Physical Conditions in Ultra-fast Outflows in AGN

S. B. Kraemer, F. Tombesi, and M. C. Bottorff

1 Institute for Astrophysics and Computational Sciences, Department of Physics, The Catholic University of America, Washington, DC 20064, USA; kraemer@cua.edu
2 Department of Astronomy, University of Maryland, College Park, MD 20742, USA; ftombesi@astro.umd.edu
3 NASA/Goddard Space Flight Center, Code 662, Greenbelt, MD 20771, USA
4 Department of Physics, Southwestern University, Georgetown, TX 78626, USA; bottorfm@southwestern.edu

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Abstract

*XMM-Newton* and *Suzaku* spectra of Active Galactic Nuclei (AGN) have revealed highly ionized gas, in the form of absorption lines from H-like and He-like Fe. Some of these absorbers, ultra-fast outflows (UFOs), have radial velocities of up to 0.25c. We have undertaken a detailed photoionization study of high-ionization Fe absorbers, both UFOs and non-UFOs, in a sample of AGN observed by *XMM-Newton*. We find that the heating and cooling processes in UFOs are Compton-dominated, unlike the non-UFOs. Both types are characterized by force multipliers on the order of unity, which suggest that they cannot be radiatively accelerated in sub-Eddington AGN, unless they were much less ionized at their point of origin. However, such highly ionized gas can be accelerated via a magneto-hydrodynamic (MHD) wind. We explore this possibility by applying a cold MHD flow model to the UFO in the well-studied Seyfert galaxy, NGC 4151. We find that the UFO can be accelerated along magnetic streamlines anchored in the accretion disk. In the process, we have been able to constrain the magnetic field strength and the magnetic pressure in the UFO and have determined that the system is not in magnetic/gravitational equipartition. Open questions include the variability of the UFOs and the apparent lack of non-UFOs in UFO sources.

Key words: accretion, accretion disks – galaxies: active – X-rays: galaxies

1. Introduction

According to the standard paradigm, Active Galactic Nuclei (AGN) are powered by accretion of matter onto a supermassive black hole (SMBH). The reservoir of fuel is thought to be an accretion disk surrounding the black hole, from which outflowing winds may arise (e.g., Rees 1987). More than 50% of Seyfert 1 galaxies, relatively local (z < 0.1), modest luminosity (Lbol < 10^{45} erg s^{-1}) AGN, show intrinsic X-ray and UV absorption (Crenshaw et al. 2003), suggesting that the absorbers have global covering factors of C_g ∼ 0.5. Blueshifted absorption lines in their UV (Crenshaw et al. 1999) and X-ray (Kaastra et al. 2000; Kaspi et al. 2004) spectra reveal significant outflow velocities (up to ∼4000 km s^{-1}; Dunn et al. 2007). The inferred mass-loss rates typically exceed the accretion rates needed to produce the observed luminosities of AGN (e.g., Crenshaw et al. 2012). Hence, mass outflows are a critical component in the structure, energetics, and evolution of AGN. Specifically, the relationship between bulge mass and black hole mass is thought to be regulated by AGN outflows, i.e., AGN feedback (Begelman 2004). Various acceleration mechanisms have been proposed for these outflows, specifically radiative driving (e.g., Murray et al. 1995), thermal winds (Begelman et al. 1983), and magneto-hydrodynamic (MHD) flows (e.g., Blandford & Payne 1982; Fukumura et al. 2010; Chakravorty et al. 2016).

If AGN-driven outflows are an important feedback mechanism, they must be energetic enough to clear the gas in the bulge of the host galaxy and quench star formation. Their strength can be expressed in the form of kinetic luminosity, L_{KE} = \frac{1}{2} M_{out} v_r^2, where the mass outflow rate is M_{out} = 4\pi r N_H \mu m_p C_g v_r, and r is the radial distance of the gas, N_H is the column density, \mu is the mean atomic mass per proton (=1.4 for solar abundances), m_p is the proton mass, C_g is the global covering fraction of the gas, and v_r is the radial velocity. For effective feedback, L_{KE} ∼ 0.5%–5% of L_{bol}, the bolometric luminosity of the AGN (Hopkins & Elvis 2010; King & Pounds 2015). Since L_{KE} ∝ v_r^3, the amount of kinetic energy deposited into the host galaxy rises quite rapidly with the velocity. One caveat is that the theoretical models for feedback require that the AGNs are radiating close to their Eddington limit (e.g., King & Pounds 2015), or L_{bol}/L_{Edd} ≈ 1 (but see below).

Crenshaw et al. (2012, 2015) have explored the impact of feedback from outflowing UV and X-ray absorbers and optical emission-line gas, in the narrow line region (NLR), of a sample of nearby Seyfert galaxies. For half of the sample, L_{KE} ≤ 5% L_{bol}, and most of these sources are significantly sub-Eddington, hence cannot effectively drive feedback. In their study of the Seyfert 2 galaxy, Mrk 573, Fischer et al. (2017) find that, while the AGN is radiating at near the Eddington limit, gas is not being radiatively accelerated at radial distances ≥1 kpc. These results call into question the effectiveness of AGN feedback, at least in the local Universe.

However, there are more extreme phenomena, so-called ultra-fast outflows (UFO), which are defined as massive, highly ionized, possibly relativistic outflows. They are identified by narrow Fe K-shell blueshifted absorption lines from Fe XXV/XXVI, with v_r ∼ 0.03–0.3c (Chartas et al. 2003; Pounds et al. 2003; Reeves et al. 2003; Tombesi et al. 2010). The lines are quite prominent, with EWs in the range of 10–100 eV (Tombesi et al. 2010). UFOs might drive a significant amount of mass and, most importantly, energy outwards, and therefore could be a critical component of AGN feedback. Photoionization modeling of UFOs predict column densities on the order of...
$N_H \sim 10^{23}$–$10^{24}$ cm$^{-2}$, and very high ionization, in the range of $^{8}$ log $X_i \sim 3$–6. There are also highly ionized absorption components that do not fit within the UFD parameterization, showing log $X_i < 3$ and $\gamma_r < 0.03c^2$, which are classified as non-UFDs (Tombesi et al. 2010).

