IS THE BROAD-LINE REGION CLUMPED OR SMOOTH? CONSTRAINTS FROM THE Hα PROFILE IN NGC 4395, THE LEAST LUMINOUS SEYFERT 1 GALAXY

Ari Laor, 1 Aaron J. Barth, 2 Luis C. Hο, 3 and Alexei V. Filippenko 4

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ABSTRACT

The origin and configuration of the gas that emits broad lines in Type I active galactic nuclei is not established yet. The lack of small-scale structure in the broad emission-line profiles is consistent with either a smooth gas flow or a clumped flow with many small clouds. An attractive possibility for the origin of many small clouds is the atmospheres of bloated stars, an origin that also provides a natural mechanism for the cloud confinement. Earlier studies of the broad-line profiles have already put strong lower limits on the minimum number of such stars, but these limits are sensitive to the assumed width of the lines produced by each cloud. Here we revisit this problem using high-resolution Keck spectra of the Hα line in NGC 4395, which has the smallest known broad-line region (∼1.6′). Only a handful of the required bloated stars (each having r* ≈ 10^14 cm) could fit into the broad-line region of NGC 4395, yet the observed smoothness of the Hα line implies a lower limit of ∼10^4–10^5 on the number of discrete clouds. This conclusively rules out the bloated-stars scenario, regardless of any plausible line-broadening mechanisms. The upper limit on the size of the clouds is ∼10^12 cm, which is comparable to the size implied by photoionization models. This strongly suggests that gas in the broad-line region is structured as a smooth rather than a clumped flow, most likely in a rotationally dominated thick disk-like configuration. However, it remains to be clarified why such a smooth, gravity-dominated flow generates double-peaked emission lines only in a small fraction of active galactic nuclei.

Subject headings: galaxies: active — galaxies: individual (NGC 4395) — Seyfert — quasars: emission lines

1. INTRODUCTION

Type I active galactic nuclei (AGNs) are defined by the presence of permitted lines with a kinematically distinct broad component, usually with full width at half-maximum intensity (FWHM) ≥ 1000 km s^{-1}. The broad lines are emitted by gas in the broad-line region (BLR) that is being photoionized by the central compact continuum source. Detailed photoionization calculations yield rather tight constraints on the density, temperature, ionization level, and chemical abundances of the photoionized gas (e.g., Ferland et al. 1998; Hamann & Ferland 1999), while reverberation mapping techniques constrain the size and velocity field of the gas (e.g., Peterson 2001). However, the structure and origin of the photoionized gas in the BLR remains a largely unsolved problem.

1.1. Proposed Models for the BLR

The gas in the BLR may be structured in small clumps (hereafter “clouds”). A particularly appealing model is that of bloated stars, where the clouds are identified with the surface layers of supergiant stars, which are further bloated by the ionizing radiation field (Edwards 1980; Scoville & Norman 1988; Penston 1988; Kazanas 1989; Tout et al. 1989; Alexander & Netzer 1994, 1997). This model is attractive because it relies on a relatively small modification of known objects (supergiants), and it also provides a natural mechanism for the cloud confinement, although a self-consistent BLR structure within this model appears problematic (Bagelman & Sikora 1992; Krolik 1999).

Alternative suggestions for the origin of BLR clouds include gas streams produced by tidally disrupted stars (Hills 1975; Roos 1992), or by star-disk collisions (Zurek et al. 1994; Vilkovskij & Czerny 2002), or clumps in a gravitationally unstable outer disk (Collin & Hure 2001). Other scenarios invoke density inhomogeneities produced by wind interaction with nearby obstacles (Perry & Dyson 1985), such as stellar atmospheres (Torricelli-Ciamponi & Pietrini 2002), supernova remnants (Pittard et al. 2003), or the accretion disk surface (Cassidy & Raine 1996). Alternatively, it has been suggested that the clouds are density enhancements produced by shocks in an accreting gas (Fromerth & Melia 2001). The physical viability of some of the proposed mechanisms remains unclear (e.g., Mathews 1986; Mathews & Doane 1990).

