ON THE EFFECTS OF DISSIPATIVE TURBULENCE ON THE NARROW EMISSION-LINE RATIOS IN SEYFERT GALAXIES

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ABSTRACT

We present a photoionization model study of the effects of microturbulence and dissipative heating on emission lines for number and column densities, elemental abundances, and ionizations typical for the narrow emission line regions (NLRs) of Seyfert galaxies. Earlier studies of NLR spectra generally found good agreement between the observations and the model predictions for most strong emission lines, such as [O iii] 5007, [O iii] 3727, [N ii] 6583, [Ne iii] 3869, and the H and He recombination lines. Nevertheless, the strengths of lines from species with ionization potentials greater than that of He II (54.4 eV), e.g., N iv and Ne v, were often underpredicted. Among the explanations suggested for these discrepancies were (selectively) enhanced elemental abundances and contributions from shock-heated gas. Interestingly, the NLR lines have widths of several 100 km s⁻¹, well in excess of the thermal broadening. If this is due to microturbulence, and the turbulence dissipates within the emission-line gas, the gas can be heated in excess of that due to photoionization. We show that the combined effects of turbulence and dissipative heating can strongly enhance N v λ1240 (relative to He ii λ1640), while the heating alone can boost the strength of [ Ne v] λ3426. We suggest that this effect is present in the NLR, particularly within ~100 pc of the central engine. Finally, since microturbulence would make clouds robust against instabilities generated during acceleration, it is not likely to be a coincidence that the radially outflowing emission-line gas is turbulent.

Subject headings: galaxies: Seyfert — line: formation — turbulence

1. INTRODUCTION

Seyfert galaxies are relatively nearby (z < 0.1), low-luminosity (bolometric luminosities Lbol < 10⁴⁵ ergs s⁻¹) examples of active galactic nuclei (AGNs). Based on the widths of their optical emission lines, Seyfert galaxies are generally divided into two types (Khachikian & Weedman 1971). Seyfert 1 galaxies (Seyfert 1s) possess broad permitted lines, with full width at half-maxima (FWHMs) ≥ 10⁵ km s⁻¹; narrower forbidden lines, with FWHM ~ 500 km s⁻¹; and optical continua, which are dominated by nonstellar emission (e.g., Oke & Sargent 1968). Seyfert 2 galaxies (Seyfert 2s) show only narrow emission lines, and the nonstellar contribution to their optical continua is much weaker (Koski 1978). The broad emission lines in Seyfert 1s vary on short timescales in response to changes in the continuum flux, which indicates that this emission arises in dense gas within tens of light-days of the central source (e.g., Peterson et al. 2004), in what is referred to as the broad-line region (BLR). The narrow lines detected in both Seyfert 1s and 2s can extend ~1 kpc from the AGNs (e.g., Schmitt & Kinney 1996; Schmitt et al. 2003), forming the so-called narrow-line region (NLR). Spectrokinemetry studies revealed the presence of strongly polarized continua and broad permitted line emission in several Seyfert 2s. This discovery led to the unified model for Seyfert galaxies (Antonucci 1993), which posits that the differences between the two types is the result of viewing angle, with Seyfert 2s characterized by the obscuration of their broad-line regions and central engines by a dustily circumnuclear torus. In this model, the torus collimates the ionizing radiation, and the resulting illumination pattern produces a roughly biconical NLR (Schmitt & Kinney 1996). If the AGN is viewed at high inclination, the bicone axis is roughly in the plane of the sky, maximizing the projected angular size of the NLR.

