PHOTOIONIZATION MODELING OF THE LOW-LUMINOSITY SEYFERT 1 NUCLEUS IN NGC 3516

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ABSTRACT
Spectroscopic observations of the low-luminosity Seyfert 1 nucleus in NGC 3516 obtained with the Hubble Space Telescope show that the visible spectrum is dominated by Balmer emission lines of hydrogen (H) and a continuum luminosity that rises into the UV. The anomalous Hα/Hβ emission line ratio, the Balmer emission line luminosity, and the distinctive shape observed for the Hα emission line profile serve as important constraints for any photoionization model aimed at explaining the visible emission line spectrum of NGC 3516. Photoionization modeling using Cloudy demonstrates that the central UV–X-ray source is able to completely ionize the H gas in between the Balmer and dust reverberation radii if the electron density is \( \leq 3 \times 10^7 \) cm\(^{-3}\) throughout. Thus, according to this model the region responsible for producing the visible H lines is a dust-free shell of ionized H gas. Interestingly, the model predicts a rapid rise in the electron temperature as the central UV–X-ray source is approached, mirrored by an equally precipitous decrease in the Balmer line emissivity that coincides with the Balmer reverberation radius, providing a natural explanation for the finite width observed for H Balmer lines. Collectively, the merit of the model is that it explains the relative intensities of the three brightest Balmer lines and the shape of the Hα emission line profile. However, questions remain concerning the unusually weak forbidden lines that cannot be addressed using Cloudy due to limitations with the code.

Key words: galaxies: individual (NGC 3516) – galaxies: Seyfert – quasars: emission lines

1. INTRODUCTION
The visible spectrum of the nucleus of NGC 3516 was first described by Seyfert (1943) and includes bright and unusually broad permitted Balmer emission lines of hydrogen (H) and a continuum luminosity that rises into the UV. The anomalous Hα/Hβ emission line ratio, the Balmer emission line luminosity, and the distinctive shape observed for the Hα emission line profile serve as important constraints for any photoionization model. Seyfert likened the visible spectrum of NGC 3516 to that of a planetary nebula, which bears some geometrical resemblance to the BLR photoionization model of Netzer & Laor (1993).

Of all telescopes, the Hubble Space Telescope (HST) provides the clearest view of the bright AGN in NGC 3516. Consequently, the main objective of this paper is to interpret the exquisite visible spectra obtained with HST in the context of the Netzer & Laor (1993) photoionization model. An important constraint in any such model is the shape and amplitude of the ionizing continuum. Recent observations with XMM-Newton allowed Vasudevan & Fabian (2009) to constrain the ionizing continuum of the AGN in NGC 3516 as the combination of emission from an accretion disk and an X-ray power law. That ionizing continuum is adopted here as an input to the photoionization code Cloudy (Ferland et al. 2013), which can predict the relative intensity of the Balmer emission lines for various radial density distributions of photoionized gas. Additionally, since the central black hole (BH) mass is known (Denney et al. 2010) the shape of the broad Balmer emission lines can be used to constrain the BLR size, given a kinematic description for the gas. When combined with the X-ray luminosity, the BH mass implies that the AGN in NGC 3516 is radiating at \( \sim 0.6\% \) the Eddington luminosity limit (Vasudevan & Fabian 2009) and is therefore unable to sustain a radiatively driven outflow. Thus, the BLR gas kinematics are most likely dominated by gravity. Time-resolved spectra discussed by Denney et al. (2009) indicate that the BLR is actually an inflow of H gas. Paradoxically, the AGN in NGC 3516 may also be associated with an outflow (Barbosa et al. 2009, and the references therein) driven by two jets, the orientation and geometry of which have been discussed previously by Ferruit et al. (1998); such jets are comprised of a relativistic plasma producing extended radio continuum and collisionally excited forbidden line emission, but little or no Balmer emission. Consequently, the broad Balmer emission lines most likely originate in H gas that is photoionized by the...
central UV–X-ray source. The main objective of this paper is to test that conjecture.

The paper is organized as follows. A review of the UV and visible spectra of NGC 3516 obtained with the Space Telescope Imaging Spectrograph (STIS) is presented in Section 2. These observations are combined with a model for the ionizing continuum presented in Section 2.2. Emission line ratios, corrected for dust extinction, constrain a Cloudy photoionization model for the BLR in NGC 3516, which is described in Section 3. A discussion follows in Section 4 and conclusions are presented in Section 5.

2. RESULTS

The HST/STIS observations, described in more detail in the following, provide fluxes and relative intensities for the H Balmer emission lines, along with a measure of their line profile shapes. These observational results provide key constraints for a photoionization model for the BLR in NGC 3516 that is presented in Section 3.

