Evolution of the Outflows in NGC 3516

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Received 2017 September 29; revised 2018 January 15; accepted 2018 January 17; published 2018 February 23

Abstract

We analyze the 2011 HST/COS spectrum of the Seyfert 1 galaxy NGC 3516, which demonstrates clear changes in one of the intrinsic absorption troughs (component 5), slight evidence of change in a second trough (component 6), and the appearance of a new absorption trough (component 9). We interpret both the changes and the appearance of the new trough as bulk motion across the line of sight. The implied lower limit on the transverse velocity of component 5 is 360 km s⁻¹, compared to the earlier 2001 HST/STIS spectrum, while the lower limits for components 6 and 9 are 920 km s⁻¹, based on 2009 FUSE data. Component 5 also exhibits a shift in velocity centroid. This is only the second known case of this behavior in a Seyfert galaxy. Due to the high quality of the HST/COS spectrum, we identify a previously undetected trough due to an excited state of Si II for component 1. In combination with the resonance trough of Si II and photoionization modeling, we directly determine the distance of the component 1 outflow to be 67.2 pc.

Key words: galaxies: active – galaxies: evolution – galaxies: Seyfert – quasars: absorption lines

1. Introduction

Active galactic nuclei (AGNs) are extremely luminous objects due to matter accreting onto a supermassive black hole (SMBH). Seyfert galaxies are AGNs that are relatively nearby (z ≤ 0.15) and only moderately luminous (log Lbol erg⁻¹ s⁻¹ = 43–45), and are known to be highly variable in continuum flux (e.g., Dunn et al. 2006, and references therein) on both short and long timescales. The variability is likely due to changes in the mass inflow rate of the accretion disk, which is constrained to a small volume. In approximately 50% of Seyfert galaxies, we observe blueshifted absorption troughs due to outflowing material ejected from the AGN (i.e., intrinsic absorption Crenshaw et al. 2003, and references therein). These mass outflows in AGNs are potentially an important feedback mechanism that helps regulate the SMBH mass and explain the coevolution of the SMBH and galactic bulge (Di Matteo et al. 2005; Hopkins & Elvis 2010). Similar to the nuclear continuum, absorption troughs due to outflows tend to show variability in structure or number in Seyfert galaxies. In one survey of this phenomenon, Dunn et al. (2008) found a lower limit for absorption line variability in the far-UV of approximately 40% of Seyfert Galaxies in a sample of 72 sources.

While the energetics of mass outflows are beginning to become constrained by observations, the dynamics of these winds is still unclear (e.g., Granato et al. 2004; Di Matteo et al. 2005; Menci et al. 2008; King 2010; Fabian 2012; Faucher-Giguère & Quataert 2012; Zubovas & King 2012; Costa et al. 2014, 2015; Nayakshin 2014; Zubovas & King 2014; King & Pounds 2015). In order to determine which driving mechanisms (radiation pressure, MHD acceleration, thermal flows) play important roles in the ejection of the material, we require critical information about the outflows in general, such as transverse velocities. The most direct technique to constrain transverse velocity requires variations in the troughs as observed over multiple epochs where the gas presumably moves into or out of the line of sight and is uncorrelated with continuum variations, suggesting that ionization changes are not responsible for the absorption variability (Kraemer et al. 2001; Crenshaw & Kraemer 2007).

It follows that Seyfert galaxies provide excellent testbeds for exploring dynamical scenarios due to their proximity and highly variable nature. NGC 3516 (z = 0.00884) is a well-studied Seyfert galaxy that exhibits intrinsic absorption. Kraemer et al. (2002) characterized the absorption in the Space Telescope Imaging Spectrograph (STIS) 2001 observation as eight distinctive kinematic components and used photoionization modeling to place distance limits on each component from the nucleus. In X-ray spectra, Holczer & Behar (2012) found that the absorption structure showed variability over the span of ~5 years. Crenshaw & Kraemer (2012) provided a summary of the physical constraints on both UV and X-ray absorbers in NGC 3516. In this work, we explore the absorption trough variability of the ultraviolet lines in NGC 3516, as well as the benefits of detecting previously unknown troughs due to the significantly higher signal-to-noise ratio (S/N) in the UV spectra from the Cosmic Origins Spectrograph (COS) on board the Hubble Space Telescope (HST).