Previous studies (Cappi et al. 2006; Tombesi et al. 2010, 2011, 2012, 2014) have identified UFOs in archival XMM-Newton observations of samples of both radio-quiet and radio-loud galaxies. Many of them were later confirmed in the same sources in Suzaku spectra by Gofford et al. (2013, 2015). These authors have derived qualitative information on the UFO spectral characteristics, kinematics, and possible location. Tombesi et al. (2012) noted that there seems to be tight correlations between the location of UFO with respect to the SMBH, the ionization state, column density, and the velocity of the outflowing gas. The high state of ionization combined with relativistic velocities suggests an origin in the inner accretion disk. Furthermore, King & Pounds (2015) argue that UFOs are required for AGN feedback. For example, based on 3D hydrodynamic simulations, Wagner et al. (2013) suggested that UFOs lose their dependence on the opening angle upon their initial interaction with the interstellar medium of the host galaxy, hence they produce larger-scale feedback than lower-velocity winds (see also Asahina et al. 2017). Despite intense study, the origin and acceleration mechanism of UFOs are still unclear. There is evidence for variability on timescales of years (Cappi et al. 2008; Reeves et al. 2008; Pounds & Reeves 2009), or as short as days, as in the case of Mrk 766 (Tombesi et al. 2010), which suggests an origin close to the AGN, although it is possible that the variability is due to instabilities within the absorbers (e.g., Takeuchi et al. 2013). Gofford et al. (2013) and King & Pounds (2015) argue for acceleration by radiation. However, given their high-ionization state (Tombesi et al. 2011; Gofford et al. 2013), this can only occur via electron scattering, which is not likely as most AGN with UFO detections are radiating at a small fraction of Eddington, unless there are multiple scatterings, which are not feasible given the UFO column densities (e.g., Tombesi et al. 2011).

On the other hand, it has been suggested that the radiative acceleration of UFOs via UV line-driving is possible if they were in a sufficiently low ionization state near their launch points (e.g., Hagino et al. 2015, 2017; Nomura et al. 2016; Nomura & Ohsuga 2017). In this scenario, as the UFOs flow outwards, they become increasingly ionized, until only H- and He-like Fe lines can be detected. These models predict that fast flows can be generated in sub-Eddington sources.

However, it is also plausible that there is a non-radiative means of acceleration, specifically through a magneto-hydrodynamic (MHD) wind (e.g., Fukumura et al. 2010, 2014; Chakravorty et al. 2016). In this paper, we explore this possibility as follows. First, we perform a photoionization modeling analysis of the UFOs, and non-UFOs, studied by Tombesi et al. (2010). In doing so, we obtain constraints on the physical conditions within the absorbers, including density, electron temperature, and the heating and cooling processes at work. We then review the cold MHD flow model proposed by Blandford & Payne (1982, hereafter BP82). Finally, in the case of NGC 4515, a Seyfert galaxy for which we have tight constraints on black hole mass, luminosity, and inclination, we show that the UFO could be part of an MHD-driven outflow.

### 2. Photoinionization Models

#### 2.1. Model Inputs

In order to characterize the absorbers, Tombesi et al. (2011) and Gofford et al. (2015) fit spectra using photoionization models generated with XSTAR (Kallman et al. 2004). From the models, they were able to constrain the range in the ionization parameter and the column density of the individual absorbers. As noted above, the models were parameterized in terms of $X_i$.

Our principle goal is to derive the physical conditions within the absorbers. To do so, we generated photoionization models using Cloudy (Ferland et al. 2013), from which we were able to constrain quantities such as electron temperature, $T_e$, relative contributions to heating and cooling, including Compton processes, and the force multiplier (FM), the ratio of the photo-absorption cross-section to the Thomson cross-section, in a physically self-consistent manner. Models were optimized to match the derived Fe XXV and Fe XXVI column densities. These were determined from the the line equivalent width values reported in Table A.2 of Tombesi et al. (2010) using the curve of growth analysis described in Tombesi et al. (2011). We used only lines with an unambiguous identification as Fe XXV or Fe XXVI. We assumed line broadening due to a turbulent velocity of 1000 and 3000 km s$^{-1}$ for those associated with non-UFOs and UFOs, respectively. This is consistent with the upper limits obtained from the spectral fits in their Table 3. However, the broadening may, in fact, be due to velocity gradients along the line of sight through the absorbers, rather than micro-turbulence, a point we will revisit in Section 3.2.2. Therefore, we did not include micro-turbulence in the Cloudy models.

The model results depend on the choice of input parameters, specifically the spectral shape of the incident radiation or spectral energy distribution (SED), the radial distances of the emission-line gas with respect to the central source, $n_H$, and column density ($N_H$) of the gas and its chemical composition. We assumed an SED similar to that used by Tombesi et al. (2011), in the form of a power law of $F_\nu = K\nu^{-\alpha}$, with $\alpha = 1.0$ for $1.4 \times 10^{-4}$ eV $< \hnu < 100$ keV, with exponential cutoffs above and below the limits. This SED is simpler than the broken power law (e.g., Laor et al. 1997) that we have used in our modeling of Seyfert spectra (see Couto et al. 2016), but its use maintains consistency with the previous UFO analysis. As in our most recent warm absorber studies (e.g., Couto et al. 2016), we have assumed roughly 1.5 times solar elemental abundances (e.g., Asplund et al. 2005) as follows (in logarithm, relative to H, by number): He: $-1.00$, C: $-3.47$, N: $-3.92$, O: $-3.17$, Ne: $-3.96$, Na: $-5.76$, Mg: $-4.48$, Al: $-5.55$, Si: $-4.51$, P: $-6.59$, S: $-4.82$, Ar: $-5.60$, Ca: $-5.66$, Fe: $-4.4$, and Ni: $-5.78$.