The other option for the BLR structure is a smooth continuous flow, rather than a clumped flow, which might, for example, be identified with the illuminated and photoionized accretion disk surface (e.g., Dumont & Collin-Souffrin 1990a, 1990b). Alternatively, it could originate in a wind driven off an accretion disk by radiation or magnetic pressure gradients (Shlosman et al. 1985; Emmering et al. 1992; Königl & Kartje 1994; Murray et al. 1995; Chiang & Murray 1996; Bottorff et al. 1997).

1.2. Earlier Constraints

The minimal size of the photoionized clouds can be estimated from simple Strömgren depth arguments. Equating the H ionization rate to the recombinational rate per unit area yields the column density of the photoionized H ii layer, where most of the line emission is produced. This argument yields \( \Sigma_{\text{ion}} \approx 10^{23} U \text{ cm}^{-2} \), where \( U \equiv n_e/n_p \) is the ionization parameter, and \( n_p \) and \( n_e \) are (respectively) the ionizing photon and the electron number densities. Typical BLR parameters are \( U \approx 0.1 \) and \( n_e \approx 10^{10} \text{ cm}^{-3} \), implying a typical thickness of the H ii layer of \( d \approx 10^2 \text{ cm} \) (although there may be a large range of \( d \) values in the BLR; e.g., Baldwin et al. 1995). The equivalent widths of
the H H recombination lines imply that the BLR gas covers \( \Omega_{BLR}/4\pi \approx 0.1 \text{–} 0.2 \) of the ionizing continuum source (e.g., Ferland et al. 1998). The photoionized gas could be made of clumps that are as small as \( d \), or it may reside in a thin photoionized surface layer over more extended bodies. The latter option is supported by the strength of some of the low-ionization lines (e.g., lines from Fe II, Ca II, Na I) which originate in deeper layers at \( \Sigma > \Sigma_{\text{ion}} \), where \( H \) is only partially ionized (e.g., Ferland & Persson 1989; Baldwin et al. 2003). How can one then determine if the BLR is clumped or smooth?

The number of clouds in the BLR, \( n_c \), and their size, \( r_c \), can be constrained based on the smoothness of the emission-line profiles. The level of fluctuations in the emission-line profiles is proportional to \( n_c^{-1/2} \), assuming the cloud velocities are randomly distributed within the line profile (in proportion to the line flux). The solid area subtended by all the BLR clouds is \( \Omega_{BLR}/4\pi = n_c\sigma^2/4\pi r_c^2 \), where \( R_{BLR} \) is the radius of the BLR; since \( \Omega_{BLR}/4\pi \approx 0.1 \text{–} 0.2 \), we find that \( r_c \approx R_{BLR}/n_c^{1/2} \). High-resolution spectroscopy at a high signal-to-noise ratio (S/N) can place tight constraints on the level of fluctuations, which then translates into a large lower limit on \( n_c \), and thus a tight upper limit on \( r_c \), which may exclude some clumped BLR models.

The first application of this method was made by Capriotti et al. (1981), who deduced \( n_c \gtrsim 10^4 \) in a sample of Seyfert galaxies. Atwood et al. (1982) improved the limit to \( n_c \gtrsim 5 \times 10^4 \) for Mrk 509, and Laor et al. (1994) obtained \( n_c \gtrsim 10^4 \) for a sample of bright quasars, using Hubble Space Telescope spectroscopy of the C IV and Ly \( \alpha \) lines. Significantly improved limits of \( n_c \gtrsim 3 \times 10^6 \) and \( 3 \times 10^7 \) were obtained for Mrk 335 (Arav et al. 1997) and NGC 4151 (Arav et al. 1998) using high-quality Keck spectra of the H\( \alpha \) emission line. Finally, Dietrich et al. (1999) obtained the highest limit of \( n_c \gtrsim 10^9 \) in the luminous quasar 3C 273.

Since \( R_{BLR} \propto \sigma^{-0.6} \) (Kaspi et al. 2005), while \( r_c \approx R_{BLR}/n_c^{1/2} \), tighter constraints on \( r_c \) can be obtained in lower-luminosity objects. In 3C 273, \( \nu L_\nu(5100\AA) \approx 6 \times 10^{45} \text{ ergs s}^{-1} \), and the lowest luminosity object where \( n_c \) was constrained is NGC 4151, where \( \nu L_\nu(5100\AA) \approx 7 \times 10^{42} \text{ ergs s}^{-1} \) (Kaspi et al. 2000).

