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10 Yr Transformation of the Obscuring Wind in NGC 5548

Missagh Mehdipour¹ , Gerard A. Kriss¹ , Elisa Costantini^{2,3} , Liyi Gu^{2,4,5} , Jelle S. Kaastra^{2,5} , Hermine Landt⁶, and Junjie Mao^{2,7}

¹ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; mmehdipour@stsci.edu

² SRON Netherlands Institute for Space Research, Niels Bohrweg 4, 2333 CA Leiden, The Netherlands

³ Anton Pannekoek Institute, University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands

⁴ RIKEN High Energy Astrophysics Laboratory, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

⁵ Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands

⁶ Centre for Extragalactic Astronomy, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK

⁷ Department of Astronomy, Tsinghua University, Haidian DS 100084, Beijing, People's Republic of China

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Abstract

A decade ago, the archetypal Seyfert-1 galaxy NGC 5548 was discovered to have undergone major spectral changes. The soft X-ray flux had dropped by a factor of 30 while new broad and blueshifted UV absorption lines appeared. This was explained by the emergence of a new obscuring wind from the accretion disk. Here we report on the striking long-term variability of the obscuring disk wind in NGC 5548 including new observations taken in 2021–2022 with the Swift Observatory and the Hubble Space Telescope's Cosmic Origins Spectrograph. The X-ray spectral hardening as a result of obscuration has declined over the years, reaching its lowest in 2022, at which point we find the broad C IV UV absorption line to have nearly vanished. The associated narrow low-ionization UV absorption lines, produced previously when shielded from the X-rays, are also remarkably diminished in 2022. We find a highly significant correlation between the variabilities of the X-ray hardening and the equivalent width of the broad C IV absorption line, demonstrating that X-ray obscuration is inherently linked to disk winds. We derive for the first time a relation between the X-ray and UV covering fractions of the obscuring wind using its long-term evolution. The diminished X-ray obscuration and UV absorption are likely caused by an increasingly intermittent supply of outflowing streams from the accretion disk. This results in growing gaps and interstices in the clumpy disk wind, thereby reducing its covering fractions.

Unified Astronomy Thesaurus concepts: [Accretion \(14\)](#); [Active galactic nuclei \(16\)](#); [Broad-absorption line quasar \(183\)](#); [High resolution spectroscopy \(2096\)](#); [X-ray active galactic nuclei \(2035\)](#)

1. Introduction

Winds in active galactic nuclei (AGNs) bridge the supermassive black holes (SMBHs) to their environment. They transport mass and energy away from the central engine and into the host galaxy of the AGN. This injection of momentum and energy can have important implications for the co-evolution of SMBHs and galaxies through the resulting feedback mechanism between the AGN activity and star formation (e.g., King & Pounds 2015; Gaspari & Sądowski 2017; Harrison et al. 2018). Thus, ascertaining the physical properties and energetics of different types of AGN winds, and understanding how they are launched and driven, is important for determining their role and impact on AGN feedback.

Bright Seyfert-1 galaxies are useful laboratories for ascertaining the physical structure of AGN winds. Most notably, NGC 5548 has been at the forefront of discoveries. The first X-ray absorption lines of “warm-absorber outflows” were found in NGC 5548 with Chandra soon after its launch (Kaastra et al. 2000). At that epoch, this archetypal Seyfert-1 galaxy was in its usual X-ray-bright state. Thirteen years later, in 2013, a large multiwavelength campaign, including XMM-Newton, NuSTAR, Swift, and HST, was performed on NGC 5548 for a comprehensive mapping of its warm absorber. However, unexpectedly, NGC 5548 was discovered to have

become obscured in the X-rays (Kaastra et al. 2014; Mehdipour et al. 2015) while new UV absorption lines, such as broad C IV and narrow C II lines, were found in the HST/Cosmic Origins Spectrograph (COS) spectra (Arav et al. 2015; Kriss et al. 2019a). Also, pronounced soft X-ray emission lines stood out above the obscured X-ray continuum of NGC 5548 (Kaastra et al. 2014; Mao et al. 2018), reminiscent of the X-ray spectra of Seyfert-2 galaxies, such as NGC 1068 (Grafton-Waters et al. 2021). Studies of this new state of NGC 5548 showed that the central X-ray source is being obscured by a massive stream of outflowing gas in the vicinity of the accretion disk, extending to and beyond the broad-line region (BLR). This is referred to as an “obscuring disk wind,” or “obscurer” for short.