Ionic columns densities were fit by adjusting $X_i$ and $N_H$ within the constraints determined by Tombesi et al. (2011). For a given $X_i$, $n_H$ is a function of the radial distance, $r$, and the ionizing luminosity, $L_{ion}$; for the latter, we assumed the values from Tombesi et al. (2012). We set the upper limits for the radial distance by requiring that the physical depth, $\Delta r$, not exceed $r$, or $\Delta r/r < 1$. Noting that $\Delta r = N_H/n_H$, from the

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$^8$ The ionization parameter $X_i = L_{ion}/n_H^2$, where $L_{ion}$ is the ionizing luminosity of the AGN, $n_H$ is the hydrogen number density, and $r$ is the radial distance (Tarter et al. 1969). We use $X_i$ rather than the Greek letter $\xi$ to avoid confusion with the scaling parameter used for self-similar MHD solutions.
Table 1
Model Predicted Properties

| Name                  | $r$ (cm) | $\log X_i$ | $\log N_{H}$ (cm$^{-2}$) | $\log n_{H}$ (cm$^{-3}$) | $\log T$ (K) | HC$^a$ (%) | FM  |
|-----------------------|---------|------------|--------------------------|--------------------------|-------------|-----------|-----|
| **UFOs**              |         |            |                          |                          |             |           |     |
| NGC 4151              | 15.5    | 4.33       | 22.9                     | 7.4                      | 7.32        | 96.5      | 1.01 |
| IC 4329a              | 16.1    | 4.87       | 23.1                     | 7.1                      | 7.45        | 99.0      | 1.00 |
| Mrk 509 obs1          | 15.8    | 5.16       | 23.9                     | 7.5                      | 7.49        | 99.4      | 1.00 |
| Mrk 509 obs2          | 15.7    | 5.15       | 23.6                     | 7.7                      | 7.49        | 99.4      | 1.00 |
| Mrk 509 obs3          | 16.5    | 4.25       | 23.7                     | 7.3                      | 7.28        | 95.1      | 1.01 |
| Ark 120               | 16.3    | 4.55       | 23.7                     | 7.5                      | 7.39        | 97.8      | 1.00 |
| Mrk 79                | 16.5    | 4.19       | 23.1                     | 6.7                      | 7.25        | 94.8      | 1.01 |
| NGC 4051 obs1         | 14.9    | 4.37       | 23.0                     | 8.1                      | 7.34        | 96.9      | 1.01 |
| Mrk 766 obs1          | 17.1    | 3.73       | 22.4                     | 5.3                      | 6.88        | 81.3      | 1.06 |
| Mrk 766 obs2          | 15.9    | 4.28       | 23.0                     | 7.3                      | 7.29        | 96.0      | 1.01 |
| Mrk 841               | 17.0    | 3.91       | 23.0                     | 6.0                      | 7.05        | 88.5      | 1.03 |
| Mrk 290               | 16.3    | 3.91       | 23.4                     | 7.1                      | 7.05        | 87.9      | 1.03 |
| Mrk 205               | 15.7    | 4.62       | 23.8                     | 8.1                      | 7.42        | 98.1      | 1.00 |
| MCG~5–23–16           | 16.6    | 4.25       | 22.7                     | 6.1                      | 7.28        | 95.7      | 1.01 |
| NGC 4057              | 15.9    | 4.53       | 23.0                     | 7.1                      | 7.39        | 97.9      | 1.00 |
| **Non-UFOs**          |         |            |                          |                          |             |           |     |
| Mrk 279               | 17.9    | 3.33       | 22.2                     | 5.0                      | 6.34        | 46.9      | 1.32 |
| NGC 3516 obs1         | 16.6    | 3.73       | 22.5                     | 5.9                      | 6.87        | 81.3      | 1.06 |
| NGC 3516 obs2         | 16.8    | 3.76       | 22.5                     | 6.4                      | 6.90        | 82.7      | 1.05 |
| NGC 3783 obs1         | 18.0    | 3.13       | 22.5                     | 4.5                      | 6.09        | 24.4      | 1.73 |
| NGC 3783 obs2         | 17.8    | 3.23       | 22.4                     | 4.6                      | 6.20        | 33.7      | 1.45 |
| NGC 3783 obs3         | 18.0    | 3.13       | 22.5                     | 4.5                      | 6.09        | 24.4      | 1.73 |
| ESO 323-G77           | 17.0    | 3.53       | 23.5                     | 6.5                      | 6.62        | 65.3      | 1.12 |

Note. $^a$ HC is the fractional contribution of Compton heating.

definition of $X_i$ we obtain the expression $r \geq L_{\text{ion}}/(X_i N_H)$. Then, by substituting this back into the definition of $X_i$, $n_H \leq X_i N_H^2/L_{\text{ion}}$.

2.2. Model Results

Model parameters are listed in Table 1 and the predicted Fe XXV and Fe XXVI column densities, compared with the measured values, are shown in Table 2. The model-predicted ionic column densities are all within a factor of 2 of the measured values, which we deem sufficiently accurate given uncertainties in the iron abundance. As shown in Table 1, Cloudy models predict that both UFOs and non-UFOs have large columns, $N_H \sim 10^{22.5–24}$ cm$^{-2}$, of highly ionized (log $X_i = 3.13–5.16$) gas. However, there is a difference between the two classes. Non-UFOs generally possess smaller $N_H$ and $X_i$, as is shown clearly in Figure 1. The one outlier among non-UFOs, in terms of $N_H$, is ESO 323–G77. This is due to the fact that the Fe XXV and Fe XXVI column densities in this object are quite large (see Table 2). For the UFOs, the model prediction for the first observation of Mrk 766 places it with the non-UFOs in Figure 1. However, the Fe XXVI column densities are nearly the same in both observations, there may be some uncertainty in the range in $N_H$ (see Tombesi et al. 2011).

