GIANT BROAD LINE REGIONS IN DWARF SEYFERTS

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ABSTRACT

High angular resolution spectroscopy obtained with the Hubble Space Telescope (HST) has revealed a remarkable population of galaxies hosting dwarf Seyfert nuclei with an unusually large broad-line region (BLR). These objects are remarkable for two reasons. Firstly, the size of the BLR can, in some cases, rival those seen in the most luminous quasars. Secondly, the size of the BLR is not correlated with the central continuum luminosity, an observation that distinguishes them from their reverberating counterparts. Collectively, these early results suggest that non-reverberating dwarf Seyferts are a heterogeneous group and not simply scaled versions of each other. Careful inspection reveals broad H Balmer emission lines with single peaks, double peaks, and a combination of the two, suggesting that the broad emission lines are produced in kinematically distinct regions centered on the black hole (BH). Because the gravitational field strength is already known for these objects, by virtue of knowing their BH mass, the relationship between velocity and radius may be established, given a kinematic model for the BLR gas. In this way, one can determine the inner and outer radii of the BLRs by modeling the shape of their broad emission line profiles. In the present contribution, high quality spectra obtained with the Space Telescope Imaging Spectrograph (STIS) are used to constrain the size of the BLR in the dwarf Seyfert nuclei of M81, NGC 3998, NGC 4203, NGC 3227, NGC 4051, and NGC 3516.

Subject headings: galaxies: Seyfert, galaxies: individual (M81, NGC 3998, NGC 4203, NGC 3227, NGC 4051, NGC 3516), quasars: emission lines

1. INTRODUCTION

The physics behind the production of broad emission lines in active galactic nuclei (AGN) has challenged generations of astronomers since the phenomenon was first reported in a seminal paper by [Seyfert 1943]. Much has been learned over the intervening years, primarily as a result of reverberation mapping [Peterson 1993], which has led to an estimate for the size of the BLR producing the broad Balmer emission lines. For reverberating AGN, the broad H emission line flux varies typically by ~15% in a correlated response to larger ~30% changes in the level of the adjacent continuum. The light-travel-time delay between the brightening of the broad H emission line, following a brightening of the continuum, leads to an estimate for the size of the BLR. There is some difference of opinion over what size is actually being measured. One possibility is that the size is a luminosity-weighted radius as proposed by [Korista & Goad 2004]. Another possibility is that it is the inner radius of a much larger region of ionized gas, as suggested most recently by [Devereux & Heaton 2013].

Regardless of the definition of the word “size”, there is no question that a superb correlation exists between the size and the continuum luminosity for reverberating AGN, a correlation characterized in detail by [Kaspi et al. 2005]. That correlation shows that the smallest BLR occurs in the lowest luminosity reverberating AGN. It thus came as a complete surprise when using a different technique, line profile fitting, an enormous size was inferred for the BLR of the low luminosity active galactic nuclei (LLAGN) M81 [Devereux & Shearer 2007], NGC 3998 [Devereux 2011a], and NGC 4203 [Devereux 2011b]. Similarly large BLR sizes have been inferred for other LLAGN, using different analysis techniques, by [Wang & Zhang 2003], Zhang, Dultzin-Hacyan & Wang [2007], and Balmaverde & Capetti [2014]. Collectively, these studies lead inevitably to the strange and unexpected conclusion that many LLAGN, the so-called dwarf Seyferts [Ho, Filippenko & Sargent 1997; Ho et al. 1997], possess giant BLRs.

2. THE LINE PROFILE FITTING METHOD FOR DETERMINING BLR SIZE

The line profile fitting method for estimating the size of the region producing broad Balmer line emission has been described previously [Devereux 2011a]. Briefly, the method employs a Monte Carlo simulation of ~10^4 particles of light moving under the influence of gravity in free-fall according to the familiar equation \( v(r) = \sqrt{2GM_*/r} \), where \( v \) is velocity, \( G \) is the gravitational constant, \( M_\bullet \) is the BH mass, and \( r \) is the distance of each point from the central supermassive BH. Discrete particle models have the advantage that they reproduce the small-scale structure seen in broad emission line profiles, which is caused by random clumping in radial velocity space, as noted previously by [Capriotti, Foltz & Byard 1981].