While obscuration is generally associated with Type 2 AGNs and broad-absorption lines (BALs) are typically found in powerful BAL quasars, NGC 5548 showed their presence together in a Seyfert-1 galaxy. Interestingly, in quasars, such shielding of the UV-absorbing gas from the ionizing X-ray source is required in order to facilitate radiative driving of their outflows (Proga & Kallman 2004). However, the potential role of this X-ray shielding in radiation-driven winds remains debatable in the literature: The hydrodynamical simulation study of Higginbottom et al. (2014) finds that the shielding may not be effective in keeping the outer UV absorbers from being overionized because of reprocessing and scattering of the ionizing X-rays, and the study of BAL quasars by Luo et al. (2014) suggests that they are intrinsically X-ray faint and do not need shielding to drive winds.



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The obscuring wind in NGC 5548 shields the warm-absorber outflows that are located farther out in the torus region and the narrow-line region (NLR), causing them to become less ionized (Arav et al. 2015; Kriss et al. 2019a). This is evident from the appearance of new low-ionization narrow absorption lines, such as C II in the UV (Arav et al. 2015) and He I in the infrared (Wildy et al. 2021). The effects of obscuration in NGC 5548 are not limited only to the line-of-sight absorption. Extraordinary periods of decorrelation between the variabilities of the UV continuum and the BLR emission lines were found in NGC 5548 (Goat et al. 2016). This has been explained as a consequence of global obscuration in all directions, shielding the BLR from the ionizing source (Dehghanian et al. 2019b). Thus, the obscurer in NGC 5548 alters the ionization state of both the warm-absorber outflows (Dehghanian et al. 2019a) and the BLR (Dehghanian et al. 2019b), impacting our interpretation of their characteristics and variability. The transient nature of the obscuring disk wind in the BLR and the persistent nature of the warm absorber in the NLR suggests that these outflows are not physically connected at the epoch of the observations. However, the origin and formation history of the warm absorbers, and whether or not they are disk winds, are still open questions.

The Swift Observatory has played an instrumental role in the studies of obscuring winds in NGC 5548 (Mehdipour et al. 2016) and other AGNs. Swift monitoring searches have led to target-of-opportunity observations with XMM-Newton, NuSTAR, and HST in additional Seyfert-1 galaxies, including NGC 3783 (Mehdipour et al. 2017; Kriss et al. 2019b) and NGC 3227 (Mehdipour et al. 2021; Mao et al. 2022). There are, however, puzzling differences between the characteristics of the obscuring winds in NGC 5548 and other AGNs. The obscurer in NGC 5548 has been continuously present for one decade, since at least 2012 February in Swift data (Mehdipour et al. 2016) and 2011 June in HST/COS data (Kaastra et al. 2014). However, in other targets, the obscuration is seen to be a transient event lasting weeks/months (Kaastra et al. 2018). It is currently uncertain what physical factors govern the occurrence and the duty cycle of the obscuration events. Also, the UV absorption counterpart of the X-ray obscuration is not always detected, such as in NGC 3227 (Mao et al. 2022). It is unclear whether this is due to ionization or geometrical effects. Thus, a general understanding of the relation between X-ray obscuration and UV absorption is yet to be achieved. NGC 5548, with its extensive database and comprehensive studies, is a pivotal target for advancing further our understanding of the obscuring winds in AGNs.