As shown in Table 1, Compton heating is the dominant mechanism for UFOs, with cooling due to Compton and free–free processes. For non-UFOs, while Compton heating can sometimes dominate, heating via ionization becomes important, and cooling via emission lines dominates for the lowest ionization cases, e.g., NGC 3783. The difference in heating and cooling processes among UFOs and non-UFOs is clearly illustrated in a thermal stability plot (S-Curve; Figure 2), in which the UFOs lie primarily on the flat Compton-dominated section. The non-UFOs are found along the negatively sloped portion of the curve, suggesting that they are thermally unstable (e.g., Bottorff et al. 2000). However, the shape of the vertical section of the S-Curve depends on the SED, which is unusually flat for these models (see above) and the atomic data, which may be incomplete for M- and L-shell iron ions that dominate cooling in these conditions (e.g., Kraemer et al. 2015). Also, as suggested by Bottorff et al. (2000), a sufficiently strong magnetic field could stabilize the gas (see their Appendix A3). At a minimum, this result illustrates the difference in the physical conditions within the non-UFOs as compared to the UFOs. In Figure 2 we have also plotted the position of the highest ionization component of warm absorption in NGC 4151, XHIGH (see Couto et al. 2016), modeled for two continuum flux states. As suggested by Tombesi et al. (2011), there is a continuum between UFOs, non-UFOs, and the highest ionization warm absorbers.

Cloudy model predictions for the FM provide constraints on the acceleration mechanism for the absorbers. As shown in Table 1, the FMs for the UFOs are all close to unity, while the maximum value for the non-UFOs is 1.7. This indicates that the main source of opacity is electron scattering and, therefore, radiative driving will be inefficient, unless the sources are
assuming that UFOs are at radiating at Eddington or there are multiple scatterings (see Gofford et al. 2015), which will not be possible for the predicted column densities. However, we cannot rule out the possibility that the UFOs were in a much lower ionization, hence characterized by much larger FMIs, at their launch points, as noted above.

2.3. Regarding Induced Compton Scattering

As discussed above, the electron temperature in a UFO, $T_e$, is set by the balance of heating, due to Compton scattering, and cooling, due to inverse Compton scattering, with some contribution from free–free scattering. If only Compton processes are involved, the electron, or Compton, temperature is proportional to the average photon energy (e.g., Krolik et al. 1981). If the incident continuum flux is strong enough that the photon occupation number is high, and the source is anisotropic, induced Compton scattering can become important (Kompaneets 1956). Unlike inverse Compton scattering, all photon–electron interactions in induced Compton scattering result in an increase in the electron’s kinetic energy. As a result, the electron temperature can far exceed the Compton temperature (Levich & Sunyaev 1970).

Induced Compton scattering becomes important if we consider the minimum radial distances of the UFOs, $r_{\text{min}}$. Tombesi et al. (2012) computed $r_{\text{min}}$ assuming that UFOs are at distances at which $v_e$ equals the escape velocity. Under these conditions, Cloudy models predicted significant contributions from induced Compton scattering. However, Cloudy calculates the induced Compton heating based on the formalism in Levich & Sunyaev (1970), which is only valid if $kT_e < m_e c^2$, where $k$ is Boltzmann’s constant and $m_e$ is the electron mass. The result is that $T_e$ will continue to increase with the photon occupation number, without any physical limit. However, as discussed in Sazonov & Sunyaev (2001), as electrons become increasingly relativistic, the efficiency of the energy transfer via induced Compton scattering drops and the maximum $T_e$ generally will not exceed $10^9 \text{K}$. Since Cloudy only considers the non-relativistic limit, the model predictions are not valid in the induced Compton regime. Therefore, we were not able to constrain the physical conditions of the UFOs at $r_{\text{min}}$.

3. MHD Flows

The physics of MHD outflows from accretion disks has been described in detail by BP82, for a cold MHD flow, in which the

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Table 2

| Name          | $N_{Fe^{23}}$ (cm$^{-2}$) | $N_{Fe^{24}(mes)}$ (cm$^{-2}$) | $N_{Fe^{25}(mes)}$ (cm$^{-2}$) |
|---------------|---------------------------|-------------------------------|-------------------------------|
| NGC 4151      | 14.4                      | 16.6                          | 17.7                          |
| NGC 4329a     | 12.8                      | 15.6                          | 17.4                          |
| Mrk 509 obs1  | 13.0                      | 16.0                          | 18.0                          |
| Mrk 509 obs2  | 12.5                      | 15.5                          | 17.6                          |
| Mrk 509 obs3  | 15.7                      | 17.7                          | 18.7                          |
| Ark 120       | 14.6                      | 17.0                          | 18.4                          |
| Mrk 79        | 15.2                      | 17.2                          | 18.1                          |
| NGC 4051 obs1| 14.3                      | 16.6                          | 17.8                          |
| Mrk 766 obs1  | 16.1                      | 17.4                          | 17.7                          |
| Mrk 766 obs2  | 16.4                      | 17.6                          | 17.8                          |
| Mrk 841       | 16.1                      | 17.7                          | 18.2                          |
| Mrk 290       | 16.6                      | 18.1                          | 18.6                          |
| Mrk 205       | 14.5                      | 17.0                          | 18.4                          |
| MCG−5−23−16   | 14.5                      | 16.6                          | 17.6                          |
| NGC 4507      | 13.8                      | 16.2                          | 17.6                          |

Note.
* $^{a} \text{Mes}$ refers to the column densities derived from the curve of growth (Section 2.1).

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Figure 1. Log $\xi$ vs. $N_H$, for the photoionization models discussed in Section 2. The blue crosses represent UFOs and the green asterisks represent non-UFOs. These results show that the UFOs and non-UFO occupy different regions of the parameter space.