Here we report on high-quality Keck spectroscopy of the \( H\alpha \) line in NGC 4395, which is a factor of 1000 fainter than NGC 4151, having \( \nu L_\nu(5100\AA) = 5.9 \times 10^{39} \text{ ergs s}^{-1} \) (Petrosian et al. 2005). This is the least luminous known Seyfert 1 nucleus (Filippenko & Sargent 1989; Filippenko et al. 1993), and despite its extreme low luminosity, it appears to have a rather normal broad emission-line spectrum (apparently with a lower than solar metal abundance; Kraemer et al. 2005). The low luminosity of NGC 4395 implies an expected \( R_{BLR} \) of just \( \sim (0.5 \text{–} 1.7) \times 10^{14} \text{ cm} \), based on the most recent expression for the mean Balmer line time lag versus \( \nu L_\nu(5100\AA) \) in Kaspi et al. (2005; see their Table 3). Bloated stars are predicted to have a size of \( \sim 10^{14} \text{ cm} \) (Alexander & Netzer 1994), and thus at most a handful of such stars can be accommodated in the BLR of NGC 4395. This will inevitably produce large-amplitude features in the line profile.

The earlier studies of Arav et al. (1997, 1998) and Dietrich et al. (1999) ruled out the bloated-stars idea, assuming the width of the lines produced by the individual clouds are not much above the thermal width. However, significant nonthermal broadening through radiation pressure ablation of the BLR clouds, or through magnetic pressure effects, is likely and possibly inevitable. This broadening reduces the lower limit on \( n_c \) (e.g., Bottorff & Ferland 2000; Bottorff et al. 2000), and it may leave the bloated-stars idea as a viable option. As we show below, the bloated-stars idea can be conclusively ruled out in the compact BLR of NGC 4395, regardless of the velocity width of the lines produced by the individual clouds. The upper limit obtained is comparable to \( d \), strongly suggesting that the broad lines are produced by a smooth gas flow. In § 2 of this paper we describe the observations and method of analysis, and the results are discussed in § 3.

2. OBSERVATIONS AND ANALYSIS

The spectra we use here were obtained in three observations of NGC 4395 with the Keck I and Keck II 10 m telescopes. Two of the observations were made with the High Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994); the spectral resolution was \( \lambda/\Delta \lambda = 38,000 \), or 0.173 Å near H\( \alpha \), sampled at 0.0473 Å per pixel. The third observation was made with the Echellette Spectrograph and Imager (ESI; Sheinis et al. 2002); the spectral resolution was \( \lambda/\Delta \lambda = 8000 \), or 0.820 Å near H\( \alpha \), sampled at 0.259 Å per pixel. The first HIRES observation (hereafter HIRES1), described by Filippenko & Ho (2003), was a 20 + 40 minute exposure obtained on 1994 April 14 UT, which yielded a S/N ranging from 20 per pixel at the continuum near H\( \alpha \) to 300 at the line peak. The second HIRES observation (hereafter HIRES2) was a 30 + 60 minute exposure taken on 2002 February 4 UT, yielding a S/N ranging from 30 to 300, as above. The ESI observation was a 20 + 20 minute exposure made on 2002 December 2 UT, and the S/N ranges from 50 to 400, as above.

All of the spectra were reduced using the MAKEE reduction software. Cosmic ray hits were manually removed from the spectra by comparing the two exposures available for each of the spectra. We did not use standard cosmic ray removal tasks, as they sometimes leave small residual features, which will affect the fluctuation analysis. We used a simple summation for the extractions rather than an optimal extraction in order to preserve the correct emission-line profiles, since an optimal extraction might produce incorrect results for the narrow-line profiles, and it could potentially produce small distortions in the broad lines as well.

The rest-frame wavelength scale was converted to a velocity scale with respect to the rest wavelength of H\( \alpha \), 6562.8 Å. We applied a slight offset to the velocity scale in each spectrum, such that the narrow H\( \alpha \) peak falls at \( v = 0 \text{ km s}^{-1} \) in all cases. We next subtracted a constant continuum level from each spectrum, in order to get the net line flux. Absolute flux calibration is available only for the ESI spectrum, and an arbitrary flux scale is used for the two HIRES spectra. The lack of an absolute flux calibration does not affect our analysis, as we are only interested in the H\( \alpha \) profile shape here.

