ON THE ABSENCE OF BROAD Mg II EMISSION LINE VARIABILITY IN NGC 3516 DURING 1996

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ABSTRACT

During the 1996 Hubble Space Telescope/Faint Object Spectrograph monitoring campaign of the Seyfert 1 galaxy NGC 3516, the UV continuum showed a factor of 5 variation; correspondingly, the strongest broad UV emission lines (e.g., Lyα, C IV) displayed somewhat weaker, although still significant, variations (a factor of 2). In contrast, no variation was detected in the strong broad Mg II + UV Fe II emission line complex. While historically the flux in the broad Mg II emission line has varied (a factor of 2 within a few years), the profile shape has not been observed to change over the past decade. In contrast, the high ionization lines (HIILs) show both emission-line flux and profile changes on relatively short timescales, which appear to be correlated with changes in the continuum level. Significantly, on 1996 February 21, the profile shapes of the HIILs (e.g., Lyα, C IV) and low ionization lines (e.g., Mg II) were identical, at which time the continuum level was at its highest. These results impose stringent constraints upon viable kinematic models of the broad-line region in NGC 3516, some of which we discuss in this Letter.

Subject headings: galaxies: individual (NGC 3516) — galaxies: kinematics and dynamics — galaxies: Seyfert

1. INTRODUCTION

NGC 3516 is a Seyfert 1 galaxy with a well-documented history of short-timescale, large-amplitude continuum and emission line variability (Koratkar et al. 1996). Historically, IUE/Short-Wavelength Prime (SWP) spectra of NGC 3516 have also displayed what has previously been referred to as a strong, variable, broad absorption line (VAL: FWHM ~ 200 km s\(^{-1}\)) (Kolman et al. 1993; Walter et al. 1990; Voit, Shull, & Begelman 1987), presumed to be similar to that observed in broad absorption line quasars (Weymann et al. 1991). The subsequent disappearance of the supposed VAL between 1989 and the onset of the 1993 IUE/SWP monitoring campaign (Koratkar et al. 1996) may be associated with the increased ionization state of the gas inferred from the observed variation in the strength of the X-ray–warm absorber detected by ROSAT (Mathur, Wilkes, & Aldcroft 1997).

However, recent high-resolution UV observations of the C IV emission line region in NGC 3516 with the Hubble Space Telescope (HST)/Goddard High-Resolution Spectrograph (Crenshaw, Maran, & Mushotzky 1998) show that NGC 3516 displays multiple intrinsic absorption lines that are all blue-shifted and relatively narrow (FWHM ~ 500 km s\(^{-1}\)), appear to remain invariant on timescales of ~6 months, and are thought to originate in the narrow-line region gas. In light of these observations, Goad et al. (1999) argue that the supposed VAL is in fact multiple, narrow absorption line systems which appear broad at the lower resolution of IUE. In this picture, the historical variation in the strength of the VAL results from variations in the number of narrow-line clouds coupled with changes in the shape of the underlying broad emission line.

In an ongoing effort to determine the nature of the broad emission/absorption line regions and their long-term evolution, we obtained five HST/Faint Object Spectrograph (FOS) cycle 6 observations of NGC 3516 from 1995 December to 1996 November, covering the wavelength range λ ~ 1150–3300 Å. In this Letter, we present the first results of this study, highlighting the absence of emission-line flux variations in the broad Mg II and UV Fe II emission lines and its implications in terms of viable kinematic models of the broad-line region (BLR).

1.1. Results from the 1996 HST/FOS Monitoring Campaign

Goad et al. (1999) show that during the 1996 HST/FOS monitoring campaign, NGC 3516 displayed the following continuum and emission-line variability characteristics: (1) large-amplitude, wavelength-dependent, continuum flux variations (a factor of 5 at λ1365 Å, cf. a factor of 3 at λ2230 Å), (2) correlated, large-amplitude, UV broad emission line flux variations (a factor of 2 for both Lyα and C IV), and (3) the complete absence of variations in both the strength and shape of the broad Mg II and UV Fe II emission line complex (Fig. 1).