Figure 2. Thermal Stability (S-Curve) for the photoionization models; same as above with the red triangles showing two states of the highest ionization warm absorber in NGC 4151 (XHIGH; Couto et al. 2016). Note that the three types of absorbers occupy different regions of the S-curve, with the UFOs primarily on the flat, Compton-dominated section.
magnetic pressure exceeds the gas pressure, primarily in the context of relativistic jets. For radio-quiet AGN, i.e., Seyfert galaxies, similar MHD models have been invoked to explain the dynamics of broad emission-line clouds (Emmering et al. 1992, hereafter, EBS92) and warm/UV absorbers (Bottorff et al. 2000). However, most warm absorbers are characterized by FM $\gg 1$, hence it is likely that acceleration by radiation pressure is dominant (e.g., Couto et al. 2016). On the other hand, Cloudy models predict FMs $\approx 1$ for all of the UFOs and for most of the non-UFOs analyzed here. As noted above, Gofford et al. (2013) suggested the possibility of radiative acceleration of UFOs via electron scattering. This would require multiple scatterings, which would not be expected for the column densities of the UFOs, which are $<10^{24}$ cm$^{-2}$. Therefore, magnetic acceleration is a possible mechanism. Also, Fukumura et al. (2014) have suggested that MHD winds can account for the properties of both UFOs and warm absorbers, in the form of a radially stratified wind.

3.1. Parameterization of Cold MHD Flows

The MHD wind model developed in BP82 consists of a self-similar axisymmetric flow. Self-similarity is achieved by parameterizing the cylindrical poloidal components of the position vector $\mathbf{r}$ in such a way that flow lines, originating in the Keplerian disk at radial footprint, $r_0$, are easily traced (Bottorff et al. 2000). This is achieved by invoking a dimensionless free parameter $\chi$ and a dimensionless function $\xi(\chi)$ so that the position vector $\mathbf{r}$, in cylindrical coordinates $r$, $\phi$, and $z$, is given by

$$\mathbf{r} = [r_0 \xi(\chi), \phi, r_0 \chi],$$

(BP82). By varying $\chi$ the set $(r, z) = (r_0, \xi(r_0), r_0 \chi)$ traces the poloidal portion of flow streamlines (and magnetic field lines) having the footprint $r_0$. $\chi = 0$ corresponds to the disk plane so it is required that $\xi(0) = 1$.

As shown in BP82, the velocity vector along a flow streamline is given by

$$\mathbf{v} = \left[\xi'(\chi)f(\chi), g(\chi), f(\chi)\right]\left(\frac{GM}{r_0}\right)^{1/2},$$

where the prime denotes differentiation with respect to $\chi$, $M$ is the BH mass, and the square-root term is the Keplerian velocity at the disk. The functions $f(\chi)$, $g(\chi)$, and $\xi(\chi)$ can be determined iteratively from the cold MHD flow equations (see Section 2 of BP82). The flow starts in a Keplerian orbit, so $g(0) = 1$, and the initial poloidal velocity is zero, so $f(0) = 0$.

An alternative approach for finding the functions $f(\chi)$ and $g(\chi)$ is to assign $\xi(\chi)$, as in EBS92, and then $f(\chi)$ and $g(\chi)$ are found semi-analytically and self-consistently with the choice of $\xi(\chi)$ and the cold MHD flow equations. The form of $\xi(\chi)$ used by EBS92 is

$$\xi(\chi) = \left(\frac{\chi}{0.5 \tan \theta_o} + 1\right)^{1/2},$$

where $\theta_o$ is the launch angle of the flow with respect to the disk. This form of $\xi(\chi)$ has a value of 1 at $\chi = 0$ and gives the poloidal part of the flow lines (and magnetic field lines) a parabolic shape. While this approach limits analysis to one class of solutions possible from BP82, it illustrates relevant physical characteristics of MHD outflows, so it is adopted here.

To fully characterize the flow along a streamline five inputs are required: $M$, $r_0$, $\theta_o$, $\lambda$, and $\kappa$. The constant $\lambda$ is the ratio of the total specific angular momentum, in both matter and the magnetic field, to the specific angular momentum in the disk at $r_0$ (Equations (2.2) and (2.7) b of BP82). The constant $\kappa$ is given by Equation (3.13) of EBS92. Once $f(\chi)$ and $g(\chi)$ have been determined, the square of the Alfvén Mach number, $m$, is determined using Equations (3.14) and (3.15) in EBS92, and the density along the streamline and the magnetic pressure, $p_{\text{mag}}$, are obtained from Equations (3.16) and (3.17) of EBS92, respectively.

Key to constraining the input parameters are two relationships from Bottorff et al. (2000). The first is a linear relationship between the footprint radius $r_0$ and the magnitude of $r$. The conversion from one to another is a function of angles $\theta_o$ and $i$, the angle between the observer’s line of sight and the disk axis. It can be written as

$$r_0 = |\mathbf{r}| \sin(i) \left(\sqrt{1 + \cot^2(i) \cot^2(\theta_o)} - \cot(\theta_o) \cot(i)\right).$$

The second relationship is the projected line-of-sight velocity of the flow

$$v_{\text{obs}} = \left[\xi'(\chi)f(\chi)\sin i + f(\chi)\cos i\right]\sqrt{\frac{GM}{r_0}}.$$ 

If we have constraints on $M$, $i$, and $|\mathbf{r}|$, we can obtain the footprint radius, $r_0$, for a given $\theta_o$. Then with $M$, $i$, $r_0$, and $v_{\text{obs}}$, we can determine the value of $f(\chi)$ (at the location of the UFO). But along the line of sight $\chi = z/r_0 = |\mathbf{r}| \cos(i)/r_0$, so $\chi$ is determined. The input parameters $\lambda$ and $\kappa$ can be adjusted until the model reproduces the observationally inferred $f(\chi)$ at the observationally inferred $\chi$. This fixes the flow solution enabling the estimation of the spatial extent of the absorption system, given the velocity width of observed spectral features and the column density. In the next subsection, we apply this form of a cold MHD solution to the UFO in NGC 4151, for which we use values for $M$ and $i$ from previous studies and the constraint on $|\mathbf{r}|$ from our photoionization analysis.