The minimum number of clouds is estimated as follows. We first find for each observed profile, \( f_{k,\text{obs}}^\text{sim} \), the smoothest acceptable fit, \( f_{k,\text{fit}}^\text{sim} \)—that is, a fit which yields \( \chi^2_k \approx 1 \) for the given flux measurement errors, \( f_{k,\text{fit}}^\text{sim} \). We then generate a Monte Carlo (MC) realization of the observed profile by adding the emission of \( n_c \) lines, each one having a Gaussian line shape with a velocity dispersion \( \sigma \). Each line is further convolved with the instrumental resolution, approximated as a Gaussian with FWHM = 8 km s\(^{-1}\) for HIRES, and 38 km s\(^{-1}\) for ESI. We then measure \( \chi^2_k \) of the MC simulated profile, \( f_{k,\text{sim}}^\text{sim} \), with respect to the smooth-fit profile, as a function of \( n_c \) and \( \sigma \). For a given \( \sigma \), we find the minimum \( n_c \) required to obtain \( \chi^2_k \approx 1 \). This procedure provides us with an estimate of the minimum \( n_c \), as a function of \( \sigma \), required so that the level of fluctuations produced by the finite number of clouds does not exceed the observed level of fluctuations (produced by the flux measurement errors).

\(^5\) See http://www2.keck.hawaii.edu/inst/hires/makeewww/index.html.
To obtain the smooth model fit, each line is fit with a spline function, where we iterate manually over the number and positions of the points selected for the spline fit, until the fit yields a reduced $\chi^2 \approx 1$ over the velocity range of $-2500$ to $2500\ km\ s^{-1}$ (or smaller, as set by the available spectra). The error spectrum, $f_{\text{err}}$, obtained together with $f_{\text{obs}}$ in the MAKEE pipeline reduction, is used for calculating the spline fit. The broad H$\alpha$ line is blended with the narrow H$\alpha$ component and with the narrow [N$\text{II}$] $\lambda$6548 and [N$\text{II}$] $\lambda$6583 doublet lines. To make sure that the spline fit is made only in regions dominated by the broad-component emission, we add the additional constraint that the residual flux in the two narrow [N$\text{II}$] line profiles should match. The [N$\text{II}$] profile was also used as a guide for the expected shape of the narrow H$\alpha$ component, and the broad H$\alpha$ spline fit was constructed to yield a narrow H$\alpha$ profile similar (but not identical) to the [N$\text{II}$] profile. This procedure allowed us to determine the velocity ranges affected by narrow-line contamination, which we find are $-900\ km\ s^{-1}< v < -550\ km\ s^{-1}$, $-210\ km\ s^{-1}< v < 230\ km\ s^{-1}$, and $700\ km\ s^{-1}< v < 1200\ km\ s^{-1}$. We exclude these velocity ranges in the $\chi^2$ calculation.

Figure 1 displays the HIRES1, HIRES2, and ESI H$\alpha$ profiles, the smooth fits, and the residuals from the fit. Achieving $\chi^2 \approx 1$ required about 14 spline points per spectrum. These were spaced about 150 km s$^{-1}$ apart close to the line core (between the [N$\text{II}$] lines), and about 250 km s$^{-1}$ or more apart in the line wings. The $\chi^2$ and the number of degrees of freedom obtained through the spline fit are 432/400 for ESI, 1118/1446 for HIRES1, and 688/812 for HIRES2. Thus, the fluctuations on scales smaller than the spline smoothing length are consistent with the level expected from $f_{\text{err}}$. There is no evidence for significant intrinsic profile structure beyond pure noise. There are significant, although weak (amplitude $\sim$1%), features in the broad-line profiles close to the core on scales $\sim$150 km s$^{-1}$, as indicated by small and non-monotonic changes in the smooth-fit profile curvature. At the wings the smooth fit appears featureless; however, since the S/N drops, such broad weak features would not be detectable there.

For the MC simulation, each one of the $n_c$ clouds is assumed to emit a line with a Gaussian profile with the same total flux and velocity dispersion $\sigma$. The clouds differ only in their centroid velocity $v$. We next need the velocity probability distribution

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6 The measured flux ratio of [N$\text{II}$] $\lambda$6583/[N$\text{II}$] $\lambda$6548 in the spectra is $\sim$3, which agrees with the theoretically predicted value.