A key measurement from Swift monitoring is the X-ray hardness ratio (R), defined as $R = (H - S)/(H + S)$, where H and S are the Swift X-ray Telescope (XRT) count rates in the hard (1.5–10 keV) and soft (0.3–1.5 keV) bands, respectively. The hardness ratio R is a useful tracer of X-ray obscuration. The study of Mehdipour et al. (2016) showed that R variability in NGC 5548 is directly related to changes in the X-ray covering fraction (C_X) of the obscurer. Figure 1 shows the Swift R lightcurve of NGC 5548 spanning from its first observation in April 2005 to the latest one in April 2022. The data suggest long-term obscuration changes, declining in recent years. To further investigate the disk wind evolution and ascertain the relation between its X-ray obscuration and UV absorption, we obtained new spectra in 2021–2022, which are described in the following section.

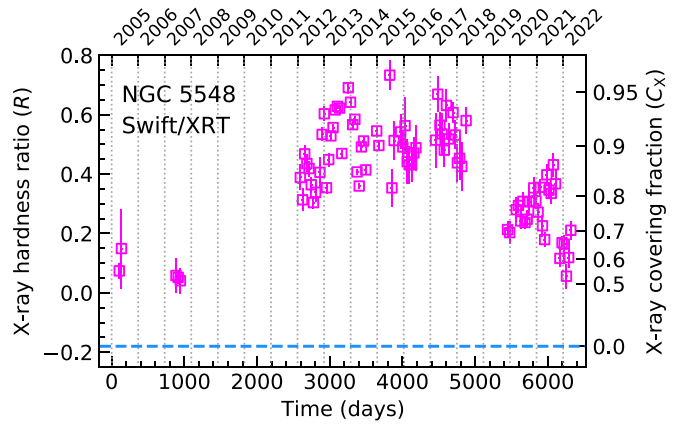


Figure 1. Swift/XRT hardness ratio (R) lightcurve of NGC 5548. It spans from 2005 April to 2022 April with a time binning of one month. Vertical dotted lines are drawn on the first day of each calendar year for reference. For data since 2012, the corresponding X-ray covering fraction (C_X) of the obscuring wind is shown on the right axis. The 2005 and 2007 data are not obscured (see Section 3). The horizontal dashed line is drawn at R with zero obscuration ($C_X = 0$) derived from the 2002 unobscured Chandra spectrum. The long-term rise and decline of the obscuration are evident.

2. New Observations

Our new HST/COS observations of NGC 5548 (ID: 16842) were taken on 2021 December 30 (1 orbit) and 2022 January 31 (1 orbit). The data can be accessed via [10.17909/4p21-1m98](https://archive.stsci.edu/hst/cos/16842). Each visit used the G130M and G160M gratings to measure the Ly α and C IV lines. The spectra from the two visits are very similar. The COS data were processed with the latest calibration pipeline, CalCOS v3.3.11. The Swift/XRT data products of NGC 5548 are obtained from the UK Swift Science Data Centre tools (Evans et al. 2007, 2009) and prepared for modeling according to Mehdipour et al. (2016). The 2022 Swift/XRT data (15 ks) were used for producing a time-averaged X-ray spectrum for the current epoch. Also, new Chandra High Energy Transmission Grating (HETG) observations were taken for the spectroscopy of the Fe K α line and the warm absorber in the hard X-ray band, which will be presented separately in a future paper. To measure changes in the obscurer, which is the aim of this paper, the Swift/XRT spectrum is more suitable than HETG as it covers the full 0.3–10 keV band and has a higher signal-to-noise ratio (S/N).

To compare the new 2022 spectra with those from epochs of zero obscuration (2002) and strong obscuration (2013), as shown in Figure 2, we retrieved the following archival spectra: the 2002 HST Space Telescope Imaging Spectrograph (STIS) spectrum, the 2002 Chandra Low Energy Transmission Grating (LETG) spectrum, the 2013 HST/COS spectrum, and the 2013 Swift/XRT spectrum. These archival STIS, COS, and LETG spectra are taken from Kaastra et al. (2014), and the time-averaged 2013 XRT spectrum is produced following the procedure described in Mehdipour et al. (2016).