2. Update on the UV Spectra of NGC 3516

Using the HST/COS, we obtained new high-resolution (R = 20,000) spectra of NGC 3516 (z = 0.00884; R.A.: 11 06 47.491; decl.: +72 34 06.89) on 2011 January 22. We list the details of these spectra in Table 1. We downloaded the processed spectra (Fox et al. 2015) from the Mikulski Archive for Space Telescopes (MAST) website. As each spectrum covers a different wavelength range, we coadded the spectra for a similar epoch and average overlapping regions, weighting by exposure time. The final coadded spectrum has an S/N of 6.2 near 1550 Å, which is 2.5× higher than the previous HST/STIS spectra.

We also obtained a 16,700 s spectrum of NGC 3516 on 2007 January 23 with the Far Ultraviolet Spectroscopic Explorer (FUSE, Moos et al. 2000). We downloaded all of the available FUSE spectra of NGC 3516 from the MAST archive and
processed the spectra using the CalFUSE data reduction software (v3.2.3, Dixon et al. 2007). To correct for the so-called “worm” feature frequently observed in the LiF2A segment, we fit the average ratio of LiF2A to LiF1B with a spline and corrected the LiF2A continuum to match the LiF1B segment (similar to Kriss et al. 2011). We coadded the eight spectral FUSE segments and scale the fluxes in the overlapping regions of each segment to match the LiF1A, which is the primary channel used for pointing the instrument (see Dunn et al. 2008).

3. Changes in the Continuum Flux and Absorption Troughs

In Figure 1 (top), we show an updated UV continuum flux history of NGC 3516 measured at 1460 Å in the observed frame (Dunn et al. 2006). The continuum flux level in the HST/COS spectrum is consistent with the previous continuum flux measurements taken from HST/STIS spectra in 2000. This hints that the continuum flux of NGC 3516 has remained in a relatively low flux state over the last ∼ 10 years. We also show the continuum flux light curve measured at 1160 Å for the FUSE data in Figure 1 (bottom). While the source has variation, the general flux level appears to have remained in a low state, as seen in both the HST/COS and FUSE flux measurements.

To evaluate the changes in the absorption troughs, we begin by plotting the three previous HST high-resolution
spectra with the coadded HST/COS spectrum for C IV (Figure 2) and identifying the previously known troughs (Kraemer et al. 2002). The most notable differences occur at high velocity. First, we label a new high-velocity kinematic component 9, which is visible at approximately 1553 Å or a radial velocity of −1700 km s⁻¹. This trough is detected at 5σ above the level of the flux uncertainties for the N V doublet and 4σ for the C IV doublet. Second, the component 5 trough visible in the HST/STIS spectrum, located at approximately 1555 Å, has had considerable change in the radial velocity of the centroid and overall profile. This difference in the radial velocity does not appear to be due to variation in the core emission profile, as the change is evident after normalizing the emission. Moreover, the component 7 trough, which is similar in depth and equivalent width and closer to the emission core in radial velocity, does not exhibit any measurable change. Finally, we find that the component 1 trough in the red member of the C IV doublet (λ1551) has become notably shallower.

We plot in Figure 3 spectral segments from HST/STIS and the HST/COS for lines from commonly observed ions to search for changes in other components. Component 9 is clearly detected in both the C IV and N V data but is not visible in Si IV or Lyα. The lack of a Lyα trough is likely due to the presence of the Galactic Lyα trough. Similar to C IV, the component 5 trough also appears to have undergone change in N V, although the difference is not as distinct. Also noteworthy in the N V doublet is the lack of the component 6 trough. The trough was only weakly detected by Kraemer et al. (2002) in the HST/STIS spectrum and has potentially vanished by the time of the HST/COS observation. This is based on the poorer S/N level in the HST/STIS spectrum. Finally, as with the C IV doublet, the component 1 trough in Si IV (λ 1402) appears to be significantly shallower in the HST/COS spectrum.