While historically there has been some debate about the importance of collisional and/or shock ionization of the NLR (e.g., Kriss et al. 1992; Wilson & Raymond 1999), the narrowness of radiative recombination continua detected in HMM-Newton spectra (Sako et al. 2000; Kinkhabwala et al. 2002; Turner et al. 2003; Armentrout et al. 2007) is a clear indication that the emission-line gas is photoionized by the central source. We have analyzed Hubble Space Telescope Faint Object Spectrograph (HST FOS) observations of the NLR in the Seyfert 1s NGC 5548 (Kraemer et al. 1998a) and NGC 4395 (Kraemer et al. 1999) and the Seyfert 2 galaxy NGC 1068 (Kraemer et al. 1999b), and HST Space Telescope Imaging Spectrograph (STIS) observations of NGC 1068 (Kraemer & Crenshaw 2000a, 2000b), the Seyfert 1 galaxy NGC 4151 (Nelson et al. 2000; Kraemer et al. 2000), and the Seyfert 2 galaxy Mrk 3 (Collins et al. 2005). The STIS observations were obtained in the low-resolution/long-slit mode (see Woodgate et al. 1998), with which we were able to spatially resolve the NLRs and explore the nature of the emission-line clouds as a function of distance from the central sources. Using photoionization models, we were able to constrain the densities, column densities, dust/gas ratios, and ionization state of the emission-line gas. In general, we were able to fit nearly all of the observed emission-line fluxes and ratios by assuming the gas was photoionized solely by the central source. Nevertheless, we found discrepancies in the predicted strengths of a few emission lines, typically those from the higher ionization states (i.e., those with ionization potentials above the He ii Lyman limit), such as N v λ1240.5 [Ne v] λ3346, 3426,
and [Fe v] λ6087. Usually, our models underpredicted the strengths of these lines by factors of ~2, although the discrepancies were often much greater for N v. The poor fit to high-ionization lines was also noted by Oliva (1997), and may be rectified by adjusting the elemental abundances or by including additional ionization/excitation mechanisms (e.g., Kriss et al. 1992). In the modeling of the NLR emission in NGC 5548 (Kraemer et al. 1998a) and NGC 1068 (Kraemer et al. 1998b), we were able to improve the fit for the N v and [Ne v] lines by assuming supersolar abundances of nitrogen and neon. However, including higher abundances for selected elements resulted in overpredictions of lines from lower ionization states, e.g., N iv λ1486. Indeed, in most cases, the strengths of the lower ionization lines from these elements, e.g., [Ne iii] λ3869 and [N ii] λλ6548, 6583, are consistent with roughly solar abundances (see § 2.1).

In addition to photoionization model studies of the NLR, we have also used spatially resolved STIS spectra to analyze the kinematics of the emission-line gas in NGC 1068 (Crenshaw & Kraemer 2000; Das et al. 2006), Mrk 3 (Ruiz et al. 2001, 2005), and NGC 4151 (Crenshaw et al. 2000; Das et al. 2005). Although the kinematic studies used the [O iii] λ5007 line, we have found that the higher ionization lines are spatially colocated with the [O iii] knots (e.g., Collins et al. 2005); therefore, it is probable that similar dynamical effects drive the higher ionization gas. Each of these sources shows a similar kinematic profile, in which the projected radial velocity, \( v_r \), gradually increases from the central point source out to \( r \sim 100 \) pc, after which the velocities abruptly begin to decrease toward systemic. We have been able to model the kinematics by assuming the gas is confined to a hollow, biconical envelope, whose apex is roughly coincident with the AGN. The gas is continuously accelerated, then begins to undergo a rapid deceleration. The dynamics of this process is not still clear (e.g., Everett & Murray 2007; Das et al. 2007), but it is likely that radiation pressure from the continuum source makes an important contribution. The [O iii] lines are also quite broad in these objects, e.g., FWHM > 1000 km s\(^{-1}\) near the apex of the bicone and \( \geq 500 \) km s\(^{-1}\) throughout the inner 200 pc of the NLR. In general, the widths appear to decrease with distance from the AGN, although there are points of abrupt increases, particularly in the case of NGC 1068 (Crenshaw & Kraemer 2000; Das et al. 2006), which occur near the velocity turnover points. The physical conditions that produce these line widths is unclear (see § 5). It is possible that they result from the superposition of multiple individual kinematic components; if so, the flow may simply become more chaotic at the turnover points, broadening the profiles. However, it is also possible that the emission-line knots possess significant microturbulence. Whatever process slows the knots could conceivably boost the microturbulence. Another piece of evidence that the outflowing gas is turbulent is found in the blueshifted UV absorption detected along the line of sight to many Seyfert 1s (Crenshaw et al. 1999, 2003; Dunn et al. 2007). The absorption lines nearly always have widths (>tens of km s\(^{-1}\)) in excess of thermal (~several km s\(^{-1}\)), and, in several cases, we have measured FWHMs greater than several hundred km s\(^{-1}\) (e.g., Kraemer et al. 2001b). The absorption lines appear/disappear over short timescales (e.g., Crenshaw & Kraemer 1999; Kraemer et al. 2001a; Crenshaw et al. 2003) without obvious changes in their widths, which is suggestive of turbulent knots passing across our line of sight.

