 5.38^{+1.40}_{-1.38} \times 10^{22} \text{cm}^{-2}\) for gas out of the line of sight that reprocesses the X-ray emission. We find a high relative normalization between the Compton-scattered emission and transmitted continuum, which is indicative of time lags between the primary X-ray source and reprocessing gas. We predict that the Fe Kα line will respond to the decrease in AGN flux, which would manifest as a decrease in the Fe Kα EW.

Key words: galaxies: Seyfert – X-rays: individual (Mrk 1018)

1. Introduction

Active galactic nuclei (AGNs) are powered by accretion onto a supermassive black hole and liberate energy that shapes their surroundings. In a hot corona near the accretion disk, optical and ultraviolet photons are Compton upscattered to X-ray energies. Gas near the black hole, which is photoionized by accretion disk photons, orbits rapidly, thus imprinting Doppler broadened lines on the optical spectrum. Slower moving gas hundreds to thousands of parsecs away can still be energized by the accretion disk, which produces prominent narrow emission lines in optical spectra (Baldwin et al. 1981). In some AGN, both broad and narrow spectral emission lines are observed (Type 1), while only narrow emission lines are observed in others (Type 2). According to the AGN unification model (Antonucci 1993; Urry & Padovani 1995), a parsec-scale torus of dust and gas enshrouds the central engine such that the line of sight to this system determines whether or not broad lines are visible. This obscuring material can have a sufficiently high column density (i.e., \(N_{\text{H}} > 10^{20} \text{ cm}^{-2}\)) that can affect even powerful X-ray emission.

However, the unified model fails to explain the spectral states of some AGN. So-called “changing-look” AGNs are sources that have transitioned optical spectral type, from Type 1 to intermediate types (Type 1.8 and 1.9) to Type 2, or vice versa (Tohline & Osterbrock 1976; Penston & Perez 1984; Tran et al. 1992). Changes in the X-ray emission have been observed in other AGN (Risaliti et al. 2009, 2011; Ricci et al. 2016), and are sometimes accompanied by optical spectroscopic transitions (Shappee et al. 2014). Though some of these sources can be explained by the passage of occulting clouds in concordance with the unified model (e.g., Storchi-Bergmann et al. 1993; Goodrich 1995; Risaliti et al. 2009, 2011), others are more likely triggered by a change in the ionizing power emanating from the accretion disk (LaMassa et al. 2015; Merloni et al. 2015; MacLeod et al. 2016; Ruan et al. 2016; Runnoe et al. 2016).

Mrk 1018 is a particularly interesting changing-look AGN as it is one of only four sources known to have transitioned across the spectral sequence twice (Aretxaga et al. 1999; Denney et al. 2014; MacLeod et al. 2016). Cohen et al. (1986) reported that Mrk 1018 changed from a Type 1.9 to Type 1 between 1979 and 1984. More recently, McElroy et al. (2016) discovered that Mrk 1018 returned to the Type 1.9 state, with the broad lines disappearing between 2009 and 2015. An analysis of the optical spectrum suggested that a decrease in the accretion rate was responsible for the spectral transition. The X-ray properties of this source were reported in Husemann et al. (2016) where they demonstrated that the observed 2–10 keV flux decreased by a factor of 7.5 between a Chandra spectrum from 2010, and self-consistently model absorption, reflection, and Fe Kα line emission in the X-ray spectra from 2016. We jointly fit the Chandra and NuSTAR spectra from 2016 using the physically motivated MYTorus model, and find that the torus orientation is consistent with a face-on geometry and that lines of sight intersecting the torus are ruled out. While we measure no line-of-sight absorption, we do measure a column density of \(N_{\text{H}} = 5.38^{+1.40}_{-1.38} \times 10^{22} \text{cm}^{-2}\) for gas out of the line of sight that reprocesses the X-ray emission. We find a high relative normalization between the Compton-scattered emission and transmitted continuum, which is indicative of time lags between the primary X-ray source and reprocessing gas. We predict that the Fe Kα line will respond to the decrease in AGN flux, which would manifest as a decrease in the Fe Kα EW.
Here we revisit the analysis of the *Chandra* and *NuSTAR* spectra of Mrk 1018 because column densities that are derived via absorbed single power-law fits to X-ray spectra can be unreliable (Turner et al. 1997a, 1997b; Panessa et al. 2006; LaMassa et al. 2009, 2011). We first examine the *Chandra* spectra from 2010 and 2016, where we carefully account for the effects of pileup (a phenomenon where two X-ray photons are read as a single event in bright sources) in the *Chandra* spectrum from 2010. From this exercise, we measure the Fe Kα equivalent width (EW) from both epochs of X-ray observations because an increase in the EW may signal an increase in the line-of-sight obscuration (Krolik & Kallman 1987; Ghisellini et al. 1994; Turner et al. 1997b; Levenson et al. 2002) while the Fe Kα line photons form within the obscuring medium, the transmitted continuum (against which the line is measured) is suppressed. However, time delays between the continuum and the gas reprocessing the X-ray emission can also conspire to boost the Fe Kα EW. We then self-consistently model the transmitted, reflected, and Fe Kα emission from the *Chandra* and *NuSTAR* spectra in 2016 using the physically motivated MYTorus model (Murphy & Yaqoob 2009). From this modeling, we measure the column density of the gas responsible for reprocessing the X-ray emission and gain insight into the physical processes that drive the observed change in X-ray flux.

