STIS Spectroscopy of the Central 14 pc of NGC 3998: Evidence for an Inflow.

Nick Devereux

Department of Physics, Embry-Riddle Aeronautical University, Prescott, AZ 86301
devereux@erau.edu

ABSTRACT

Prior imaging of the lenticular galaxy, NGC 3998, with the Hubble Space Telescope (HST) revealed a small, highly inclined, nuclear ionized gas disk, the kinematics of which indicate the presence of a 270 million solar mass black hole. Plausible kinematic models are used to constrain the size of the broad emission line region (BELR) in NGC 3998 by modeling the shape of the broad Hα, Hβ and Hγ emission line profiles. The analysis indicates that the BELR is large with an outer radius $\sim 7$ pc, regardless of whether the kinematic model is represented by an accretion disk or a spherically symmetric inflow. The electron temperature in the BELR is $\leq 28,800$ K consistent with photoionization by the AGN. Indeed, the AGN is able to sustain the ionization of the BELR, albeit with a high covering factor ranging between 20% and 100% depending on the spectral energy distribution adopted for the AGN. The high covering factor favors a spherical distribution for the gas as opposed to a thin disk. If the gas density is $\geq 7 \times 10^3$ cm$^{-3}$ as indicated by the broad forbidden [S II] emission line ratio, then interpreting the broad Hα emission line in terms of a steady state spherically symmetric inflow leads to a rate $\leq 6.5 \times 10^{-2}$ M$_{\odot}$/yr which exceeds the inflow requirement to explain the X-ray luminosity in terms of a radiatively inefficient inflow by a factor of $\leq 18$.

Subject headings: galaxies: Seyfert, galaxies: individual (NGC 3998), quasars: emission lines

1. Introduction

NGC 3998 is a lenticular galaxy located at a distance of 14.13 Mpc (Tonry et al. 2001). Prior imaging with the Hubble Space Telescope (HST) revealed a small ($\sim 3''$) highly inclined
nuclear ionized gas disk (Pogge et al., 2000) the kinematics of which indicate the presence of a $2.7^{+1.5}_{-1.0} \times 10^8$ M$_\odot$ supermassive black hole (BH) (De Francesco, Capetti & Marconi, 2006). NGC 3998 also hosts a time variable, compact core, flat-spectrum radio source (Wrobel & Heeschen, 1984) and two extended regions, described as double lobes by Filho, Barthel, & Ho (2002). The nucleus of NGC 3998 is also variable in the ultra-violet (UV) as summarized by Maoz (2007) and in X-rays (Pian et al., 2010). Eracleous, Hwang & Flohic (2010a) have compiled the radio to X-ray spectral energy distribution revealing that the nucleus of NGC 3998 is radiating at $4 \times 10^{-4}$ of the Eddington luminosity limit. Spectroscopically, the nucleus of NGC 3998 is classified as a LINER, with broad H$_\alpha$ and H$_\beta$ emission lines (Ho, Filippenko, Sargent & Peng, 1997, and references therein) and a broad Mg II $\lambda$2800 emission line (Reichert et al., 1992) which did not vary during the 3 year span of the International Ultraviolet Explorer (IUE) observations. Little is known about the time variability, or lack thereof, for the broad emission lines seen in the visible.

NGC 3998 has been a frequent target for the Hubble Space Telescope (HST). Visible and UV spectra have been obtained with the Space Telescope Imaging Spectrograph (STIS) at three different epochs spanning 5 years, from 1997 to 2002, allowing an investigation of whether or not the broad emission lines (BELs) respond to the aforementioned continuum variations. Additionally, the HST spectroscopy was obtained with considerably higher angular and spectral resolution than the IUE observations. Thus, the HST observations provide a renewed opportunity to investigate the origin of the UV continuum and the excitation of the associated emission lines for an unresolved but smaller $\sim 14$ pc diameter region centered on the active galactic nucleus (AGN).

NGC 3998 is one of an important subset of single peaked broad line AGNs whose central mass has been measured (De Francesco, Capetti & Marconi, 2006). Since the broad line region (BLR) is unresolved, the spatial distribution of emission cannot be directly measured. However, the three dimensional gravitational field strength is known, thus the relationship between velocity and radius may be established, given a kinematic model for the broad emission line gas. In this way, one can, in principle, exploit the exquisite velocity resolution of STIS to model the broad emission line profiles and determine a size for the BLR that heretofore has previously only been possible using reverberation mapping techniques (Peterson, 1993, 2001). Profile fitting complements reverberation mapping as the latter yields BLR sizes for a different sample of more luminous AGNs. NGC 3398 radiates well below the Eddington luminosity limit and is unable to drive an outflow thereby simplifying the interpretation of the broad emission lines by eliminating one of the possible explanations for their origin. The wider context for this investigation is to better understand the origin of single peaked broad lines, as these are by far the most ubiquitous type of broad line associated with AGNs (Strateva et al., 2003).
The layout of the paper is as follows. In section 3, the BELs seen in NGC 3998 are evaluated in the context of the various models proposed for their origin, namely inflow, outflow, rotating gas disks and the atmospheres of stars illuminated by the AGN. Viable models are discussed in section 4 with the conclusion following in section 5 that inflow provides the best explanation for the BELs in NGC 3998. We begin, however, with section 2 and a review of the emission lines observed in the nucleus of NGC 3998.

2. NGC 3998 Emission Lines

NGC 3998 has been observed with STIS twice using the G750M grating, twice using the G430L grating and one time using each of the G230L and the G140L gratings. Table 1 summarizes the observations and the resulting spectra are presented in Fig 1. A STIS spectrum showing the broad H$_\alpha$ emission line has been presented previously by De Francesco, Capetti & Marconi (2006) based on observations obtained under PID 7354. Gonzales Delgado et al. (2004) presented the G430L spectrum obtained under PID 8839. However, the G130L and G230L spectra are shown for the first time in Fig. 1.

Multiple exposures obtained using the same grating and with the same integration time have been combined using the STSDAS task ocrreject. Dithered exposures were shifted using the STSDAS task sshift prior to combining. Subsequently, the STSDAS task x1d was used to perform a 7 pixel wide extraction along the slit direction and centered on the nucleus. Each extraction samples $\geq 80\%$ of the encircled energy for an unresolved point source (Proffitt et al. 2010).