7 This also rules out the presence of detectable stellar absorption features from the underlying host galaxy light.
function, \( P(\nu) \), for the MC simulation. This \( P(\nu) \) should give \( f^\text{sim}_k \rightarrow f^\text{fit}_k \) in the limit of \( n_c \rightarrow \infty \). As an estimate for \( P(\nu) \) we use the inverse function of

\[
g_c = C \int_{-\infty}^{v} f_c(d\nu)
\]

(\( C \) is set such that \( g_c = 1 \), as required for the integral of a distribution function), where \( f_c \) is \( f^\text{fit}_k \) converted to a velocity scale. The use of an inverse function is a general procedure allowing one to transform a uniform random distribution from \( 0 \) to \( 1 \) (generated by any standard random-number generator) into any given normalized distribution (\( f_c \); here; see also Press et al. 1992, chap. 7.2). The MC profile, \( f^\text{sim}_k \), is generated by adding the contribution of the \( n_c \) individual profiles, each one at its respective \( \nu \). The goodness of fit for each MC realization is measured by calculating the \( \chi^2 \) of \( f^\text{sim}_k \), with respect to \( f^\text{fit}_k \), using \( f^\text{err}_k \) for the flux errors. Since each MC realization yields a somewhat different value of \( \chi^2 \), we performed 20 different MC simulations for each set of \( n_c \) and \( \sigma \) values, and obtained the average value \( \chi^2_{av} \) and \( \Delta \chi^2 \), the dispersion of \( \chi^2 \) in the 20 simulations, which is used to verifying that \( \chi^2_{av} \) is accurate enough (i.e., \( \Delta \chi^2_{av}/\chi^2_{av} < 1 \)). A model was defined as acceptable if \( \chi^2_{av} = 1 \pm \Delta \chi^2_{av} \).

The observed line profile is a convolution of the cloud velocity distribution function, \( P(\nu) \), and the line profile produced by each cloud. Above we have made the approximation that \( P(\nu) \) is proportional to the observed profile, and the accuracy of this approximation drops as \( \sigma \) increases. Specifically, we find that for \( b \geq 50 \text{ km s}^{-1} (b = \sqrt{2}\sigma) \) the above procedure does not yield \( f^\text{sim}_k \rightarrow f^\text{fit}_k \) for \( n_c \rightarrow \infty \). The simulated line profile becomes broader than the observed peak due to the effect of the convolution. Another difficulty arises from the fact that the spline fit we use follows profile features on scales \( \approx 150 \text{ km s}^{-1} \), and thus features on this scales are filtered out of the observed residuals spectrum (\( f^\text{obs}_k - f^\text{fit}_k \)). On the other hand, an MC simulation of clouds with a given \( \sigma \) produces spectral features on a scale of \( \sigma \). Thus, for large \( \sigma \), \( f^\text{sim}_k - f^\text{fit}_k \) shows large-scale features, while such features do not exist in the observed residuals spectrum. These features can produce significant \( \chi^2 \) even for large values of \( n_c \). To overcome these two problems we added the following iteration. We took \( f^\text{sim}_k \) obtained for a specific simulation, and fit it with a spline (using the same velocities used in the observed line fit), in order to get a revised estimate of \( f^\text{fit}_k \). We now use the revised \( f^\text{fit}_k \), to measure the \( \chi^2 \) of \( f^\text{sim}_k \) with respect to the revised \( f^\text{fit}_k \).

Figure 2 demonstrates the effect of \( n_c \) and \( \sigma \) on the level of fluctuations in the MC simulations, compared to the observed residuals (shown for the HIRES2 spectrum). As expected, the simulated profile becomes smoother with increasing \( n_c \) and \( \sigma \). In particular, for \( b = 10 \text{ km s}^{-1} \), that corresponds to pure thermal broadening of \( T \approx 10^4 \text{ K} \) gas, the MC fluctuations are comparable to the observed ones for \( n_c = 10^5 \), while for \( b = 50 \text{ km s}^{-1} \), \( n_c = 3 \times 10^5 \) is enough to produce fluctuations which are about comparable to the observed ones. A more quantitative measure of the fluctuations level is obtained by calculating the \( \chi^2 \) of the fluctuations, as mentioned above.