### 2. Data Analysis

#### 2.1. Chandra Data Reduction

Mrk 1018 was first observed on 2010 November 27 for 23 ks (PI: Mushotzky; ObsID: 12868) with a 1/8 subarray (frame time = 0.4 s) with the ACIS-S detector. Pursuant to the discovery of the optical spectroscopic transition, it was re-observed under a Director Discretionary Time request on 2016 February 6 for 27 ks (PI: Tremblay; ObsID: 18789), with the same set-up as the observation from 2010. We reduced both spectra with CIAO v4.8 and with CALDB v. 4.7.2. We used the CIAO task CHANDRA_REPRO to produce a filtered level 2 events file with the latest calibration files.

The *Chandra* spectra from both epochs of observations were extracted with the CIAO routine SPECEXTRACT. Due to the high count-rate from Mrk 1018 in 2010 (~2.4 counts s⁻¹), the first spectrum was heavily affected by pileup, which occurs when two or more photons are recorded as a single event by the charged-coupled device (CCD) detector. This results in an under-sampling of the point-spread function and a flattening of the spectrum. For piled-up sources, it is recommended that the spectrum be extracted from a 2″ radius, which corresponds to 4 ACIS pixels (Davis 2001). As the latter observation was not piled, we extracted the spectrum with a 3″ radius to encompass all the flux from the source. For both observations, we extracted the background spectrum from an annulus around the source with an inner radius of 5″ and outer radius 15″. The data were grouped with a minimum of 15 counts per bin.

#### 2.2. NuSTAR Data Reduction

*NuSTAR* is a focusing hard X-ray telescope with two co-aligned focal plane modules (FPMA and FPMB) that provide coverage from 3 to 79 keV (Harrison et al. 2013). Mrk 1018 was observed by *NuSTAR* in 2016 February 10 for 21 ks as part of the Extended Groth Strip extragalactic survey. Using NuSTARDAS v1.6.0, we ran NUPipeline to produce filtered events files. From these files, we extracted the source spectrum from a 45° radius using the NUPRODUCT task; the background was extracted from a source-free region on the detector. We extracted spectra separately from FPMA and FPMB, and grouped by a minimum of 15 counts per bin.

In the spectral modeling below, all errors are reported at the 90% confidence level.

### 3. Results

#### 3.1. Accounting for Pileup in the Chandra Spectrum from 2010

In the *Chandra* spectrum from 2016, Fe Kα emission at 6.4 keV (rest-frame) is visually apparent although it is not as discernible in the observation from 2010 (Figure 1, top panel). However, we can test whether this feature may be present in the earlier epoch observation by modeling the *Chandra* spectrum phenomenologically. In SHERPA, we modeled the spectrum with a power law to account for the AGN continuum, added a Gaussian component at the energy of the Fe Kα emission line, and included the JDPILEUP model to correct for the effects of pileup.4 From this exercise, we find an Fe Kα flux of $2.8_{-1.9}^{+2.6} \times 10^{-5}$ photons s⁻¹ cm⁻², with an EW of $0.18_{-0.12}^{+0.17}$ keV.

Is the Fe Kα flux consistent with that from the 2016 observation, given the effects of pileup on the former observation? To test this, we fitted the *Chandra* spectrum from 2016 with the same phenomenological model as above, sans the pile-up model. We note that the Fe Kα EW significantly increased during this second epoch observation (0.61±0.25 keV). Although the line flux is somewhat lower ($8.9_{-3.6}^{+3.9} \times 10^{-6}$ photons s⁻¹ cm⁻²), it is consistent with the value measured in 2010, given the uncertainties on the measurements.