The G750M spectra reveal a broad H$_\alpha$ line with a FWHM $\sim 2000$ km/s. Another broad line appears at $\sim 6650\AA$ but this is actually a blend of two [SII] lines. The two sets of G750M spectra are virtually identical even though the observations are separated by four years. The G430L spectrum reveals a wide swath of emission lines and is virtually identical to the one obtained two years later. Collectively, the G750M and G430L spectra resolve the H$_\alpha$, H$_\beta$ and H$_\gamma$ lines. The G240L spectrum reveals the broad Mg II $\lambda 2800$ and the bright C II $\lambda 2326$ line reported previously by Reichert et al. (1992). However, the higher signal to noise ratio and spectral resolution of the modern spectra reveal many more emission lines on a flat continuum that extends into the G140L spectrum which also shows a broad He II $\lambda 1650$ emission line, strongly absorbed C IV $\lambda 1549$ and Ly$\alpha$ emission and several other absorption lines. A more detailed description of the spectra follows, beginning with the Hydrogen (H) Balmer lines.
2.0.1. Broad $H\alpha$ Emission

The broad $H\alpha$ emission line profile is featureless and is virtually identical in the two separate G750M observations. There is no direct evidence for the $[N\ II]$ vacuum wavelength $6549.85$ and $6585.28$ Å emission lines in a 7 pixel extraction centered on the nucleus. Such lines are expected, however, if only due to foreground gas in the host galaxy, plus, they are seen in $STIS$ observations of other AGNs (e.g. Noel-Storr et al. 2003). Evidently, they must be overwhelmed by the broad $H\alpha$ emission in NGC 3398. Consequently, a model for the $[N\ II]$ emission lines is employed which, following their subtraction, will yield a more realistic estimate for the broad $H\alpha$ emission line flux. A systemic velocity of $1206$ km/s is deduced from the peak of the $H\beta$ emission line which can be clearly seen in the G430L spectrum (Fig. 1). Atomic physics sets the wavelength of the fainter $[N\ II]$ line relative to the brighter $[N\ II]$ line, it constrains the flux of the fainter $[N\ II]$ line to be $1/3$ that of the brighter $[N\ II]$ line, and requires that the $[N\ II]$ lines share the same width. A single component gaussian with a width of $1000$ km/s was chosen for the $[N\ II]$ lines, similar to the model for the flanking $[O\ I]$ and $[S\ II]$ emission lines, motivated by the fact that these forbidden lines have similar widths in $STIS$ spectra of other AGNs for which the lines can be clearly seen (Noel-Storr et al. 2003). The flux for the brightest $[N\ II]$ emission line has been chosen so that the difference spectrum does not show an ‘over-subtraction’ of the broad $H\alpha$ profile. The procedure is valid because the observed broad $H\alpha$ emission line profile is otherwise smoothly varying. Since the $[N\ II]$ lines are not directly observed, this procedure effectively sets an upper limit on the $[N\ II]$ line fluxes and a lower limit to the flux of the broad $H\alpha$ emission line. The flux for the narrow component of the $H\alpha$ line is poorly constrained. However, inspection of $STIS$ spectra for other AGNs reveals that the narrow component of the $H\alpha$ line is almost always fainter than the brightest $[N\ II]$ line (Noel-Storr et al. 2003) which motivated the model shown in Fig. 2. Although subjective, the model for the superimposed lines is vindicated as the difference spectrum reveals a broad $H\alpha$ line profile that is very similar to the $H\beta$ and $H\gamma$ lines described in the next section.

The $STSDAS$ contributed task $specfit$ was used to model and subtract the forbidden lines and the results are reported in Table 2 along with the fluxes for the two broad $[S\ II]$ vacuum wavelength $\lambda 6718.29$ and $\lambda 6732.67$ Å emission lines and the two broad $[O\ I]$ vacuum wavelength $\lambda 6302.04$ and $\lambda 6365.53$ Å emission lines. The broad $H\alpha$ emission line flux deduced from the G750M spectra is $\sim 70\%$ larger than estimated previously by Ho, Filippenko, Sargent & Peng (1997) using ground based observations with good agreement on the broad line width.

Figure 2 illustrates that the consequence of subtracting the forbidden emission line model is to reveal a broad $H\alpha$ emission line symmetric about the $\lambda 6591$Å wavelength expected for
the systemic velocity of 1206 km/s. Thus, there is no apparent red shift between the broad \( \text{H}\alpha \) emission line and the systemic redshift of the host galaxy.

2.0.2. Broad \( \text{H}\beta \) and \( \text{H}\gamma \) Emission

The \( \text{H}\beta \) (Fig. 3) and \( \text{H}\gamma \) (Fig. 4) emission lines are virtually identical in the two separate observations obtained using the G430L grating. They are compromised only slightly by [O III] emission lines which were modeled and subtracted using the STSDAS contributed task \texttt{specfit} as illustrated in Fig. 3 and Fig. 4. The [O III] vacuum wavelength \( \lambda 4364.44 \) Å deserved special attention as it is very faint and unresolved. A model was employed for the [O III] \( \lambda 4364.44 \) line in which the wavelength and line width was fixed and the flux adjusted so as to not over-subtract the \( \text{H}\gamma \) line in the difference spectrum (Fig. 4). This yielded the upper limit for the [O III] \( \lambda 4364.44 \) line reported in Table 3. Subtracting the [O III] lines reveals broad \( \text{H}\beta \) and \( \text{H}\gamma \) emission lines, both of which are symmetric about the central wavelengths expected for a systemic velocity of 1206 km/s. Unfortunately the analysis can not reliably be extended to include other Balmer lines as they are simply too faint and even more confused with emission from other ions. Consequently, emission line fluxes are reported in Table 3 for all the lines that can be reliably resolved and measured in the G430L spectrum including \( \text{H}\beta \), \( \text{H}\gamma \), the blend of the vacuum wavelength \( \lambda \lambda 3727.09, 3729.88 \) Å [O II] lines, the two [O III] vacuum wavelength \( \lambda 4960.30 \) Å and \( \lambda 5008.24 \) Å emission lines, and the upper limit for the vacuum wavelength \( \lambda 4364.44 \) Å [O III] emission line.

2.0.3. Similar Balmer Line Profiles

Figure 5 illustrates the striking similarity between the three broad H Balmer lines in NGC 3998 when they are normalized to their respective peak intensities and the wavelength scales converted to velocity using the non-relativistic Doppler equation. The similarity between the emission line profiles is particularly impressive considering the variety of models employed to subtract the superimposed forbidden lines.

The Balmer line profiles are similar to those seen in M81 (Devereux & Shearer 2007) if slightly narrower. Such single peaked line profiles may be produced by radiation from a spherically symmetric shell of gas in radial motion as noted previously by Devereux & Shearer (2007). Single peaked emission line profiles may also be produced by accretion disks (Chen & Halpern 1989; Eracleous & Halpern 2001), bipolar flows (Zheng, Binette & Sulentic 1990) and the atmospheres of stars orbiting close to the AGN (Scoville & Norman 1988; Alexander & Netzer 1988).
2.0.4. Balmer Decrets

The observed Balmer decrements, $H\alpha/H\beta = 3.43 \pm 0.05$ and $H\beta/H\gamma = 2.83 \pm 0.11$, are significantly different from the Case B values, 2.75 and 2.1, respectively in the sense that the observed values are systematically 25% and 35% higher, respectively. Interpreting these ratios in terms of dust extinction leads to a color excess $E(B - V) \sim 0.2$ mag and $\sim 0.7$ mag respectively, values that are inconsistent with each other and higher than the $\sim 0.1$ mag of reddening estimated to the AGN X-ray emission by Eracleous, Hwang & Frohle (2010a). Such deviations from recombination theory have been noted for other LINERs (e.g. Bower et al. 1996; Filippenko & Hapern 1981) and have been attributed to collisional excitation in gas of high density. However, the requisite high densities are not achieved in the region producing the broad emission lines in NGC 3998 as explained further in section 4.5.