2.1. HST/STIS Observations

NGC 3516 has been visited twice with STIS. First, it was visited in 1998 when it was observed intensively for a period of two days using the G430L and G140L gratings, then a second short visit was conducted just over two years later in 2000, when it was observed again with the G430L grating and also the G750M grating. The STIS observations for both visits are summarized in Table 1, and the visible spectra are presented in Figure 1. Some details of those observations have been reported previously by Edelson et al. (2000) and Balmaverde & Capetti (2014). A thorough analysis of the UV emission line spectrum of NGC 3516 has been presented previously by Goad et al. (1999a, 1999b).

Multiple calibrated exposures obtained through each of the G750M and G430L gratings were shifted and combined for each grating but separately for each visit using the STSDAS task occreject. Subsequently, emission line fluxes were measured using the STSDAS contributed task specfit. Between 1998 and 2000 the visible continuum measured with the G430L grating decreased quite conspicuously, specifically by ≈20%, as illustrated in Figure 2. The decrease in continuum brightness may have been caused in part by the smaller slit size employed for the year 2000 observation. However, NGC 3516 is also known to be reverberating (Denney et al. 2010) and the ∼5% decrease in the Hβ emission line flux between the two observations is consistent with prior observations. Intriguingly, the flux in the core of the Hβ emission line changed less than the flux in the wings, as shown in more detail in the inset in Figure 2.

2.2. Emission Line Ratios

Emission line ratios, corrected for dust extinction, constrain a Cloudy photoionization model for the BLR in NGC 3516. Emission line ratios are derived using the Cloudy photoionization code (Ferland et al. 1998), as described in Section 3.

Table 1

| PID | Observation Date | Grating | Spectral Range (Å) | Slit (arcsec) | Dispersion (Å/pixel) | Plate Scale (arcsec/pixel) | Integration Time (s) | Data Sets |
|-----|------------------|---------|--------------------|--------------|----------------------|--------------------------|--------------------|----------|
| 7355 | 1998 Apr 13      | G140L   | 1150–1730          | 52 × 0.5     | 0.6                  | 0.0246                  | 32820              | o4st01010 – o4st01070 |
| 7355 | 1998 Apr 13      | G430L   | 2900–5700          | 52 × 0.5     | 2.73                 | 0.05                    | 122891             | o4st02010 – o4st13030 |
| 8055 | 2000 Jun 18      | G750M   | 6295–6867          | 52 × 0.2     | 0.56                 | 0.05                    | 1956               | o56c01020 – o56c01030 |
| 7355 | 2000 Jun 18      | G750M   | 6295–6867          | 52 × 0.1     | 0.56                 | 0.05                    | 60                 | o56c01040 |
| 8055 | 2000 Jun 18      | G430L   | 2900–5700          | 52 × 0.2     | 2.73                 | 0.05                    | 600                | o56c01050 |

Note. * Omitting o4st06030, o4st06040, o4st07030, o4st11020, o4st11030.

Figure 1. Visible spectra of NGC 3516 as seen through the following gratings. Left panel: G430L. Right panel: G750M. The black line shows data obtained under PID 7355. The red (lighter shade) line for both panels shows data obtained under PID 8055.
line. A model for the brighter [N ii] line was constructed that, when removed, did not over-subtract the broad Hα emission line profile, which is otherwise smoothly varying. Although it cannot be seen, the fainter vacuum wavelength 6549.85 Å [N ii] emission line is constrained by atomic physics to have the same width and one-third the flux of the brighter line. Line fluxes are reported in Table 2 for all the emission lines seen in the G750M spectrum, including the broad Hα emission line, the [N ii] forbidden emission lines, the density sensitive [S ii] vacuum wavelength 6718.29 Å, and 6732.67 Å lines, plus the two [O i] vacuum wavelength 6302.04 Å, and 6365.53 Å lines.

The Balmer series of H continues into the G430L spectrum. Emission line fluxes are reported in Table 2 for Hβ, Hγ, Hδ, and Hε. The latter two lines are considerably fainter, and the adjacent continuum is not flat, which introduces an additional model-dependent systematic uncertainty, due to the continuum variation, that is difficult to quantify. Fluxes are also reported for the vacuum wavelength 4960.30 Å and 5008.24 Å [O iii] emission lines. An upper limit is reported in Table 2 for the vacuum wavelength 4364.44 Å [O iii] emission line that is overwhelmed by the broad Hγ line. A flux is also reported for the unresolved vacuum wavelength 3727.09, 3729.88 Å [O ii] doublet.

Collectively, the HST spectra bear an uncanny resemblance to the spectrum described by Seyfert (1943). Using photographic plates he measured the relative intensities of the Balmer lines and the [O iii]λλ4959,5007 forbidden emission lines to be within 25% of the values measured with STIS. However, an inconsistency has been found with Edelson et al. (2000), who report Hβ and Hγ emission line fluxes that are one order of magnitude larger than those cited in Table 2. Including the forbidden [N ii] emission lines, the broad Hα flux reported by Balmaverde & Capetti (2014) agrees with the value cited in Table 2 within the 3% uncertainty expected for plausible, but different models of the underlying continuum.