A comparison of the Mg II emission-line strength determined from IUE/Long-Wavelength Prime (LWP) observations taken in 1993 (Koratkar et al. 1996) with the present data show that the flux in Mg II has apparently remained constant for at least 4 years. The absence of significant variability in the Mg II emission-line strength, despite large-amplitude continuum and high ionization line flux variations, has also been noted in lower resolution (pre-1989) IUE/LWP data (Koratkar et al. 1996) when the Mg II emission line strength was a factor of 2 weaker. Interestingly, the observed doubling of the strength of the broad Mg II emission line between 1989 and 1993 appears to coincide with the disappearance of the higher velocity narrow absorption line components that comprise the so-called VAL. It remains to be seen whether these two phenomena are related. Significantly, despite the notable increase in the Mg II emission line strength between 1989 and 1993, its shape has remained unchanged for over a decade (Fig. 2). Moreover, in the present campaign, the shapes of the broad Lyα, C IV, and Mg II emission lines as observed on 1996 February 21, when the continuum was in its highest state, are indistinguishable from one another (Fig. 3a; N.B. Lyα is not shown).
2. IMPLICATIONS FOR KINEMATIC MODELS OF THE BLR

A viable kinematic model of the BLR in NGC 3516 must explain (1) the absence of both short-timescale (~months) and long-timescale (~a few years) variations in the Mg II emission line flux and shape, despite significant changes in the strength of the ionizing continuum and (2) the remarkable similarity between the line shapes of the high ionization lines (HILs) and low ionization lines (LILs) at high continuum levels, when clearly these lines form under very different physical conditions.

2.1. Flux Variability Constraints

An absence of response in the Mg II emission line can result for a variety of physical reasons: (1) the continuum band driving the line is invariant; (2) the emission line is insensitive to continuum variations; and (3) the line-emitting region is physically extended.

Here we address the shortcomings of each of these scenarios.

1. While it is true that Mg II and Lyα respond to very different continuum bands (Mg II is mostly sensitive to the continuum from 600 to 800 eV [Krolik & Kallman 1988], whereas Lyα is driven mainly by Lyman continuum photons), simultaneous multwavelength observations of a small number of active galactic nuclei in the UV, optical, and soft X-ray bandpasses indicate that the amplitude of the continuum variations generally increase toward shorter wavelengths (Romano & Peterson 1998). Although we cannot confirm whether such a trend holds at 600–800 eV, the Seyfert 1 galaxies for which simultaneous observations were made in the UV/EUV—NGC 5548 (Marshall et al. 1997) and NGC 4051 (Cagnoni et al. 1998)—showed increased variability at shorter wavelengths. Thus, the evidence suggests that the lack of Mg II and Fe II variations is not due to an absence of continuum variability in the bandpass responsible for driving these lines.

2. Goad et al. (1993), Goad (1995), and O’Brien, Goad, & Gondhalekar (1995) demonstrated that the line responsivity $h$, the fractional change in line emissivity for a given fractional change in the continuum level, is relatively modest for Mg II ($\eta \sim 0.2–0.3$) when compared to the approximately linear response ($\eta \approx 1$) of the HILs. This difference arises because for a single cloud and a fixed continuum shape, the variation in the position of the hydrogen ionization front is generally small compared to the overall extent of the partially ionized zone in which LILs such as Mg II are formed. For a fixed continuum shape, this condition holds true over a large range in ionizing continuum luminosity (factors of 10 or more). Although the Mg II line responsivity is small, given the factor of 2 change in the C IV emission line flux, we should have detected ~40%
variation in the Mg II emission line flux. Since no significant (less than 7%) variation was detected, low emission line responsibility cannot be the sole explanation for the absence of Mg II emission line variations.

3. Finally, the lack of response in the Mg II emission line can also result if the Mg II line-emitting region is physically large and has thus yet to respond to the observed continuum variations. While plausible, given the short-timescale response of the C IV emission line to the continuum variations (∼4.5 days; Koratkar et al. 1996), it is difficult in this picture to explain the similarity in shape of the C IV and Mg II emission line profiles at high continuum levels, particularly if the size of the regions from which these lines originate differ by a few orders of magnitude.