2.0.5. C II$\lambda$ and Broad Mg II Emission Lines

A very broad vacuum wavelength $\lambda 2798 \text{ Å}$ Mg II emission line appears in the G230L spectrum. Strong absorption prevents an accurate determination of the central wavelength but adopting a systemic velocity of 1206 km/s for NGC 3998 leads to the conclusion that the Mg II line is asymmetric with more emission on the blue side compared to the red side. With a FWHM $\sim 6000$ km/s, and a FWZI $\sim 13000$ km/s, the Mg II line is by far the broadest emission line detected in NGC 3998. The Mg II emission line flux noted in Table 4 agrees reasonably well with an IUE measurement reported previously by Reichert et al. (1992) as does the vacuum wavelength $\lambda 2324 \text{ Å}$ C II$\lambda$ emission line flux. The C II$\lambda$ emission line is much narrower than the Mg II emission line, as already noted by Reichert et al. (1992), but the modern spectrum shows that the C II$\lambda$ emission line is broader than the H Balmer lines and shares an asymmetry similar to the Mg II emission line. Other emission lines are detected in the G230L spectrum, the most important of which are an unresolved pair of [O II$\lambda$] lines with a vacuum wavelength of $\lambda 2471$ Å. The [O II$\lambda$] lines have a high critical density corresponding to $\sim 4 \times 10^6 \text{ cm}^{-3}$ and provide an important data point for the line width - critical density relation described in the next section.
2.0.6. Broad Forbidden Emission Lines

NGC 3998 is very unusual in that it exhibits a number of broad forbidden lines which are as broad as the H Balmer lines thus blurring the distinction between the canonical *broad* and *narrow* line regions in this AGN. A comparison of the line widths is illustrated in the upper panel of Fig. 6 where the FWHM has been plotted against the ionization potential for forbidden and permitted lines whose line widths could be measured. Although the line widths are technically *broad* it is a misnomer to refer to them as originating from a *broad line region*. This is because the forbidden line widths are comparable to the Balmer line widths which is an attribute of the *narrow line region*. Thus, to avoid confusion, henceforth, the emission lines will be referred to as originating from a *broad emission line region* (BELR), the physical properties of which are the main focus of this paper. The [S II] and [O III] lines, in particular, will provide an important measure of the electron number density and temperature, respectively, for the BELR of NGC 3998 as discussed further in section 4. The lower panel of Fig. 6 illustrates that there is no correlation between the line width and critical density for the forbidden lines in NGC 3998. According to the diagnostic diagram of Kewley et al. (2006, their Fig. 5) the [O III] 5008.24 /[O II] 3727.09, 3729.88 and [O I] 6324.99/Hα emission line ratios measured with STIS qualify NGC 3998 as a Seyfert and the similarity between the permitted and forbidden line widths further qualifies NGC 3998 as a Seyfert 2.

2.0.7. Flat UV Continuum with Absorption Lines

The G140L spectrum reveals a flat UV continuum and absorption features including N V λ1241, Si II λ1260, Si IV λ1394, 1403, CII λ1335 and tentatively Si II λλ1304,1309 and O I λλ1302, 1304, 1306. Tentative because the absorption feature appears wider than the wavelength spread of the lines attributed to it. All of the absorption features can be identified with resonance lines and are most likely produced by absorption within the host galaxy because their central wavelengths imply a redshift that corresponds to the systemic velocity of NGC 3998. The flat UV continuum can be traced back to the visible through the G230L, G430L and G750M spectra.

1The absence of strong Fe emission lines disqualifies NGC 3998 as a Narrow Line Seyfert 1 (Osterbrock & Pogge 1985).
3. Broad Line Region Models

3.1. Outflow Model

A radiatively driven outflow of gas can be ruled out for NGC 3998 because the diminutive luminosity generated by the AGN is simply unable to provide sufficient radiation pressure to overcome the gravitational force of the BH as demonstrated in the following.

The condition for a radiatively driven wind is given by,

$$\frac{\kappa L}{4\pi cG} > M$$

where $M$ and $L$ are the mass and luminosity respectively, interior to a radius $r$, $c$ is the speed of light, and $G$ the gravitational constant. For NGC 3998, this condition is not satisfied by three orders of magnitude, if one adopts the Thompson scattering opacity $\kappa = 0.4 \text{ cm}^2/\text{g}$ for a pure hydrogen gas, $M = 2.7 \times 10^8 M_\odot$ [De Francesco, Capetti & Marconi 2006], and a bolometric luminosity, $L = 3.5 \times 10^9 L_\odot$ [Eracleous, Hwang & Flohic 2010a]. The disparity is simply too large to overcome even by invoking line opacities, as line driven winds are viable only for objects that radiate close to the Eddington luminosity limit [King & Pounds 2003, Murry et al. 1995, Shlosman, Vitello, & Shaviv 1985] whereas NGC 3998 radiates at substantially below that limit, by a factor of $4 \times 10^{-4}$.

A VLBI observation has revealed a jet-like structure on the northern side of the nucleus of NGC 3998 [Filho, Barthel, & Ho 2002], but this is an unlikely source for the observed broad Balmer line emission as that outflow consists of a relativistic plasma that is ejected essentially perpendicular to the line of sight and perpendicular to the STIS slit orientation. Gas entrained by such jets would produce a narrow line centered at the systemic redshift which is contrary to the broad emission line that is observed.

3.2. Inflow Model

A steady state spherical inflow is able to reproduce the broad Balmer emission line profiles observed for NGC 3998 and with the minimum of assumptions.

The relationship between velocity and radius is determined by the mass distribution, $M(r)$, to be

$$v(r) = -\sqrt{2GM(r)/r}$$
where \( M(r) \) includes a point mass, \( M_\bullet \), representing the black hole, embedded in the center of an extended star cluster. In a spherical coordinate system, the observed radial component of the velocity for a particle at position \((r, \theta, \phi)\), is given by

\[
v_o = v(r)\cos\theta\cos\phi
\]  \hspace{1cm} (3)

where \(-\pi/2 \leq \theta \leq \pi/2\) and \(0 \leq \phi \leq 2\pi\)

As illustrated in Fig. 5, a broad line profile, \( \Phi(v) \), with the characteristics of the one observed in NGC 3998 may be produced by generating a histogram of observed velocities \(\{v_{o,i}\}\) for a system of particles indexed by \(i\) and distributed randomly within a spherical volume

\[
\Phi(v) = \#\{i|v \leq v_{o,i} \leq v + dv\}.
\]  \hspace{1cm} (4)

Here \(v_{o,i}\) denotes the observed velocity of the \(i^{th}\) particle. Implicit in this model is the assumption that the particles share the same emissivity and emit isotropically.

For a steady state flow the particle number density distribution is determined by mass conservation to be

\[
N(r) \propto r^{-3/2}.
\]  \hspace{1cm} (5)

The distribution is used to produce a broad line profile by creating a series of concentric spherical shells \(\{S_j\}\) of radii \(\{r_j\}\) selected randomly between \(r_{inner}\) and \(r_{outer}\). On each shell, \(\{S_j\}\) a total of \(N(r_j)\) particles is distributed randomly in position, \((\theta, \phi)\). The model differs from Bondi flow (Bondi 1952) in that the particles are discrete and do not constitute a fluid.