The broad Hα emission line has a single peak, but is obviously asymmetric due to a “bump” on the blue side of the profile illustrated in Figure 3. This feature was seen and commented on previously by Boksenberg & Netzer (1977), Wanders et al. (1993), and Popović et al. (2002). Evidently, the feature is real, and has persisted for at least 25 years, Adopting a heliocentric recession velocity of 2508 ± 60 km s⁻¹ for NGC 3516, measured using the peak of the brightest [O iii] emission line (Figure 1), allows wavelength to be converted into rest-frame velocity for each of the Hα, Hβ, and Hγ emission line profiles. Figure 3 shows that the emission line profile shapes are very similar to each other after they have been normalized to their respective peak intensities. The “bump” on the blue side is seen in Hα, Hβ, and Hγ. The fact that the Balmer emission line profiles are so similar suggests that the dust extinction in the visible part of the spectrum, internal to the BLR, is essentially zero.
Using the results provided in Table 2, observed ratios involving the fluxes for the three brightest Balmer lines, Hα/Hβ, and Hβ/Hγ, are reported in Table 3 along with the canonical Case B values expected for an idealized nebula of uniform electron temperature, corresponding to 10^4 K, and a uniform electron density of 10^4 cm^{-3} (Hummer & Storey 1987). Interestingly, the Hα/Hβ ratio measured with STIS agrees with the average of the values reported previously in Boksenberg & Netzer (1977), and is almost a factor of two larger than the Case B value. Such deviations from recombination theory have been noted for other AGN (Devereux 2013, and the references therein) and can be explained in terms of collisional excitation, enhancing just Hα relative to the other Balmer lines. However, the Balmer emission line ratios can also be affected by dust extinction, which is addressed in the next section.

### 2.2. UV–X-Ray Continuum, and Foreground Dust Extinction

Vasudevan & Fabian (2009) modeled the UV–X-ray continuum of NGC 3516 in terms of a blackbody, representing an accretion disk, and a power law. The amplitude of that continuum model, recapitulated in Figure 4, is constrained by a single XMM-OM observation obtained at the end of the year 2001. However, the model continuum agrees with that measured in the G430L spectrum and the mean extinction-corrected 1365 Å continuum discussed previously by Goad et al. (1999b). Consequently, the model continuum presented in Figure 4 provides a useful constraint on the production rate of H ionizing photons by the central UV–X-ray source. For a distance of 38 Mpc (R.B. Tully 2015, private communication) numerically integrating the continuum yields 1.2 × 10^{53} H ionizing photons s^{-1}, of which the majority, ~75%, are produced by the accretion disk and the remainder are produced by the power law. These results constrain a photoionization model for the BLR in NGC 3516 that is discussed further in Section 3.

As illustrated in Figure 4, the G430L continuum measured in 1998 coincides almost identically with the model accretion disk, but the contemporaneous G140L spectrum lies significantly below. Although one cannot rule out time variability as the reason for the discrepancy, the likelihood that the observed continuum is representative of the mean provides an opportunity to estimate the dust extinction by comparison with the model continuum. If one assumes a Galactic form for the reddening law, A_λ / E(B − V) = 3.2 (Cardelli et al. 1989), then a least squares analysis of the difference between the model continuum and the continuum measured in the contemporaneous G430L and G140L spectra yields the following significant result,

\[ A_λ = \frac{(1163 \pm 95)}{λ(Å)} - 0.06 \text{ mag.} \]

which predicts a color excess of E(B − V) = 0.05 ± 0.01, consistent with the range of values for the Galactic extinction quoted by Goad et al. (1999b). Consequently, the foreground extinction toward NGC 3516 at the wavelength of the Hα emission line is likely to be small, ~0.1 mag. Values for the ratios Hα/Hβ and Hβ/Hγ are reported in Table 3, corrected for Galactic extinction using Equation (1).

### 3. PHOTOIONIZATION MODELING OF THE BLR USING CLOUDY

Evidently, the reason that the LLAGN in NGC 3516 is so bright is because the foreground visible dust extinction is essentially zero. Furthermore, the dust extinction internal to the BLR may also be zero since the Balmer emission line profile shapes are so similar (see Figure 3). Thus, the AGN is essentially completely exposed, allowing a very clear view of the BLR. This is perhaps not entirely unexpected, as Koshida et al. (2014) measure the dust reverberation radius to be significantly larger than the Balmer reverberation radius (Denney et al. 2010). Collectively, the HST/STIS observations suggest a model for the BLR of NGC 3516, advocated previously by Netzer & Laor (1993), in which the central UV–X-ray source is able to sublimate dust from a sizeable volume of H gas, permitting it to be photoionized. The implications of such a model are explored in the following using version 13.02 of Cloudy (Ferland et al. 2013).