In Figures 1–3, we show the N v λ1240/He II λ1640, C iv λ1550/He II λ1640, and [Ne v] λ3426/He II λ1640 ratios as a function of projected radial distance, \( r \), and FWHM. There is some evidence for higher values at \( r \lesssim 100 \) pc, although there are some points with high-ionization ratios at greater radial distances for C iv and [Ne v]. More evident is the correlation of the line ratios with FWHM. As the broader lines are found in more highly excited components, if the broader lines are found in more highly excited components, it suggests some physical connection. Therefore, our hypothesis is that the line widths result, at least partly, from internal microturbulence, which in turn affects the observed line ratios.

A related issue is that the broad emission lines in AGNs are smooth (e.g., Dietrich et al. 1999). If the lines are thermally broadened, there must be an inordinately large number of individual clouds within the BLR. To address this problem, Bottorff & Ferland (2000) proposed that the clouds are internally turbulent, with microturbulent velocities that exceed their thermal velocities. Using photoionization models, they were able to generate smooth line profiles from a small number of clouds. Bottorff & Ferland (2002, hereafter BF02) expanded on this by examining the effects of dissipative turbulence. In the case of nondissipative turbulence, the turbulent motions persist, whereas, in the dissipative case, the motion is converted into heat. The corresponding increase in electron temperature will affect the emissivity of emission lines, particularly those that are collisionally excited. There is evidence for dissipative heating in the diffuse interstellar medium of the Milky Way Galaxy (Minter & Balser 1997); hence, BF02 argued that such processes were likely to occur within the BLR gas in AGNs. Since the thermal motions will decay due to the heating losses, there must be some continual external source of turbulence. Possibilities include the intense radiation pressure experienced by
gas close to the AGN and magnetic fields. Interestingly, both radiation pressure and magnetohydrodynamic (MHD) flows have been suggested as mechanisms for mass loss in AGNs (see Crenshaw et al. 2003 and references therein); hence, it is possible that forces that drive the outflows also maintain the microturbulence.

BF02 parameterized the dissipative heating as a function of turbulence velocity, as follows:

\[ Q = \eta_0 \rho \frac{v_t^3}{D} \text{ ergs cm}^{-3} \text{ s}^{-1}, \]

where \( \eta_0 \) is of order unity (see Stone et al. 1998), \( v_t \) is the magnitude of the turbulence velocity, \( \rho \) is the mass density of the gas, and \( D \) is the scale length over which the turbulence dissipates. BF02 assumed that \( D \) corresponds to the physical depth of a BLR cloud, or \( \sim 10^{13} \text{ cm} \), based on typical BLR hydrogen number densities \( \left( n_H \sim 10^{10} \text{ cm}^{-3} \right) \) and column densities \( \left( N_H \sim 10^{23} \text{ cm}^{-2} \right) \) (Kwan & Krolik 1981). For their models, they reparameterized the heating rate, as follows:

\[ Q \approx 2.3 \times 10^{-3} \frac{v_3^3 n_{10}}{L_{13}} \text{ ergs cm}^{-3} \text{ s}^{-1}, \]

where \( v_3 \) is the turbulence velocity in units of 1000 km s\(^{-1}\), \( n_{10} \) is the hydrogen number density in units of \( 10^{10} \text{ cm}^{-3} \), and \( L_{13} \) is the physical depth of the cloud, in units of \( 10^{13} \text{ cm} \). In this paper, we examine the effects of dissipative turbulence in the NLR gas and have used equation (2) to calculate the heating. Following BF02, we assumed that the turbulence dissipates over the full depth of the cloud. However, although the column densities of the NLR tend to be much lower than the canonical BLR value (Kraemer et al. 1998a, 1998b, 2000; Kraemer & Crenshaw 2000a, 2000b), the physical depths are several orders of magnitude larger, due to the much lower densities.

2. PHOTOIONIZATION MODELING

We have calculated a set of photoionization models to investigate the effects of microturbulence and dissipative heating on the NLR emission-line ratios. The elemental abundances and other model input parameters are detailed in §§ 2.1–2.2.