Approximately 12,000 particles are included in the model. The velocity histogram is binned by 25 km/s and subsequently smoothed using a 10 bin moving average. The resulting model velocity resolution is comparable to that of the G430L spectra but considerably lower than the G750M spectra. The details of the resulting line profile shape are sensitive to the range of values employed for \(\theta\) and \(\phi\). For example, restricting the range of \(\theta\) such that \(-0.96\pi/2 \leq \theta \leq 0.96\pi/2\) simulates the cavity expected to be occupied by the radio jets and causes the model profile to more closely mimic the observed profile in the region near the peak.

In the inflow model, the velocity width at the top of the line is determined by

\footnote{A feature of the inflow model is that it produces a delta function at zero velocity, a consequence of the large number of clouds moving perpendicular to the line of sight. Such a delta function is not present in the observed spectra and is therefore mitigated in the current model by invoking a cavity.}
the outer radius, \( r_{\text{outer}} \), and the width at zero intensity is determined by the inner radius, \( r_{\text{inner}} \), and these values are largely insensitive to the range of \( \theta \) and \( \phi \). Thus, given a density distribution and a velocity law, one can use the profile shape to determine the physical size of the emitting region. Values that produce a reasonable representation of the broad Balmer emission line profiles, shown in Figure 5, correspond to an outer radius, \( r_{\text{outer}} = 7 \) pc, and an inner radius, \( r_{\text{inner}} = 0.08 \) pc. The model is illustrative and does not represent a unique solution or the result of a full exploration of the parameter space. However, experience indicates that the model values determined for the inner and outer radius would have to change substantially, by more than \( \sim 30\% \), to cause the model to seriously misrepresent the observed profile. Fig. 5 illustrates that the residuals between the observed profiles and the model prediction are \( \sim 10\% \).

### 3.3. Accretion Disk Model

Next, the kinematics of a rotating axisymmetric Keplerian disk are considered as an explanation for the shape of the broad Balmer emission line profiles. While there has been a novel proposal (Murty & Chiang 1997) to generate a single peak profile using a disk wind, it is not adopted here because the AGN in NGC 3998 radiates at \( 4 \times 10^{-4} \) of the Eddington luminosity limit. Therefore, if an accretion disk wind is present it is expected to be feeble and not influence the propagation of Balmer line photons (see section 3.1 and the discussion of Arp 102B by Halpern et al. 1996). Instead, the simplest possible model is considered which involves an axisymmetric, relativistic accretion disk developed by Chen & Halpern (1989), and adopted later by Eracleous & Halpern (2001) to explain the single peak broad line profile in the LINER nucleus NGC 3065. In addition to Doppler shifts, this model includes self-consistently all relevant relativistic effects, such as Doppler boosting and transverse and gravitational redshifts.

The axisymmetric disk model invokes five free parameters, a dimensionless inner radius, \( \xi_1 \), and outer radius, \( \xi_2 \), an inclination angle measured from the disk normal to the line of sight, \( i \), an emissivity law of the form \( \epsilon \propto r^{-q} \), and a velocity dispersion for the gas, \( \sigma \) in km/s. The line profile is calculated by numerically integrating eqn. 7 of Chen & Halpern (1989) using a wavelength resolution of 2.5 Å which is comparable to the G430L spectra but lower than the G750M spectra. Values of the parameters that best reproduce the Balmer line profiles observed in NGC 3998 are summarized in Table 5 and include a large outer radius corresponding to \( r_{\text{outer}} = 7 \) pc. The model is illustrative and does not represent a unique solution or the result of a full exploration of the parameter space. However, experience indicates that the model parameters would have to change substantially, by more than \( \sim \)
30%, to cause the model to seriously misrepresent the observed profile. Fig. 5 illustrates that the residuals between the observed profiles and the model prediction are \( \sim 10\% \).

4. Discussion

Evidently, both a spherically symmetric inflow and an accretion disk are able to reproduce the shape of the broad Balmer emission line profiles observed for NGC 3998. The mass distribution determines that the emitting region is large; \( \sim 7 \) pc (0.1") in radius for both models. Whereas it is already known that NGC 3998 hosts a small \( (\sim 3") \) highly inclined nuclear ionized gas disk (Pogge et al., 2000), the kinematic evidence for a spherically symmetric inflow would represent a new phenomena for NGC 3998. Which of the two explanations is most likely to be correct is discussed in the following.

All previous studies in which the broad Balmer emission lines have been attributed to an accretion disk have involved line profiles whose shapes are very different and much broader than the adjacent and overlapping \([\text{N II}], [\text{S II}] \) and \([\text{O I}] \) forbidden lines (e.g. Eracleous & Halpern 2003; Barth et al., 2001; Shields et al. 2000; Eracleous et al. 1995; Storchi-Bergmann et al. 1993; Eracleous & Halpern 1994). Indeed, the distinction between the broad permitted lines and the much narrower forbidden lines has motivated the notion that the former are produced by gas that has a density exceeding the critical density of the forbidden lines and arises from a kinematically and physically distinct gas component identified with an accretion disk. NGC 3998 is different. The Balmer and forbidden line widths are similar suggesting that they have a common origin. The question is do the broad emission lines originate in an accretion disk or in an inflow? The answer to this question may lie in the covering factor, explored in more detail in the next section.

4.1. Broad Line Region Ionization

The ionizing continuum in NGC 3998 may be represented as a power law,

\[
L_\nu = L_o (\nu/\nu_o)^{-\alpha}
\]  

which may be integrated to yield the number of ionizing photons, \( N_{\text{ion}} \),

\[
N_{\text{ion}} = \int_{\nu_o}^{\nu_{\text{max}}} [L_\nu/h\nu] d\nu
\]
to yield

\[ N_{\text{ion}} = L_0 v_0^\alpha (v_0^{-\alpha} - v_{\nu_{\text{max}}}^{-\alpha}) / (h\alpha) \text{ photons s}^{-1} \]  \(8\)

Adopting an optical to X-ray spectral index \(\alpha = 1\) \cite{Eracleous2010a} to represent the shape of the ionizing continuum in NGC 3998, predicts just enough ionizing photons to explain the luminosity of the broad \(H\alpha\) line. The central AGN produces \(7.6 \times 10^{51}\) ionizing ph/s, integrated between 13.6 eV and 100 keV, after correcting for extinction. For comparison, the broad \(H\alpha\) emission line flux (Table 2) corresponds to an \(H\alpha\) luminosity, \(L(H\alpha)\), of \(2.6 \times 10^{6}\) \(L_\odot\), which, assuming 45% of the ionizing photons are converted into \(H\alpha\) photons (Case B recombination at a temperature of \(10^4\) K) requires \((7.4 \pm 0.2) \times 10^{51}\) ionizing ph/s using,

\[ N_{\text{ion}} = L(H\alpha)\alpha_B / \alpha_{H\alpha}^{\text{eff}} h\nu_{H\alpha} \]  \(9\)

where \(\alpha_{H\alpha}^{\text{eff}} = 1.16 \times 10^{-13}\) cm\(^3\) s\(^{-1}\) is the effective recombination coefficient and \(\alpha_B = 2.59 \times 10^{-13}\) cm\(^3\) s\(^{-1}\) is the total Case B recombination coefficient. The number of ionizing photons required to excite the \(H\alpha\) line, estimated using eqn. 9, is independent of the gas density and the filling factor but the comparison with the ionization available from the AGN does imply a very high covering factor corresponding to \(97 \pm 3\%\). If the broad \(H\alpha\) emission line flux is corrected for \(A_v = 0.3\) mag of extinction \cite{Eracleous2010a} then the number of ionizing photons required to excite the \(H\alpha\) line exceeds that available from the AGN by 28%, causing NGC 3998 to join M81 as an example of an AGN with a BELR ionizing deficit \cite{Devereux2007, Ho1996}.