Table 4 summarizes the parameters employed to model photoionization of the BLR in NGC 3516, a full description of which can be found in the Cloudy documentation. Briefly, they describe a spherically symmetric distribution of neutral H gas that is photoionized by the central UV–X-ray source.

The radial number density distribution for the neutral gas is represented by an \( r^{-a} \) power law, normalized by a number density at the inner radius, \( ρ \). A grid of photoionization models

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### Table 3

| Ratio          | Observed | Extinction Corrected | Case B$^a$ | Cloudy |
|----------------|----------|----------------------|------------|--------|
|                | (1)      | (2)                  | (3)        | (4)    | (5)    |
| Hα/Hγ          | 5.2 ± 0.01 | 5.0 ± 0.01            | 2.8        | 5.2    |
| Hβ/Hγ          | 2.0 ± 0.01 | 2.0 ± 0.01            | 2.1        | 1.9    |
| [O ii] λ 5007/Hβ | 0.31 ± 0.02 | 0.30 ± 0.02          | ...        | 0.37$^b$ |
| [O ii] λ 4595/Hβ | 0.10 ± 0.02 | 0.10 ± 0.02          | ...        | 0.12$^b$ |

Notes.

$^a$ Assuming a uniform electron temperature of 10^4 K, and a uniform electron density of 10^4 cm^{-3}.

$^b$ 1/3 solar metallicity. See Table 4.

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**Figure 4.** The visible–UV–X-ray continuum of NGC 3516. The solid green line is the model unabsorbed continuum, and the dotted red line is a model representation of H photoelectric absorption. There are data for both lines, plus the single XMM-OM measurement represented by the blue dot, courtesy of Vasudevan & Fabian (2009). STIS spectra obtained under PID 7355 are plotted in pink (lighter shade), and PID 8055 are plotted in purple (darker shade).
spanning $0 \leq n \leq 1.5$ and $7.0 \leq \log_{10} \rho (\text{cm}^{-3}) \leq 8.0$ was constructed in order to discover the intersection of model predictions for the intrinsic $\text{H} \alpha / \text{H} \beta$, $\text{H} \beta / \text{H} \gamma$, and $[\text{O} \text{iii}] \lambda \lambda 4959,5007 / \text{H} \beta$ emission line ratios with the extinction-corrected values. Subsequent optimization of the density versus outer radius yielded emission line ratios that are within $\sim 5\%$ of the observed extinction-corrected values reported in Table 3. As explained in more detail in the following sections, the modeling results point to low-density and possibly low-metallicity gas as the origin of the visible emission line spectrum observed for NGC 3516.

### 3.1. Radial Structure and Physical Properties of the BLR in NGC 3516

Of particular interest for understanding the physical conditions that may exist in the BLR is what the photoionization code Cloudy has to say about the radial distributions of the ionization fraction, the electron density, the electron temperature, the $\text{H} \alpha$ emission line emissivity, and the ionization parameter. These results, depicted in Figure 5, represent the model parameters listed in Table 4. Some interesting trends are apparent. First, the upper panel in Figure 5 shows that the $\text{H} \alpha$ ionization fraction is predicted to be $100\%$ inside the dust reverberation radius measured by Koshida et al. (2014). Plus, a significant ionization gradient is predicted, in the sense that $\text{O}^{2+}$ is inevitably ionized to $\text{O}^{3+}$, as the central UV–X-ray source is approached. Consequently, the $\text{H}$- and $\text{O}$-emitting regions are spatially disparate, the $\text{H}$ emission being produced in a dust-free shell, surrounded by a potentially dusty $\text{O}$-emitting region. Second, the lower panel of Figure 5 shows that inside a radius of $\sim 0.1 \text{pc}$, the electron density exceeds the critical density of $7 \times 10^5 \text{ cm}^{-3}$ for collisional de-excitation of the $^3 \text{D}_2$ level of $\text{O}^{2+}$. Third, the lower panel in Figure 5 shows a rapid increase in electron temperature inside the region where $\text{H}$ is fully ionized. Cloudy predicts that the electron temperature exceeds $10^7 \text{ K}$ at the Balmer reverberation radius. Such a rapid rise in temperature correlates with an equally rapid decline in the $\text{H} \alpha$ emission line emissivity. This phenomenon leads to a central void, visualized in Figure 6, inside of which there is no $\text{H}$ line emission. The perimeter of this central void coincides with the Balmer reverberation radius. Thus, the Balmer reverberation radius appears to be just the inner radius of a larger volume of ionized gas that is producing Balmer line emission. The reverberating gas, identified with the inner ring of points in Figure 6, represents $15\%$ of the total, based on the same percentage of the total Balmer line emission flux that is observed to be time-variable, according to the $F_{\text{var}}$ statistic.
number of points at each radius. In the context of the inflow model there are two free parameters available to model the line shape and they are the inner and outer radii of the emitting volume. The inner radius defines the full velocity width at zero intensity of the model broad emission line, and the outer radius defines the maximum intensity of the model broad emission line at zero velocity. Thus, comparing a normalized version of the observed broad emission line with the model one effectively constrains the inner and outer radii of the emitting volume using chi-squared minimization. For a BH mass of $31.7_{-5.2}^{+2.5} \times 10^8 M_\odot$ (Denney et al. 2010) one finds that the inner radius $r_i$ of the region emitting the Balmer emission lines is $4.1_{-1}^{+1} l.d.$, which, within the uncertainties, is comparable to the Balmer reverberation lag, $\tau_{\text{peak}} = 7.2_{-1}^{+1} l.d.$, measured by Denney et al. (2010). Whereas the outer radius, $r_o$, of the region emitting the Balmer emission lines is $47_{-10}^{+16} l.d.$, which coincides with the smallest of the dust reverberation radii measured by Koshida et al. (2014).