We then set-up a toy model to describe the *Chandra* spectrum from 2010 assuming the same Fe Kα line strength that was observed in 2016. We used the best-fit power-law parameters that were returned from fitting the 2010 spectrum to describe the AGN continuum in its bright state, plus the Gaussian parameters from fitting the 2016 spectrum to mimic the Fe Kα emission observed in the faint state (see Table 1). We ran *Chandra* ray trace simulations with MARX (Davis et al. 2012) to produce a simulated *Chandra* ACIS-S image of this model description. Using MARXPILEUP, we simulated an events file that accounts for the effects of pileup and extracted a spectrum from this simulated image.

We fitted this simulated spectrum with the same phenomenological model we used when fitting the spectrum from 2010 (i.e., POWERLAW + GAUSS + JDPILEUP). We found an Fe Kα flux of $1.8_{-1.4}^{+2.2} \times 10^{-5}$ photons s⁻¹ cm⁻², which is consistent with the flux we measured from the earlier epoch *Chandra* spectrum (as well as the latter epoch *Chandra* spectrum), and an EW more akin to that from 2010 instead of 2016.

We thus conclude that the enhanced EW from the observation in 2016 is not due to an increase in the Fe Kα flux, but rather a decrease in the observed AGN continuum. This effect can be caused by: (i) the AGN flux dimming, or (ii) an occulting cloud.

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4 The only free parameters in the JDPILEUP model are α, which parameterizes the grade migration and gives the probability that a piled event is not rejected by the spacecraft software and f, which is the fraction of events to which the pile-up model will be applied. See [http://cxc.harvard.edu/ciao/download/doc/pileup_abc.pdf](http://cxc.harvard.edu/ciao/download/doc/pileup_abc.pdf) for more information.
with sufficient column density \(N_H > 10^{22} \text{ cm}^{-2}\) to block a significant portion of the transmitted light.

3.2. Increase in Obscuration or Decrease in AGN Power?

From our phenomenological modeling, we find that the hard X-ray (2–10 keV) flux decreased by an order of magnitude between epochs, from \(1.46 \pm 0.10 \times 10^{-11}\) to \(1.31 \pm 0.09 \times 10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\), which is a more significant drop than that found by Husemann et al. (2016). They found a lower hard X-ray flux from the bright state spectrum \((9.2 \pm 0.2) \times 10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\)) than we did—which is likely due to the different methods employed to deal with pileup on the Chandra spectrum. They thus find a lower decline in the hard X-ray flux (factor of 7.5).

To gain insight as to whether the drop in X-ray flux is due to obscuration, we fit the Chandra spectrum from 2016 with the NuSTAR FPMA and FPMB spectra in XSPEC using the physically motivated MYTorus model, which self-consistently fits the transmitted AGN continuum, reflected emission, and fluorescent Fe Kα and Fe Kβ emission lines. In the MYTorus model, the X-ray reprocessor takes the form of a uniform torus (in the default mode) with a fixed opening angle of 60°. With an inclination angle greater than 60°, the line of sight intersects the torus. An inclination angle of 0° is face-on such that there is no absorption along the line of sight, and yet reprocessing still occurs in the circumnuclear medium, which shapes the X-ray spectrum we observe. A schematic of this model is:

\[
\text{model} = \text{MYTorusZ} \times \text{powerlaw} + A_s \times (\text{MYTorusS} + \text{MYTorusL}),
\]

where the power law describes the intrinsic AGN emission, MYTorusSZ represents the line-of-sight attenuation, MYTorusS describes the Compton-scattered emission, MYTorusL accounts for the fluorescent line emission, and \(A_s\) is the relative normalization between the Compton-scattered emission with respect to the transmitted continuum. This normalization constant encompasses several unknown quantities, which includes time delays between the transmitted continuum and

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Footnote 5: Here we assume the Fe Kα line is not resolved.
Gauss normal-
fraction of 30%,
spectrum with a POWERLAW Gaussian model parameters from the dim state. We spectral resolution.
and Chandra MYTorus model setup. We include a constant factor in the scattered and line emission, different torus half opening angles, and/or elemental abundances than those assumed in the MYTorus model setup. We include a constant factor in the model to account for cross-calibration normalizations between Chandra and NuSTAR.