That the central AGN produces \(7.6 \times 10^{51}\) ionizing ph/s, integrated between 13.6 eV and 100 keV, is a factor of 3 lower than an independent estimate of the ionizing photon rate by \cite{Eracleous2010b}. The discrepancy is due to different assumptions concerning the spectral energy distribution in the far-UV which is complicated by the fact that the nucleus of NGC 3998 is time variable. The G140L and G230L HST spectra obtained in 2002 show that \(f_\lambda\) is approximately constant in the UV (1200 - 3000 Å) at \(\sim 2 \times 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\). This is consistent with the 2120 Å measurement of \(\sim 2.5 \times 10^{-15}\) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\) obtained in 2001 with the XMM Newton Optical Monitor by \cite{Ptak2002}.

The ionizing deficit widens to 80% if the extinction is estimated from the \(H\alpha/H\beta\) ratio and a factor of 7 if the extinction is estimated from the \(H\beta/H\gamma\) ratio, although it is not obvious that the anomalous Balmer decrements should be interpreted in terms of dust extinction given the similar and symmetric Balmer line profile shapes.

\(^3\)The ionizing deficit widens to 80% if the extinction is estimated from the \(H\alpha/H\beta\) ratio and a factor of 7 if the extinction is estimated from the \(H\beta/H\gamma\) ratio, although it is not obvious that the anomalous Balmer decrements should be interpreted in terms of dust extinction given the similar and symmetric Balmer line profile shapes.
(2004) and the F250W measurement of $2.2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ obtained in 2002 with HST by Maoz et al. (2005). However, in 1992 the nucleus was about 5 times brighter. Then the flux measured with HST in the F175W filter was at least $1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ (Fabbiano, Fassnacht & Trinchieri 1994). The nucleus has apparently been declining in brightness between 1999 and the date of the most recent published UV measurement in 2003 when the flux measured with HST in the F250W filter was $1.8 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ (Maoz et al., 2005). The ionizing photon rate estimated by Eracleous, Hwang, & Flohic (2010b) includes the high value measured by Fabbiano, Fassnacht & Trinchieri (1994) and the higher value for the 2120 Å flux favored by Ptak et al., (2004) whereas the new estimate presented here does not. As such, the rate $N_{\text{ion}} = 7.8 \times 10^{51}$ ionizing ph/s, represents the ionizing photon rate in the central 0.2$''$ of NGC 3998, circa 2002. If, on the other hand, the spectral energy distribution is represented by a quasar (Eracleous, Hwang, & Flohic 2010b), then $N_{\text{ion}}$ increases to $3.5 \times 10^{52}$ ionizing ph/s, which alleviates the ionizing deficit, but still implies a high covering factor corresponding to $\sim 20\%$.

The high covering factor $\geq 20\%$ is much easier to achieve with a spherical distribution of gas than a thin accretion disk and is the main argument that the broad emission lines seen in NGC 3998 are due to an inflow, an outflow being impossible for the reasons explained in section 3.1. The possibility of inflows has received remarkably little attention in the literature as noted recently by Gaskell (2009). Indeed, there has been nary a mention of inflows in the context of broad line profile shapes since Capriotti, Foltz & Byard (1981). Yet this most neglected of models is able to explain the broad Balmer emission lines seen in NGC 3998 and another low luminosity AGN, M81, as noted previously by Devereux & Shearer (2007).

4.2. Stellar Atmospheres Illuminated by the Central AGN Model

Another contending explanation for the broad emission lines seen in NGC 3998 is that they result from the ionization of the extended mass loss envelopes of red giant stars orbiting close to the AGN (e.g. Scoville & Norman 1988; Alexander & Netzer 1997). Stellar winds provide a natural explanation for the confinement and replenishment of the so called ‘broad line clouds’, which is otherwise a major problem (Mathews & Ferland 1987). Such a model may explain the in NGC 3998, because the intensity of ionizing photons in the BELR at a distance, $r \sim 5$ pc, from the AGN is sufficient to penetrate the mass loss wind to a density $\sim 10^4$ cm$^{-3}$ which is comparable to that inferred for the BELR from the [S II] lines (section 4.5). Following Devereux & Shearer (2007), it can be shown that for a power law of spectral index $\alpha = 1$, the density, $n$, in the wind at the penetration depth, $d$, of the ionizing photons is given by,
Representative values for NGC 3998 are \( r = 5 \text{ pc} \), \( L_{1500} = 1.6 \times 10^7 L_\odot \), \( v_W = 10 \text{ km/s} \) for the wind velocity, and \( \dot{M} = 10^{-5} M_\odot/\text{yr} \) (Scoville & Norman 1988) and \( \dot{M} = 10^{-6} M_\odot/\text{yr} \) for the stellar mass loss rates (Alexander & Netzer 1997). One finds that \( n(d) \) is \( 7.8 \times 10^3 \text{ cm}^{-3} \) and \( 1.7 \times 10^4 \text{ cm}^{-3} \) respectively, values that are comparable to the gas densities inferred for the BELR from the \([\text{S II}]\) lines discussed further in section 4.5. Alexander & Netzer (1997) have explored the so called 'bloated stars' (BSs) model in some detail although not for the specific characteristics of the AGN/BEL combination in NGC 3998. Such an investigation may be worth revisiting, however, as the properties of the gas in NGC 3998 may be explained in the context of a low density, optically thin, stellar mass loss wind which would allow the production of broad forbidden emission lines with velocity widths similar to the Balmer lines. Previously, Alexander & Netzer (1997) were restricted to models that suppressed the formation of broad forbidden lines by invoking stellar mass loss winds of unrealistically high density, but it appears that the density restriction can now be lifted, at least in the case of NGC 3998. Another attractive feature of the BSs model is that it can potentially achieve the high covering factor needed to explain the near equality between the ionization provided by the AGN and that required by the broad Balmer lines. Stellar mass loss is also the most likely origin for the inflowing gas invoked to explain the broad Balmer line profiles.