The H$\beta$ emissivity predicted by Cloudy does a reasonably good job of reproducing the overall shape of the observed H$\alpha$ emission line as illustrated in Figure 7, although there are some differences in detail. By design the model H$\alpha$ emission line is symmetric, whereas the observed profile is not. Additionally, the model does not explain the high-velocity wings seen in the STIS spectra, suggesting a less precipitous decrease in the H$\beta$ emissivity at small radii than predicted by Cloudy. Nevertheless, the success of the Cloudy model is that the H$\alpha$-emitting region, defined above, can explain both the H$\alpha$ emission line profile shape (see Figure 7) and the Balmer emission line ratios (see Table 3), but it underestimates the extinction-corrected H$\beta$ luminosity by $\sim 60\%$. Since the Balmer emission line emissivity is spatially extended (see Figure 5) the model emission line luminosity can be increased to the observed value by increasing the outer radius to a luminosity radius of 112 l.d., although that change causes the model Balmer emission line profile shape to deviate more from the observed one, and the model Balmer emission line ratios to no longer agree with the extinction-corrected values listed in Table 4. In summary, there are several measures of BLR size and they include the Balmer reverberation radius, the dust reverberation radius, the inner and outer radii of the volume required to explain the shape and relative intensities of the Balmer emission lines, and lastly, the Balmer luminosity radius. These various size estimates are illustrated in Figure 5.

4. DISCUSSION

Collectively the STIS observations constrain a Cloudy model for the BLR in NGC 3516 that consists of $\sim 500 M_\odot$ of dust-free H gas that is free-falling toward the central BH at a steady-state rate of $\sim 1 M_\odot \text{yr}^{-1}$. Even assuming radiatively inefficient accretion (e.g., Merloni et al. 2003), the bolometric luminosity measured for this LLAGN (Vasudevan & Fabian 2009) indicates that no more than 2% of the inflowing material reaches the event horizon of the BH (Barbosa et al. 2009), begging the question where does the majority of the inflowing mass go? Evidently, the inflow is diverted into an outflow. The mass outflow rate estimated for NGC 3516 by Barbosa et al. (2009) accounts for only about 5% of the inflowing mass quoted above. However, this discrepancy could be easily

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Figure 7. Cloudy model representation of the H$\alpha$ emission line profile shape (black line) produced by the region depicted in Figure 6. The red line represents the observed normalized H$\alpha$ emission line profile. The residual between the observed, and model line, is represented by the thinner red line.

(Denney et al. 2009, 2010) Although it is variously labeled, that statistic is routinely used to quantify variability amplitude by providing a measure of the fractional excess variance in the emission line flux (e.g., Edelson et al. 2000).

NGC 3516 is the third LLAGN following NGC 3227 (Devereux 2013) and NGC 4051 (Devereux & Heaton 2013) for which the inner radius of the volume emitting the Balmer emission lines coincides with the Balmer reverberation lag. Various measures of BLR size in NGC 3516 are provided in the next section.

3.2. BLR Size Estimates

Knowing both the H$\alpha$ emission line emissivity and the central BH mass allows one to construct a model H$\alpha$ emission line profile, an example of which is illustrated in Figure 7. The line profile fitting method for estimating the size of the region producing broad Balmer line emission has been described previously (Devereux 2011). Briefly, the method employs a Monte Carlo simulation of a spherically symmetric distribution of $\sim 10^4$ particles of light, the radial distribution of which is described by the H$\alpha$ emission line emissivity predicted by Cloudy (see Figure 5).