2.1. Elemental Abundances

The relative strengths of emission lines strongly depend on the elemental abundances. Since the thermal equilibrium in the optical emission-line gas is driven largely by collisional cooling, the electron temperature is quite sensitive to the relative fraction of heavy atoms (neutral and ionized) in gas phase. For example, for heavy-element abundances more than several times solar values, the collisionally excited lines can actually be weaker than for lower abundances due to the increased line cooling rates. While the abundances of common elements such as C, O, and Ne scale with \( Z/Z_{\odot} \) (where \( Z_{\odot} \) indicates “solar abundances”), N scales as \( (Z/Z_{\odot})^2 \) (e.g., Vila-Costas & Edmunds 1993). Hence, N/C-O-Ne can become quite large at supersolar abundances, which should result in

\[ Q = \eta_0 \rho \frac{v_t^3}{D} \text{ ergs cm}^{-3} \text{ s}^{-1}, \]

where \( \eta_0 \) is of order unity (see Stone et al. 1998), \( v_t \) is the magnitude of the turbulence velocity, \( \rho \) is the mass density of the gas, and \( D \) is the scale length over which the turbulence dissipates. BF02 assumed that \( D \) corresponds to the physical depth of a BLR cloud, or \( \sim 10^{13} \text{ cm} \), based on typical BLR hydrogen number densities \( \left( n_H \sim 10^{10} \text{ cm}^{-3} \right) \) and column densities \( \left( N_H \sim 10^{23} \text{ cm}^{-2} \right) \) (Kwan & Krolik 1981). For their models, they reparameterized the heating rate, as follows:

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the enhancement of lines such as N \( \lambda 1240 \) and the N \( \lambda 1486 \) multiplet compared to lines from these other elements.

In our previous NLR studies (see § 1), we have assumed “roughly solar” abundances (e.g., Grevesse & Anders 1989). Recently, Groves et al. (2004) revisited the issue of elemental abundances in the NLR, and incorporated the latest efforts to define solar abundances (e.g., Grevesse & Sauval 1998), which suggested somewhat lower N/H than previous studies. In order to reproduce the observed strengths of the [N II] \( \lambda 6548, 6583 \) lines with their photoionization models, Groves et al. had to assume twice the solar N/H ratio (interestingly, this is quite close to the “roughly” solar value that we had used in our previous NLR modeling). It is worth noting that similarly elevated abundances were determined for the blueshifted UV absorbers in the Seyfert 1 galaxy Mrk 279 (Arav et al. 2007), particularly since the UV absorbers and the emission-line gas in the inner NLR may be associated (Crenshaw & Kraemer 2005). Assuming all the elements have scaled together, this corresponds to a overall abundance of \( Z/Z_\odot \approx 1.4 \). For this paper, we used the abundances from Asplund et al. (2005), scaled in the manner suggested by Groves et al. The logs of the abundances relative to H by number are as follows. He: -1.0; C: -3.46; N: -3.92; O: -3.19; Ne: -4.01; Mg: -4.33; Si: -4.34; S: -4.69; and Fe: -4.5. Note that the Ne/O ratio is \( \approx 0.15 \), in agreement with current estimates that include the effect of solar CNNe mixing (see Delahaye & Pinsonneault 2006).

Although much of the NLR gas may be dusty (Kraemer & Harrington 1986; Groves et al. 2004) we have not included dust in these models. The reasoning is twofold. First, there would be no depletion of neon and little if any of nitrogen (in the absence of ice mantles) onto grains. Second, we have found evidence that the dust/gas ratios in the NLR are below that of the interstellar medium, and, in some cases (e.g., NGC 1068; Kraemer & Crenshaw 2000a), the gas in the inner NLR appears to be dust-free.

### 2.2. Model Input Parameters

The photoionization models used for this study were generated using the Beta 5 version of Cloudy (Ferland et al. 1998). As per convention, the models are parameterized in terms of the ionization parameter, \( U = Q(4\pi r^2 c n_H) \), where \( r \) is the distance between the emission-line gas and the central source, \( n_H \) is the hydrogen number density, \( c \) is the speed of light, and \( Q = \int_0^{\infty} L_{\nu} / \nu dv \), or the number of ionizing photons s\(^{-1}\) emitted by a source of luminosity \( L_{\nu} \). We assumed a plane-parallel (“slab”) geometry. For the incident continuum, we used the spectral energy distribution (SED) that we employed in our modeling of NGC 4151 (Kraemer et al. 2005), which is parameterized as a broken power law of the form \( L_\nu \propto \nu^{\alpha_1} \) for \( \nu < \nu_{\text{c}} \), and \( \nu^{\alpha_2} \) for \( \nu \geq \nu_{\text{c}} \), with \( \nu_{\text{c}} = 10^{13} \) Hz.