3.2. NGC 4151: A Case Study

While MHD models have been successful in predicting the general properties of warm absorbers (e.g., Proga 2000) and UFOs (Fukumura et al. 2014), there have not been any tight constraints on critical parameters, such as density, location, and magnetic field strengths, based on observational analysis. We are now able to do so in the case of NGC 4151, for which we have constraints on the properties of the UFO and the inclination of the accretion disk.

Based on the constraint $\Delta r/r < 1$, the maximum radial distance for the UFO in NGC 4151 is $r = 3.2 \times 10^{15}$ cm (see Table 1). We also use an inclination of $\sim45^\circ$ (Das et al. 2005) and a black hole mass of $M = 4.57 \times 10^7 M_\odot$ (Bentz et al. 2006).

3.2.1. Predicted Properties of the Flow

To characterize the flow, we use the method outlined in Section 3.1 to calculate the footprint radius as a function of the launch angle and the flow scaling parameters at the position of the UFO. In Table 3, we give the values of the parameters characterizing the flows for launch angles $\theta_o = 20^\circ$, $30^\circ$, and $40^\circ$. For a given inclination, as the launch angle increases, the radial distance of the footprint increases. However, the position...
This can be understood in terms of means that the are plotted against . This is the result of a greater magnetic of the UFO relative to the critical point.

The Alfvén critical point, as noted above. In Figure 6, we plot indicated for all three. Note that for , the UFO is at a sub-Alfvénic point. Note that for , the UFO is at a sub-Alfvénic point.

| $\theta_0$ | $\chi_{\text{UFO}}$ | $\lambda_\Sigma$ | $f_{\text{UFO}}$ | $f_\infty$ | $\lambda$ | $\kappa$ | log($r_0$) (cm) | log($v_0$) (cm s$^{-1}$) |
|-----------|------------------|----------------|----------------|-----------|---------|--------|----------------|----------------|
| 20°       | 5.64             | 0.36           | 0.73           | 0.98      | 2.95    | 2.10   | 14.59         | 9.59          |
| 30°       | 3.71             | 1.06           | 0.91           | 1.46      | 4.68    | 0.65   | 14.77         | 9.51          |
| 40°       | 2.73             | 3.91           | 1.08           | 2.42      | 10.3    | 0.14   | 14.91         | 9.43          |

Along the flow where the streamline intersects our line of sight decreases, as evidenced by the decrease in $\chi_{\text{UFO}}$. In Figures 3 through 9, the physical parameters of the flow for the different values of $\theta_0$ are plotted against $\chi$.

As shown in Figure 3, the ratio of $v_\Sigma$ to the Kelperian velocity at the footprint increases with $\chi$ along the streamline, eventually reaching the asymptotic values, $f_\infty$, listed in Table 3. In Figure 4, the ratio of the poloidal component of the flow, $\sqrt{v^2 + v^2_\Sigma}$, to the azimuthal component, $v_\phi$, as a function of $\chi$, is shown for $\theta_0 = 20°, 30°$, and $40°$. For each $\theta_0$, the flow becomes increasingly poloidal with increasing $\chi$. Note that for $\theta_0 = 40°$, the outflow is sub-Alfvénic at the position of the UFO. This is the result of a greater magnetic field strength compared to the other cases (see below).

The density, $\rho$, relative to that at the Alfvén critical point, is shown in Figure 5. As shown in EBS92, $\rho$ decreases with increasing $m$. For a given $\chi$, $\rho$ is smaller for larger $\theta_0$. This is largely due to the value of $\kappa$ (see, Table 3 and EBS92, Equation (3.15)), hence $\rho/\rho_A$ is greater for smaller launch angles. This is clearly evident for $\theta_0 = 40°$, when the UFO lies below the Alfvén critical point, as noted above. In Figure 6, we plot $P_{\text{mag}}$ relative to that at the Alfvén critical point. The values for different $\theta_0$ can be understood in terms of $m$ and the proximity of the UFO relative to the critical point.

Since the flow velocity depends on the magnetic field strength, it is instructive to compare the magnetic pressure with the energy density. Rees (1987) suggested that the broad emission-line region (BLR) clouds in AGN are magnetically confined and, furthermore, that there is equipartition between the magnetic field and gravity. If so, the magnetic pressure and the gravitational energy density should be roughly equal, or

$$P_{\text{mag}} \approx \frac{GM\rho}{r}. \quad (6)$$

In its role in cloud-confinement, the $B$ field is not directly affecting the BLR dynamics. However, in the case of an MHD wind, the $B$ field is the mechanism that drives the outflow, and, therefore, there is no reason to expect equipartition.

In Figures 7–9, we show the ratio of $P_{\text{mag}}$ to gravitational energy density. In each case, conditions are close to equipartition near the footprint. For $\theta_0 = 20°$, the ratio rises, but the flow stays close to equipartition. However, at greater $\theta_0$, the ratio rapidly exceeds equipartition. This is consistent with the corresponding greater $B$ field strengths (see Table 4).

A larger $\theta_0$ means that the field lines are more coiled on top of one another. The field must be strong enough to buoy a vertical column of outflowing material in the MHD wind. As shown in Table 4, all of the components of the $B$ field are

**Figure 3.** Ratio of $v_\Sigma$ to the Kelperian velocity at the footprint of the flow, plotted against $\chi$, for launch angles $\theta_0 = 20°$ (solid), $30°$ (dotted), and $40°$ (dashed). The Alfvén critical points (X) and position of the UFO (U) are indicated for all three. Note that for $\theta_0 = 40°$, the UFO is at a sub-Alfvénic point.

**Figure 4.** Ratio of the poloidal to the azimuthal components of velocity, plotted against $\chi$, for all $\theta_0$, as in Figure 4. The Alfvén critical and UFO positions are indicated.

**Figure 5.** Density relative to that at the Alfvén critical point, as a function of $\chi$ for $\theta_0 = 20°$ (solid), $30°$ (dotted), and $40°$ (dashed).
greater at the position of the UFO. The toroidal component, $B_{\phi}$, increases the most with larger $\theta_0$, as expected.