Time-resolved spectra discussed by Denney et al. (2009) indicate an infall component to the BLR in NGC 3516. However, since the time-variable component of the H$\beta$ emission line represents only about $\sim 15\%$ of the total line flux, it is difficult to judge whether this observation is representative of the kinematical state of the BLR as a whole. Nevertheless, for the purposes of computing the model line profile, every particle is assumed to be moving under the influence of gravity, and in free-fall according to the familiar equation $v(r) = \sqrt{2GM/r}$, where $v$ is velocity, $G$ is the gravitational constant, $M$ is the BH mass, and $r$ is the distance of each point from the central supermassive BH. Such spherically symmetric free-fall models produce single peak broad Balmer emission line profile shapes. Discrete particle models also have the advantage that they reproduce the small-scale structure seen in broad emission line profiles, which is caused by random clumping in radial velocity space, as noted previously by Capriotti et al. (1980).

The central mass determines the relationship between velocity and radius for each point of light and the emissivity determines the
reconciled if the gas density in the outflow were about a factor of 20 higher than Barbosa et al. (2009) assumed. Then mass would be conserved since the outflow rate would be similar to the inflow rate. Furthermore, angular momentum would also be conserved because theoretically, both idealized linear jets and spherically symmetric inflows posses none. A mechanism that would allow such an efficient redirection of matter most likely involves a magnetohydrodynamic process, since thermal energy and BH spin appear to be insufficient (e.g., Akhtar et al. 2015). A few other puzzles concerning NGC 3516 are discussed in the following sections.

4.1. X-Ray Warm Absorber, Ionization Parameter, and H Column Density

Cloudy predicts that inside the Balmer reverberation radius the H gas is a $10^7$ K plasma producing no H lines at all because the primary source of opacity is electron scattering. This inner sanctum is where the X-ray emission originates. Thus, according to this model, the X-ray and Balmer emission are mutually exclusive, which would naturally explain the discordance between the time variability of these two types of radiation (Edelson et al. 2000). Furthermore, according to this picture, the X-rays would have to pass through the ionized H to reach the observer which could explain the X-ray absorption features at $\sim1$ keV described by Netzer et al. (2002).

In fact, the properties of the warm absorber constrained by Netzer et al. (2002)—thin shell with an electron density $\geq 2.4 \times 10^6$ cm$^{-3}$, an electron temperature $\sim 3.5 \times 10^7$ K, and a radius $\leq 0.2$ pc—almost perfectly describe the physical properties of the BLR gas illustrated in Figure 5. The implication is that the BLR is the X-ray warm absorber. Subsequently, Huerta et al. (2014, and the references therein) have identified several warm absorbers covering a range of ionization parameters, $U(r)$, similar to the range predicted by Cloudy, as illustrated in Figure 5. However, Huerta et al. (2014) advocate $U(r)$ increasing with radius which is completely opposite to the dependence predicted by Cloudy (See Figure 5). Furthermore, integrating the neutral H column of the Cloudy model over the entire range of radii depicted in Figure 5 leads to a H column density $\sim 2 \times 10^{24}$ atoms/cm$^{-2}$, which is an order of magnitude larger than that estimated for any of the warm absorbers described by Huerta et al. (2014, and the references therein).

Consequently, it is difficult to associate any of the absorbers identified by Huerta et al. (2014) with the BLR gas.

4.2. Forbidden Emission Lines

What is visually striking about the spectra obtained with STIS for NGC 3516 is how faint the forbidden emission lines are compared to the H Balmer emission lines. For example, the observed [O III]/Hβ, [O I]/Hα, [N II]/Hα, and [S II]/Hα emission line ratios are so small that they render NGC 3516 unclassifiable according to the diagnostic diagrams of Kewley et al. (2006). However, when one compares the observed emission line ratios to the intrinsic ones predicted by the photoionization code Cloudy, none of the forbidden lines cited above are expected to be very bright except [O III]. Cloudy predicts the forbidden [O III] emission lines to be about one order of magnitude brighter than observed, even though the model electron density exceeds the critical density for collisional de-excitation of the $^3D_2$ level of O$^{2+}$, as mentioned previously in Section 3.2. Thus, if the Cloudy calculation is to be believed, then something is diminishing the brightness of the [O III] emission lines seen in NGC 3516.

Looking at Figure 5, one possibility is dust obscuration. According to the results presented in the upper panel of Figure 5, dust could selectively obscure emission lines produced by any of the first four ionization stages of O. Furthermore, although this is not shown in the figure, the ionization gradient for O is similar to that of other ions, including C, N, and S, because all these elements have similar ionization potentials. Thus, forbidden lines from those elements may also be obscured. Given that the dust extinction is virtually negligible to the H located inside the dust reverberation radius, any dust would have to be distributed in a face-on ring, or annulus, in order to selectively affect just the forbidden lines. Such a geometry envisaged for the dust is reminiscent of a torus, which is the basis for a unified model of AGN (Netzer 2015, and the references therein).

