SCALING ULTRAVIOLET OUTFLOWS IN SEYFERTS
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ABSTRACT

X-ray and UV absorbing outflows are frequently seen in AGN and have been cited as a possible feedback mechanism. Whether or not they can provide adequate feedback depends on how massive they are and how much energy they carry, but it depends in a more fundamental way upon whether they escape the potential of the black hole. If the outflows have reached their asymptotic velocity when we observe them, then all of these properties critically depend on the radius of the outflow: a value which is difficult to measure. The tightest limit on the distance of an X-ray warm absorber from the ionizing source is that of Krongold et al. (2007) for NGC 4051. We use NGC 4051 to model other observed UV outflows, and find that on the whole they may not provide meaningful feedback. The outflow velocities are below or just above the escape velocity of the black hole. This may be because they are not yet fully accelerated, or the duty cycle of high-velocity outflows may be small. Another possibility is that they may only provide meaningful feedback in higher-luminosity AGN, as we find a weak correlation between the ratio of outflow velocity to escape velocity and AGN continuum luminosity.

Subject headings: galaxies: active — galaxies: Seyfert — galaxies: evolution — quasars: absorption lines — ultraviolet: galaxies

1. INTRODUCTION

A large fraction of AGN show signs of circumnuclear outflows, which manifest themselves as UV absorption lines and as X-ray “warm absorbers” (Reynolds 1997; George et al. 1998; Crenshaw et al. 2003; and references therein). Understanding the kinematics and dynamics of these outflows and their detailed physical conditions is important for a complete understanding of the nuclear region of AGN (e.g. Mathur et al. 1994; Krolik & Kriss 1995; Mathur et al. 1995; Elvis 2000). Theoretical models such as that of Proga (2007) make specific predictions about the properties of the outflow and their relation to the properties of the AGN. Direct comparison between the models and observations is still lacking, however, because measuring the mass and energy outflow rates is a difficult problem.

Additional impetus for studying the outflows comes from the fact that they provide a possible mechanism for feedback. Feedback from AGN has been invoked to attempt to solve a number of astrophysical problems, from cluster cooling flows to the structure of galaxies. Feedback from jets appears to be sufficient to keep the AGN from cluster cooling flows to the structure of galaxies. Feedback from AGN (e.g. McNamara et al. 2001; Oh & Benson 2003), and may be sufficient to regulate black hole (BH) growth in central cluster galaxies (e.g. Rafferty et al. 2006). Only about 10% of all quasars are radio-loud, however (White et al. 2007), so either feedback from powerful radio jets cannot be universal or the duty cycle is small. Circumnuclear outflows could potentially be a more common form of quasar feedback, as intrinsic absorption appears in approximately 60% of all AGN (Ganguly & Brotherton 2008).

We know from absorption and emission-line studies (e.g. Fields et al. 2007) that high-metallicity gas is present near galactic nuclei, so these outflows might also be responsible for enriching the intergalactic medium with metals. In order to do so, the outflows must escape the global gravitational potential and must entrain this high-metallicity gas. Understanding the physical conditions in the absorbers thus becomes very important, particularly their energy outflow rates and their masses.

While non-jet feedback has proved important in theoretical models, we do not really know if it works or really occurs. In theoretical examinations of intragalactic AGN feedback, energy injection efficiencies range from the order of unity (\(\frac{L_{\text{outflow}}}{L_{\text{bolometric}} \approx 1}\)) to a minimum of 5% (e.g. Silk 2003; Scannapieco & OL 2004). Do we know whether actual AGN UV/X-ray warm absorber outflows indeed carry such energy, if naively considered as already at their asymptotic velocity? This is a challenging measurement to make, one which is critically dependent upon finding the radius of the absorber.