We begin by keeping $A_S$ frozen to the default value of unity as this is often an adequate description of X-ray spectra of AGN (Yaqoob 2012; LaMassa et al. 2014). We find that the inclination angle is constrained to be under 60°, indicating that our line of sight does not intercept the torus. As the exact value of the inclination angle is otherwise unconstrained, we freeze it to 0°, which is consistent with a face-on geometry. As Figure 2 depicits, we obtain a good fit to the global spectrum ($\chi^2 = 245.4$ for 271 degrees of freedom), but fail to accurately model the Fe Kα line.

We then allow the relative normalization between the transmitted and Compton-scattered components to be a free parameter. As shown in Figure 3, the Fe Kα emission line is now well modeled, and according to the $f$-test, the improvement to the fit is statistically significant ($P = 0.0001$). Again, we find that the inclination angle is below 60°, which indicates that the gas reprocessing the X-ray emission does not intersect our line of sight. This result confirms the findings of Husemann et al. (2016) who did not find line-of-sight absorption. However, the global medium (out of the line of sight) has a measurable, non-zero column density of $5.38^{+4.0}_{-3.0} \times 10^{22} \text{ cm}^{-2}$ (see Table 2). We note that the exact value of the column density also depends on the iron abundance. However, as MYTorus assumes a fixed iron abundance of solar, we are unable to test the effects of varying the iron abundance on $N_{\text{H}}$.

In order to achieve this acceptable fit to both the global spectrum and the Fe Kα line, the relative normalization of the Compton-scattered emission was forced to a remarkably high value. In Figure 4, we show the two-parameter confidence contours of $A_S$ and $N_{\text{H}}$, where $A_S$ is constrained to be over 3 at the 99% confidence level. Although $A_S$ encapsulates our ignorance of several unknown parameters, time delays between the continuum and the scattering medium would play the biggest role in boosting $A_S$ to such a high level.

Finally, we test whether we can measure an upper limit to the column density along the line of sight. To measure a line-of-sight $N_{\text{H}}$ that is independent from the circumnuclear gas out of the line of sight that produces the Fe Kα emission, we run MYTorus in “decoupled mode.” Here, the MYTORUS and MYTORUSL components have an inclination angle fixed at 0°, which mimicks a face-on torus. The transmitted continuum that is potentially attenuated by line-of-sight absorption is generally represented by MYTORUSZ in the decoupled realization of the model. However, since this model component has a lower limit of $N_{\text{H}} = 10^{22} \text{ cm}^{-2}$, which we find to be too high for this source, we replace this component with ZPHABS; as Compton-scattering does not appreciably affect the spectrum at column densities below $10^{22} \text{ cm}^{-2}$, this swap does not affect the self-consistency of the model. From this exercise, we find that the line-of-sight column density is below $3 \times 10^{20} \text{ cm}^{-2}$ at the 90% confidence level, which is consistent with being X-ray unabsorbed along the line of sight.

We thus conclude that the increase in the Fe Kα EW between 2010 and 2016 is due to a precipitous drop in the AGN continuum. The gas responsible for reprocessing the X-ray emission has not yet fully responded to this change. However, McElroy et al. (2016) demonstrated that the mid-infrared Widefield Infrared Survey Explorer (WISE) flux of this source at 3.4 and 4.6 μm, ascribed to torus emission, decreased between 2010 and 2015. Although the Fe Kα line flux between 2010 and 2016 is consistent given the errors, the nominal flux is lower during the second epoch, which hints that the X-ray reprocessing gas is starting to respond to the change from the central engine, which is consistent with the mid-infrared variability. Additionally, the dusty torus and X-ray reprocessing gas can span different size scales, which leads to differential time lags with respect to the direct continuum. If this interpretation is correct, we expect that the Fe Kα EW will decrease over time. Continued monitoring of this source will reveal whether the Fe Kα EW responds, and will provide insight into the size of the reprocessing region and how it