The similar ionization potential of Fe II and Mg II suggests that these lines are formed in similar regions; hence it is unsurprising that the Fe II emission lines display a similar lack of response to continuum variations (N.B. relatively few of the Fe II lines [although strong] are resonance lines, although others are pumped by the continuum, especially in the presence of extra thermal particle speeds). The smoothness of the Fe II complex in NGC 3516 when compared to similar observations of I Zw 1 (Goad et al. 1999), a quasar with strong narrow Fe II emission lines (Laor et al. 1997), supports this finding and suggests that the Fe II lines in NGC 3516 are indeed produced in high-velocity gas (FWHM ∼ 4500 km s⁻¹).

3. PROFILE VARIABILITY CONSTRAINTS

The similarity in shape between the HILs and LILs at the highest continuum levels suggests that in the high state, both C IV and Mg II arise in kinematically similar regions. However, if the lack of response of Mg II is not the result of an absence of variability in the continuum band driving this line, then the difference in response timescale between the HILs and Mg II suggest that these lines do arise in spatially distinct regions, with Mg II formed in a region that extends over several light-months or more. Figure 3b indicates that between the low and high states, the core of the C IV emission line shows a deficit of response redward of line center from 0 to +4000 km s⁻¹ (even after allowing for possible contamination by the variable absorption line and narrow emission line components) and an enhanced response in the far red wing (greater than 5000 km s⁻¹). This may result from (1) reverberation within a radial flow, (2) a change in the radiation pattern of the ionizing continuum, or (3) a change in the spatial distribution of the line-emitting gas.

Taken together, this evidence places severe constraints upon the spatial distribution and kinematics of the line-emitting gas in NGC 3516. For example, based on this data, the following models can be excluded:

1. Radial flows at constant velocity, illuminated by either an isotropic or anisotropic continuum source (Goad & Knigge 1999).

2. Radial flows in which Mg II and C IV arise in azimuthally separated cloud populations, either through spatial segregation or anisotropic illumination.

3. A spherical distribution of clouds in Keplerian motion and illuminated by an isotropic continuum source.

We propose two models that may account for the observed emission-line variations: (1) an anisotropic continuum source model and (2) a terminal wind model (i.e., a flow that accelerates from rest until it reaches constant velocity).

1. The anisotropic continuum model of Wanders et al. (1995) can broadly reproduce the gross details of the observations reported here. In this model, the continuum is assumed to be comprised of two components: an anisotropic variable component responsible for driving the variations in the HILs and an isotropic nonvariable component responsible for producing the Mg II and Fe II emission. To match the observed variations, the BLR must be comprised of two distinct cloud populations: a low column density population producing significant HIL emission and a spatially distinct high column density population producing both HILs and LILs. The variable ionizing continuum component preferentially illuminates the low column density population, giving rise to the variations in Lyα and C IV emission lines, whereas the LILs arise predominantly from the high column density clouds illuminated by the nonvariable isotropic continuum component. If the ionization parameter $U$ is large enough and the EUV is not absorbed, these high column density clouds could also produce significant HIL emission. To account for the similarity in profile shape in the high state, we further assume that the variable ionizing...
continuum component becomes more isotropic when brighter, so that the C iv emission arises predominantly from the high column density clouds. Since the FWHM of the low- and high-state C iv emission line profile is effectively the same, the velocity field cannot be predominantly radial, otherwise a different range in projected velocity for the HILs and LILs will result. Instead, a randomized or chaotic flow is favored. While plausible, this model requires a high degree of fine tuning to produce the detailed profile changes observed in the HILs. Hardest to explain are the reversals in HIL profile shape, from red asymmetric at low continuum levels to blue asymmetric at high continuum levels (Fig. 3b).