3. Modeling of the Obscuring Wind

In order to investigate any new changes in the parameters of the obscuring wind, we apply the spectral models that we derived in our previous X-ray (Mehdipour et al. 2016) and UV (Kriss et al. 2019a) studies of the obscurer in NGC 5548. This enables a uniform and consistent comparison of the parameters' variabilities, allowing us to examine the long-term evolution of the obscuring wind. The study of Mehdipour et al. (2016)

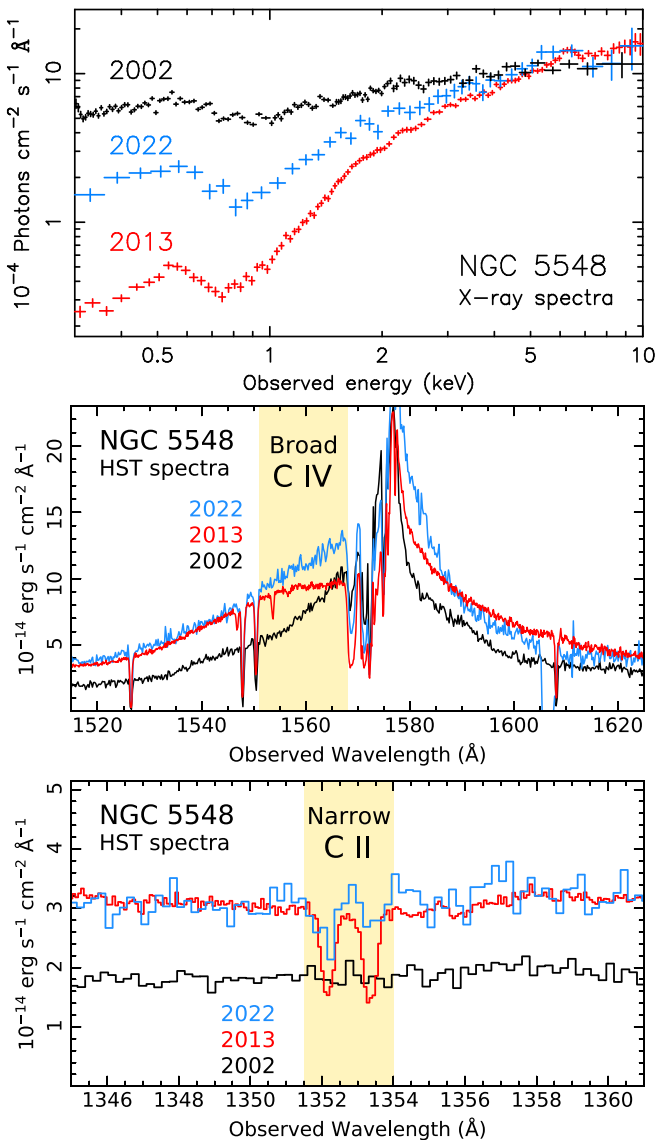


Figure 2. X-ray (top panel) and UV (middle and bottom panels) spectra of NGC 5548 taken at epochs of zero obscuration (2002), strong obscuration (2013), and diminished obscuration (2022). The 2002 spectra are from Chandra/LETG and HST/STIS. The 2013 and 2022 spectra are from Swift/XRT and HST/COS. The UV spectral regions of interest are highlighted in yellow. In 2022, the X-ray obscuration (top panel), the broad C IV absorption (middle panel), and the narrow C II absorption (bottom panel) are diminished together.

incorporated the continuum spectral energy distribution (SED) model of NGC 5548 from Mehdipour et al. (2015) and the models of Kaastra et al. (2014) for the warm absorber, the X-ray emission lines, and the X-ray obscurer to fit the Swift data. This modeling with the `SPEX` package (Kaastra et al. 1996, 2020) uses the `xabs` absorption model (de Plaa et al. 2004; Steenbrugge et al. 2005), which calculates both the photoionization solution and the X-ray spectrum, as described in Mehdipour et al. (2016) for modeling the Swift data. The X-ray covering fraction (C_X) is one of the parameters of the `xabs` model.