4.3. BELR Size

Perhaps the most surprising result to have emerged from the analysis of the broad Balmer emission line profiles is the large outer radius, \( \sim 7 \text{ pc} \), inferred for BELR of NGC 3998 corresponding to an angular diameter of 0.2". An independent analysis of the angular size based on the encircled energy, illustrated in Fig. 7, shows that the BELR of NGC 3998 is spatially unresolved with the 0.1" wide slit employed for the STIS G750M observations. This is because the percentage of the broad line flux measured in 1 pixel wide and 2 pixel wide extractions, as compared with the flux measured in a 7 pixel wide extraction, is consistent

\[ n(d) = 98 \times 10^6 \frac{L_{1500}}{10^5 L_\odot}^{2/3} \frac{r}{10^{15} \text{cm}}^{-4/3} \frac{v_W}{10 \text{ km/s}}^{1/3} \frac{\dot{M}}{10^{-5} M_\odot/\text{yr}}^{-1/3} \text{cm}^{-3} \]

(10)
with that expected for a point source. Additionally, there is no perceivable difference between the Hα profile obtained with a 0.1″ slit and the Hβ and Hγ profiles which were obtained with a 0.2″ slit. However, no large difference is expected based on the modeling. Even if the ‘poles’ of the model spherical inflow are excluded, as would be the case when the slit width is 0.1″ and slightly smaller than the 0.2″ diameter of the inflow, the model line profile shape remains unchanged. This is because only a few points are excluded from the model. Additional evidence that the BELR is unresolved is that the Balmer line profiles are similar even though the observations were made with a variety of slit orientations that differed by as much as ~25 degrees in position angle.

The size inferred for the BELR causes NGC 3998 to not conform to the correlation between BLR size and UV luminosity established for quasars and high luminosity AGNs using reverberation mapping (Peterson 2001, 1993; Kaspi et al., 2005). However, as noted by Kaspi et al. (2005), the correlation appears to break down for low luminosity AGNs, which, with $L(1450 \, \text{Å}) = 6.3 \times 10^{40} \, \text{erg/s}$, estimated from the G140L spectrum, would include NGC 3998, even allowing for the variability which is discussed in more detail in section 4.1. Nevertheless, an extrapolation of the BLR size - luminosity relationship of Kaspi et al. (2005) down to the low UV luminosity estimated for the AGN in NGC 3998, predicts a size for the BLR that is about 200 times smaller than the inner radius of the BELR determined for NGC 3998 by profile fitting. Conversely, the large outer radius determined for the BELR of NGC 3998 using profile fitting makes it larger than any BLR measured using reverberation mapping, 24 times larger than the previous record holder; the quasar 3C 273 (Kaspi et al., 2005). Even though NGC 3998 is known to be variable in the UV (Maoz 2007), no variability has been detected in the Balmer lines on a timescale of 4.4 years precluding an estimate of its reverberation based BLR size. Of course, the BLR size - luminosity relationship of Kaspi et al. (2005) is defined by quasars and AGNs that are orders of magnitude more luminous than NGC 3998. Thus, the very large discrepancy arising from the comparison strongly suggests that the BELR in NGC 3998 is not simply the BLR of a scaled down quasar.

4.4. Virial Black Hole Masses

Estimating the mass of the BH in NGC 3998 using the so called ‘virial method’ leads to a value that is substantially lower than the kinematically determined mass. For example, the formalism of Greene & Ho (2005), which uses the FWHM and luminosity of the broad Hα

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5 Compared to the size predicted using the FITEXY method of Kaspi et al. (2005) at 1450Å.
emission line, underestimates the mass of the BH in NGC 3998 by a factor of 413. On the other hand, the BH in NGC 3998 does conform to the BH mass - bulge mass correlation as noted previously by De Francesco, Capetti & Marconi (2006). This dichotomy is regarded as further evidence that the BELR in NGC 3998 is very different from the BLR in more luminous AGNs.

4.5. Constraints on the BELR Gas Density and Temperature

The fact that the two [S II] lines are nearly as broad as the Balmer lines provides an opportunity to set a lower limit on the gas density in the BELR. The nominal value for the observed [S II] $\lambda 6742/\lambda 6754$ intensity ratio $= 0.58 \pm 0.24$, corresponding to $n \sim 7 \times 10^3$ cm$^{-3}$, but the large uncertainty permits gas densities in the range $10^3$ cm$^{-3} \leq n \leq 10^4$ cm$^{-3}$. These densities are much lower than the $10^6$ cm$^{-3}$ often quoted for the BLRs of more luminous AGNs. However, the fact that the Balmer lines are wider than either of the [S II] lines may suggest that the gas density is higher than $7 \times 10^3$ cm$^{-3}$ in the region emitting the Balmer lines if the gas density increases closer to the BH.

The limit for the observed [O III] ratio ($\lambda 4960.30 + \lambda 5008.24$) / $\lambda 4364.44 \geq 24$ yields $T \leq 28,800$ K for the electron temperature if $n = 7 \times 10^3$ cm$^{-3}$, which is judged to be representative of the temperature in the BELR because the vacuum wavelength [O III] $\lambda 4960.30$ and $\lambda 5008.24$ lines are observed to be as broad as the Balmer lines.

The ionization parameter, $\Gamma$, given by

$$\Gamma = N_{ion}/4\pi r^2 c n$$

(11)

corresponds to $0.006 \leq \Gamma \leq 48$ for gas in the BELR with $7 \geq r$(pc) $\geq 0.08$ pc and ionized by the central AGN. Such values for the ionization parameter are similar to those expected inside an HII region ionized by an O5 star. That is not to say that the ionization in NGC 3998 is provided by O5 stars, but rather that the electron temperature is expected to be similar and consistent with the limit $\leq 28,800$ K determined from the [O III] ratio ($\lambda 4960.30 + \lambda 5008.24$) / $\lambda 4364.44$. 
4.6. The Mass of Ionized Gas Required to Produce the Broad H\(\alpha\) Emission Line

The mass of emitting gas may be deduced from the broad H\(\alpha\) emission line luminosity assuming standard (Case B) recombination theory;

\[
M_{\text{emitting}} = L(H_\alpha) m_H / n_H \alpha_{H_\alpha}^{\text{eff}} h \nu_{H_\alpha}
\] (12)

Using an effective recombination coefficient \(\alpha_{H_\alpha}^{\text{eff}} = 8.6 \times 10^{-14} \text{ cm}^3 \text{ s}^{-1}\), assuming a constant average density \(n \geq 7 \times 10^3 \text{ cm}^{-3}\), and a luminosity \(L(H_\alpha) = 2.6 \times 10^6 \text{ L}_\odot\) based on the broad line flux reported in Table 1, leads to an upper limit on the mass of ionized gas emitting the broad H\(\alpha\) line, \(M_{\text{emitting}} \leq 4600 \text{ M}_\odot\). If only a fraction of the gas is ionized then the upper limit on the total (ionized + neutral) gas mass could, of course, be much higher. Thus, the total mass of gas in the BELR of NGC 3998 could be substantial.