Determining the mass and energy of an outflow (and the feedback that it naively can provide) begins with the properties directly observable from absorption-line studies: column densities for a variety of ions. Photoionization modeling allows us to convert the ionic column densities to the column densities of metals. To go from column density to mass requires knowing the metallicity of the gas and the location and geometry of the absorbing medium. In general, data on associated absorption systems in Seyferts have not been sensitive to metallicity, but super-solar metallicity absorbing gas has recently been discovered in two Seyferts (Fields et al. 2005, 2007). Inferred energy and mass loss rates depend strongly on the geometry of the absorber. If it is a shell of gas located far from the nuclear black hole, for example, then the implied mass can be quite large compared with an absorber.
located closer in for a given column density. Once the geometry has been established (assumed or observed), the energy outflow rate can then be calculated from the mass and velocity (measured from the blueshifts of lines). It is vital to know the location of the absorber to reliably measure the amount of energy that feedback can inject into the surrounding medium. The distance of the absorbing region ($R$) from the ionizing source, however, is degenerate with the density ($n_e$) in the equation for the photoionization parameter ($U \propto L/n_e R^2$). This degeneracy can be broken if we can determine the density independently. Since the recombination times are inversely proportional to density, the response of absorption lines to continuum variations during the ionizing phase provides a robust density diagnostic. We must therefore probe the appropriate time domain for an ionizing/recombining (rather than photoionization-equilibrium) plasma.

This observationally challenging technique has mostly produced upper limits on the distances of outflows from the source (which can be reasonably argued to be closely related to upper limits on the radii of the outflows) but it has been successfully employed to calculate outflow mass and energy rates for the high ionization parameter component in NGC 4051 (Krongold et al. 2007). We concentrate on the low ionization parameter component, for which Krongold et al. (2007) also established a tighter limit, because it is associated with the UV absorption.

The outflow distance for this component is small, at most $8.9 \times 10^{15}$ cm or 3.4 light-days. The motivation behind this paper is their surprising discovery that the observed outflow rates are four to five orders of magnitude below those naively required for efficient feedback. The X-ray outflow velocity in NGC 4051 is only 490 km s$^{-1}$, a small fraction of the escape velocity at its location. Can we generalize this result to all AGN, or even just to Seyferts? After all, NGC 4051 is an unusual object, a narrow-line Seyfert 1 galaxy with low luminosity and a low-mass black hole, and it is highly variable. Perhaps in other AGN the outflow velocity ($v_{\text{out}}$) is larger than the escape velocity ($v_{\text{esc}}$), allowing feedback to occur even if the outflows are at their asymptotic velocities. To test whether this is indeed the case, we compared the two in a number of AGN. We discuss our method in §2.2 and we conclude in §4.

2. DATA AND METHODS

In order to compare the ratio $v_{\text{out}}/v_{\text{esc}}$ of NGC 4051 to other AGN, we should ideally consider the velocity of the X-ray outflow, as Krongold et al. (2007) do. However, there are not very many high-resolution grating X-ray observations which have measured the outflow velocity, $v_{\text{out}}$, so we have compiled $v_{\text{out}}$ as measured in UV outflows. The X-ray outflow found by Krongold et al. (2007) for NGC 4051 is $492 \pm 17$ km s$^{-1}$, while it shows UV outflows with $v_{\text{out}}$ ranging from 48 to 727 km s$^{-1}$, and a median of around 360 (Collinge et al. 2001; Dunn et al. 2008). The UV and X-ray outflow velocities in NGC 4051 are the same order of magnitude; to the extent that they are different, the median UV outflow velocity slightly underestimates the outflow energy, but the difference is small. It should be noted that a consistent picture of the nature of the highly ionized X-ray absorbers has emerged from recent observations of several AGN. The absorbers have at least two components: one with a low ionization parameter (LIP) and one with a high ionization parameter (HIP). The LIP and HIP phases appear to be in pressure equilibrium, and so likely emerge from the common wind (e.g. Netzer et al. 2003; Krongold et al. 2003). The LIP component is also responsible for the UV absorption lines, which often show multiple components unresolved in X-ray, but the HIP is not. The UV outflow velocity is then essentially the $v_{\text{out}}$ of the LIP component of the X-ray outflow.

The outflow velocities we use are from the literature, derived from intrinsic absorption lines in the near and far ultraviolet, including Ly$\alpha$, Ly$\beta$, Nv, C1, CII, CIV, O1, OVI, AlIII, SiII, and SiIV (Brotherton et al. 2002; Collinge et al. 2001; Crenshaw et al. 1999, 2001, 2002, 2003a, 2005; Kraemer et al. 2001b, 2002, 2003; Kriss et al. 2003; Romano et al. 2002). See Table 1. The spectra were taken with the Goddard High-Resolution Spectrograph (GHS), the Faint Object Spectrograph (FOS), the Space Telescope Imaging Spectrograph (STIS) on HST, or with the Far Ultraviolet Spectroscopic Explorer (FUSE). We exclude objects for which we do not have reasonable black hole mass estimates (ESO265-G23, RX J1230.8+0115, and TOL1238-368).