The total column density N_H of the warm absorber in the 2002 unobscured epoch is $1.2 \times 10^{22} \text{ cm}^{-2}$ (Kaastra et al. 2014). In the obscured epoch (i.e., 2012 onwards), new additional absorption by the obscurer with a total column density N_H of $1.1 \times 10^{23} \text{ cm}^{-2}$

appears (Kaastra et al. 2014). The spectroscopy and timing analysis of Mehdipour et al. (2016) examined the variability of different spectral components and their parameters in NGC 5548. It was found that the variability of the X-ray hardness ratio R is predominantly caused by changes in C_X of the obscurer providing good fits to all obscured data. Compared to the dominant C_X variability, the signature of any N_H variability is relatively too small for Swift measurements. Thus, adopting a constant obscurer N_H during the obscured epoch (2012 onwards), a relation expressing C_X as a function of R , was derived in Mehdipour et al. (2016): $C_X = 0.46 + 1.34R - 0.91R^2$. We use this relation to obtain the C_X of the obscurer for Swift data up to 2022.

In the R lightcurve of Figure 1, the corresponding C_X of the obscurer is shown on the right axis, which applies to the 2012–2022 obscured data. The earlier 2005 and 2007 Swift data are not obscured, but rather their X-ray continuum is intrinsically fainter and harder (Mehdipour et al. 2016; Detmers et al. 2008). We verified that the R – C_X relation is applicable to the recent Swift data because the C_X that is measured from fitting the 2022 Swift spectrum (Figure 2) matches the one given by the relation. Thus, the R – C_X relation is tried and tested for $0.5 < C_X < 1$.

The new HST/COS spectra were analyzed following the spectral modeling and method of Kriss et al. (2019a), where all HST/COS data prior to our 2022 observations are presented, including the lightcurve of the broad C IV absorber. The model consists of multiple Gaussian components for fitting the profile of each emission line, namely C IV and Ly α . The broad-absorption feature on the blue side of the emission line is fitted with Gaussian absorption components, accounting for the blending of the C IV doublet lines. The shift, width, and line ratios of the components are tied together in a physically consistent fashion. These broad UV absorption lines from optically thick gas are saturated. However, they do not appear as “black” lines because they partially cover the underlying UV radiation. The spectral fitting of the line profiles, described fully in Kriss et al. (2019a), yields the equivalent width (EW) and the corresponding covering fraction of the UV absorber, which is assumed to apply uniformly to the line and continuum emission. In Figure 3 the EW of the broad C IV absorber ($\text{EW}_{\text{C IV}}$) and its covering fraction (C_{UV}) are plotted versus the X-ray parameters R (top panel) and C_X (bottom panel). These data correspond to when contemporaneous HST/COS and Swift observations are available, which are taken in 2013, 2014, 2016, and 2022. Compared to the extended long-term monitoring with Swift (Figure 1), there is less coverage with HST over the years. A time bin size of one week is used to average the displayed data in Figure 3. Interestingly, we find highly significant correlations between the UV absorption and the X-ray obscuration parameters, which we discuss and interpret below.

4. Discussion and Conclusions

NGC 5548 is a key target for ascertaining the general characteristics of obscuring winds in AGNs. The long-term Swift monitoring of NGC 5548 shows that its X-ray hardness ratio R has gradually declined over the years, reaching a minimum in 2022 (Figure 1). Our study of the corresponding X-ray spectra finds that the long-term R decline is caused by a reduction in the X-ray absorption of the obscuring wind. The new Swift and HST/COS spectra (Figure 2) show that as the X-ray obscuration diminishes, the broad C IV absorber nearly