The model produces a single peak broad emission line profile for a spherically symmetric distribution of points organized according to a power law, \( \rho(r) \propto r^{-n} \). The index value \( n = 1.5 \) is special as it produces the line profile shape expected for a steady-state inflow\(^1\) of points. In this case, there are only two free parameters; the inner and outer radii of the volume containing the model points, which can be varied to produce a wide variety of model broad

\(^1\) Or outflow, the only difference being a minus sign representing the direction of the velocity vector.
emission line profile shapes. The inner radius of the volume defines the full velocity width at zero intensity of the model emission line, and the outer radius of the volume defines the maximum intensity of the model emission line at zero velocity. Thus, comparing a normalized version of the observed broad emission line with the model one effectively constrains the inner and outer radii of the emitting volume with high precision using chi-squared minimization. A merit of applying the line profile fitting method to LLAGNs is that they radiate well below the Eddington limit and are therefore unable to sustain a radiatively driven outflow. Consequently, gravity dominates the kinematics of the BLR gas, and the three dimensional gravitational field strength is known by virtue of knowing the central mass.

3. RESULTS

There are presently six LLAGNs whose BLR size has been deduced by modeling the shape of the H Balmer lines including three non-reverberating dwarf Seyferts (M81, NGC 3998 and NGC 4203), and three reverberating ones (NGC 3227, NGC 3516 and NGC 4051). Some basic observables are listed in Table 1, and their BLR size-luminosity relationship is illustrated in Figure 1. The three non-reverberating dwarf Seyferts lie far from the correlation defined by reverberating AGNs. The other three LLAGN are reverberating, and their inner radii consistently lie on the correlation defined by other reverberating AGN. This latter result is important as it shows that the line profile fitting coincides almost identically with the reverberation radius as demonstrated for NGC 3227 (Devereux et al. 2013), NGC 4051 (Devereux & Heaton 2013) and NGC 3516 (Devereux 2015, in prep). This coincidence between the reverberation radius and the inner radius determined from line profile fitting can be understood if both are measuring the gas closest to the BH. With hindsight, this coincidence is perhaps not too surprising as both reverberation mapping and line profile fitting employ the familiar velocity equation \( v(r) = \sqrt{\frac{\gamma GM}{r}} \), where \( \gamma \) is a constant describing the gas kinematics. However, by virtue of utilizing the entire broad emission line flux, not just the \( \sim 15\% \) or so that is reverberating, line profile fitting yields the full extent of the BLR with greater efficacy than reverberation mapping. Consequently, one discovers that the outer radius of the BLR is quite large even for the reverberating dwarf Seyferts but not as large as for the non-reverberating ones, which, by comparison, have a giant broad line region.

An illustration of the relative sizes of the BLR, on a linear scale, is provided in Figure 2. The angular size of the BLR in NGC 3998 and M81 is so large that it is partially obscured by the 0.1" slit employed for the STIS observations. NGC 4051 is a narrow line Seyfert 1 for which the line profile fitting method yields only a lower limit to the outer radius as discussed previously (Devereux & Heaton 2013).

### TABLE 1

| Object          | Morphology | Distance (Mpc) | Spectral Classification | Object          | Morphology | Distance (Mpc) | Spectral Classification |
|-----------------|------------|----------------|-------------------------|-----------------|------------|-----------------|-------------------------|
| NGC 3031 (M81)  | SA(s)ab    | 3.6            | S1.5                    | NGC 3227        | SAB(s)ab   | 20.8           | S1.5                    |
| NGC 3998        | SA0        | 14.1           | L1.9                    | NGC 3516        | SB0        | 38.0           | S1.2                    |
| NGC 4203        | SAB0       | 15.1           | L1.9                    | NGC 4051        | SBbc       | 17.9           | S1.2                    |