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**Table 1**

| Parameter | 2010 Observation | 2016 Observation | Simulated Spectrum |
|-----------|-----------------|-----------------|--------------------|
| $\Gamma$  | $1.97^{+0.03}_{-0.04}$ | $1.66^{+0.06}_{-0.05}$ | $1.94^{+0.05}_{-0.05}$ |
| Power-law Normalization ($10^{-5}$) | $5.4^{+0.4}_{-0.3}$ | $0.30^{+0.02}_{-0.01}$ | $4.2^{+2.2}_{-1.0}$ |
| Gauss $E$ | $6.37^{+0.05}_{-0.06}$ | $6.42^{+0.11}_{-0.10}$ | $6.30^{+0.14}_{-0.14}$ |
| Gauss $\sigma$ | $0.01^{+0.01}_{-0.00}$ | $0.16^{+0.04}_{-0.04}$ | $<0.13$ |
| Gauss normal- | $2.8^{+2.6}_{-1.9}$ | $0.89^{+0.09}_{-0.07}$ | $1.8^{+2.3}_{-1.4}$ |
| $N_{\text{Fe Kα Flux}}$ ($10^{-13}$ erg s$^{-1}$ cm$^{-2}$) | $2.6^{+0.7}_{-0.8}$ | $0.86^{+0.38}_{-0.36}$ | $1.7^{+2.0}_{-1.3}$ |
| $N_{\text{Fe Kα EW (keV)}}$ | $0.18^{+0.17}_{-0.12}$ | $0.61^{+0.27}_{-0.25}$ | $0.12^{+0.14}_{-0.09}$ |

**Notes.**

a This model also included a JDPILEUP component, where we found a pile-up fraction of 30%, $\alpha = 0.56^{+0.03}_{-0.02}$, and $f = 0.927^{+0.020}_{-0.010}$.

b Our toy model where the AGN continuum is described by the power-law fit parameters from the bright state and the Fe Kα line emission is set by the Gaussian model parameters from the dim state. We fitted this simulated spectrum with a POWERLAW + GAUSSIAN + PILEUP MODEL.

c Power-law normalization in units of photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.

d Rest-frame energy.

e Frozen to a lower limit of 0.01 keV, which is several times lower than the Chandra spectral resolution.

f Total photons cm$^{-2}$ s$^{-1}$ in line.

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**Table 2**

| MYTorus Fit Parameters | Value |
|------------------------|-------|
| $\Gamma$ | $1.76^{+0.06}_{-0.06}$ |
| Power law Normalization ($10^{-5}$) | $3.03^{+0.13}_{-0.17}$ |
| $N_{\text{H}}$ ($10^{22}$ cm$^{-2}$) | $5.38^{+4.0}_{-3.0}$ |
| $\chi^2$ (dof) | 232.5 (270) |

**Note.**

a Normalization in units of photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.
relates to the geometric structure of the dusty torus based on the time delay of this response.

4. Conclusions

We have undertaken a rigorous analysis of the Chandra and NuSTAR spectra of the changing-look AGN Mrk 1018 to determine the cause of the reported decrease in X-ray flux (Husemann et al. 2016). We modeled the effects of pileup on the Chandra spectrum from 2010 to assess, as accurately as possible, the intrinsic AGN power-law continuum during the bright state of Mrk 1018. We used a phenomenological model to fit the Chandra spectra from 2010 and 2016, where we included a Gaussian component for Fe Kα line emission. From this exercise, we demonstrated that the Fe Kα EW increased from $0.18 \pm 0.12$ to $0.61 \pm 0.27$ keV between 2010 and 2016.

To test whether the Fe Kα line flux was consistent between epochs—such that we can attribute the change in the EW to suppression of the continuum—we used the Chandra ray-tracing simulator MARX to account for the effects of pileup on the spectrum. Here, we set-up a toy model to describe the AGN
spectrum from 2010, where the AGN continuum (i.e., power law) represents that which we measured when fitting the spectrum from 2010 with the JDPILEUP model and the Fe Kα line flux matches which we measured from the Chandra spectrum in 2016. When simulating a source with this spectrum in MARX, including the effects of pileup, we find an Fe Kα flux consistent with that which we measured from the Chandra 2010 spectrum. We thus conclude that the variation in the Fe Kα EW is due to attenuation of the continuum and not an increase in the line flux.

We jointly fitted the Chandra spectrum from 2016 with the NuSTAR spectra from 2016 using the MYTorus model (Murphy & Yaqoob 2009), which self-consistently models the transmitted, Compton-scattered, and fluorescent line emission in obscured AGN. This model indicates that the orientation of the circumnuclear obscuration is consistent with a face-on geometry, i.e., power-law decline in the Fe Kα line that formed within the X-ray reprocessing gas still has flux from the AGN continuum.

Although mid-infrared emission from this source shows a decline (McElroy et al. 2016), which is consistent with the dusty torus starting to respond to the fading of the AGN, the Fe Kα line that formed within the X-ray reprocessing gas still has to catch-up to this change, which would manifest as a decrease in the Fe Kα EW. The timescale of this change would indicate the distance to the X-ray reprocessing gas and how it relates to the dusty torus.

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Facilities: CXC, NuSTAR.

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