In Figures 7–9, we also show the ratio of $P_{\text{mag}}$ to the kinetic energy density, $v_{\text{tot}}^2$, where $v_{\text{tot}}^2$ is the sum of the squares of the poloidal and toroidal components of velocity. For each $\theta_0$, the ratio is relatively flat, which is consistent with the dependence of both quantities on $m$. Finally, in Table 4 we list the log of the ratio of $P_{\text{mag}}$ to the gas pressure, $P_{\text{gas}}$, at the position of the UFO. In each case, $P_{\text{mag}} \gg P_{\text{gas}}$, which is consistent with a cold MHD flow.

### Table 4

| Angle (°) | $B_\phi$ | $B_z$ | $B_{\phi}$ | $B_{\text{tot}}$ | $\log(P_{\text{mag}}/P_{\text{gas}})$ |
|-----------|---------|-------|---------|----------------|-------------------------------|
| 20°       | 12.9    | 6.2   | 46.3    | 48.4           | 2.76                          |
| 30°       | 31.6    | 14.7  | 110.3   | 115.7          | 3.52                          |
| 40°       | 83.6    | 36.5  | 360.4   | 371.8          | 4.53                          |

Notes.

* Evaluated at $r_{\text{UFO}}$.

** $B_i$ is the i-component of the magnetic field in units of G.

### 3.2.2. Constraints on Velocity Structure

The UFO detected in the XMM observation of NGC 4151 was resolved, with a dispersion of $\sigma = 5.1(+1.8/-1.4) \times 10^3 \text{ km s}^{-1}$, or FWHM $=1.2(+0.4/-0.3) \times 10^4 \text{ km s}^{-1}$ (Tombesi et al. 2010). As noted above, Tombesi et al. (2011) fit the spectrum with XSTAR models by including micro-turbulence. Bottorff & Ferland (2000) suggested that the smoothness of the BLR emission lines were the result of micro-turbulence and that turbulent BLR clouds could exist if magnetically confined. Hence, in the presence of strong $B$ fields, such as those calculated in the MHD modeling, it is possible that the UFOs are highly turbulent.

On the other hand, a large FWHM can result from a large velocity gradient along our line of sight through the absorbing material. This scenario was discussed in detail in Bottorff et al. (2000). Here we use their Equation (14), reformatted in terms of $\Delta r / r$. This allows for more direct comparison of the MHD
model kinematics to our photoionizing model results. The relationship is

$$\frac{\Delta r}{r} = 4 \left( \frac{\Delta v}{2v_r} \right) \left[ 1 - \left( \frac{\Delta v}{2v_r} \right)^2 \right]^{-2},$$

(7)

where $\Delta v$ is FWHM, and $v_r$ is the radial velocity of the UFO. From this, $\Delta r/r \approx 0.8$, which is consistent with the constraint on the Cloudy models that $\Delta r/r \leq 1$ (see Section 2.1). This can occur if our line of sight passes through streamlines originating at different launch radii (see Bottorff et al. 2000, Figure 1). We suggest that the observed FWHM is more likely due to a radial velocity gradient, rather than micro-turbulence.

4. Discussion

As shown in the previous section, the UFO in NGC 4151 can be characterized as part of a cold MHD flow, with an origin in the accretion disk. Mass outflow has been well-studied in NGC 4151 (e.g., Crenshaw et al. 2015), and we have constraints on the physical conditions and radial distances of the various components of absorption (Kraemer et al. 2005). Therefore, we are able to consider the UFO in the context of mass outflow in this source.

As discussed in Kraemer et al. (2005, 2006) and Couto et al. (2016), there are two main components of absorption in NGC 4151: XHIGH, which was initially detected by the presence of Mg xii, S xiv, and S xvi absorption lines, and D+EA, which causes the broadband soft X-ray absorption and has a UV signature in the form of saturated C IV, N V, and O VI lines. Even though most of the Chandra and XMM-Newton observations of NGC 4151 found the source in very low flux states, with $L_{bol}/L_{Edd} \sim$ a few percent, Couto et al. (2016) demonstrated that D+EA could be radiatively accelerated. However, XHIGH was too highly ionized for radiative acceleration in a sub-Eddington source, hence it could be MHD-driven.

Fukumura et al. (2014, and references therein) suggest that an MHD-driven disk wind will result in a continuous distribution of $N_\text{H}$ per decade of ionization parameter, which results in a density law of the form $n(r) \propto r^{-\alpha}$, where $\alpha \sim 1$. As discussed in Couto et al. (2016), the similar values of $N_\text{H}$ for D+EA, XHIGH, and the UFO are consistent with this scenario. However, the density and location of D+EA relative to the UFO yields $\alpha \sim 0.5$, which is inconsistent with the requirement for MHD by Fukumura et al. (2014). Based on photoionization modeling, Kraemer et al. (2005) argued that XHIGH must be closer to the continuum source than D+EA, and Couto et al. (2016) determined that the conditions in XHIGH are in agreement with the MHD model proposed by Fukumura et al. (2014). Overall, this picture is suggestive of stratification of the outflow in which the interior sections are MHD-driven while, at sufficiently large radial distances, radiation-driving dominates. Also, XHIGH’s properties overlap the lower ionization end of the non-UFOs. Hence, one can envision a scenario in which UFOs are launched at the smallest radii and non-UFOs, while still MHD-driven, form further out. This is consistent with our photoionization modeling analysis (see Table 1).