*Ho, Filippenko & Sargent (1997)*

Fig. 1.— Broad line region size in light-days versus the continuum luminosity at 5100 Å in erg/s. Open circles identify the non-reverberating dwarf Seyferts with a giant broad line region (M81, NGC 3998 and NGC 4203). Filled circles identify the reverberating dwarf Seyferts (NGC 4051, NGC 3227 and NGC 3516). Vertical red lines connect the inner and outer radii of the BLR determined using line profile fitting. The arrow indicates that only a lower limit could be determined for the outer radius of the BLR in NGC 4051. For the reverberating dwarf Seyferts the inner radius coincides with the reverberation radius. The correlation between reverberation radius and luminosity established for reverberating AGN is identified by the blue-shaded band. Even the reverberating dwarf Seyferts have large outer radii, but much smaller than the non-reverberating dwarf Seyferts which have giant broad line regions.
The increased scatter in the size-luminosity relationship for LLAGNs illustrated in Figure 1 is not to be confused with the contraindication of low scatter in the size-luminosity correlation discussed recently by Kilerci Eser et al. (2015). Evidently, there are two AGN populations that have very different size-luminosity relations. Firstly, there are the well known reverberating AGN which define the size-luminosity correlation. Then there are the other, lesser known but more populous, LLAGN that are not reverberating, and for which the BLR size is evidently not correlated with AGN continuum luminosity. It is this latter, rather neglected, but larger segment of the LLAGN population, that is the main focus of this paper. Collectively, LLAGN exhibit no correlation between size and luminosity as illustrated in Figure 1. Consequently, it is inappropriate to estimate BH masses for non-reverberating AGN using the size-luminosity relationship established for reverberating AGN (e.g., Greene & Ho 2005, 2007).

Non-reverberating LLAGN are distinguished from their reverberating counterparts in four ways. First, the size of the BLR is much larger. Second, the size of the BLR is not correlated with the AGN continuum luminosity indicating that they are not simply scaled versions of each other. Third, even though in some cases the UV continuum may be time variable [Maoz et al., (2005)], there is as yet no correlated response measured for the Balmer emission lines. Fourth, at least two objects M81 and NGC 4203 exhibit time variable, double-peak broad Balmer emission lines (Devereux et al. 2003, Devereux 2011b). For the latter object, the Balmer line fluxes increased by a factor of two over a time interval of a decade with no perceptible change in the adjacent continuum. Such emission line variability is an order of magnitude larger than seen among the reverberating population.

Figure 2 graphically illustrates that the BLR in the non-reverberating dwarf Seyfert NGC 3998 is by far the largest of the six objects included in this study. It is also the first AGN to be identified with broad forbidden lines including [O iii]λλ4959,5007 and [S ii]λλ6718,6732. That the forbidden [S ii] lines have the same width as the permitted H$eta$ Balmer lines allows a useful limit to be placed on the average electron density of the BLR gas corresponding to $\sim 7 \times 10^3$ cm$^{-3}$. As explained in more detail by Devereux (2011a), the BLR in NGC 3998 is most easily explained in terms of an ionization bounded, low density inflow of H gas that is photoionized by the central UV-X-ray source.

One property common to both the reverberating and non-reverberating dwarf Seyferts is the existence of a central hole or cavity in the photoionized H gas, evidenced by the finite width at zero intensity of the H Balmer lines. The apparent absence of Balmer line emission inside the inner radius, synonymous now with the reverberation radius, is most easily explained if the electron temperature exceeds $\sim 10^6$ K, in which case the primary source of opacity is electron scattering.

5. CONCLUSIONS

High angular resolution spectroscopic observations obtained with HST have revealed a previously unrecognized population of non-reverberating dwarf Seyferts with a giant broad-line region. The existence of these objects significantly diminishes the correlation between the central continuum luminosity and BLR size among LLAGN. With a diameter of $\sim 14$ pc, the BLR in NGC 3998 is the largest recorded to date. However, the size of the BLR remains to be established for approximately 20 additional non-reverberating dwarf Seyferts residing in the local universe.

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