2. One possible scenario that may account for the above observations is a terminal wind model for the BLR. A terminal wind is the one physical structure that can display the same range in projected velocities on both small and large spatial scales. The wind may be spherical or nonspherical. For a nonspherical wind, for example a biconical flow, similar profiles for the HILs and LILs will result regardless of their respective radial emissivity distributions, provided that the opening angle of the cone remains constant. However, to produce profiles similar to that observed here (i.e., broad wings and narrow cores), we require a strong azimuthal dependence on the velocity field or a significant circularized velocity component to the flow (Goad & Knigge 1999). That is, the simplest terminal flow model in which the velocity field is constant everywhere cannot produce the correct profile shapes. However, hydrodynamic wind models (e.g., Emmering, Blandford, & Shlosman 1992; Bottorff et al. 1997) do exhibit these basic properties. While the emission-line flux variations of the HILs are assumed to be driven by continuum variations, we propose that in this model the changes in profile shape at low continuum levels are in part due to changes in the formation radius of the HILs. Specifically, we propose that in the low state, conditions within the BLR gas are such that a large fraction of the C iv emission arises at the base of the wind, in the region in which the gas begins to accelerate (Goad & Knigge 1999).

4. Conclusions

The picture we envisage is one in which the steady state profile is dominated by the dynamics of the system, with lines formed in kinematically similar regions, possibly a terminal flow. The stability of the Mg ii profile on timescales of several years provides strong supporting evidence for the existence of such a structure. Moreover, the absence of significant flux variations in the Mg ii line on timescales of a few years suggest that this region is physically extended in size. The historic variation in the Mg ii emission line flux, but not its profile, could be the result of an accretion event, a disk instability, or an increase in the wind density, and it may be linked to the disappearance of the C iv VAL.

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REFERENCES

Bottorff, M., Korista, K. T., Shlosman, I., & Blandford, R. D. 1997, ApJ, 479, 200
Cagnoni, I., Fruscione, A., McHardy, I. M., & Papadakis, I. E. 1999, Mem. Soc. Astron. Italiana, in press
Crenshaw, D. M., Maran, S. P., & Mushotzky, R. F. 1998, ApJ, 496, 797
Emmering, R. T., Blandford, R. D., & Shlosman, I. 1992, ApJ, 385, 460
Goad, M. R. 1995, Ph.D. thesis, Univ. College London
Goad, M. R., & Knigge, C. 1999, in preparation
Goad, M. R., Koratkar, A. P., Kim-Quijano, J., Korista, K. T., O’Brien, P. T., & Axon, D. J. 1999, ApJ, submitted
Goad, M. R., O’Brien, P. T., & Gondhalekar, P. M. 1993, MNRAS, 263, 149
Kolman, M., Halpern, J. P., Martin, C., Awaki, H., & Koyama, K. 1993, ApJ, 403, 592
Koratkar, A. P., et al. 1996, ApJ, 470, 378
Krolik, J. H., & Kallman, T. R. 1988, ApJ, 324, 714
Laor, A., Jannazi, B. T., Green, R. F., & Boroson, T. A. 1997, ApJ, 489, 656
Marshall, H. L., et al. 1997, ApJ, 479, 222
Mathur, S., Wilkes, B. J., & Alexander, T. 1997, ApJ, 478, 182
O’Brien, P. T., Goad, M. R., & Gondhalekar, P. M. 1995, MNRAS, 275, 1125
Romano, P., & Peterson, B. M. 1999, in ASP Conf. Ser., Structure and Kinematics of Quasar Broad Line Regions, ed. C. M. Gaskell, W. N. Brandt, M. Dietrich, D. Dultzin-Hacyan, & M. Eracleous (San Francisco: ASP), in press
Voir, G. M., Shull, J. M., & Begelman, M. C. 1987, ApJ, 316, 573
Walter, R., Ulrich, M.-H., Courvoisier, T. J.-L., & Buson, L. M. 1990, A&A, 233, 53
Wanders, I., et al. 1993, A&A, 269, 39
Wanders, I., et al. 1995, ApJ, 453, L87
Wehmann, R. J., Morris, S. L., Foltz, C. B., & Hewett, P. C. 1991, ApJ, 373, 23