Ideally, one would use Cloudy to model the impact of dust on the forbidden line emission. Unfortunately, Cloudy has a serious limitation in that it has not reliably predicted emergent emission line intensities for all versions of the code, including and predating v13.02. Although not widely publicized, an admission of this effect is documented on the Cloudy simulations wiki hosted by Yahoo Groups$^3$ in a series of e-mail exchanges$^4$ at the end of 2014.

According to the Cloudy documentation, the emergent line intensities include the radiative transfer effects involving dust beyond the region where the various emission lines are formed. Thus, the bug is related to the inclusion of dust in the Cloudy models. Regrettably dust is included in all models by default unless the user specifies no grains to disable it. A recent comparison of photoionization codes (Péquignot et al. 2001) did not address the inclusion of dust, which is perhaps why this problem has gone unnoticed for so long.

The other half of the standard output generated by Cloudy, titled Intrinsic line intensities, is apparently unaffected by the bug, and it is those results that are used in this paper. However, according to the Cloudy documentation, the intrinsic line intensities do not include the radiative transfer effects involving dust beyond the region where the various emission lines are formed. Consequently the intrinsic line intensities are inappropriate for interpreting observed emission line spectra, unless the dust extinction to each region emitting each emission line is known a priori and corrected for. Of special concern in this regard are several oft cited and consequently influential papers dealing with the spectroscopy of AGN that do not employ a dust extinction correction beyond the Galactic value. Collectively, several hundred papers utilizing Cloudy have been published in the professional literature. However, since it is not customary among the authors of those papers to declare which output they have been using, be it intrinsic or, emergent, or whether or not the no grains command was implemented, the reliability of any of the results presented is difficult to judge. This all underscores the pitfall associated with a discipline that relies almost entirely on a single photoionization code, in this case Cloudy. Having said all this, Cloudy intrinsic line intensities may be useful for interpreting the visible Balmer emission line spectrum of NGC 3516, because for this particular AGN, it has been demonstrated in Sections 2.1 and 2.2 that the visible dust extinction is virtually negligible to the H in the BLR.

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$^3$ https://groups.yahoo.com/neo/groups/cloudy_simulations/info

$^4$ For example, message numbers; 2504, 2501, 2485, 2481.
4.3. Low Metallicity

If dust is not responsible for the weak forbidden [O III] emission lines observed for NGC 3516, then the only alternative is low metallicity. A metallicity that is a factor of 10 lower than the ISM value causes Cloudy to reproduce the observed [O III]/Hβ ratio shown in Table 3. Metal-poor gas suggests an origin in the circumgalactic medium. Perhaps the inflow, which we perceive as the BLR in NGC 3516, is just the terminus of a much larger inflow that originates from outside the galaxy. Such inflows of metal-poor gas appear to be commonplace, observed in our own Galaxy and others (Lehner et al. 2013), but this is perhaps the first suggestion of an association between the BLR of an AGN, and a low-metallicity accretion flow from the circumgalactic medium. Such inflows could also explain the low duty cycle observed for AGN activity in the local universe.

4.4. A UV–Visible Dichotomy?

The main feature of the model presented here to explain the visible emission line spectrum of NGC 3516 is photoionization of low-density gas $n_e \lesssim 10^3 \text{cm}^{-3}$, which leads to a spatially extended nebula surrounding the central UV–X-ray source. In contrast, Goad et al. (1999b) use Cloudy to explain the UV spectrum of NGC 3516, in terms of photoionization of an ensemble of optically thick broad-line clouds with high density, $10^5 \text{cm}^{-3} \lesssim n_e \lesssim 10^{11} \text{cm}^{-3}$. These two models are mutually exclusive. The differences could be reconciled if there are two photoionization mechanisms at work, one in the visible, and one in the UV. In effect, a UV–visible dichotomy emerges, whereby the UV emission lines are produced by the accretion disk, and the visible emission lines are from the photoionized nebula surrounding it. As noted previously in Section 2.1, the largest variance in the visible Balmer emission line flux occurs in the line wings. However, the converse is true for the Lyα emission line where the largest variance occurs in the line core (Goad et al. 1999b). This distinction, if confirmed, would establish a basis for further investigation.

Cloudy predicts that the photoionized nebula will produce Lyα and C iv λ1542 emission lines, in addition to the visible lines already mentioned (see Section 3.1). However, according to this model the nebular C iv λ1542 emission would occur in the vicinity of the dust reverberation radius, which is quite likely attenuated by dust extinction, and is sufficiently distant from the central BH that it is expected to contribute only to the narrow component of C iv λ1542 discussed by Goad et al. (1999b). However, the nebula is expected to contribute significantly to the observed broad Lyα emission, although it is difficult to explore to what extent the nebula lines contribute in the UV given the shortcomings with Cloudy explained previously in Section 4.2.