Comparing XMM-Newton (Tombesi et al. 2010, 2011) and Suzaku (Gofford et al. 2015) observational results, there are cases of large velocity differences occurring on relatively short timescales. For example, for the UFO in NGC 4151, Tombesi et al. (2010) found $v_{obs}/c = 0.106 \pm 0.007$, while, in a Suzaku spectra taken $\sim$18 days later, Gofford et al. (2015) found $v_{obs}/c = 0.055 \pm 0.023$. A more extreme difference was seen in Mrk 279, with $v_{obs}/c = 0.007$ (Tombesi et al. 2011) versus $0.222 \pm 0.006$, approximately 3.5 years later (Gofford et al. 2015). In the case of NGC 4151, the difference in $v_{obs}$ might be consistent with a change in the direction of the velocity vector, as suggested for a component of UV absorption in NGC 3783 (Gabel et al. 2003), but such a scenario would require a small covering factor for the UFO, which seems unlikely given its large column density and the possibility that our line of sight passes through different streamlines, as discussed above. We suggest that it is more plausible that these are individual components of absorption, whose velocity differences result from different launch radii or different physical conditions, such as the magnetic field strengths, at the times of ejection.

Other than NGC 4151, there do not appear to be sources that harbor UFOs and non-UFOs, at least in the same epoch. Based on our model constraints, the non-UFOs are at larger distances (see Table 1), which implies that the may have originated at larger $r_\text{f}$. In the context of an MHD outflow, the lower values of $v_r$ are consistent with lower Kelperian velocities at the launch points, hence lower outflow velocities. However, this does not explain why the two types cannot be present in the same objects. One possibility is that the conditions in the disk are such that either UFOs or non-UFOs are created. If this is related to magnetic field strength, there may be associated changes in the core radio emission.

Crenshaw et al. (2012) found that $L_{KE} = (0.25–1.6) \times 10^{41}$ erg s$^{-1}$, or $(0.34–2.0) \times 10^{-3} L_{bol}$, for the combined UV and X-ray absorbers in NGC 4151. Including the optical/UV NLR emission-line gas increases $L_{KE}$ to a peak of $4.3 \times 10^{41}$ erg s$^{-1}$ (0.006–0.008 of $L_{bol}$). This is barely sufficient for feedback. Based on our characterization of the UFO, we obtain $L_{KE} = 3.5 \times 10^{43}$ erg s$^{-1}$, for $C_e = 0.5$, which is on the same order as $L_{bol}$. Therefore, if the UFO has a large covering factor, and can maintain its integrity as it moves into the galactic bulge, it has sufficient kinetic luminosity for effective AGN feedback.

If MHD-driven UFOs play an important role in AGN feedback, the interaction between the SMBH and the host galaxy is via the magnetic properties of the disk. This is opposed to feedback due to radiatively driven winds, which is the more typically invoked scenario. Interestingly, the cold MHD model discussed by BP82 was intended to explain radio jets. Therefore, the form of UFO feedback we describe in the present paper is simply a less energetic form of the same phenomenon. Since UFOs can form in sub-Eddington sources, which do not seem to be able to produce the high $L_{KE}$ winds required for feedback, perhaps a more broadly defined radio-mode feedback, which includes UFOs, is the dominant means of SMBH/host interaction.

5. Conclusions

Starting with a sample of AGN with intrinsic Fe xxv and Fe xxvi absorption detected by XMM-Newton (Tombesi et al. 2010, 2011), we have analyzed the physical conditions within the absorbers, using photoionization models generated with Cloudy (Ferland et al. 2013). We have determined the following:

1. It has been shown that there is a continuum of properties, with decreasing ionization and (generally) column density, over
the range from UFOs to non-UFOs to warm absorbers (e.g., Tombesi et al. 2011). The highest ionization warm absorbers appear to overlap the non-UFO region, which suggests there may be some connection between these phenomena. We have shown that UFOs and non-UFOs occupy different regions on an S-curve, with little overlap, with the former in the Compton-dominated range, while the latter are in the vertical range where other cooling mechanisms become important. Based on our model constraints, the non-UFOs lie at greater radial distances than the UFOs. Overall, this is consistent with $n_{\text{H}} \propto r^{-\alpha}$, with $\alpha < 2$, in which case the ionization state of the absorbers decreases with distance, with an associated change in the heating and cooling processes.

2. Cloudy models predict that UFOs and non-UFOs are characterized by FM $\sim$ unity, hence they are too highly ionized to be radiatively accelerated in sub-Eddington sources, unless the UFOs were in a much lower ionization state at their launch points. This suggests another means of acceleration, such as an MHD-driven flow.

3. To explore the possibility of MHD-driving, we applied the cold MHD model detailed in BP82 and EBS92 to case of NGC 4151, for which the inclination of the black hole/ accretion disk has been constrained (Das et al. 2005). Specifically, we followed the flow parameterization in EBS92, for which the poloidal part of the streamlines are parabolic, with a footprint in the accretion disk. For a range of launch angles, we find that the observed velocity is consistent with MHD acceleration along a streamline and we are able to trace the origin of the UFO back to its footprint radius. Also, with this geometry, the observed relationship between the FWHM and $\nu_{\text{obs}}$ of the UFO in NGC 4151 is consistent with a velocity gradient through different flow streamlines.

4. For NGC 4151 we have been able to constrain the magnetic field strength and magnetic pressure in the flow. We find that the magnetic pressure far exceeds the gas pressure predicted by the Cloudy models, consistent with the definition of a cold flow. Also, the magnetic pressure generally exceeds the gravitational energy density, therefore equipartition does not apply.

Given the simplicity of this model, such as the assumptions of rigid field lines and parabolic geometry, we do not suggest that these results be taken as the final word on MHD-driven outflows. Rather, the physical parameters, such as density and magnetic field strength along the streamlines, will be useful inputs to more sophisticated models, such as those developed by Fukumura et al. (2014). However, if, as we suggest, these outflows are magnetically driven disk-winds, understanding their variability and the different origins of UFOs and non-UFOs may provide new insight into the physics of accretion disks in AGN. It would be particularly interesting if there was a connection between UFO properties and the radio emission from these objects. Finally, if UFOs are an important feedback mechanism, particularly in sub-Eddington AGN, it implies that magnetic properties of the disk can affect the host galaxy, as is the case for radio-mode feedback.

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