Figure 3 presents our derived limits on the minimum \( n_c \), as a function of \( b \), required to yield \( \chi^2 \leq 1 \) for the HIRES1/2.
fluctuations are anywhere proportional to the square root of the number of clouds contributing to a given bin, and so are \( f_2^{\text{line}} \)^\(1/2\). Thus, the ratio of available S/N to the MC simulation fluctuations, which indicates the detectability of the predicted fluctuations, is \( \propto f_2^{1/2} \); i.e., it approaches zero at the wings.

3. DISCUSSION

The earlier studies of Arav et al. (1997, 1998) and Dietrich et al. (1999) have already ruled out the bloated-stars scenario based on the lack of the expected level of fluctuations in the line profiles. However, the fluctuation level is reduced if the line width generated by each cloud is much larger than the thermal width \( c_s \approx 10 \text{ km s}^{-1} \), leaving the possibility of a clumped BLR if \( \sigma \gg c_s \). Such a large \( \sigma \) may be produced by, for example, radiative ablation effects (e.g., Scoville & Norman 1995; Pier & Voit 1995).

The predicted level of fluctuations is \( \propto n_c^{-1/2} \). Since \( n_c \approx (R_{\text{BLR}}/r_c)^2 \), the largest fluctuations are expected in objects with the smallest \( R_{\text{BLR}} \)—that is, in the lowest-luminosity objects. Here we report on analysis of Keck observations of the H\( \alpha \) profile in NGC 4395, which is a factor of \( \sim 10^3 \) less luminous than the lowest-luminosity object previously analyzed (NGC 4151; Arav et al. 1998), and is the lowest-luminosity type I AGN known by a significant factor (compare with Barth et al. 2004; Greene & Ho 2004). Peterson et al. (2005) recently measured a size of \( 1.0 \times 10^{14} \text{ cm} \) for the C\( iv \) emitting region in NGC 4395. The Balmer line emitting region is measured to be about twice as large as the C\( iv \) emitting region in the few objects were both lines were measured (Korista et al. 1995; Onken & Peterson 2002), and comparison of the H\( \alpha \) and C\( iv \) line widths suggests it could be as much as 5 times larger here, so one may expect \( R_{\text{BLR}} \approx (2-5) \times 10^{14} \text{ cm} \) for the H\( \alpha \) line. Thus, if the bloated stars have \( r_c \approx 10^{10} \text{ cm} \) (Alexander & Netzer 1994), then only a handful of them can fit in the BLR of NGC 4395, and this will produce large profile features, essentially regardless of the line width generated by each cloud. Such a model is clearly ruled out by the observed smoothness of the H\( \alpha \) line, which implies \( n_c \gtrsim 10^4-10^5 \) for \( r_c \approx 10-100 \text{ km s}^{-1} \).

The presence of \( r_c \approx 10^{14} \text{ cm} \) stars at such a small distance from the black hole can also be ruled out based on tidal disruption arguments, as noted by Alexander & Netzer (1997). A star with a mass \( M_\ast \) and radius \( r_\ast \) will be tidally disrupted once it crosses inward of \( r_{\text{tdal}} \approx r_\ast (M_\ast / M_\odot)^{1/2} \). In NGC 4395, \( M_\ast = 3.6 \times 10^5 M_\odot \) (Peterson et al. 2005), implying \( r_{\text{tdal}}/r_\ast \approx 70 \), and thus bloated stars, which presumably have \( M_\ast \approx M_\odot \), will be disrupted already at \( r_{\text{tdal}} \approx 7 \times 10^{15} \text{ cm} \). Stars that survive down to \( R_{\text{BLR}} \) without being tidally disrupted need to be smaller than \( (3-7) \times 10^{12} \text{ cm} \), or \( 40-100 R_\odot \); they can at most be red giants, or blue supergiants. A minimum population of \( \sim 5000 \) such stars is required in NGC 4395 to produce the necessary BLR covering factor (using \( R_{\text{BLR}}/r_\ast \geq 70 \)). Such a population will have a bolometric luminosity of \( \sim 10^{39}-10^{40} \text{ ergs s}^{-1} \) (e.g., Table 3.14 of Binney & Merrifield 1998), and its \( I \)-band magnitude will be comparable to (or larger than) the unresolved point-source magnitude measured by Filippenko & Ho (2003). In any case, physical collisions will destroy such an extremely dense stellar system (\( \gtrsim 10^{15} M_\odot \) pc\(^{-2} \)) in a few dynamical times (a few weeks). Thus, a stellar origin for the BLR clouds in NGC 4395 is ruled out both on theoretical grounds, and directly through the profile fluctuation analysis.