4.7. The Filling Factor and the Inflow Rate for the BELR of NGC 3998 and an Assessment of the Inflow Scenario

It is straightforward to calculate the filling factor, \(\epsilon\), for a spherically symmetric inflow, once the dimensions of the emitting region have been established. For a uniform density medium occupying a spherical volume of radius \(r\), one finds

\[
\epsilon = 3L(H_\alpha) / 4\pi n_H^2 \alpha_{H_\alpha}^{\text{eff}} h \nu_{H_\alpha} r^3
\] (13)

Again, using an effective recombination coefficient \(\alpha_{H_\alpha}^{\text{eff}} = 8.6 \times 10^{-14} \text{ cm}^3 \text{ s}^{-1}\), assuming a constant average gas density \(n \geq 7 \times 10^3 \text{ cm}^{-3}\), and a luminosity \(L(H_\alpha) = 2.6 \times 10^6 \text{ L}_\odot\) based on the broad line flux reported in Table 1, leads to an upper limit on the filling factor, \(\epsilon \leq 2 \times 10^{-2}\), for NGC 3998 if the size of the BELR, \(r = 7 \text{ pc}\). The very low filling factor suggests that the inflow is not continuous but composed of many ionized, density bounded, gas filaments. Such filaments would have approximately the same gas density and hence the same emissivity regardless of their location with respect to the central AGN, they would be optically thin and hence emit isotropically. Ionized gas filaments embrace all the essential elements of the inflow model and are commonly seen in the nuclei of active galaxies (Storchi-Bergmann 2009).

Having established the dimensions of the emitting region and the filling factor one can calculate the mass inflow rate, \(\dot{m}\), for the ionized gas, using the equation of continuity;
\( \dot{m} = \varepsilon 4 \pi r^2 v n_H m_H \) (14)

The velocity at the inner radius of 1 pc is determined by the mass distribution to be 1550 km/s. Setting the gas density in the flow, \( n \geq 7 \times 10^3 \text{ cm}^{-3} \), one obtains an upper limit to the mass inflow rate, \( \dot{m} \leq 6.5 \times 10^{-2} \text{ M}_\odot /\text{yr} \). However, if only a fraction of the inflowing gas is ionized, then the upper limit on the total mass inflow rate could, of course, be higher.

The 2–10 keV X-ray luminosity adopted for the AGN in NGC 3998, \( L_{2-10 \text{ keV}} \), is \( 2.6 \times 10^{41} \text{ erg s}^{-1} \) (Eracleous, Hwang & Flohic 2010a). Assuming this is powered by radiatively inefficient accretion leads to the following formula (Merloni, Heinz, & Di Matteo 2003)

\[
L_{2-10 \text{ keV}} = 7 \times 10^{38} M_\bullet^{0.97} \dot{m}^{2.3}
\] (15)

where \( L_{2-10 \text{ keV}} \) is in \text{erg s}^{-1} and \( M_\bullet \) is in solar masses. Under these circumstances the accretion rate required to power the observed X-ray emission, \( \dot{m} \sim 3.6 \times 10^{-3} \text{ M}_\odot \text{ yr}^{-1} \).

5. Conclusions

A new technique has yielded a size for the BELR in NGC 3998 by modeling the shape of the broad H\( \alpha \), H\( \beta \) and H\( \gamma \) emission line profiles. The principal conclusion is that the BELR is large, \( \sim 14 \text{ pc} \) in diameter, and represents an inflow, likely sustained by stellar mass loss. The large size determined for the BELR in NGC 3998 is inconsistent with an extrapolation of the reverberation based BLR size - luminosity relationship. Additionally, the virial method for estimating BH masses using the broad H\( \alpha \) emission line width and luminosity lead to an inconsistent BH mass for NGC 3998. Both of these relationships are defined by the broad emission lines of quasars and high luminosity AGNs. It is therefore concluded that the BELR in NGC 3998 is not the BLR of a scaled down quasar but more likely identified with the narrow line region. The AGN is able to sustain the ionization of the BELR, albeit with a high covering factor ranging between 20% and 100% depending on the adopted spectral energy distribution. Such a high covering factor is most easily provided by a spherical distribution of gas as opposed to a thin disk. The electron temperature in the BELR is \( \leq 28,000 \text{ K} \) consistent with photoionization by the AGN. The gas density is pivotal in constraining the mass of gas in the BELR. If the gas density is high, \( \geq 7 \times 10^3 \text{ cm}^{-3} \), then interpreting the broad H\( \alpha \) emission line in terms of a steady state spherically symmetric inflow leads to a rate \( \leq 6.5 \times 10^{-2} \text{ M}_\odot /\text{yr} \) which exceeds the requirement to explain the X-ray luminosity in terms of a radiatively inefficient inflow by a factor of \( \leq 18 \).
This research has made extensive use of the NASA Astrophysics Data System, the Atomic Line List, [http://www.pa.uky.edu/~peter/newpage/] and the STSDAS task ionic for calculating the critical densities of various ions. Support for Program number HST-AR-11752.01-A was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555. The author thanks Michael Eracleous for help with estimating the ionizing photon rate provided by the AGN and Ari Laor for emphasizing the subtle distinction between broad lines and broad line regions.

Facilities: HST (STIS)

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Fig. 1.— Visual and UV spectra of NGC 3998 as seen through the following gratings: Top left panel: G140L. Top right panel: G230L. Lower left panel: G430L. Red line shows data obtained under PID 8839. Lower right panel: G750M. Red line shows data obtained under PID 7354. Black lines for all panels show data obtained under PID 9486.
Fig. 2.— Broad Hα emission line in NGC 3998.  
**Top panel:** The observed spectrum is shown in black and a model for the forbidden lines is shown in red (see also Table 2).  
**Lower panel:** The broad Hα emission line profile after the forbidden lines have been subtracted. The central wavelengths of the subtracted lines are indicated in red. The vertical black line corresponds to the observed (redshifted) central wavelength of the Hα line.
Fig. 3.— Broad H\(\beta\) emission line in NGC 3998. *Top panel:* The observed spectrum is shown in black and a model for the forbidden lines is shown in red (see also Table 2). *Lower panel:* The broad H\(\beta\) emission line profile after the forbidden lines have been subtracted. The central wavelengths of the subtracted lines are indicated in red. The vertical black line corresponds to the observed (redshifted) central wavelength of the H\(\beta\) line.
Fig. 4.— Broad H$\gamma$ emission line in NGC 3998. *Top panel:* The observed spectrum is shown in black and a model for the forbidden line is shown in red (see also Table 2). *Lower panel:* The broad H$\gamma$ emission line profile after the forbidden line has been subtracted. The central wavelength of the subtracted line is indicated in red. The vertical black line corresponds to the observed (redshifted) central wavelength of the H$\gamma$ line.
Fig. 5.— (Left Panel). Model representation of the broad Balmer line emission in NGC 3998 in terms of a spherically symmetric inflow. (Right Panel). Model representation of the broad Balmer line emission in NGC 3998 in terms of an accretion disk. The observed Hα, Hβ and Hγ emission lines are shown in red, green and blue respectively. The model is shown in black. The inner, r_i and outer radii, r_o are indicated. Residuals for each profile are plotted as thinner colored lines.
Fig. 6.— Encircled energy as a function of extraction width. The solid line illustrates the dependence for a point source observed with G750M and a 0.1″ slit adapted from Fig 13.86 in Proffitt et al. (2010). Symbols identify the percentage of the flux measured in 1 and 2 pixel extractions as compared with the flux measured in a 7 pixel extraction. The fact that the symbols fall near the line indicates that the BELR in NGC 3998 is spatially unresolved with STIS.
Fig. 7. — Top panel: FWHM vs. ionization potential for forbidden and permitted emission lines in NGC 3998. The figure illustrates that the forbidden lines are as broad as the Balmer lines blurring the distinction between the narrow and broad line regions in this AGN. Lower panel: FWHM vs. critical density for forbidden emission lines in NGC 3998.
Table 1. NGC 3998 Spectral Datasets