We also plot in Figure 4 the FUSE spectra for Lyβ λ1026 and the O VI doublet λλ1032,1037. We coad the available spectra to achieve the highest possible S/N. Component 9 does not seem to appear between the HST/STIS and FUSE observations, as it is not readily detected in either the Lyβ or the O VI λ1032 troughs, although it would be obscured by geocoronal emission in O VI λ1037. Component 6 is also not detected in either ion. However, given that it was not strongly detected in the HST/STIS spectrum, it may not have strong
associated Lyβ or O VI troughs. Component 5 appears shallow in Lyβ and is relatively correlated in velocity with the HST/COS data, which implies the change occurred between the FUSE and HST/COS observations.

We also detect the presence of a previously unobserved trough due to the metastable, excited state line Si II λ1265 for component 1. The trough is weak but is clearly detected and was probably not visible in the HST/STIS spectrum due to the comparably lower S/N. The trough in conjunction with that from the resonance line Si II λ1260 seen in both the HST/COS and HST/STIS data provides key information on the number density of the gas and its distance from the nucleus (Section 5).

### 4. Column Density Measurements

To extract the ionic column densities (N) of the identified troughs, where available we use the velocity-dependent pure partial covering method (C(v); de Kool et al. 2002; Arav et al. 2005, 2008; Dunn et al. 2010). We simultaneously determine the optical depth and partial covering factor at every velocity element for each doublet or line series (i.e., the Lyman series), which have known ratios of oscillator strength. We show an example of this for the column density of Si IV in Figure 5. For the Si II and C II lines of component 1, we assume the covering factor from their higher ionization state counterparts (i.e., C IV and Si IV). For single lines or to provide an absolute lower limit for the column density, we also calculate the apparent optical depth (AOD; Savage & Sembach 1991). We also measure the new column density of components 5 and 9 based purely on AOD for the blue members of the doublets, as the red members are blended with other components. We list in Table 3 the new column density determinations for components 1, 5, and 9 and the previously measured column density values for components 1 and 5 from Kraemer et al. (2002) for comparison. For component 1, the measured column densities have exhibited little to no change between epochs, despite the slight change in the depths of some of the troughs.

For the hydrogen column density, we use the higher-order Lyman lines visible in the FUSE spectra, as there appears to be little evidence for change in continuum flux. The Lyβ λ1026 trough appears to be shallower than the Lyα λ1216 trough in a normalized spectrum, which suggests non-saturated troughs. However, the underlying continuum in the FUSE spectrum is probably contaminated due to the much larger aperture. Thus, we treat the measured column density from Lyβ as a lower limit. It is also noteworthy that in the Lyγ λ973 trough, despite the poor S/N, the component 1 trough clearly appears to have a narrow, high-velocity sub-component and hints of a second lower-velocity trough.

The C(v) and AOD methods only provide lower limits for traditionally saturated troughs such as the C IV doublet λλ1548,1551. To attempt a more accurate determination, we begin by creating a template from the Si IV λ1402 trough, which appears to be non-saturated, as it has a notably shallower depth than its doublet counterpart (λ1393). We scale the template in optical depth until the wing of the template matches the trough wall (see the “wing” fitting technique in Dunn et al. 2010). We show the fit for the C IV λ1551 line in Figure 6, which provides the largest lower limit on the column density. From the match, it is clear that the Si IV template cannot match the full velocity range of the C IV troughs when we scale the trough to match the wing, which we discuss further in the next section.

Finally, we find the upper limits for column densities of C III and P V for component 1. Because there are no clear indications of troughs for either the P V doublet λ, λ1118, 1128 or the C III excited state line λ1175, we scale the Si IV template for component 1 and compare it to the region where these lines would be detected. We vary the scaling in optical depth to the noise level to find the largest possible optical depth that could be buried without detection. We integrate across the template to determine the column density limits and list the values in Table 2.

### 5. Implications of the New Column Densities and Variability

We find four kinematic components in absorption that show evidence of change despite very little evidence of significant changes in the continuum flux. Comparing the measured column densities for component 1 in the HST/COS spectrum to those measured by Kraemer et al. (2002) for the HST/STIS...
Figure 6. Plot of normalized flux as a function of velocity of the spectral region for C IV λ1551 (in black) showing component 1. We also plot the Si IV λ1393 trough for comparison. Using the Si IV trough as a template, we scale the trough in optical depth until the trough wall matches the C IV wall, shown in blue. While the blue wing of the saturated template does agree with the C IV trough, the red wing is radically disparate. Unless the trough shape is entirely determined by partial covering, the Si IV template cannot adequately match the C IV trough. To determine the column density limit for C IV over the same range as the Si IV trough, we integrate the scaled optical depth of the Si IV template.