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\(^8\) The number of clouds contributing to each velocity bin in the spectrum is \( \propto n_c \), and also \( \propto b \), i.e., it is \( \propto b \times n_c \). The number of clouds in each velocity bin sets the fluctuation level in the spectrum. Thus, at a fixed level of fluctuations, for example the one that corresponds to \( \chi^2 = 1 \), one expects \( n_c \propto b^{-1} \).

\(^9\) Significantly more massive stars are unlikely due to their short lifetime, while compact stars are unlikely due to their high surface gravity.
The tidal disruption argument can also be used to place a lower limit on the density of any self-gravitating cloud at the BLR, regardless of its size. A cloud of density $\rho_c$ and mass $M_c = 4\pi\rho_c r_c^3/3$ can avoid tidal disruption at the BLR if $\rho_c > 3/4\pi M_{\text{BH}}/r_{\text{BLR}}$. This gives a minimum number density, $N_c > 10^{18}$ cm$^{-3}$ in NGC 4395, about $10^8$ times larger than the density indicated by photoionization models (Kraemer et al. 1999). Thus, any clumped emission-line gas in the BLR will be subject to the strong shearing effect of the black hole gravity, which will stretch clouds by $\Delta r_c \approx r_c$ within one dynamical time.

Our lower limit on $n_c$ of $\sim 10^4-10^5$ implies $r_c \leq (1-3) \times 10^{12}$ cm, which is comparable to d, the minimum size implied by photoionization models. Since we do not have a robust indication here that $r_c \ll d$, the BLR gas may still be composed of clumps with the minimum acceptable size. However, it is not clear what mechanism can create, confine, and maintain such small individual clouds in a steady state (e.g., Done & Krolik 1996; Krolik 1999). Thus, the most plausible scenario appears to be a smooth, or quasi-smooth, gas flow. Reverserersion mapping indicates that the BLR Balmer line velocity is dominated by gravity, and a pure inflow or outflow is excluded (e.g., Peterson 2001). Thus, the only remaining velocity field appears to be a rotation-dominated flow, most likely in a geometrically thick configuration (to subtend the required covering factor). Direct evidence for an outflowing warm ionized gas is present in UV (Crenshaw et al. 2004) and X-ray observations (Shi et al. 2003), and this outflow may originate in the inner denser BLR component.

A rotation-dominated gas flow should produce double-peaked lines. Such lines are indeed observed in AGNs with very broad lines (e.g., Eracleous & Halpern 2003; Strateva et al. 2003), but the majority of AGNs show single-peaked lines. Chiang & Murray (1996) suggested that a sufficiently large radial velocity gradient can modify the line emissivity and produce a single-peaked emission line. However, lower optical depth lines, such as semiforbidden lines and the higher H-series lines, should still show double-peaked structure, unlike what is generally observed.

We note in passing that indirect indications for strongly blended “hidden” double peaks are provided by the rotation of the polarization angle across the H$\alpha$ line profile observed in some objects (Smith et al. 2005), and by the distinct variability characteristics of the red and blue line wings observed sometimes (e.g., Veilleux & Zheng 1991; Wanders & Peterson 1996). Both effects were interpreted as evidence that the Balmer lines originate in a rotating disk. The lack of a double-peak structure could be induced by a large velocity broadening mechanism in the BLR, which makes the double peaks blend into a single peak, although the double-peak structure would still be discernible through the different polarization and variability characteristics of the two blended peaks. The two peaks appear to separate out in objects where the Balmer lines are broad enough (e.g., Strateva et al. 2003).

To summarize, although the BLR gas is likely to reside in a smooth flow, the origin of the gas, the structure of the flow, and its dynamics remain to be clarified.

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