5. CONCLUSIONS

A model has been presented that explains the relative intensities of the Hα, Hβ, and Hγ emission lines in terms of a spatially extended, spherically symmetric distribution of neutral H gas that is photoionized by the central UV–X-ray source. Photoionization modeling with Cloudy indicates that the Hα/Hβ emission line ratio is a proxy for gas density, and constrains the neutral H density, $\rho$, to be $\log_{10} \rho (\text{cm}^{-3}) = 7.4$ at the Balmer reverberation radius. Collectively, the observations support a model, suggested previously by Netzer & Laor (1993), in which the central UV–X-ray source is able to sublimate dust from a sizeable volume of H gas, permitting it to be photoionized. Modeling with the photoionization code Cloudy yields the following insights. First, the Balmer emission line emissivity is essentially zero inside the Balmer reverberation radius. Thus, the Balmer reverberation radius marks the perimeter of a central cavity inside of which there is no Balmer emission, providing a natural explanation for the finite width observed for the Balmer emission lines. Second, the H gas is totally ionized between the Balmer reverberation radius and the dust reverberation radius. That same H gas is associated with an Hα emissivity that reproduces the overall shape of the observed Hα emission line expected for gas in free-fall. The Cloudy model further predicts forbidden [O III] emission lines that are one order of magnitude brighter than observed. The discrepancy may indicate that the observed [O III] emission lines are attenuated by dust, or that the photoionized gas is of low metallicity, or both. A problem with the emergent line intensities computed by the Cloudy photoionization code precludes further investigation of this particular observation.

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REFERENCES

Aktar, R., Das, S., & Nandi, A. 2015, MNRAS, 453, 3414
Baldwin, J., Ferland, G., Korista, K., & Verner, D. 1995, ApJ, 455, 119
Balmaverde, B., & Capetti, A. 2014, A&A, 563, 119
Barbosa, F. K. B., Storchi-Bergmann, T., Cid Fernandes, R., et al. 2009, MNRAS, 396, 2
Boksenberg, A., & Netzer, H. 1977, ApJ, 212, 37
Capriotti, E., Foltz, C., & Byard, P. 1980, ApJ, 425, 396
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Denney, K. D., Peterson, B. M., Pogge, R. W., et al. 2009, ApJ, 704, 80
Denney, K. D., Peterson, B. M., Pogge, R. W., et al. 2010, ApJ, 721, 715
Devereux, N. 2011, ApJ, 727, 93
Devereux, N. 2013, ApJ, 764, 79
Devereux, N., & Heaton, E. 2013, ApJ, 773, 97
Edelson, R., Koratkar, A., Nandra, K., et al. 2000, ApJ, 534, 180
Ferland, G. J., Porter, R. L., van Hoof, P. A. M., et al. 2013, RMxAA, 49, 137
Ferruit, P., Wilson, A. S., & Mulchaey, J. S. 1998, ApJ, 509, 646
Goad, M. R., Koratkar, A. P., Axon, D. J., et al. 1999a, ApJ, 512, 95
Goad, M. R., Koratkar, A. P., Kim-Quijano, J., et al. 1999b, ApJ, 524, 707
Ho, L. C. 2008, ARA&A, 46, 475
Huerta, E. M., Krongold, Y., Nicastro, F., et al. 2014, ApJ, 793, 61
Hummer, D. G., & Storey, P. J. 1987, MNRAS, 224, 801
Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, MNRAS, 372, 961
Koshida, S., Minezaki, T., Yoshii, Y., et al. 2014, ApJ, 788, 159
Lehner, N., Howk, J. C., Tripp, T. M., et al. 2013, ApJ, 770, 138
Popović, L. Ć., Mediavilla, E. G., Kubíček, A., & Jovanovic, P. 2002, A&A, 390, 473
Merloni, A., Heinz, S., & Di Matteo, T. 2003, MNRAS, 345, 1057
Netzer, H. 2015, ARA&A, 53, 365
Netzer, H., Chelouche, D., George, I. M., et al. 2002, ApJ, 571, 256
Netzer, H., & Laor, A. 1993, ApJL, 404, L51
Péquignot, D., Ferland, G., Netzer, H., et al. 2001, in ASP Conf. Ser. 247, Spectroscopic Challenges of Photoionized Plasmas, ed. G. Ferland, & D. W. Savin (San Francisco, CA: ASP), 533
Seyfert, C. K. 1943, ApJ, 97, 28
Vasudevan, R. V., & Fabian, A. C. 2000, MNRAS, 321, 664
Wanders, I., van Groningen, E., Alloin, D., et al. 1993, A&A, 269, 39