In order to calculate the escape velocity at the wind-launching radius, we need to estimate the radius. As discussed above, the distance of the absorber from the ionizing source has not been reliably measured for any AGN other than NGC 4051, so we scale the absorber radius of the other AGN from the NGC 4051 distance. We use two different scalings.

The first of these is

$$R \propto \sqrt{\lambda L},$$  

the relationship demonstrated by Bentz et al. (2006a, 2008) for the radius of the broad-line region. It is logical to extend this essentially geometrical relationship to other radii which are defined by photoionization, like that of the UV/X-ray warm absorbers. We used 5100 Å starlight-subtracted continuum luminosity from Bentz et al. (2008) or Vestergaard & Peterson (2006) when available. When not, we used luminosities from Grupe et al. (2004), Botte et al. (2004), and Dunn et al. (2008).

For the second of these scalings, we try an alternative, gravitational scaling, again using the radius of the warm absorber of NGC 4051 measured by Krongold et al. (2007) and scaling linearly by the black hole mass.

$$R \propto M_{\text{BH}}$$

This scaling is not motivated by theory; it is merely an attempt to scale to one of the few remaining fundamental parameters of the system.

To calculate the escape velocity at the scaled radius of the absorber, we used reverberation mapping rms black hole masses Grier et al. (2008; Peterson et al. 2004; Bentz et al. 2006a) when available, then masses from single-epoch scaling relations calculated with starlight-corrected continuum luminosities when possible (Vestergaard & Peterson 2006). We also use single-epoch scaling relations from Dunn et al. (2008), Grupe et al. (2004), Marziani et al. (2003), and Watson et al. (2007).

3. RESULTS AND DISCUSSION

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In Figure 1 we plot the ratio of the outflow velocity to the escape velocity determined from the first scaling relationship (eqn. 1). The large open star marks the median UV outflow velocity of NGC 4051. The smaller symbols are the observed (line-of-sight) outflow velocities. The outflow velocity ratios for the other objects, which we obtained by scaling, are plotted as squares; again the median $v_{out}$ for each object is plotted with a larger symbol. It is interesting to note that for more than two thirds of the AGN, the maximum outflow velocity is less than half the escape velocity. Assuming that the (unknown) transverse velocities of the outflows are similar to their line-of-sight velocities, this would imply that the outflows in over two-thirds of these objects are moving at less than the escape velocity. We find a weak (0.42) correlation between the median values of $\log(v_{out}/v_{esc})$ and $\log(\lambda L_\lambda/\lambda L)$, with a 2% probability of appearing by chance. (This and all correlation coefficients in this paper are Spearman’s rank.) The similar correlation for the maximum observed outflow velocity in each AGN is much weaker, and is consistent with statistical fluctuations. This correlation may imply that feedback is more efficient for higher-luminosity AGN, but it may simply mean that since the location for which we observe the UV outflows in higher-luminosity AGN is farther away from the black hole, they have been more highly accelerated before reaching the point at which we observe them. Because it is a weak correlation, it is likely that if there is real physics here, we are observing a secondary rather than a primary effect. Some of the spread may be due to the fact that we use the published intrinsic absorption velocities from whatever epochs are available, but we only use a single continuum luminosity value for each object, because in general $\lambda L_\lambda$ (5100 Å) measurements are not published for the same epochs, much less the starlight-subtracted values we favor for these low-luminosity AGN. It would be interesting to see how the outflow velocities vary with continuum luminosity changes for a single object, and compare this to expectations for radiatively- or thermally-driven winds.

In Figure 2 the same velocity ratio is plotted, but with the wind radius estimated using the mass scaling relationship (eqn. 2). Again, we see that for all but two AGN the observed $v_{outflow} < v_{esc}$. The general conclusion that the outflow velocities for these Seyferts are generally a small fraction of the escape velocities appears to be independent of the scaling relation used. There is no significant trend for this scaling relation with the black