### Table 1: Model Parameters

| Turbulence Velocity (km s\(^{-1}\)) | Heating\(^a\) (ergs s\(^{-1}\) cm\(^{-3}\)) |
|------------------------------------|-------------------------------|
| 50                                 | \( 2.9 \times 10^{-15} \)     |
| 100                                | \( 2.3 \times 10^{-14} \)     |
| 150                                | \( 7.8 \times 10^{-14} \)     |
| 200                                | \( 1.8 \times 10^{-13} \)     |
| 250                                 | \( 3.6 \times 10^{-13} \)     |

*Note.—For the set of models, we assumed \( N_H = 10^{21} \) cm\(^{-2}\), \( n_H = 10^5 \) cm\(^{-3}\), and the elemental abundances listed in § 2.1.

\(^a\) For comparison, the radiative heating is \( 9.5 \times 10^{-14} \) and \( 1.1 \times 10^{-13} \) ergs s\(^{-1}\) cm\(^{-3}\), for \( \log (U) = -1.5 \) and -1.0, respectively.

### 3. MODEL RESULTS

In our models, we tested the effects of turbulence/heating on two emission lines that are strong and often underpredicted by photoionization models: N \( \lambda 1240 \) and [Ne v] \( \lambda 3426 \). As shown in Figure 4, the He \( ^{2+} \) zone, in which there is the strongest contribution to the He \( \Pi \) recombination lines, is coincident with the N \( ^{4+} \) and Ne \( ^{3+} \) zones. Therefore, the results are given as line ratios relative to the He \( \Pi \lambda 1640 \) recombination line.

For resonance lines such as N \( \lambda 1240 \), there can be a contribution from photoexcitation to the upper level by continuum radiation. This has been suggested as the mechanism responsible for the strong resonance lines from He-like and H-like ions of Ne, O, and N detected in X-ray spectra of Seyfert galaxies (e.g., Sako et al. 2000; Kinkhabwala et al. 2002; Armourent et al. 2007). If the gas is turbulent, the absorption profiles are broadened, which

![Fig. 4.—Selected fractional ionic abundances as a function of column density for an ionization parameter \( \log (U) = -1.0 \). Note that the fractions of N\(^{4+}\) and Ne\(^{3+}\) become negligible for \( N_H > 21.5 \), which at point the gas has become optically thick above the He \( \Pi \) Lyman limit.](image-url)
increases the number of continuum photons that the gas can absorb before becoming optically thick to the incident radiation, thereby increasing the contribution from photoexcitation. To test the effect of photoexcitation alone, we generated a set of models with turbulence but no dissipative heating. The results for N v are shown in Figure 5. In the absence of turbulence, the maximum N v/He ii ratio is ~1.4, which occurs near an ionization parameter of log (U) = −0.4. The N v/He ii ratio increases with turbulence, reaching a value of ~4 for v_t = 250 km s^{-1}. The shape of the turnover at log (U) > −0.4 depends on the predicted He ii λ1640, which is relatively stronger at high turbulence as the model diverges from the case B approximation (e.g., Osterbrock 1989). Therefore, elevated N v/He ii ratios can be achieved for large microturbulence, although there is no effect on forbidden lines such as [Ne v] λ3426. However, the range in ionization parameter for which N v/He ii ratios >2 are predicted is rather narrow and covers a range for which the gas is so highly ionized that most of the nitrogen is in higher ionization states than N^{+4}. The N v is enhanced in this case because the smaller N^{+4} column densities result in lower N v optical depths. The effect of turbulence alone is not as strong at the ionization parameter at which the largest column density of N^{+4} is predicted, log (U) ≈ −1.3, since the line becomes optically thick close to the irradiated face of the slab. Also, the NLR must include gas at lower ionization, which still produces He ii emission; hence, the contribution from turbulent gas with high N v/He ii ratios will be diluted. Therefore, photoexcitation, even when maximized by high turbulence, may not be sufficient to produce the highest observed N v/He ii ratios (see Fig. 1), unless the nitrogen abundances are ≥ several times solar.