Table 2

FUSE Observations of NGC 3516

| Data Set   | Start Date  | Start Time (UT) | Exposure Time (s) | Aperture |
|------------|-------------|-----------------|-------------------|----------|
| P1110404000 | 2000 Apr 17 | 10:58:04        | 16335             | LWRS     |
| P2110102000 | 2002 Feb 14 | 01:46:54        | 20686             | LWRS     |
| P2110103000 | 2003 Jan 28 | 06:17:55        | 16901             | LWRS     |
| P2110104000 | 2003 Mar 29 | 05:44:39        | 16329             | LWRS     |
| G9170101000 | 2006 Feb 09 | 17:12:24        | 28687             | LWRS     |
| G9170102000 | 2007 Jan 23 | 06:38:51        | 16847             | LWRS     |

Table 3

Ionic Column Densities

| Ion    | N_{ion}(C I) (COS) | N_{ion}(C I) (STIS) | N_{ion}(C IV) (COS) | N_{ion}(C IV) (STIS) | N_{ion}(C IV) (COS) |
|--------|-------------------|---------------------|---------------------|---------------------|---------------------|
| C II   | 73.2 ± 10.6       | 79 ± 25             | ...                 | <25                 | ...                 |
| C II * | 99.1 ± 11.6       | 144 ± 30            | ...                 | <25                 | ...                 |
| C III  | <14               | ...                 | ...                 | ...                 | ...                 |
| C IV   | >495              | >1026               | >160                | 211 ± 30            | >50                 |
| Si II  | 15.5 ± 1.4        | ...                 | ...                 | ...                 | ...                 |
| Si II *| 4.7 ± 1.3         | ...                 | ...                 | ...                 | ...                 |
| Si IV  | 126 ± 51          | >186                | ...                 | <4                  | ...                 |
| H I    | >980              | >599                | 97 ± 18             | ...                 | ...                 |
| O VI   | >1020             | ...                 | ...                 | ...                 | ...                 |
| N V    | >1090             | >2048               | 165 ± 39            | >150                | ...                 |
| P V    | <12               | ...                 | ...                 | ...                 | ...                 |

Notes.

a Units of 10^{12} cm^{-2}.

b As measured by Kraemer et al. (2002).

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still viable for the HST/COS data and further supports the argument that NGC 3516 has been stable since the 2000 HST/STIS observation.

Because of the apparent lack of change in flux, column densities, and ionization state, both the appearance of component 9, the disappearance of component 6, and the changes in component 5 are most easily explained as material moving into or out of the line of sight due to transverse velocity. As these are absorbing light from the broad line region (BLR), we limit the transverse velocity based on the crossing time across the line of sight to the BLR. The size of the BLR in CIV for NGC 3516 is estimated to be approximately 4.5 ld (Goad et al. 1999) and the time between the last HST/STIS and HST/COS observations is 4020 days. This yields a lower limit on the transverse velocities for components 5, 6, and 9 of greater than 360 km s^{-1}. However, since the troughs for components 6 and 9 were also not detectable in the FUSE spectrum of 2007, we estimate a more robust lower limit of 920 km s^{-1}.

Examining the C IV λ1551 trough of component 1, the slight change could also be an indication of a changing column density. Unlike components 5 and 9, since the change only occurred in C IV, it is more plausible that the difference between the HST/STIS and HST/COS spectra is due to the larger aperture of HST/COS. The HST/COS spectrum likely contains an underlying continuum and emission due to active star formation. The structure of component 1 as a whole appears to be a blend of two distinct kinematic components, as evidenced by the fit to C IV and the Lyγ trough. This potentially provides observational support to the two photoionization models necessary (1a and 1b) to match the ionic column densities measured for component 1 (Kraemer et al. 2002).