| $\log \lambda L_\lambda$ (5100 Å) | $\sigma_L/L$ | Object | $M$ | $\sigma_M/M$ | Ref (\(MBH^a; \lambda L^{b}; v_{out}^{c}\)) |
|------------------------|-------------|--------|-----|-------------|-----------------|
| 43.59                  | 0.25        | WPVS 007 | 1.15 $\times 10^7$ | 1.4 | 2; C, 3, 7 |
| 44.79                  | 0.22        | I Zw 1   | 2.76 $\times 10^7$ | 1.4 | 7; F, 3 |
| 44.27                  | 1.5         | TON 5180 | 1.02 $\times 10^7$ | 1.4 | 4; D, 7 |
| 43.16                  | 1.5         | Mrk 1044 | 1.7 $\times 10^7$ | 1.2 | 8; D, 7 |
| 43.80                  | 1.5         | NGC 985  | 2.03 $\times 10^8$ | 1.4 | 4; D, 7 |
| 44.87                  | 1.5         | IRAS F04250-5718 | 1.44 $\times 10^8$ | 1.4 | 4; D, 7 |
| 43.65                  | 0.0069      | Mrk 79   | 5.24 $\times 10^7$ | 0.27 | 6; A, 7 |
| 43.08                  | 0.3         | Mrk 10   | 2.56 $\times 10^7$ | 1.4 | 2; B, 7 |
| 45.39                  | 0.18        | IRAS F07546+3928 | 1.77 $\times 10^8$ | 1.4 | 5; E, 7 |
| 42.48                  | 0.10        | NGC 3227 | 4.22 $\times 10^7$ | 0.51 | 6; A, 4 |
| 42.62                  | 0.57        | NGC 5416 | 4.27 $\times 10^7$ | 0.34 | 6; A, 3.7,12 |
| 43.02                  | 0.14        | NGC 3783 | 2.98 $\times 10^7$ | 0.18 | 6; A, 3.7,8,10 |
| 41.88                  | 0.18        | NGC 4051 | 1.91 $\times 10^6$ | 0.41 | 6; A, 2.7 |
| 41.92                  | 0.49        | NGC 4151 | 4.57 $\times 10^7$ | 1.3 | 1; A, 3.6,7,11 |
| 44.84                  | 0.03        | PG 1351+640 | 6.73 $\times 10^8$ | 1.4 | 7; F, 7 |
| 43.66                  | 0.18        | Mrk 279  | 3.49 $\times 10^7$ | 0.26 | 6; A, 7, 9 |
| 43.98                  | 1.5         | RX J1355.2+5612 | 9.4 $\times 10^6$ | 1.4 | 2; D, 7 |
| 44.38                  | 0.039       | PG 1404+226 | 7.75 $\times 10^6$ | 1.4 | 7; F, 7 |
| 43.31                  | 0.054       | NGC 5548 | 6.71 $\times 10^7$ | 0.39 | 6; A, 1.3,6 |
| 43.64                  | 0.064       | Mrk 817  | 4.94 $\times 10^7$ | 0.16 | 6; A, 7 |
| 43.69                  | 0.023       | Mrk 290  | 1.60 $\times 10^8$ | 1.4 | 7; F, 7 |
| 44.73                  | 0.22        | Mrk 876  | 2.79 $\times 10^8$ | 0.46 | 6; A, 7 |
| 44.16                  | 0.23        | Mrk 509  | 1.43 $\times 10^8$ | 0.84 | 6; A, 3.7,13,14 |
| 44.40                  | 0.066       | II Zw 136 | 3.8 $\times 10^7$ | 0.39 | 3; A, 3.7 |
| 43.62                  | 0.3         | Akn 564  | 4.8 $\times 10^6$ | 1.4 | 2; B, 3.5,16 |
| 42.76                  | 0.23        | IRAS F22456-5125 | 1.55 $\times 10^8$ | 1.4 | 2; C, 7 |
| 44.64                  | 0.092       | MR 2251-178 | 2.40 $\times 10^8$ | 1.4 | 2; C, 7 |
| 43.30                  | 0.12        | NGC 7469 | 1.22 $\times 10^7$ | 0.11 | 6; A, 3.7,15 |