The effect of dissipative heating scaled with microturbulence on the N v/He ii ratio is shown in Figure 6. The peak ratio increases with heating, peaking at ~11 for v_t = 250 km s^{-1}. Comparing these results to the models generated without heating, in addition to predicting high ratios over a broader range of ionization parameter, the ionization parameters at which N v/He ii peaks drop with increased heating/turbulence. This demonstrates the relative contributions from photoexcitation and dissipative heating: when heating is included, there is a significant enhancement of the line in the more optically thick models, and the heating becomes the dominant effect for v_t > 200 km s^{-1}. Including heating has a significant effect on the [Ne v]/He ii ratio, as well, as shown in Figure 7. The slight trend to lower values of U for the peak ratio is due to the higher electron temperatures for the models with the greatest Ne^{+4} fraction. As these results indicate, [Ne v]/He ii ratios greater than unity require the heating resulting from v_t > 100 km s^{-1}.

Since we have included dissipative heating, we examined the thermal stability of the gas. The thermal stability curves (e.g., Krolik et al. 1981) are shown in Figure 8. Although the unstable region, characterized by negative slope, is more pronounced for the models with v_t = 250 km s^{-1}, the gas will be thermally stable for the range of ionization parameters from which we examined emission-line ratios, i.e., log (U) < 0.0.

4. COMPARISON WITH OBSERVATIONS

Since the underprediction of the N v/He ii and [Ne v]/He ii ratios is the motivation for this study, we now demonstrate to what extent the models predict correct values in the observed range.

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Fig. 5.—Ratio of N v λ1240/He ii λ1640 as a function of U, for microturbulence velocities v = 0 (solid line), 50 (long-dashed line), 100 (triple-dot–dashed line), 150 (dash-dotted line), 200 (short-dashed line), and 250 (dotted line) km s^{-1}. Dissipative heating was not included in these models; hence, the enhancement of the N v results solely from photoexcitation.

Fig. 6.—Same as Fig. 5, but with dissipative heating incorporated in the models (see Table 1). Note that (1) the maximum N v/He ii ratio predicted is a factor of nearly 3 times that for the turbulence-only models, and (2) the peak shifts to lower values of U as a function of v_t as a result of the increased dissipative heating at high turbulence velocities.

Fig. 7.—Same as Fig. 6, showing the [Ne v] λ3426/He ii λ1640 ratio. As noted in the text, for the densities and elemental abundances used in these models, [Ne v]/He ii ratios greater than unity require the heating predicted for v_t > 100 km s^{-1}.
degree the addition of dissipative heating can reduce these discrepancies. As discussed in §1, kinematic studies have found that the (O iii) λ5007 lines in the NLR can be broad. For example, the brightest components in NGC 1068 typically have FWHM of \( \leq 700 \) km s\(^{-1}\) (Das et al. 2006), while those in NGC 4151 have FWHM of \( \leq 500 \) km s\(^{-1}\) (Das et al. 2005). Also, the largest FWHM detected among the strong UV absorption components in NGC 4151 is \( \approx 435 \) km s\(^{-1}\) (Kraemer et al. 2001b). In order to test the effects of microturbulence, we have opted to be somewhat conservative and have generated models with turbulence velocities of 50, 100, and 150 km s\(^{-1}\) (which corresponds to FWHM \( \approx 120\), 235, and 350 km s\(^{-1}\)) for comparison with the observed line ratios. The values assumed for \( U \), \( \eta_\text{II} \), and \( m_\text{II} \) are as described in §2.2.

In Figure 9 we compare the model predictions for N \( \lambda 1240/\) He \( \lambda 1640 \) versus [Ne iv] \( \lambda 1550/\) He \( \lambda 1640 \) and [Ne v] \( \lambda 1640/\) He \( \lambda 1640 \) against the observed ratios. Although there are a large number of data points for which both the N iv and [Ne iv] lines are relatively weak, it is apparent that turbulence combined with dissipative heating is required for those points with N \( \lambda 1240/\) He \( \lambda 1640 > 1.5 \) and [Ne iv] \( \lambda 1640 > 0.5 \). The few points that lie outside the upper (\( \eta_\text{II} = 150 \) km s\(^{-1}\)) curve could be matched by higher turbulence/heat. In particular, note the data point for NGC 5548. In Kraemer et al. (1998a), we had suggested that the large N \( \lambda 1240/\) He \( \lambda 1640 \) and [Ne iv] \( \lambda 1640/\) He \( \lambda 1640 \) ratios in the source might be the result of high nitrogen and neon abundances. However, these results suggest that strong N iv and [Ne v] lines are more likely indicative of turbulence/heat.