| PID  | Observation Date | Grating | Spectral Range  | Slit arc sec | Dispersion Å/pixel | Plate Scale arc sec/pixel | Integration Time | Datasets  |
|------|------------------|---------|-----------------|--------------|--------------------|----------------------------|------------------|----------|
|      |                  |         | Å               | (4)          |                    |                            |                  |          |
| 7354 | 11-1-1997        | G750M   | 6295 - 6867     | 52 x 0.1     | 0.56               | 0.05                       | 328              | o4d301030 |
| 8839 | 10-2-2000        | G430L   | 2900 - 5700     | 52 x 0.2     | 2.73               | 0.05                       | 500              | 66a5010a0 |
| 8839 | 10-2-2000        | G430L   | 2900 - 5700     | 52 x 0.2     | 2.73               | 0.05                       | 500              | 66a501080 |
| 9486 | 4-7-2002         | G750M   | 6482 - 7054     | 52 x 0.1     | 0.56               | 0.05                       | 130              | 66n902010 |
| 9486 | 4-7-2002         | G750M   | 6482 - 7054     | 52 x 0.1     | 0.56               | 0.05                       | 130              | 66n902020 |
| 9486 | 4-7-2002         | G750M   | 6482 - 7054     | 52 x 0.1     | 0.56               | 0.05                       | 130              | 66n902030 |
| 9486 | 4-7-2002         | G750M   | 6482 - 7054     | 52 x 0.1     | 0.56               | 0.05                       | 130              | 66n902040 |
| 9486 | 4-7-2002         | G430L   | 2900 - 5700     | 52 x 0.2     | 2.73               | 0.05                       | 200              | 66n902050 |
| 9486 | 4-7-2002         | G430L   | 2900 - 5700     | 52 x 0.2     | 2.73               | 0.05                       | 200              | 66n902060 |
| 9486 | 4-15-2002        | G140L   | 1150 - 1730     | 52 x 0.2     | 0.60               | 0.025                      | 2571             | 66n901010 |
| 9486 | 4-15-2002        | G230L   | 1570 - 3180     | 52 x 0.2     | 1.58               | 0.025                      | 3000             | 66n901020 |
Table 2. Emission Line Parameters for the G750M Nuclear Spectrum\textsuperscript{a}

| Line   | Central Wavelength\textsuperscript{b} | Flux\textsuperscript{c} | FWHM \textsuperscript{d} |
|--------|-----------------------------------------|--------------------------|--------------------------|
|        | \( \lambda \text{ Å} \)                | \( 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \) | \( \text{km s}^{-1} \) |
| (1)    | (2)                                     | (3)                      | (4)                      |
| [O I]  | 6325 ± 2                               | 7.1 ± 1.0                | 1212 ± 244               |
| [O I]  | 6388 ± 5                               | 2.4 ± 1.1                | 1082 ± 612               |
| [N II]\textsuperscript{d} | 6576                                    | \( \leq 2.3 \)           | 1000                     |
| H\( \alpha \) (broad)\textsuperscript{e} | 6591                                    | \( \geq 44.7 \)          | 2000 ± 80                |
| H\( \alpha \) (narrow) | 6591                                    | 2.4                      | 1000                     |
| [N II] | 6612                                    | \( \leq 7 \textsuperscript{f} \) | 1000                     |
| [S II] | 6741 ± 6                               | 1.9 ± 0.8                | 1077 ± 713               |
| [S II] | 6755 ± 3                               | 3.3 ± 0.1                | 1077 ± 494               |

\textsuperscript{a}Table entries that do not include uncertainties are fixed parameters.

\textsuperscript{b}Observed wavelength

\textsuperscript{c}Measured within a 0.1” x 0.35” aperture. Continuum subtracted but not corrected for dust extinction.

\textsuperscript{d}The [NII] 6576 Å emission line flux is constrained by atomic physics to have a flux 1/3 that of the [NII] 6612 line.

\textsuperscript{e}The broad H\( \alpha \) emission line flux is an lower limit because the [NII] emission lines fluxes that were subtracted are upper limits.

\textsuperscript{f}The [NII] emission line flux is an upper limit chosen so as to not over-subtract the broad H\( \alpha \) emission line profile.
Table 3. Emission Line Parameters for the G430L Nuclear Spectrum

| Line         | Central Wavelength\(^b\) | Flux\(^c\)    | FWHM\(^d\) |
|--------------|---------------------------|---------------|-------------|
|              | \(\AA\)                  | \(10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\) | kms\(^{-1}\) |
| [O II]       | 3741 ± 1                  | 6.3 ± 0.1     | 1227 ± 23   |
| H\(\gamma\) (broad) | 4359                     | 4.6 ± 0.2     | 1750 ± 80   |
| [O III]      | 4382                      | \(< 0.5\)     | 2185        |
| H\(\beta\) (broad) | 4882                     | 13.0 ± 0.2    | 1750 ± 80   |
| [O III]      | 4975 ± 2                  | 3.7 ± 0.3     | 2185        |
| [O III]      | 5027 ± 1                  | 8.4 ± 0.4     | 2185 ± 265  |

\(^a\)Table entries that do not include uncertainties are fixed parameters.

\(^b\)Observed wavelength

\(^c\)Measured within a 0.2\(''\) x 0.35\(''\) aperture. Continuum subtracted but not corrected for dust extinction.

\(^d\)The [O III] emission line flux is chosen so as to not over-subtract the broad H\(\gamma\) emission line profile.
Table 4. Emission Line Parameters for the G230L Nuclear Spectrum

| Line   | Central Wavelength\(^b\) | Flux\(^c\) | FWHM \(^kms^{-1}\) |
|--------|--------------------------|------------|---------------------|
|        | Å                        | 10\(^{-14}\) erg cm\(^{-2}\) s\(^{-1}\) |                     |
| (1)    | (2)                      | (3)        | (4)                 |
| C II\(^d\) | 2334.4 ± 0.4               | 9.4 ± 0.1  | 2500 ± 145          |
| [O II] | 2480.4 ± 0.4               | 1.7 ± 0.1  | 1974 ± 104          |
| Mg II (broad)\(^d\) | 2809                      | ≥18        | ~6000               |

\(^a\)Table entries that do not include uncertainties are fixed parameters.

\(^b\)Observed wavelength

\(^c\)Measured within a 0.2\(^\prime\) x 0.175\(^\prime\) aperture. Continuum subtracted but not corrected for dust extinction.

\(^d\)Line is asymmetric.
Table 5. Axisymmetric Disk Model Parameters

| Model Parameter                  | Value                  |
|----------------------------------|------------------------|
| Inclination, $i$                 | $45^\circ$             |
| Inner radius, $\xi_i$           | $1,000 \, r_g$         |
| Outer radius, $\xi_1$           | $535,000 \, r_g$       |
| Broadening parameter, $\sigma$  | $300 \text{ km s}^{-1}$|
| Emissivity index, $q$           | $2.0$                  |

$^a$Radii are expressed in units of the gravitational radius, $r_g \equiv GM_*/c^2$, where $M_*$ is the mass of the central black hole.