*References for $MBH$: 1: Bentz et al. (2006b), 2: Dunn et al. (2008), 3: Grier et al. (2008), 4: Grupe et al. (2006), 5: Marziani et al. (2005), 6: Peterson et al. (2004), 7: Vestergaard & Peterson (2000), 8: Watson et al. (2007) b References for $\lambda L_\lambda$ (5100 Å): A: Bentz et al. (2008), B: Bentz et al. (2006b), C: Dunn et al. (2008), D: Grupe et al. (2004), E: Marziani et al. (2005), F: Vestergaard & Peterson (2000) c References for $v_{outflow}$: 1: Brotherton et al. (2004), 2: Collinge et al. (2001), 3: Crenshaw et al. (1999), 4: Crenshaw et al. (2002), 5: Crenshaw et al. (2002), 6: Crenshaw et al. (2003), 7: Dunn et al. (2008), 8: Gabel et al. (2004), 9: Gabel et al. (2004), 10: Kraemer et al. (2001a), 11: Kraemer et al. (2001b), 12: Kraemer et al. (2002), 13: Kraemer et al. (2003), 14: Kriss et al. (2003), 15: Kriss et al. (2003), 16: Roman et al. (2004) a""
Fig. 1.— Outflow velocity in units of escape velocity plotted against AGN luminosity. All outflow radii are scaled by $\sqrt{\lambda L}$ to the X-ray absorber in NGC 4051 for which Krongold et al. (2007) measured the radius, marked with a star. For objects with intrinsic UV absorption at several velocities, the outflow with median velocity is plotted as a large square and the others are plotted as small squares.

Fig. 2.— Outflow velocity in units of escape velocity plotted against black hole mass. All outflow radii are scaled by $M_{\text{BH}}$ to NGC 4051, marked with a star. Points as in Figure 1.

Fig. 3.— Outflow velocity plotted against AGN luminosity. Line is from Ganguly et al. (2007), a refit of the envelope found by Laor & Brandt (2002). Note that NGC 4051 (again, marked with a star) lies significantly outside the envelope. None of the information in this figure is scaled to NGC 4051.

Hole mass (Fig. 2), and there is a very weak (0.32) correlation with the luminosity that is marginally statistically significant (10% probability of chance), which we do not plot.

How do the data from which we extrapolate compare with other studies in the literature? The kinematics of UV outflows in AGN has been investigated by Laor & Brandt (2002) and more recently by Ganguly & Brotherton (2008) and Dunn et al. (2008). These studies find that there is an upper envelope to the relation between the maximum velocity of outflows and the AGN luminosity. The two are directly correlated only for the soft-X-ray weak quasars (SXWQs), which trace the envelope (Laor & Brandt 2002). The upper envelope of the trend is described by $v_{\text{max}} \propto L^\alpha$ where $\alpha = 0.662 \pm 0.004$ (Ganguly et al. 2007, who refit the SXWQs of Laor & Brandt 2002 updating to a standard ΛCDM cosmology). We overplot this envelope on the data from which we extrapolate in Figure 3. Notice that outflows for some of the AGN, including NGC 4051 (plotted with an open star) lie above the relation at this normalization, most probably because the AGN continuum luminosities we use are corrected for starlight contamination to better reflect the properties of the AGN itself. We do see a general consistency with the previously observed relationship.

3.1. Implications for the nature of outflows and the feedback mechanism

Taken at face value, Figures 1 and 2 imply that the outflow velocity in most AGN is so small compared with the escape velocity that the outflow may never leave the circumnuclear region of the AGN unless it is still being accelerated when we observe it. UV inflows (blueshifted intrinsic absorption lines) are very rarely observed in AGN, suggesting either that all such outflows do indeed escape or that they change in characteristics before falling in, perhaps becoming less dense or clumpy. Radiatively-driven outflows in an optically thin environment ought to continue to accelerate asymptotically to a final velocity $v_\infty$, because both the gravity and the radiation-pressure force decrease as $1/r^2$.

The disk-wind models of Proga (2007) have shown that efficient mass and energy outflow results from radiative-driving for a $10^8 M_\odot$ black hole at $L/L_{\text{Edd}} = 0.6$. The efficiency of these radiatively-driven outflows in turn depends upon black hole mass ($M_{\text{BH}}$) and the accretion rate relative to the Eddington limit ($L/L_{\text{Edd}}$) (Proga & Kallman 2004; Proga 2005). We see no clear dependence of $v_{\text{out}}/v_{\text{esc}}$ on $M_{\text{BH}}$ with either scaling relation (see Figs. 2 and 6). It would be nice to see how $v_{\text{out}}/v_{\text{esc}}$ depends on $L/L_{\text{Edd}}$, but these two highly-derived quantities both depend on the mass of the black hole. Any extra information to be gained is masked by...
the spurious correlation that is due to essentially plotting $\sigma_{line}^{-1}$ vs $\sigma_{line}^{-2}$, where $\sigma_{line}$ is e.g. the width of the H$\beta$ broad line. The best that can be done instead is to say that we see no dependence of $v_{out}$ on $L_{bol}/L_{Edd}$, as Fig. 3 shows, where we assume $L_{bol} \approx 9\lambda L_{\lambda}(5100 \text{ Å})$ (as Kaspi et al. 2000) and use our geometrically motivated scaling relationship (eqn. 1). Perhaps the gas is not accelerated as efficiently as in the models of Proga (2007).