In Figure 10 we show the model predictions for N \( \lambda 1240/\) He \( \lambda 1640 \) versus C iv \( \lambda 1486/\) He \( \lambda 1640 \). The model comparison shows that C iv/He \( \lambda 1640 \) ratios \( > 4 \) are consistent with turbulence/heat. We also compared the N \( \lambda 1240/\) He \( \lambda 1640 \) to N iv \( \lambda 1486/\) He \( \lambda 1640 \). While the number of data points was small due to the relative weakness of N iv, combined with the effects of reddening, there is some indication that the N iv may show the effects of dissipative heating.

An additional indication that the NLR gas is turbulent is that high L/\( \beta \)/L\emission\ gas ratios have been detected in some Seyferts. In Hopkins Ultraviolet Telescope spectra of NGC 1068, Kriss et al. (1992) measured a ratio of \( \approx 0.1 \), while, under case B conditions (Osterbrock 1989), this ratio will be \( \ll 0.01 \). In our models, we find that for log \( (U) = 1.5 \) without turbulence, L/\( \beta \)/L\emission\ \( \approx 1.4 \times 10^{-3} \). For \( \eta_\text{II} = 150 \) km s\(^{-1}\), the ratio is \( \approx 0.01 \). Decreasing the column density by a factor of 10 increases L/\( \beta \)/L\emission\ by a similar factor. Hence, this strongly suggests that the gas in the NLR is turbulent, although the column densities of the Lyman-emitting gas may be somewhat lower than those assumed here, but well within the range of values used in our previous NLR studies (e.g., Kraemer et al. 2000; Kraemer & Crenshaw 2000b).

5. DISCUSSION

The inclusion of microturbulence with associated dissipative heating has the effect of increasing the strengths of the N \( \lambda \) and [Ne v] lines, relative to He \( \lambda 1550 \). In the range of ionization parameter...
for which these lines are strongest, i.e., \(-1.5 < \log (U) < -1.3\), the volume heating rate for a turbulence velocity \(v_t = 150 \text{ km s}^{-1}\) is on the same order as the radiative heating rate. Spatially resolved spectra of the NLR of Seyferts (see § 1) reveal that the emission-line knots remain quite broad (FWHM > several hundred km s\(^{-1}\)) throughout the inner ~200 pc of the NLR. This suggests that if this is due to microturbulence, the turbulence is being continuously driven, perhaps by the continuum radiation from the central source. For example, in NGC 4151, which has a luminosity in ionizing photons of \(10^{53} \text{ photons s}^{-1}\) (Kraemer et al. 2005), an emission-line cloud, characterized by \(\log (U) = -1.5\), \(n_\text{H} = 10^4 \text{ cm}^{-3}\), and \(N_{\text{H}} = 10^{21} \text{ cm}^{-2}\), would lie in the base that have nothing to do with turbulence or an outwardly propagating disturbance. Our kinematic studies have shown that the emission-line gas is accelerated to velocities ~1000 km s\(^{-1}\) within the inner 100 pc of the NLR. Over the same distance scales, the FWHM of the lines decrease from 1000 km s\(^{-1}\) to a few hundred km s\(^{-1}\) (with some notable exceptions). Although this is consistent with superposition of velocity components, taken together with the correlation between the \(N/\text{He II} \), \(C/\text{He II}\), and \([\text{Ne} v]/\text{He II}\) ratios and FWHM of these lines, we interpret this as evidence that it is turbulence (largely) and not systematic nonradial components of the outflow that contribute to the line widths.