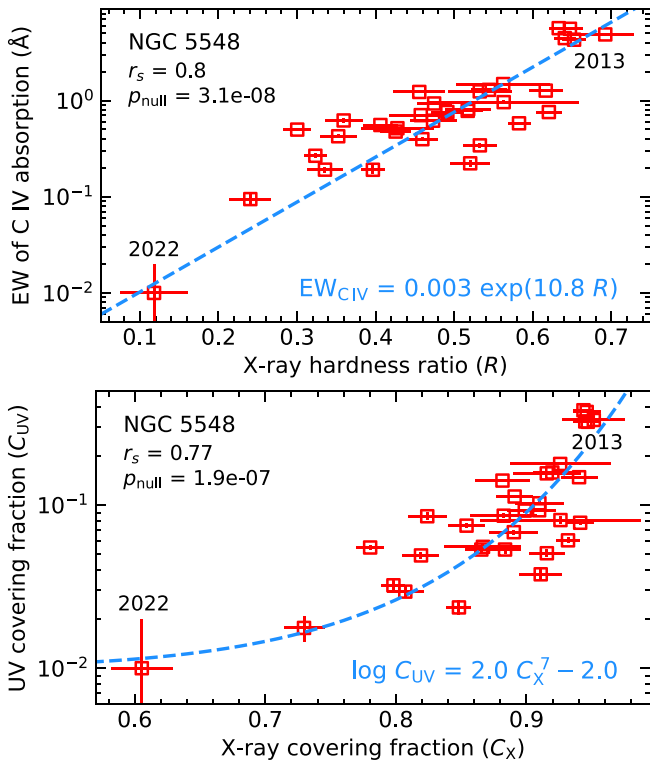


Figure 3. Top panel: relation between the equivalent width (EW) of the broad C IV UV absorption feature and the X-ray hardness ratio (R). Bottom panel: relation between the C IV UV covering fraction (C_{UV}) and the X-ray covering fraction (C_X) of the obscuring wind. Data correspond to contemporaneous Swift and HST/COS observations, taken in 2013, 2014, 2016, and 2022. A time bin size of one week is used to average the data. The Spearman's rank correlation coefficient (r_s) and the null hypothesis probability (p_{null}) are given in the inset, showing both relations are statistically highly significant. The best-fit function describing each relation is given in the inset and displayed as a dashed line.

vanishes, affirming their physical connection. This is while the intrinsic continuum (UV and hard X-rays) in 2013 and 2022 are very similar (Figure 2). Furthermore, the fact that the narrow C II absorption lines are diminished in the 2022 COS spectrum (Figure 2, bottom panel) demonstrates that the obscurer no longer extensively shields the warm absorber from the ionizing Lyman continuum.

Our long-term variability study of NGC 5548 reveals highly significant correlations between the broad C IV absorber and the parameters of the X-ray obscurer (Figure 3). We note that these UV/X-ray correlations, probing 2013–2022, remain statistically significant regardless of the time bin size. In Figure 3 the relation between EW_{CIV} and R is best represented by an exponential function, while a power law best describes $\log C_{UV}$ as a function of C_X . The functions are provided inset in the panels of Figure 3. These empirical relations between the UV and X-ray parameters are not simple linear relations because the observed parameters are the culmination of multiple inextricable aspects, such as the sizes of the X-ray and UV sources (in both the disk and the BLR), and the different lines of sight and their clumpiness toward the X-ray and UV sources. In other words, because of inhomogeneities in the wind and size differences of the UV and X-ray sources, the local properties of the gas responsible for the UV absorption are not necessarily identical to that responsible for the X-ray absorption. Nonetheless, the UV and X-ray parameters increase/decrease together. Our discovered

$EW_{CIV}-R$ and $C_{UV}-C_X$ relations in NGC 5548 support the premise that X-ray obscuration and UV BALs in AGNs are generally interconnected.