We know that high velocity outflows exist in broad absorption line quasars (BALQSOs), which make up approximately 17-40% of all luminous quasars (Knigge et al. 2008; Dai et al. 2008). (Estimates vary, due in part to quasar selection criteria and in part to differing definitions of what constitutes a BALQSO (Weymann et al. 1991; Trump et al. 2006; Ganguly & Brotherton 2008; Knigge et al. 2008). Their highest velocities, up to about 0.4c (Chartas et al. 2002), are so large that they reach escape velocity even if they arise in the inner parts of accretion disks. There may then be a qualitative difference between the properties of the outflows in the Seyfert galaxies in our sample and luminous BALQSOs.

The geometry of the outflow may be such that we almost always observe the UV outflow before it is fully accelerated. This may happen, for example, if the opening angle of the biconical funnel (e.g. Elvis 2000) is small, making a view down the throat of the funnel highly unlikely (see Figure 5). If that is the case, then not only may we be observing them before they are fully accelerated, but it also may be that there is always a large component of transverse velocity in the UV outflows that we observe, though we only measure line-of-sight velocity. Limits on transverse velocities are generally of the same order as the radial velocities (e.g. Crenshaw et al. 2003; Gabel et al. 2003b). The total velocity of these outflows, then, may be high enough for them to provide meaningful feedback. In such a geometry, however, the energy deposition would necessarily be highly anisotropic. The same conceptual problem arises for jets, which also may provide only very localized energy deposition. In both cases,

the interaction between the outflow and the surrounding medium serves to isotropize the feedback to a certain extent. Can narrow outflows lead to effective feedback for the regulation of bulge growth and star formation in a galaxy? A second possible way out is if neither of our two scaling relationships is valid. In that case we simply cannot extrapolate the nature of UV outflows in AGN from the case of NGC 4051. While this may be the case, it is not enough by itself to save the notion of effective feedback from UV outflows, because it begs the question of why neither a general geometric photoionization scaling nor a scaling based on mass is valid. After all, the outflow models (e.g. Hopkins et al. 2007; Scannapieco & Oh 2004) do scale with bolometric luminosity.\footnote{In the model of Scannapieco & Oh (2004), feedback is implemented as a fraction of the luminosity, which is assumed to be Eddington until the AGN disrupts its fuel source, so in effect feedback in this model scales as the mass of the black hole, as in our Figure 6.}

If feedback is inefficient or does not occur for some AGN, then it has serious consequences for the feedback models of black hole growth and BH-galaxy coevolution.

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Fig. 4.— Same scale of and plotting convention as figures 1 and 3, but plotted to show the lack of correlation between outflow velocity and Eddington ratio, assuming $L_{bol} = 9\lambda L_{\lambda}(5100 \text{ Å})$.

Fig. 5.— Schematic diagram of an outflow geometry (e.g. Elvis 2000); flare angle of winds shown with accretion disk. If the flare angle is small and if winds are not fully accelerated until the outer edge of the region then from most viewing angles the observed velocity of the winds will be misleadingly small.

Fig. 6.— Outflow velocity ratios with escape velocity scaled with our primary scaling relationship ($\propto \sqrt{L}$) but plotted against mass. Compare with feedback models such as that of Scannapieco & Oh (2004), which implement feedback as a fraction of the luminosity of an AGN emitting at Eddington. We find no mass-dependence with this scaling to support a model like that.
This in itself may not be a problem, as there are alternative feedback models which only invoke jet AGN activity. Natarajan et al. (2008) invoke dark matter annihilation/decay as an effective feedback mechanism that is entirely uncoupled to AGN activity. Croton et al. (2006) use only radio-mode (jet) feedback, and yet they achieve most of the results of other feedback models, including the galaxy luminosity function cutoff. They do issue the caveat, however, that non-jet feedback may be compensated for in their model by enhanced stellar feedback. If stellar feedback can indeed operate at the efficiencies they invoke, then their model remains unaffected by the absence of effective intragalactic AGN feedback that our analysis suggests.