While a cloud of gas is being accelerated, the driving mechanism will generate instabilities within the cloud, such as Rayleigh-Taylor, for a radiatively driven cloud, or Kelvin-Helmholtz instabilities, for a cloud entrained in a wind. If the timescale for the instability to propagate through the cloud is less than the timescale for acceleration, e.g., to achieve the observed radial velocities, the cloud will fragment. It has been shown (e.g., Allen 1984; Smith 1993) that fragmentation is inevitable for clouds with physical parameters similar to those derived from our photoionization models (which are the basis for the range in parameters assumed in this paper). There are only two ways to reconcile this. One way is for the clouds to constantly form and evaporate within a hot wind (e.g., Krolik & Kriss 2001). The other way is for the clouds to be robust to instability-driven fragmentation via internal turbulence (Allen 1984). The turbulence could be generated by multiple shocks, which also accelerate the clouds (Marscher 1978). Interestingly, this requires turbulence velocities \(0.1v_r < v_t < v_r\), which is consistent with observations; for \(v_r > v_t\), the clouds will evaporate. Marscher (1978) further notes that stable clouds must have radii >10\(^{14}\) cm, which is consistent with our modeling results.

Microturbulence in NLR clouds will dissipate into heat on a timescale shorter than the NLR crossing time. This means that energy must be provided constantly to drive the turbulence. As mentioned above it is energetically possible for the continuum to do this. However, transferring the energy into turbulent motions at the required rate may be more problematic. If the outflow is an MHD wind, then magnetic field lines that thread NLR clouds also thread the portion of the disk from which the NLR material was originally launched. This provides a possible energy conduit to the NLR clouds. It is uncertain, however, whether disturbances launched from the disk could travel over a distance of 100 pc to be dissipated in NLR clouds. A combination of radiative driving and an MHD wind, however, offers the possibility that NLR materials can be driven against magnetic field lines, thereby exciting disturbances that would dissipate more or less locally as heating. Such a mechanism is an area for future study. At the very least the presence of magnetic fields may be necessary to avert overly strong shock formation in the highly turbulent gas.

Therefore, we suggest the following scenario. The emission-line clouds form relatively close to the central source, perhaps in the inner few parsecs of the NLR. They are accelerated outward by one of the mechanisms listed above. In the process, they develop significant microturbulence, which also serves to maintain them against disruption. As the clouds move outward, the mechanism that generates the turbulence becomes weaker, which could be the \(1/r^2\) dilution of the radiation, or a drop in density of a wind. The dissipative heating would decrease, and there would be less enhancement of these emission-line ratios, as is observed (see Figs. 1–3).

6. SUMMARY

We have explored the effects of microturbulence and associated dissipative heating on emission-line ratios for conditions applicable to the NLR of Seyfert galaxies. Based on our modeling results, we suggest the following.

1. Microturbulence can increase the effect of photoexcitation, thereby boosting the relative strengths of resonance lines such as N \(\lambda 1240\). Turbulence alone will not directly affect collisionally excited forbidden lines, such as \([\text{Ne} v]/\text{He II}\) ratios. However, we find that, if the turbulence dissipates over scale lengths equal to the physical depths of the emission-line clouds, the resulting heating is sufficient to explain the highest \([\text{Ne} v]/\text{He II}\) ratios detected in these spectra.

2. Although we found that the elemental abundances may be slightly supersolar, when turbulence and heating are included, there is no need to invoke higher abundances to explain the observed line ratios.

3. Although we cannot rule out that the emission-line widths may partly be due to superposition of kinematic components, the correlation between the line ratios and FWHM suggests that the clouds are turbulent and that the turbulence affects the relative strengths of the emission lines. This is further supported by the fact that including microturbulence of the same order of magnitude as the observed line widths can alleviate discrepancies between the models and the observations. While the turbulence appears to diminish with radial distance, the fact that the line widths exceed thermal throughout the inner ~200 pc of the NLR suggests that some process maintains the turbulence over large distances.

4. Microturbulence can make the clouds robust to the instabilities generated during cloud acceleration. This suggests that the
lifetime of nonturbulent clouds in the inner NLR may be brief. Hence, it may not be a coincidence that the emission and absorption lines observed in Seyfert galaxies have widths that far exceed their thermal widths.

In this paper, we have not attempted to fully explore the range of parameters, i.e., density, ionization, elemental abundances, and dust/gas ratio, that may exist in the NLR of Seyferts. Instead, we simply attempted to gauge the effects of turbulence/heating. In future work, it will be critical to examine the origins of the turbulence and develop a more sophisticated model for the dissipative heating, in particular regarding scale lengths and the effects of internal magnetic field. In the meantime, these results suggest that it would be appropriate to include an approximation of turbulence/heating in photoionization studies of AGNs. In a future paper, we plan to reanalyze the STIS long-slit spectra of NGC 1068 and to explore the role of turbulence in detail.

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