Apart from C IV, the broad Ly α absorption line also shows a correlation with the X-ray obscuration but with a smaller statistical significance ($r_s = 0.42$ and $p_{null} = 0.02$). We find that this weaker Ly α correlation results from the presence of a relatively constant component of the broad Ly α absorber in our line of sight. Thus, while in 2022 the C IV absorber nearly disappears, the Ly α absorber, as well as the X-ray obscuration, remain present. We explain this difference between C IV and Ly α through the clumpy nature of the wind, where higher-density (lower-ionization) zones are embedded in a lower-density (higher-ionization) medium. Because Ly α is more abundant than C IV and can originate from a wider range of ionizations, when the C IV absorption zone dissipates, the more expansive lower-density medium still produces Ly α and X-ray absorption, albeit at a diminished level. Similar behavior has been observed in the high-ionization absorption troughs of the BAL quasar SBS 1542+541, where the covering fractions of different broad-absorption lines increase with increasing ionization stage (Telfer et al. 1998). Furthermore, the clumpiness of such disk winds is supported by hydrodynamical simulations, which find that disk winds can become fragmented due to thermal instabilities as a result of intense X-ray irradiation (see, e.g., Waters et al. 2022).

Our long-term variability study of NGC 5548 shows that the C_X of the obscuring wind declined from about 0.95 in 2013 to as low as 0.5 in 2022, while C_{UV} dropped from 0.3 in 2013 to almost zero in 2022. Interestingly, the fact that the UV absorber nearly vanishes while X-ray obscuration is still substantial may explain why in some obscured Seyfert-1 galaxies no broad UV absorption counterpart was detected. In NGC 3227 (Mehdipour et al. 2021; Mao et al. 2022), obscuration with $C_X \sim 0.6$ was found without any significant broad UV absorption. In NGC 5548, when C_X is 0.6, C_{UV} is effectively negligible; see the $C_{UV}-C_X$ relation (Figure 3, bottom panel). At such C_{UV} , the broad UV absorber would have not been apparent in the lower-S/N spectrum of NGC 3227. Because the UV-radiating sources (disk and BLR) are much more extended than the compact X-ray source, a partially X-ray covering absorber may cover too little of the UV sources to produce detectable UV absorption.

A major difference between obscuration in NGC 5548 and in other Seyfert-1 galaxies, such as NGC 3783 and NGC 3227, has been the duration of the obscuration. In those AGNs, the transient obscuration lasts weeks/months; however, in NGC 5548 it has been continuously present for a decade, since at least 2012 February (Figure 1). This is likely because the obscuring wind in NGC 5548 is a much larger structure surrounding the disk (Dehghanian et al. 2019b). On short timescales (<few days), there are occasional blips when the X-ray obscuration and the broad UV absorption sharply diminish in NGC 5548 (Kriss et al. 2019a); however, they resume shortly after as inhomogeneities in the wind traverse in our line of sight. On the long timescales that we have explored in this paper, we see that the obscuration has been gradually evolving over the years, reaching a peak in strength in 2013–2017 and since then declining (Figure 1).

Our studies of the intrinsic continuum in NGC 5548 (Mehdipour et al. 2015, 2016), as well as NGC 3783 (Mehdipour et al. 2017) and NGC 3227 (Mehdipour et al. 2021), show that during the obscuration epochs changes in the continuum