Perhaps the outflow-mode feedback works, and is energetic enough and isotropic enough, but does not manifest itself as a UV or X-ray warm absorber outflow. There have been several claims of relativistic outflows observed as highly shifted X-ray absorption or emission lines (e.g. Turner et al. 2004; Dadina et al. 2005; Petrucci et al. 2007). Such outflows would certainly be energetic enough to escape and could potentially be effective as feedback. The existence of such relativistically shifted lines was questioned recently by Vaughan & Uttley (2008), who argue that the reported outflows are consistent with statistical fluctuations, given publication bias. A viable outflow mechanism is not yet known, then, that can provide effective feedback for all AGN.

One more possibility is that UV/X-ray warm absorber outflows may provide meaningful feedback, but only with a very small duty cycle, and most of the time be observed only at the relatively low velocities we see in these Seyfert galaxies. This sort of bursting behavior is superficially similar to the feedback patterns Ciotti et al. (2009) are finding as they continue to refine their 1-D hydrodynamic feedback models.

Is it possible that this kind of feedback does not occur for Seyferts but does for more luminous AGN? Perhaps the high-velocity outflows observed in some BALQSOs can provide feedback in some high-luminosity objects, but similar outflows can provide no feedback in low-luminosity objects (as our results suggest). If this were the case, and if AGN feedback is indeed necessary, then that would imply there must be some other form of feedback acting for these low-luminosity objects. That two distinct mechanisms could form one smooth M-σ relationship seems an unlikely conspiracy. We are inclined to reject the disjoint feedback mechanism hypothesis.

Another possibility is that feedback may be more efficient in higher-luminosity AGN, as perhaps suggested by the weak correlation in our Figure 1. This alone is not sufficient to solve the problem if the outflows are already at their asymptotic velocity when we observe them, however, because the most luminous quasars have bolometric luminosities around $10^{46}$ erg s$^{-1}$. Assuming again a bolometric correction of 9 to $\lambda L_{\lambda}(5100 \text{ Å})$, our objects extend four dex in luminosity, past $10^{46}$ erg s$^{-1}$, and span approximately two dex in $v_{\text{out}}/v_{\text{esc}}$. With two more dex in luminosity, we would expect a $v_{\text{out}}/v_{\text{esc}}$ increase of about one dex, for a maximum $v_{\text{out}}/v_{\text{esc}}$ of around 10. While these outflows would indeed escape the potential of the black hole, they would hardly escape far enough into the bulge with enough energy remaining to achieve the global-scale feedback that models invoke.

The final possibility to consider is that the UV outflows are experiencing continued acceleration when we observe them. There is some evidence for this at a smaller scale in AGN; outflowing clumps in the narrow-line region of NGC 4151 seem to increase in velocity linearly with distance from the nucleus (Das et al. 2005). Continued acceleration is expected for simple models of thermally or radiation-pressure-driven winds, though detailed modeling is difficult to reconcile with the observations (e.g. Everett & Murray 2007). If the UV/X-ray warm absorbers are undergoing continued acceleration, efforts like ours to localize them may be of some use in constraining wind models.

4. CONCLUSIONS

Krongold et al. (2007) find that the UV/X-ray warm absorber outflow in NGC 4051 is insufficient to provide effective feedback to its host galaxy unless it is undergoing continued acceleration. We investigated outflow velocities of other AGN but found them to fall significantly short of their escape velocities at the locations we extrapolate for them. These results imply that either outflows do not provide a viable feedback mechanism or they are experiencing continued acceleration. We have discussed caveats to these arguments, which lead to further questions. Are the opening angles of the outflow too small to intercept edge-on, so that we rarely observe their full velocities? How will we test such a scenario? And if this is indeed the case, how do they deposit energy in an isotropic fashion to regulate the bulge mass? If the outflows are experiencing continued acceleration, what is driving it? Do the outflows provide significant feedback, but only with a very small duty cycle, so we do not observe them in these Seyferts? Or do our results imply that AGN feedback in Seyferts just does not occur? If feedback does not occur, what then is the origin of the $M_{\text{BH}} - \sigma$ relation?

In order to lay to rest the question of the efficacy of UV/X-ray warm absorber outflows, it is crucial to measure the radius of the outflow region in several AGN spanning a range of luminosities and black hole masses. Additional observations with XMM-Newton and the upcoming Cosmic Origins Spectrograph (COS) on HST will be invaluable for this purpose.

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