While the column densities we measure are similar to those of Kraemer et al. (2002), due to the higher S/N we detect and
measure the column density of an excited state line of Si II for component 1. Assuming the plasma is in equilibrium, the ratio of the Si II column density to the column density of the Si I resonance line at $\lambda 1260$ provides a simple and reliable diagnostic of the electron density (Bautista et al. 2009). From the measured column densities, we determine a density of $n_{\text{Si I}}/n_{\text{H}} \approx 2.3$ for component 1.

The ionization state of the plasma is described by the ratio of the rate of hydrogen ionization to recombination, or the so-called ionization parameter given by

$$U_H = \frac{Q_H}{4\pi R^2 n_{\text{H}} c},$$

where $Q_H$ is the rate of hydrogen-ionizing photons emitted by the AGN, $R$ is the radial distance of the plasma from the nucleus, and $c$ is the speed of light. We measure $Q_H$ from the HST/COS spectrum, assuming a “UV-soft” SED (Dunn et al. 2010) and find $\log(Q_H) = 53.6$. Using the value of $\log(U_H)$ of $-0.9$ from Kraemer et al. (2002) for component 1a, we find a distance to the absorber from the nucleus of 67.2 pc. This distance is consistent with the lower limit derived by Crenshaw & Kraemer (2012) of 15.5 pc.

### 6. Conclusions and Discussion

Using HST/COS spectra of NGC 3516, we find for the first time in NGC 3516 the appearance of a new absorption trough (component 9) between the FUSE observation in 2006 and the HST/COS observation in 2012. Previous changes in troughs were all ascribed to ionization changes (Kraemer et al. 2002). We also show that component 5 has undergone measurable change in the trough structure and radial velocity, which we attribute to bulk motion. The only other known case of radial velocity change is NGC3783 (Gabel et al. 2003). The final change we find in the new spectrum is that component 6, which was a weakly detected trough in the HST/STIS spectrum, is no longer visible. Accepting the lower S/N of the HST/STIS spectrum, this disappearance could be due to motion out of the line of sight. Considering the physical properties of the AGN of NGC 3516, these changes imply lower limits on the transverse velocity of component 5 of 360 km s$^{-1}$ and components 9 and potentially component 6 of 920 km s$^{-1}$.

We also find a previously undetected trough due to the higher S/N HST/COS spectrum of an excited state line for Si II$. We use the column density for Si II$ and use the previously established photoionization models by Kraemer et al. (2002) to determine the radial distance of component 1 to be 67.2 pc. Due to the radiation-shielding arguments established in Kraemer et al. (2002), this distance agrees with the upper limits for components 2–4 but provides a new lower limit for components 5–8 that is $-4.3 \times$ larger than the previous limit. Crenshaw & Kraemer (2012) estimated the total kinetic luminosity output for NGC 3516 to be $K > 5.4 \times 10^{44}$ erg s$^{-1}$ based on the previous limits. Given the increased limit on distance and the linear relation between distance and $K$, the new lower limit for the total kinetic luminosity of NGC 3516 is $K > 2.4 \times 10^{42}$ erg s$^{-1}$.

Examining the transverse velocities of components 5 and 9 and their radial components of $-1450$ km s$^{-1}$ and $-1700$ km s$^{-1}$, respectively, we find that the limit on the transverse motion of component 9 (and perhaps 5) is comparable to the radial motion. Similar to the other higher velocity components, component 9 exhibits a high column density ratio for NV/CIV, which implies either that it is highly ionized or that its physical state is due to screening by component 1 (Kraemer et al. 2002). Because the other components with similar column density ratios only appear in low flux states, it follows that they are likely experiencing screening and are at larger radial distances than component 1. The column densities for component 9 are consistent with this scenario and suggest that it also has a radial distance beyond that of component 1. Given the limit on the distance from the nucleus for both components 5 and 9, the transverse velocities for each component are larger than the rotational velocities, which we estimate to be 67 km s$^{-1}$ based upon the SMBH mass (42.7 million $M_\odot$; Peterson et al. 2004) and gravitational potential of the host galaxy (Mulchaey et al. 1992). The large transverse velocities beyond that of galactic rotation could suggest an origin much closer to the nucleus.

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