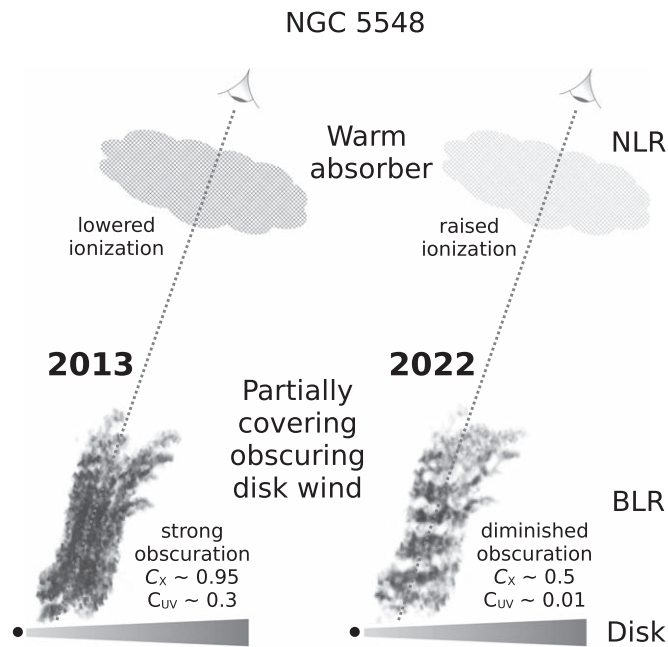


Figure 4. Illustration of the long-term transformation of the obscuring disk wind in NGC 5548. The outflowing streams from the disk have become more porous and permeable in 2022, hence the observed decline in the X-ray and UV covering fractions (C_X and C_{UV}). The originally continuous gas supply from the disk in 2013 has gradually become more intermittently powered by the disk.

parameters and the luminosities are moderate and typical of a Seyfert-1 galaxy. This is in contrast to some changing-look AGNs, such as NGC 3516 (Mehdipour et al. 2022), where the optical/UV emission from the disk and the X-ray emission from the corona have both undergone major transformations. Thus, spectral changes in the obscured AGNs and the changing-look AGNs have different characteristics. Interestingly, in NGC 5548 from 2000 to 2012, the UV and optical continuum, as well as the BLR emission lines, underwent significant dimming (Crenshaw et al. 2003; Kriss et al. 2019a). This was prior to the start of the obscuration epoch in 2012. Kriss et al. (2019a) suggest that the increase in the accretion rate associated with recovery from that earlier period reinflated the BLR and triggered the obscuring outflow in NGC 5548. Since then, however, there are no significant changes in the accretion or coronal activity (Mehdipour et al. 2015, 2016, and this work). In the recent 2022 epoch, the intrinsic UV and hard X-ray continuum are at similar levels to the 2013 epoch (Figure 2), implying similar intrinsic SEDs and luminosities. Thus, the long-term evolution of the obscuring disk wind since 2012 is not connected to any apparent accretion or coronal changes.

We illustrate how the obscuring wind in NGC 5548 may have evolved in Figure 4. Compared to the state of strong obscuration in 2013, the obscurer in 2022 is more porous and permeable. This would explain the significantly smaller C_X and C_{UV} that we observe in 2022. While in 2013, the supply of gas outflow from the disk appeared to be continuous and uninterrupted, it may have gradually become intermittent, thereby increasing gaps and interstices in the clumpy structure of the wind. This in turn may be due to the mechanism powering the disk wind not being as efficient as it used to be and perhaps eventually the obscuring wind may fully vanish. There are however no discernible long-term changes in the accretion or coronal activity of NGC 5548 since 2012.

Irradiation can play an important role in the fragmentation of the wind and hence changing its observed covering fractions. It can induce thermal instability (Waters et al. 2022) as well as raise the ionization of the lower-density interstices that grow over time. However, irradiation is likely not the primary driver of the long-term decline in the obscuration as there are no corresponding long-term changes in the ionizing SED of NGC 5548. The obscuring winds in AGN are found to be generally transient and episodic in nature. For example, in NGC 3783, the obscuration, lasting for weeks/months, episodically recurs (Kaastra et al. 2018). Also, in NGC 5548 there are short intervals where obscuration almost disappears without being a response to the ionizing SED (Mehdipour et al. 2016; Kriss et al. 2019a). Thus, such intermittent and episodic variations in the disk wind would enhance its clumpiness and partial covering over time. Long-term Swift and HST monitoring of different AGNs that undergo transient obscuration events would be useful for advancing our understanding of the driving mechanism of these disk winds.

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Facilities: HST (COS), Swift, Chandra (LETG).

ORCID iDs

Missagh Mehdipour <https://orcid.org/0000-0002-4992-4664>

Gerard A. Kriss <https://orcid.org/0000-0002-2180-8266>

Elisa Costantini <https://orcid.org/0000-0001-8470-749X>

Liyi Gu <https://orcid.org/0000-0001-9911-7038>

Jelle S. Kaastra <https://orcid.org/0000-0001-5540-2822>

Junjie Mao <https://orcid.org/0000-0001-7557-9713>

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